EXHIBIT 1

Plastic & Climate

THE HIDDEN COSTS OF A PLASTIC PLANET

ACKNOWLEDGEMENTS

The lead authors of this report are Lisa Anne Hamilton and Steven Feit at CIEL; Carroll Muffett and Steven Feit at CIEL (Chapter 3); Matt Kelso and Samantha Malone Rubright at FracTracker Alliance (Chapter 4); Courtney Bernhardt and Eric Schaeffer at EIP (Chapter 5); Doun Moon at GAIA and Jeffrey Morris at Sound Resource Management Group (Chapter 6); and Rachel Labbé-Bellas at 5Gyres (Chapter 7).

It was edited by Amanda Kistler and Carroll Muffett at CIEL.

Many people contributed to this report, including Sarah-Jeanne Royer at Scripps Institution of Oceanography (UCSD), University of California, San Diego; Marcus Eriksen; and Monica Wilson, Neil Tangri, and Chris Flood at GAIA.

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Plastic & Climate

THE HIDDEN COSTS OF A PLASTIC PLANET

Center for International Environmental Law (CIEL) uses the power of law to protect the environment, promote human rights, and ensure a just and sustainable society. CIEL seeks a world where the law reflects the interconnection between humans and the environment, respects the limits of the planet, protects the dignity and equality of each person, and encourages all of earth's inhabitants to live in balance with each other.

Environmental Integrity Project (EIP) is a nonprofit, nonpartisan organization that empowers communities and protects public health and the environment by investigating polluters, holding them accountable under the law, and strengthening public policy.

FracTracker Alliance is a nonprofit organization that studies, maps, and communicates the risks of oil and gas development to protect our planet and support the renewable energy transformation.

Global Alliance for Incinerator Alternatives (GAIA) is a worldwide alliance of more than 800 grassroots groups, non-governmental organizations, and individuals in over 90 countries whose ultimate vision is a just, toxic-free world without incineration.

5Gyres is a nonprofit organization focused on stopping the flow of plastic pollution through science, education, and adventure. We employ a science to solutions model to empower community action, engaging our global network in leveraging science to stop plastic pollution at the source.

#breakfreefromplastic is a global movement envisioning a future free from plastic pollution made up of 1,400 organizations from across the world demanding massive reductions in single-use plastic and pushing for lasting solutions to the plastic pollution crisis.

Contents

Figures, Tables, Boxes

Acronyms

AR4	IPCC's Fourth Assessment Report (See IPCC AR4)
AR5	IPCC's Fifth Assessment Report (See IPCC AR5)
°C	Degrees Celsius
CCUS	Carbon capture, usage, and storage
C_2H_4	Ethylene
CH_4	Methane
CIEL	Center for International Environmental Law
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DHS	Department of Homeland Security
EIA	Energy Information Administration
EPR	Extended producer responsibility
EPS	Expanded polystyrene
EU	European Union
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse gas
Gt	Gigaton
GWP_{100}	Global warming potential over 100 years
HDPE	High-density polyethylene
HFCs	Hydrofluorocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Chance
IPCC AR4	IPCC's Fourth Assessment Report (See AR4)
IPCC AR5	IPCC's Fifth Assessment Report (See AR5)
IPCC SAR	IPCC's Second Assessment Report (See SAR)
IPCC SR 1.5	IPCC's Special Report on Global Warming of 1.5°C (See SR 1.5)
Kg	Kilogram
kWh	Kilowatt hours
LNG	Liquefied natural gas
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MRF	Material recovery facility
MMcf	Million cubic feet
Mt	Metric ton
MSW	Municipal solid waste
MW	Megawatt
N_2O	Nitrous oxide
NEI	National Emissions Inventory
NGLs	Natural gas liquids
OGTM	Oil & Gas Threat Map
PE	Polypropylene
PET	Polyethylene terephthalate
PFCs	Perfluorocarbons
PHA	Polyhydroxyalkanoate
PHMSA	Pipeline and Hazardous Materials Safety Administration
PLA	Polylactic acid
PP	Polypropylene
PP&A	Polyester, polyamide, and acrylic fibers
PS	Polystyrene
PTF	Plastic-to-fuel
PUR	Polyurethane
PVC	Polyvinyl chloride
RECs	Reduced emissions technologies
SAR	IPCC's Second Assessment Report (See IPCC SAR)
SF_6	Sulfur hexafluoride
SR 1.5	IPCC's Special Report on Global Warming of 1.5°C (See IPCC SR 1.5)
Syngas	Synthetic natural gas
US	United States
USEPA	US Environmental Protection Agency
WTE	Waste-to-energy
WEF	World Economic Forum

Glossary of Terms

Anaerobic digestion
Process of converting organic waste to biogas in the absence of oxygen.

Biodegradable
Capable of breaking down into its chemical constituents in the natural environment.

Business as usual
The baseline or reference case scenario that represents the current rates of emissions against which market, technological, and policy initiatives to reduce emissions are measured.

Carbon budget
The total amount of carbon emissions that can be emitted for temperatures to remain at or below a specified limit.

Carbon dioxide equivalent
A measure used to compare the emissions from various greenhouse gases based upon their global warming potential.

Circular systems
Intentionally designed industrial systems in which output from one system becomes input for that system or another industrial system, thereby minimizing the creation and disposal of waste and minimizing the need for raw material extraction.

Climate forcing
Climate forcing is the dynamic whereby the varying amounts of external influences, including surface reflectivity, atmospheric aerosols, and human-induced changes in greenhouse gases alter the balance of energy entering and leaving the Earth system.

Expanded polystyrene
A lightweight foam formed from polystyrene that is commonly misidentified as the brand name Styrofoam. It is used for items such as cups, food trays, and cushioning material.

Fracking
Hydraulic fracturing, a pressurized process in which underground rock formations (shale) are cracked, or fracked, to release trapped oil and gas.

Gasification
The thermal decomposition and partial oxidation of waste materials at temperatures generally above 400°C using a limited amount of air or oxygen, resulting in solid residues and a gaseous mixture.

Gigaton
Equal to one billion metric tons.

Hauler
Waste transporter operating truck(s) that haul waste from point of collection to material recovery facility (MRF), from MRF to dump site, or both. Services are typically contracted by local governments but often managed directly by public authorities.

Incineration
Thermal decomposition and rapid oxidation of waste material at temperatures generally above 230°C with the addition of air or oxygen at sub-stoichiometric to excess levels, resulting in solid residues and a gaseous mixture.

Intergovernmental Panel on Climate Change
Established in 1988 by the World Meteorological Organization and United Nations Environment Programme, the Intergovernmental Panel on Climate Change is the international body that provides policy makers with regular assessments of the scientific basis of climate change, its impacts and risks, and options for adaptation and mitigation.

Landfilling
Disposal of waste in a waste pile that is usually underground and may be sanitary (i.e., measures have been taken to prevent leachate) or unsanitary (no prevention measures have been taken).

Low-value plastic
Plastic waste materials that do not have value in local recycling markets (e.g., grocery bags, thin films, composite plastics, and residual polypropylene). Polystyrene, polyvinyl chloride, and polypropylene are considered “medium value,” with approximately 25 percent being recycled locally.

Mandatory recycled content
Minimum requirement for use of recycled content in products.

Material design
Redesign of products to meet specifications intended to make the products either more attractive for material- or energy-extraction markets or less likely to leak into the ocean.

Material recovery facility
Facility used for separating different materials from the waste stream.

Mixed waste
Unseparated or unsorted waste.

Municipal solid waste
Waste generated by households and sometimes including streams of commercial and industrial waste.

Negative emissions
The end result of processes that remove carbon dioxide from the atmosphere.

Off-gassing
The release of gases into the air as a byproduct of a chemical process.

Petrochemicals
Fossil-fuel-derived chemicals, some of which are used to produce plastic.

Plastic waste leakage
Movement of plastic from land-based sources into the ocean.

Polymer
Chemical combination of smaller particles.

Pyrolysis
The thermal decomposition of waste materials at temperatures beginning around 200°C without the addition of air or oxygen, resulting in solid and/or liquid residues as well as a gaseous mixture.

Thin film
Mixed plastic film, typically constructed of some variation of polyethylene.

Waste
Any discarded material, such as household or municipal garbage, trash or refuse, food wastes, or yard wastes, that no longer has value in its present form but may or may not be recyclable or otherwise able to be repurposed.

Waste-to-energy
The process of treating waste through incineration or other thermal processing with a purpose of generating energy (electricity or heat).

Zero waste
The conservation of all resources by means of responsible production, consumption, reuse, and recovery of materials without incineration or landfilling.

EXECUTIVE SUMMARY

Plastic Proliferation Threatens the Climate on a Global Scale

The plastic pollution crisis that overwhelms our oceans is also a significant and growing threat to the Earth's climate. At current levels, greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to keep global temperature rise below 1.5°C. With the petrochemical and plastic industries planning a massive expansion in production, the problem is on track to get much worse.

If plastic production and use grow as currently planned, by 2030, these emissions could reach 1.34 gigatons per year—equivalent to the emissions released by more than 295 new 500-megawatt coal-fired power plants. By 2050, the cumulation of these greenhouse gas emissions from plastic could reach over 56 gigatons—10–13 percent of the entire r emaining carbon budget.

Nearly every piece of plastic begins as a fossil fuel, and greenhouse gases are emitted at each of each stage of the plastic lifecycle: 1) fossil fuel extraction and transport, 2) plastic refining and manufacture, 3) managing plastic waste, and 4) its ongoing impact in our oceans, waterways, and landscape.

This report examines each of these stages of the plastic lifecycle to identify the major sources of greenhouse gas emissions, sources of uncounted emissions, and uncertainties that likely lead to underestimation of plastic's climate impacts. The report compares greenhouse gas emissions estimates against global carbon budgets and emissions commitments, and it considers how current trends and projections will impact our ability to reach agreed emissions targets. This report compiles data, such as downstream emissions and future growth rates, that have not previously been accounted for in widely used climate models. This accounting paints a grim picture: plastic proliferation threatens our planet and the climate at a global scale.

> At current levels, greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to keep global temperature rise below 1.5°C degrees. By 2050, the greenhouse gas emissions from plastic could reach over 56 gigatons—10-13 percent of the entire remaining carbon budget.

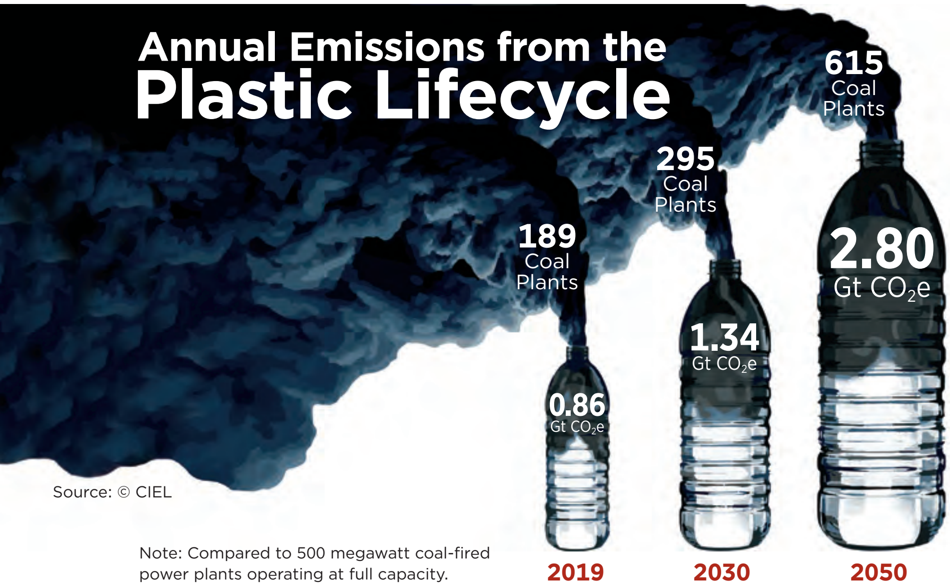
Due to limitations in the availability and accuracy of certain data, estimates in this report should be considered conservative; the greenhouse gas emissions from the plastic lifecycle are almost certainly higher than those calculated here. Despite these uncertainties, the data reveal that the climate impacts of plastic are real, significant, and require urgent attention and action to maintain a survivable climate.

The report includes recommendations for policymakers, governments, nonprofits, funders, and other stakeholders to help stop the expanding carbon emissions of plastic production. The most effective recommendation is simple: immediately reduce the production and use of plastic. Stopping the expansion of petrochemical and plastic production and keeping fossil fuels in the ground is a critical element to address the climate crisis.

Opposite: © Carroll Muffett/CIEL

FIGURE 1

Emissions from the Plastic Lifecycle



KEY FINDINGS

Current Greenhouse Gas Emissions from the Plastic Lifecycle Threaten Our Ability to Meet Global Climate Targets

In 2019, the production and incineration of plastic will add more than 850 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal power plants. At present rates, these greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to meet carbon emissions targets.

- **Extraction and Transport**
  The extraction and transport of fossil fuels for plastic production produces significant greenhouse gases. Sources include direct emissions, like methane leakage and flaring, emissions from fuel combustion and energy consumption in the process of drilling for oil or gas, and emissions caused by land disturbance when forests and fields are cleared for wellpads and pipelines.

  In the United States alone in 2015, emissions from fossil fuel (largely fracked gas) extraction and production attributed to plastic production were at least 9.5–10.5 million metric tons of CO_2 equivalents (CO_2e) per year. Outside the US, where oil is the primary feedstock for plastic production, approximately 108 million metric tons of CO_2e per year are attributable to plastic production, mainly from extraction and refining.

- **Refining and Manufacture**
  Plastic refining is among the most greenhouse-gas-intensive industries in the manufacturing sector—and the fastest growing. The manufacture of plastic is both energy intense and emissions intensive in its own right, producing significant emissions through the cracking of alkanes into olefins, the polymerization and plasticization of olefins into plastic resins, and other chemical refining processes. In 2015, 24 ethylene facilities in the US produced 17.5 million metric tons of CO_2e, emitting as much CO_2 as 3.8 million passenger vehicles. Globally in 2015, emissions from cracking to produce ethylene were 184.3–213.0 million metric tons of CO_2e, as much as 45 million passenger vehicles driven for one year. These emissions are rising rapidly: a new Shell ethane cracker being constructed in Pennsylvania could emit up to 2.25 million tons of CO_2e each year; a new ethylene plant at ExxonMobil's Baytown, Texas, refinery could release up to 1.4 million tons. Annual emissions from just these two new facilities would be equal to adding almost 800,000 new cars to the road. Yet they are only two among more than 300 new petrochemical projects being built in the US alone—primarily for the production of plastic and plastic feedstocks. As this report documents, moreover, these figures do not capture the wide array of other emissions from plastic production processes.

- **Waste Management**
  Plastic is primarily landfilled, recycled, or incinerated—each of which produces varying amounts of greenhouse gas emissions. Landfilling emits the least greenhouse gases on an absolute level, although it presents significant other risks. Recycling has a moderate emissions profile but displaces new virgin plastic on the market, making it advantageous from an emissions perspective. Incineration leads to extremely high emissions and is the primary driver of emissions from plastic waste management. Globally, the use of incineration in plastic waste management is poised to grow dramatically in the coming decades.

  US emissions from plastic incineration in 2015 are estimated at 5.9 million metric tons of CO_2e. For plastic packaging, which represents

40 percent of plastic demand, global emissions from incineration of this particular type of plastic waste totaled 16 million metric tons of CO_2e in 2015. This estimate does not account for 32 percent of plastic packaging waste that is known to remain unmanaged, open burning of plastic or incineration that occurs without any energy recovery, or practices that are widespread and difficult to quantify.

- **Plastic in the Environment**
  Plastic that is unmanaged ends up in the environment, where it continues to have climate impacts as it degrades. Efforts to quantify those emissions are still in the early stages, but a first-of-its-kind study from Sarah-Jeanne Royer and her team demonstrates that plastic at the ocean's surface continually releases methane and other greenhouse gases, and that these emissions increase as the plastic breaks down further. Current estimates address only the one percent of plastic at the ocean's surface. Emissions from the 99 percent of plastic that lies below the ocean's surface cannot yet be estimated with precision. Significantly, Royer's research showed that plastic on the coastlines, riverbanks, and landscapes releases greenhouse gases at an even higher rate.

  Microplastic in the oceans may also interfere with the ocean's capacity to absorb and sequester carbon dioxide. Earth's oceans have absorbed 20-40 percent of all anthropogenic carbon emitted since the dawn of the industrial era. Microscopic plants (phytoplankton) and animals (zooplankton) play a critical role in the biological carbon pump that captures carbon at the ocean's surface and transports

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it into the deep oceans, preventing it from reentering the atmosphere. Around the world, these plankton are being contaminated with microplastic. Laboratory experiments suggest this plastic pollution can reduce the ability of phytoplankton to fix carbon through photosynthesis. They also suggest that plastic pollution can reduce the metabolic rates, reproductive success, and survival of zooplankton that transfer the carbon to the deep ocean. Research into these impacts is still in its infancy, but early indications that plastic pollution may interfere with the largest natural carbon sink on the planet should be cause for immediate attention and serious concern.

Plastic Production Expansion and Emissions Growth Will Exacerbate the Climate Crisis

The plastic and petrochemical industries' plans to expand plastic production threaten to exacerbate plastic's climate impacts and could make limiting global temperature rise to 1.5°C impossible. If the production, disposal, and incineration of plastic continue on their present growth trajectory, by 2030, these global emissions could reach 1.34 gigatons per year—equivalent to more than 295 five-hundred-megawatt coal plants. By 2050, plastic production and incineration could emit 2.8 gigatons of CO_2 per year, releasing as much emissions as 615 five-hundred-megawatt coal plants.

Critically, these annual emissions will accumulate in the atmosphere over time. To avoid overshooting the 1.5°C target, aggregate global greenhouse emissions must stay within a remaining (and quickly declining) carbon budget of 420–570 gigatons of carbon.

If growth in plastic production and incineration continue as predicted, cumulative greenhouse gas emissions by 2050 will be over 56 gigatons CO_2e, or between 10-13 percent of the total remaining carbon budget. As this report was going to press, new research in *Nature Climate Change* reinforced these findings, reaching similar conclusions while applying less conservative assumptions that suggest the impact could be as high as 15 percent by 2050. By 2100, exceed-

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ingly conservative assumptions would result in cumulative carbon emissions of nearly 260 gigatons, or well over half of the carbon budget.

Urgent, Ambitious Action is Necessary to Stop the Climate Impacts of Plastic

This report considers a number of responses to the plastic pollution crisis and evaluates their effectiveness in mitigating the climate, environmental, and health impacts of plastic. There are high-priority actions that would meaningfully reduce greenhouse gas emissions from the plastic lifecycle and also have positive benefits for social or environmental goals. These include:

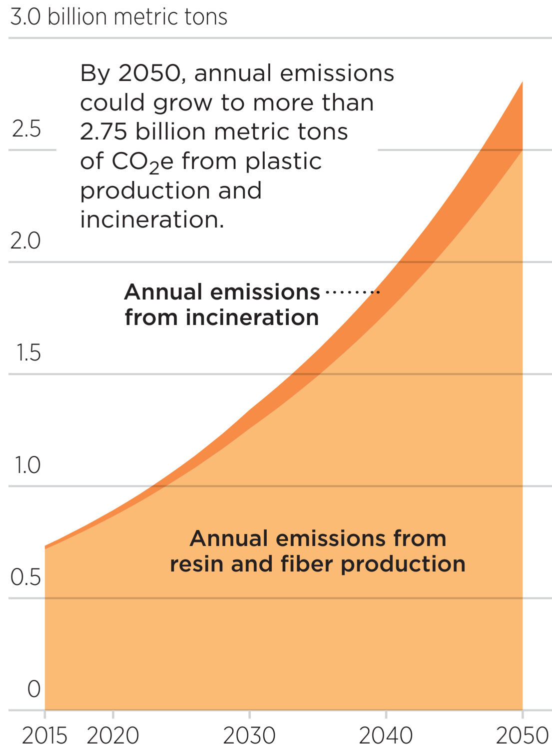
- ending the production and use of single-use, disposable plastic;
- stopping development of new oil, gas, and petrochemical infrastructure;
- fostering the transition to zero-waste communities;
- implementing extended producer responsibility as a critical component of circular economies; and
- adopting and enforcing ambitious targets to reduce greenhouse gas emissions from all sectors, including plastic production.

Complementary interventions may reduce plastic-related greenhouse emissions and reduce environmental and/or health-related impacts from plastic, but fall short of the emissions reductions needed to meet climate targets. For example, using renewable energy sources can reduce energy emissions associated with plastic but will not address the significant process emissions from plastic production, nor will it stop the emissions from plastic waste and pollution. Worse, low-ambition strategies and false solutions (such as bio-based and biodegradable plastic) fail to address, or potentially worsen, the lifecycle greenhouse gas impacts of plastic and may exacerbate other environmental and health impacts.

Ultimately, any solution that reduces plastic production and use is a strong strategy for addressing the climate impacts of the plastic lifecycle. These solutions require urgent support by policymakers and philanthropic funders and action by global grassroots movements. Nothing short of stopping the expansion of petrochemical and plastic production and keeping fossil fuels in the ground will create the surest and most effective reductions in the climate impacts from the plastic lifecycle.

FIGURE 2

Annual Plastic Emissions to 2050



Source: CIEL

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CHAPTER ONE

Introduction

Plastic is one of the most ubiquitous materials in the economy and among the most pervasive and persistent pollutants on Earth. It has become an inescapable part of the material world, flowing constantly through the human experience in everything from plastic bottles, bags, food packaging, and clothing to prosthetics, car parts, and construction materials.

Global production of plastic has increased from two million metric tons (Mt) in 1950 to 380 million Mt in 2015. By the end of 2015, 8,300 million Mt of virgin plastic had been produced, of which roughly two-thirds has been released into the environment and remains there in some form.

In the most general terms, plastics are synthetic organic polymers—giant synthetic molecules comprised of long chains of shorter molecules—derived primarily from fossil fuels. For the sake of simplicity, when this report refers to plastic, it refers to an array of polymers and products with different chemical compositions.

Because plastic does not break down in the environment, it has continued to accumulate in waterways, agricultural soils, rivers, and the ocean for decades. The last few years have seen a growing awareness of and concern about the urgent crisis of plastic in the oceans. More recently, that concern has expanded to the impact of plastic on ecosystems, on food and water supplies, and on human health, amidst emerging evidence that plastic is accumulating not only in our environment but also in our bodies.[1] Amidst this growing concern, there is another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change.

As global reliance on fossil fuels declines and plastic production rapidly expands, that emissions impact is poised to grow dramatically in the years ahead. Yet the true dimensions of plastic's contribution to the climate crisis remain poorly understood, creating significant uncertainties that threaten global efforts to avoid the most catastrophic impacts of climate change.

Because plastic does not break down in the environment, it has continued to accumulate in waterways, agricultural soils, rivers, and the ocean for decades. Amidst this concern, there's another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change.

In the 2015 Paris Climate Agreement, the world committed to work together to limit total global temperature rise to well below 2 degrees Celsius (°C) and pursue efforts to stay below 1.5°C. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) further highlighted the profound risks to humanity and the environment if warming goes above 1.5°C. To prevent these risks, the IPCC cautioned that we must transition rapidly away from the fossil fuel economy and reduce emissions by 45 percent by 2030 and to net zero by 2050. Efforts to achieve this goal and the strategies to do so have focused overwhelmingly on transforming energy and transportation systems, which account for 39 percent of annual global greenhouse gas emissions. Both of these transitions are important. At the same time, emissions from the industrial sector, which represent 30–40 percent of total global greenhouse gas emissions every year, have received much less attention.

Opposite: © Nick Lund, NPCA/FrackTracker Alliance

Meeting these climate targets will demand dramatic emissions reductions in this sector as well. This report documents how plastic is among the most significant and rapidly growing sources of industrial greenhouse gas emissions. Emissions from plastic emerge not only from the production and manufacture of plastic itself, but from *every* stage in the plastic lifecycle—from the extraction and transport of the fossil fuels that are the primary feedstocks for plastic, to refining and manufacturing, to waste management, to the plastic that enters the environment.

This report examines the sources and scale of greenhouse gas emissions across the plastic lifecycle. It builds on previous efforts to estimate plastic's contributions to climate change, analyzes gaps in those previous efforts, and takes a first step toward identifying what is known and what remains to be analyzed about the links between plastic and climate change. This report pays particular attention to the lifecycle emissions impacts of single-use, disposable plastic found in plastic packaging and an array of fast-moving consumer goods because these form the largest and most rapidly growing segment of the plastic economy.

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To calculate these climate impacts, the research begins not in the oceans, but in the oil fields and at the fracking drillpads where plastic begins its life. Over 99 percent of plastic is derived from fossil fuels; accordingly, plastic lifecycle emissions start with the extraction of its fundamental feedstocks (Chapter 4). This report tracks those feedstocks through the pipelines to the refineries and crackers where oil, gas, and coal are converted from fossil fuels into fossil plastic. Greenhouse gases are emitted in the production of plastic resins and, although information is limited, in the creation of products from those resins (Chapter 5). The climate impacts of plastic do not stop when plastic is discarded. Indeed, the vast majority of plastic's lifespan, and a large part of its climate impacts, occur only after its useful life ends. This next stage of life includes the impact of various disposal methods for plastic, including incineration and waste-to-energy processes (Chapter 6). Finally, this report examines what is known about the greenhouse gas impacts of plastic once it leaks into the environment, reviewing early research showing that plastic continues to emit greenhouse gases as it breaks down in the oceans, on shorelines, and on land (Chapter 7). This chapter also examines the potential impacts of microplastics on the ocean's ability to absorb carbon dioxide and store it deep in the ocean depths.

While much of this report builds on what is already known about plastic's climate impacts at disparate moments in the plastic lifecycle, it also highlights the critical gaps and areas where more research is needed to fully understand those impacts. For example, there are substantial gaps in reporting that make estimating the total global emissions associated with specific and important parts of the plastic lifecycle a challenge. Where global figures exist, this report uses them. Despite the limitations in data, this report concludes that the climate impacts of plastic throughout its lifecycle are overwhelming and require urgent, ambitious action.

This report focuses particular attention on the greenhouse gas emissions associated with plastic production and the petrochemical infrastructure

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buildout fueled by the hydraulic fracturing (fracking) boom in the United States. It does so for three reasons. First, the statistics associated with oil and gas extraction in the United States are better defined than for many other aspects of the plastic lifecycle globally. Second, the US fracking boom and the associated petrochemical buildout will be a major driver of plastic production and related greenhouse gas emissions in the decades to come. Finally, the fracking-based model of plastic production is rapidly being exported to other countries around the world.

The final chapter of this report evaluates the solutions that have been proposed to address the climate impacts of plastic. It highlights those solutions that offer the greatest promise and potential benefits for both the climate and the environment, identifies others that may benefit the climate or the environment but perhaps not both, identifies low-ambition solutions that do not address the problem at the scale and speed the climate crisis demands, and exposes false

These problems have not only a common cause but a common solution: the urgent and complete transition away from the fossil economy and the pervasive disposable plastic that is a ubiquitous part of it.

solutions that will be detrimental for the climate, human health, and ecosystems.

This report is offered as a first step toward what must be a larger, urgent dialogue about the role of the plastic lifecycle in the climate crisis. It builds on the recognition that, whether one considers plastic's impact on the oceans, on human health, or on the climate, these are all interwoven pieces of the same story. Unsurprisingly, therefore, these problems have not only a common cause but a common solution: the urgent and complete transition away from the fossil economy and the pervasive disposable plastic that is a ubiquitous part of it.

CHAPTER TWO

Methology

Plastic production is among the largest contributors to global greenhouse gas emissions from the industrial sector. The greenhouse gas impacts of plastic production and use are poised to grow dramatically in the coming years, driven by the ongoing rapid expansion of plastic production infrastructure—and the ongoing expansion in natural gas production that is fueling that plastic boom. Both the present scale and anticipated growth of these emissions have significant implications for humanity's efforts to rapidly reduce such emissions and avoid the most catastrophic impacts of global temperature rise.

Despite its importance to the climate debate, however, the climate impacts of plastic production, use, and disposal remain poorly understood by the general public. While a handful of studies have attempted to quantify or estimate greenhouse gas impacts associated with plastic, none has examined those impacts across the full plastic lifecycle, including plastic in the environment. Moreover, and discussed more fully in the following chapters, these gaps in coverage are compounded by limitations of the available data with respect to important emissions sources at each stage in that lifecycle.

The present report attempts to identify these gaps and, to the extent feasible, quantify or estimate the emissions hidden therein. It acknowledges and builds on existing research in the field by providing the most comprehensive snapshot of the direct and indirect sources of greenhouse gas emissions released at each stage of production for the seven types of plastic most commonly found in single-use plastic products. The report does not capture the impact of emissions sources from the broader class of petrochemicals, including fillers, plasticizers, and additives, some of which are introduced in the manufacturing of single-use plastic. Where detailed data are lacking at the global level for key segments of the plastic lifecycle, the report draws on relevant estimates from national or regional sources.

Comprehensive technical analysis is limited by uneven and often unavailable data. For example, the National Emissions Inventory (NEI), compiled by the US Environmental Protection Agency (USEPA), has a nearly comprehensive list of emissions from point sources such as compressor and metering stations. However, carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases are not included in their inventories, making a comprehensive evaluation of their greenhouse gas contributions using the NEI difficult. As a result of data gaps like this in the sources used in the present report, the emissions estimates in this report are likely to underrepresent the full emissions profile of the plastic lifecycle.

Additionally, this report adopts capacity-growth projections for plastic as a data point for additional sources of CO_2 emissions, but the relationship between capacity and actual production is an imperfect measurement for future emissions. The scale of the projected expansion of petrochemical infrastructure and the concerns about its detrimental impacts to environmental integrity and human health warrant policy interventions to ensure more comparable and robust data collection standards and access.

At each stage of the plastic lifecycle, direct and indirect emissions vary according to the raw materials—typically oil, gas, and coal—and the inputs for electricity generation used.[2] This report focuses on emissions estimates associated with the plastic production boom in the United States

Opposite: © Paul Langrock/Greenpeace

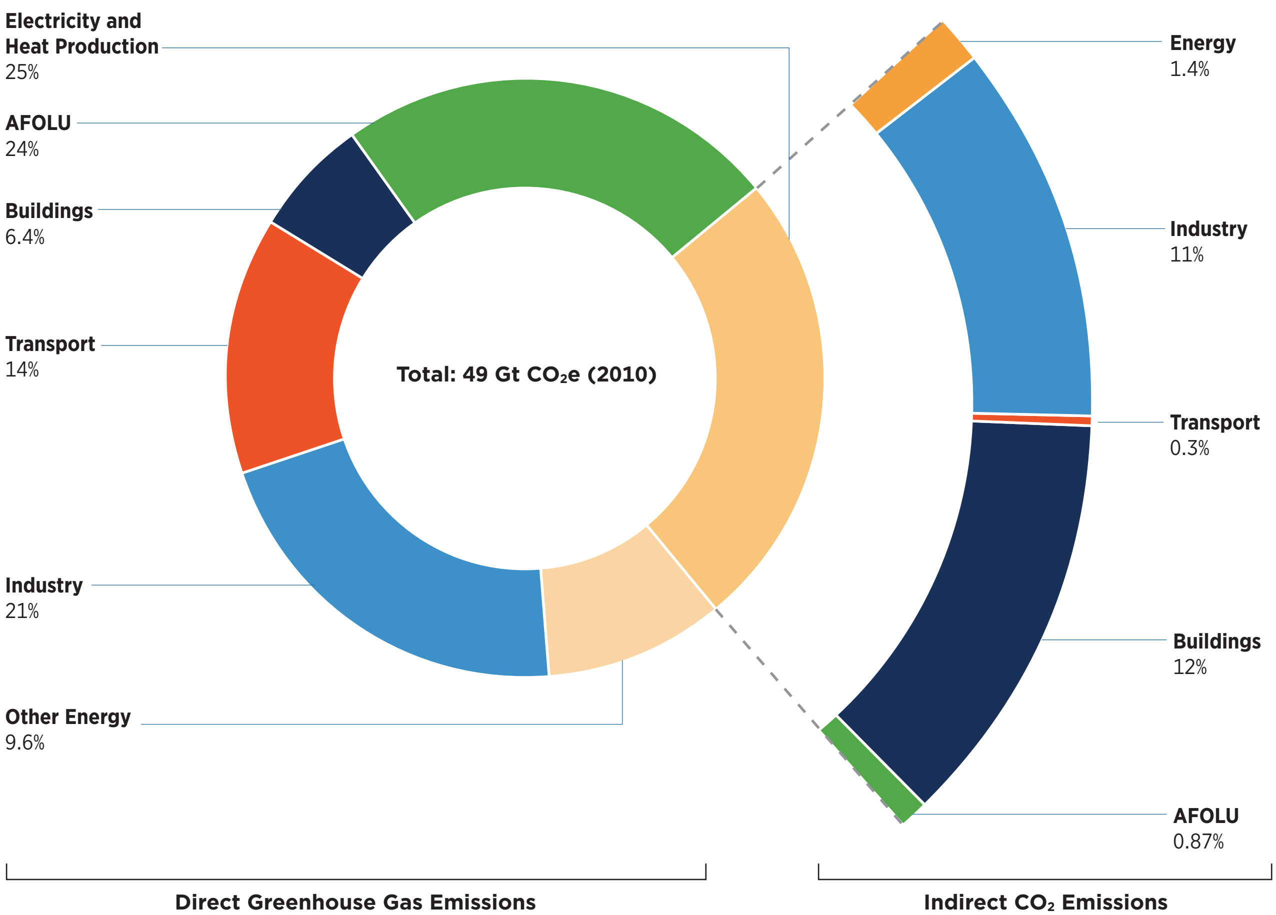
that is fueled by the availability and accessibility of shale gas. As a result, this report focuses on estimates of carbon dioxide equivalents from activities relevant to the extraction of shale gas by fracking; the transportation, storage, and refining of natural gas liquids; the manufacturing of plastic; waste management; and plastic in the environment. The report does not estimate emissions released in the use of plastic products nor does it estimate the full emissions profile of every type of plastic produced. To emphasize the impacts of the plastic lifecycle on climate change, the report highlights the largest sources of atmospheric greenhouse gases emitted to the exclusion of non-greenhouse gas air and water emissions and pollutants.

CO_2 and water vapor are the most abundant greenhouse gases, though there is a wide array of other gases, like methane, and processes that also contribute to atmospheric warming and climate change. To allow greenhouse gases and other climate-forcing agents with dissimilar characteristics to be represented on a comparable footing, climate scientists calculate their impact relative to a common baseline: the CO_2 equivalent (CO_2e).[3] Water vapor is excluded and considered a feedback for purposes of climate models.

This report adopts the methodology for measuring and collecting estimates of greenhouse gases as set forth by the IPCC's 2013 Fifth Assessment

FIGURE 3

Greenhouse Gas Emissions by Economic Sectors



Total anthropogenic greenhouse gas emissions (gigaton of CO_2e per year, greenhouse gas) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in percent of total anthropogenic greenhouse gas emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in percent of total anthropogenic greenhouse gas emissions) from electricity and heat production are attributed to sectors of final energy use. "Other energy" refers to all sources in the energy sector, other than electricity and heat productions. The emission data on agriculture, forestry, and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires, and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU). Emissions are converted into CO_2e based on 100-year Global Warming Potential (GWP_{100}), taken from the IPCC Second Assessment Report.

Source: IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 47 (Core Writing Team, R.K. Pachauri and L.A. Meyer eds, 2014), *https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf*.

Report (AR5) to identify greenhouse gases with varying climate-forcing impacts at each stage of the plastic lifecycle on comparable footing.[4] The AR5 modeled cumulative CO_2 emissions from a common starting point and over a period of 100 years, factoring in the ratio of radiative forcing of one kilogram (Kg) greenhouse gas emitted to the atmosphere to that from one kg CO_2 over the same period of time.[5] In certain instances, values from other IPCC reports, including the IPCC Second Assessment Report (SAR) and the Fourth Assessment Report (AR4), are included in this report where industry's permit data filed to USEPA or US state environmental agencies references those methodologies for reporting on emissions estimates.

This report relies on several frameworks for understanding the quantity of anthropogenic greenhouse gas emissions relative to the likelihood of attaining optimal climate stabilization targets. The IPCC has developed several scenarios to highlight the sources of emissions and modeled reduction targets to limit the concentrations of greenhouse gases to achieve climate stabilization targets. This report also uses the framework of a carbon budget to provide context for the emissions estimates collected at each stage of the plastic lifecycle. A number of institutions, including International Energy Agency (IEA), the IPCC, and Carbon Tracker, among others, have developed climate models to determine the cumulative amount of carbon dioxide emissions permissible over a period of time to keep within a certain temperature threshold.[6]

In October 2018, the IPCC released its Special Report on 1.5°C (SR 1.5), confirming the world has already warmed by more than 1°C, bringing with it dramatic changes to ecosystems, weather patterns, extreme weather events, and communities around the world. Continued warming to 1.5°C will exacerbate these problems, resulting in even more frequent and severe extreme weather events, greater impacts on marine and terrestrial ecosystems around world, and increased impacts on human society. The IPCC issued its clearest warning yet that allowing warming of 2°C will lead to still greater extreme weather events and even more catastrophic impacts.

The IPCC concluded that keeping warming to no more than 1.5°C is both necessary and achievable, but it emphasized that to do so requires rapid and dramatic reductions in greenhouse gas emissions. Specifically, it requires cutting greenhouse gas emissions 45 percent by 2030 and reaching net-zero emissions by no later than 2050.[9] While SR 1.5 concluded that reducing the carbon intensity of electricity generation is a key component of cost-effective mitigation strategies in achieving direct CO_2 emissions reductions, a focus on how to best reduce emissions from the electricity and transportation sectors alone is not sufficient to reach the 1.5°C target by 2100.

BOX 1

Greenhouse Gas Emissions

Carbon dioxide equivalents are an emissions metric that factors in different characteristics of varying greenhouse gases and other climate-forcing agents so that they can be compared. Each greenhouse gas has a different global warming potential over 100 years (GWP_{100}), the measure of how much heat a greenhouse gas puts into the atmosphere and how long it persists in the atmosphere.[7]

The three main greenhouse gases (excluding water vapor) and their GWP_{100} compared to carbon dioxide are:[8]

- **1 x carbon dioxide (CO_2)**
- **28 x methane (CH_4) – Releasing 1 Mt CH_4 into the atmosphere is equivalent to releasing 28 Mt CO_2**
- **265 x nitrous oxide (N_2O) – Releasing 1 Mt N_2O into the atmosphere is equivalent to releasing 265 Mt CO_2**

There are other greenhouse gases that have far greater global warming potentials but are much less prevalent, for example, sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

TABLE 1

Global Warming Potentials of Greenhouse Gases

Predominant greenhouse gases (along with water vapor) and their global warming potential (GWP) compared to carbon dioxide		
Greenhouse Gases	Cumulative forcing over 20 years (GWP_{20})	Cumulative forcing over 100 years (GWP_{100})
Carbon Dioxide, CO_2	1	1
Methane, CH_4	84	28
Nitrous Oxide, N_2O	264	265
Tetrafluoromethane, CF_4	4,880	6,630
Fluorinated Gases: hydroflurocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)	506	138

Source: IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 47 (Core Writing Team, R.K. Pachauri and L.A. Meyer eds, 2014), *https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf*.

CHAPTER THREE

Calculating the Climate Costs of Plastic

ESTIMATES OF CRADLE-TO-RESIN EMISSIONS RATES

This report builds on earlier attempts to identify and quantify the climate impacts of plastic.

A 2011 analysis from Franklin Associates prepared for the American Chemistry Council examined the cradle-to-resin greenhouse gas emissions for the major plastic resins. Cradle-to-resin estimates include emissions from oil and gas extraction through resin production. Franklin Associates' estimates underwent peer review before publication in the US Department of Energy's National Renewable Energy Laboratory's Life Cycle Inventory Database. Their conclusions are based on average direct emissions and energy use reported by 17 companies that operate 80 plants in North America, though industry coverage varies by resin. Since 2011, several peer-reviewed studies have examined these estimates and used them to estimate the potential impact of more sustainable alternatives. One study from Posen et al. combined the original work by Franklin Associates and other analyses to produce midpoint estimates for cradle-to-resin emissions intensities for North American plastic production. These estimates are incorporated into this analysis.

PlasticsEurope, the European industry association for the plastic industry, hosts "Eco Profiles" of various plastics, which are also cradle-to-resin estimates of emissions intensity for different plastic resins. Whereas Posen et al. focused on North American plastic production, PlasticsEurope Eco Profiles correspond to European plastic production. Notably, the emissions estimates for European plastic production are greater than North-American-made plastic, for reasons that will be discussed in greater detail in the following chapters.

These two cradle-to-resin estimates inform this report's evaluation of the likely minimum emissions from the first stages of the plastic lifecycle (extraction, transport, refining, and manufacture). As the following chapters describe in greater detail, these estimates are subject to substantial undercounting of emissions. This report will identify sources of greenhouse gases that are as yet uncounted or unquantified but are nonetheless significant contributors to the overall greenhouse gas impact of the plastic lifecycle.

For the purpose of comparing emissions over time to the constraints of global carbon budgets, this report will use an adjusted weighted average of these cradle-to-resin estimates, building in conservative assumptions that are likely to reduce the apparent climate impact of the plastic lifecycle. Specifically, the estimates of cradle-to-resin greenhouse gas intensity from both Posen et al. and PlasticsEurope are averaged for the primary plastic resins polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS). These five thermoplastics represent at least 85 percent of all plastic production and are less carbon-intense to produce than more uncommon types of plastic, though still responsible for significant carbon emissions. As such, using this lower estimate for all plastic production is likely to underrepresent the true emissions impacts from the growth of plastic production over time. However, without knowing the relative growth rate of niche plastics versus primary plastics, this bias ensures that cradle-to-resin emissions used for the sake of carbon-budget analysis represent likely emissions minimums.

Because North American plastic production primarily uses natural-gas-sourced ethane as a

Opposite: © iStockphoto/Marke Trawcinski

© Carroll Muffett/CIEL

feedstock, and European plastic production primarily uses oil-sourced naphtha, a combination of estimates provides a better representation of global production. There is no reason to believe that plastic produced in other regions is substantially less emissions-intense than plastic produced in Europe and North America. Moreover, known processes that rely on coal feedstocks are considerably more emissions-intensive than plastic production using oil or natural gas feedstocks. These coal-to-olefin processes are a small but growing share of global plastic production, and there are no reliable projections for coal-to-olefin's share of plastic production in decades to come. As a result of these data gaps, the estimates in this report do not reflect the increased emissions from the enormously carbon-intense coal-to-olefins processes and applies only the lower cradle-to-resin profile of North American and European plastic. Based on the calculations described above, this report assumes 1.89 Mt CO_2e are emitted per Mt plastic resin produced.[10]

A significant component of cradle-to-resin emissions for plastic derives from the electricity and heat that power production processes, because that electricity and heat is produced almost exclusively by the combustion of fossil fuels. As discussed in greater detail below, such processes may be performed with renewable or low-carbon energy sources, reducing the carbon intensity of one stage in the plastic production process. Both Posen et al. and Material Economics, incorporating PlasticsEurope Eco Profiles, produce estimates for the carbon intensity of resin production using low-carbon energy. Using the same process to average estimates for North America and Europe, this report assumes an average cradle-to-resin carbon intensity for plastic produced with low-carbon or renewable energy sources at 0.90 Mt CO_2e per Mt of plastic produced.

There are strong reasons to doubt that plastic production will reduce its carbon intensity quickly, even as the electricity grid shifts towards ever greater reliance on renewable and low-carbon energy. Many industrial facilities in the plastic supply chain have on-site power generation for electricity and heat,[11] meaning that an increasingly low-carbon public energy grid may have little bearing on the energy mix used for plastic production, and these sources would need to be converted. Moreover, because fossil fuel production and plastic production are closely linked—with elements of both often taking place at the same or adjacent facilities—the entrenchment of fossil fuels in the plastic production process is even harder to overcome. It is important to note that even if fully powered by renewable energy sources, plastic production would remain a significant source of greenhouse gas emissions because of the significant emissions created by the chemical processes themselves. Fully converting electricity and energy systems to rely on renewables will not address these emissions from plastic production and do not address emissions from end-of-life treatment.

The assumptions described above, coupled with the uncounted emissions described herein, strongly indicate that the true impact of plastic on atmospheric greenhouse gas concentrations is considerably greater than the numeric estimates this report suggests. Nonetheless, the calculable impact is of great concern, and the limiting assumptions only underscore the need for greater attention to plastic's large and rapidly growing climate impacts.

PREVIOUS EFFORTS TO MEASURE PLASTIC'S LIFECYCLE IMPACT

This report also draws on an analysis of present and future plastic lifecycle emissions prepared by the research group Material Economics. Significantly, in its report *The Circular Economy*, Material Economics examines the critical importance of reducing emissions from industrial sources to achieve agreed climate goals.

To reconcile the impacts of the plastic lifecycle with established carbon budgets, Material Economics addresses not only the emissions associated with plastic production itself, but associated emissions from plastic waste and the effect on emissions trajectories from the growth of plastic production through the end of the century. In combination with emissions intensities for plastic resin production based on PlasticEurope's Eco Profiles, Material Economics measures the potential cumulative climate impact of plastic through 2100.

This report builds on Material Economics' analysis in several ways. As described above, this report uses a conservative estimate of global emissions intensity for cradle-to-resin plastic production to account for both geographic differences in plastic feedstocks and the comparatively rapid growth of lower-emission plastic resin types.

For end-of-life plastic, Material Economics uses a gross figure of embedded carbon, the carbon content of solid plastic that could be released into the environment. In the subsequent chapters on Waste Management and Plastic in the Environment, the present report details the pathways through which such embedded carbon may be released into the atmosphere, quantifies the potential scale of those emissions, and highlights significant unknowns and data gaps that may influence and dramatically undervalue those measurements.

The assumptions described here strongly indicate that the true impact of plastic on atmospheric greenhouse gas concentrations is considerably greater than the numeric estimates this report suggests.

This report also assumes growth rates in line with estimates from the World Economic Forum, Mitsubishi Chemical Techno-Research, and analyses of American Chemistry Council data on investment in and growth of plastic and petrochemical production capacity. This growth rate, of 3.8 percent until 2030 and 3.5 percent at least through 2050, is perhaps the biggest indicator of the urgency of understanding the climate impacts of the current and planned expansion of plastic production. Taking into account the speed and scale of the ongoing buildout of plastic infrastructure, the growth rate through 2030 should be considered extremely conservative and is likely a significant underestimate of future growth if industry expansion plans are fully implemented.

PLASTIC PRODUCTION GROWTH ESTIMATES 2015–2100

As noted in the introduction, plastic production is growing rapidly and investments in new capacity have accelerated dramatically in recent years. Accordingly, any projection of the long-term contribution of plastic to greenhouse gas emissions must make assumptions about the pace and scale of this growth.

The World Economic Forum (WEF) projects that plastic production and use will grow 3.8 percent per year through 2030. WEF assumes this rate of growth will slow to 3.5 percent per year from 2030 through 2050.[12] WEF does not provide estimated plastic industry growth rates after 2050. A separate analysis of potential plastic-related emissions prepared by Material Economics takes a different approach, assuming that plastic production will grow at a relatively constant rate of approximately 1.6% from now until 2100.

The present report applies WEF growth estimates on the grounds that these estimates better reflect the available data on current and projected industry growth in the near to medium term. Indeed, there is a strong likelihood that WEF's estimate may understate the actual rate of industry growth, particularly during the critical period between now and 2030.

According to the American Chemistry Council, in the space of one year, the planned investments and the number of new or expanded petrochemical production facilities grew by more than 25 percent.

In September 2017, the Center for International Environmental Law (CIEL) released a report examining how the fracking boom in the United States and beyond is fueling a dramatic buildout of new infrastructure for the production of plastic.[13] In that analysis, CIEL projected that the production capacity for ethylene and propylene—the two most important plastic feedstocks—would grow by 33–36 percent by 2025.[14]

This conclusion was based on an earlier analysis by Mitsubishi Chemical Techno-Research Corporation, which projected a 35 percent growth in ethylene production capacity and a 33 percent growth in propylene production capacity between 2016 and 2025.[15] In the period since Mitsubishi's and CIEL's reports were released, the pace of industry investment in expanding plastic infrastructure has further accelerated. For example, in September 2017, the American Chemistry Council reported a total of $164 billion of investment in 260 new or expanded production facilities for petrochemicals (calculating from a 2010 baseline). By September 2018, it reported total investments of over $200 billion in more than 330 new or expanded facilities. In the space of a year, both the planned investments and the number of new or expanded facilities grew by more than 25 percent.

For some kinds of plastic, the pace of growth is dramatically greater. In February 2018, for example, the *Houston Chronicle* projected that ethane consumption, primarily for use in ethylene, would grow 30 percent by 2019. It reported that "ICIS, a global energy and petrochemical research firm with offices in Houston, has forecast that by 2022, US producers of polyethylene, the most common plastic, will have further increased their production capacity by as much as 75 percent, with much of the new production exported to foreign markets."[16]

In its *Global Ethylene Capacity and Expenditure Outlook* in the fourth quarter of 2018, the research firm Research and Markets projected that global production capacity for ethylene will grow from 180 million Mt in 2017 to 270 million Mt in 2026.[17] A parallel report on propylene projected that capacity will grow from approximately 120 million Mt per year in 2017 to more than 150 by 2026.[18] Combining the figures for ethylene and propylene yields a growth in production capacity of these feedstocks from 300 million tons per year in 2017 to 420 million tons in 2026. This represents a 40 percent growth in production capacity by 2026.

To ensure consistency in calculations, this report assumes that production capacity for key plastic feedstocks will grow by 33–36 percent by 2025. For growth estimates spanning the full period between 2015 to 2050, it applies the growth rates used by WEF. In light of the rapid economic and social transitions necessitated by both the plastic crisis and the climate crisis, this report does not attempt a growth projection for plastic production after 2050. Instead, it assumes that plastic production remains stable from 2050 through 2100. On the basis of the foregoing information, the authors consider each of these growth estimates to be conservative and a likely underestimate of the long-term growth in this industry under business-as-usual scenarios.

ESTIMATING PLASTIC'S IMPACT ON GLOBAL CARBON BUDGETS

Drawing on data from the IPCC AR5 database, Material Economics concluded that to have even a 66 percent chance of keeping warming below 2°C, cumulative emissions from the energy and industrial sectors as a whole cannot exceed 800 gigatons (Gt) by 2100. To have any chance of keeping within 1.5°C, emissions must be lower still, and net global emissions must fall to zero by 2050. An analysis of the IPCC's SR 1.5 report by Carbon Brief concludes that the total remaining carbon budget limit warning to 1.5°C is as little as 420 Gt CO_2e and no more than 570 Gt.[19]

Of the 800 Gt CO_2e carbon budget for energy and industry sectors through 2100 under a 2°C scenario, Material Economics allocates 300 Gt for industry.[20] Industrial sources comprised 40 percent of global greenhouse gas emissions in 2014.[21] Just four sectors—steel, plastic, cement, and aluminum—account for fully three quarters of these emissions. Of the four sectors, plastic is witnessing the most rapid and sustained growth, and it is projected to have the largest growth in emissions under business-as-usual scenarios.[22]

In 2015, 380 million Mt of plastic resins and fibers were produced. Using WEF's growth rate estimates—3.8 percent growth per year through 2030 and 3.5 percent growth per year at least through 2050—annual plastic production in 2050 is expected to reach 1,323 million Mt, or nearly 3.5 times as much as was produced in 2015.

Applying the cradle-to-resin emissions estimate above of 1.89 tons CO_2e/ton of plastic resin produced, plastic production could emit 1.26 Gt CO_2e per year by 2030—equivalent to the emissions from 277 five-hundred-megawatt coal plants. Even assuming the current expansion slows after 2030, annual emissions from plastic production could rise to 2.5 Gt by 2050—emitting as much CO_2 as 549 five-hundred-megawatt coal plants. Cumulative emissions between 2015 and 2050 would exceed 52 Gt, equal to nearly 30 years of emissions from all the coal, gas, and oil plants in the United States.[23] On its present trajectory, plastic production alone could consume more than 12 percent of the earth's remaining carbon budget by 2050 and 111 Gt or more if emissions continue through the end of the century.

Powering energy-intense plastic production processes with 100 percent renewable energy could reduce these production-related emissions by half, but they would not address the significant greenhouse emissions produced by the chemical conversion processes themselves. More importantly, whether and on what timeline such a conversion to renewable energy could be achieved is highly uncertain. Facilities would have to alter their on-site energy production process, and the electricity grid would need to evolve as well. While the latter is already happening to a certain extent, the challenges to the former, as explained above, are substantial.

Projections of this kind are subject to a range of uncertainties, especially as those projections apply further into the future. The scale of the plastic problem is so severe, however, that even conservative projections about emissions from plastic from 2050 to 2100 are dire. For example, even if plastic production stopped growing from 2050 to 2100, and assuming renewable energy were fully integrated into the production process, cradle-to-resin emissions for the second half of the century would still amount to an additional

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cumulative 59.5 Gt CO_2e by 2100.[24] Assuming any higher level of emissions or a moderate growth rate further accelerates the greenhouse gas impacts.

Applying conservative growth projections between now and 2050, and assuming production stabilizes and is fueled completely by renewable energy through the latter half of the century, emissions from plastic production alone could generate more than 111 Gt CO_2e by 2100—even before the substantial and growing emissions from plastic waste incineration are taken into account.

As documented in Chapter 6, greenhouse gas emissions from plastic incineration could add another 4.2 Gt CO_2e to the atmosphere by 2050, bringing total emissions production and incineration alone to more than 56 Gt CO_2e. Thus, plastic alone could consume from 10-13 percent of the earth's remaining carbon budget, undermining urgent global efforts to keep warming below 1.5°C and making even a 2°C target nearly impossible.

These projections demonstrate the magnitude of the climate threat posed by the ongoing rapid expansion in plastic production. As the following chapters demonstrate, moreover, the plastics lifecycle includes a wide array of emissions sources and emissions pathways that are almost certainly being overlooked in current assessments of plastic's climate impacts, and in the business and policy decisions based on those assessments.

CHAPTER FOUR

Extraction and Transport

Almost all plastic, including resins, fibers, and additives, is derived from fossil fuels. The molecules or monomers used to make plastic, like ethylene and propylene, are derived from oil, gas, and coal. While not all fossil-fuel-derived chemicals (petrochemicals) become plastic, nearly all plastic begins as fossil fuels.

THE ORIGINS OF PLASTIC: OLEFINS

The process for producing plastic is similar for each feedstock material, though there are important differences. In general, after oil and gas are extracted from wells, they undergo a process to separate them into component parts, some of which are used for plastic production. Those chemical components are sent to facilities, usually "cracking" plants, where they are turned into olefins, organic chemicals that form the base for most plastic. The two most important olefins are ethylene and propylene.

Olefins are monomers, small molecules that can be bound together to make much longer chains. To become plastic, olefins get stitched together to form extremely long chain molecules, or polymers, in a process called polymerization. If necessary, they are also mixed with plasticizers. Then they are cooled and shredded into pellets called nurdles. Those nurdles form the virgin plastic sold to manufacturers, who then melt and reshape those materials into products like bottles, bags, and household items.

Olefins are commodity chemicals, so ethylene made from gas is no different than ethylene made from oil or coal. The process after olefin production, therefore, depends on what is being produced, not upon the feedstock from which the olefin originated. The path from fossil fuel to olefin is different, however, depending on which fossil fuel feedstock is producing the olefin.

Producing Olefins

Oil derivatives are the primary feedstock for plastic production worldwide. After crude oil is extracted from the ground, it is transported to a refinery. The oil refining process produces, among other things, naphtha, a combination of hydrocarbons that can be turned into olefins via a process called steam cracking. Olefins can also be produced directly via fluid catalytic cracking at oil refineries, although this process is less common.

Natural gas is especially important in the production of ethylene. Natural gas is primarily methane, though heavier hydrocarbons in the form of natural gas liquids (NGLs) are produced from gas wells as well. The most common NGL is ethane. Ethane, once separated from the rest of the gas, is processed in a steam cracker to produce ethylene. Whereas steam cracking of naphtha can produce ethylene and propylene, ethane crackers are designed to optimize ethylene production. Propane may also be processed into propylene in separate facilities called propane dehydration plants.

Coal is also used to make olefins, although the process is considerably more expensive and less cost effective than olefins derived from oil and gas. Coal can be turned into synthetic natural gas (syngas) through the process of coal gasification. Once gasified, this syngas, which is methane, can be turned to methanol, which can then be turned into olefins. This process is sometimes called coal-to-olefins or methanol-to-olefins.[25]

Whether olefin producers use oil, gas, or coal as a feedstock depends on cost and availability. Companies in the Middle East and North America rely primarily on ethane from natural gas, whereas producers in Europe and Asia rely primarily on oil, with some in China also relying on coal.[26]

Opposite: © FrackTracker Alliance

BOX 2

Plastic Resins

Mass-produced plastic includes polymer resins, synthetic fibers, and additives. While there are many kinds of plastic, the most prevalent resins and fibers include PE, PP, PET, PVC, PS, and polyurethane (PUR) resins; and polyester, polyamide, and acrylic (PP&A) fibers. The largest group of non-fiber plastic production (PE, PP, PET, PVC, and PS) constitute over 85 percent of all plastic produced by weight.[27] Understanding these materials and their supply chains is critical to understanding not only the greenhouse gas emissions traceable to single-use plastic and plastic packaging, but also the impacts of plastic in general.

PE accounts for 36.3 percent of all plastic produced.[28] It is often segmented into high-density polyethylene (HDPE) and low-density polyethylene (LDPE), as well as sometimes linear low-density polyethylene (LLDPE), which have different applications. HDPE is used for products like milk and shampoo bottles, pipes, and houseware, while LDPE is used to make products such as plastic bags, food packaging films, and various kinds of trays and containers.[29] In both cases, packaging makes up the largest single-use category of polyethylene use.[30]

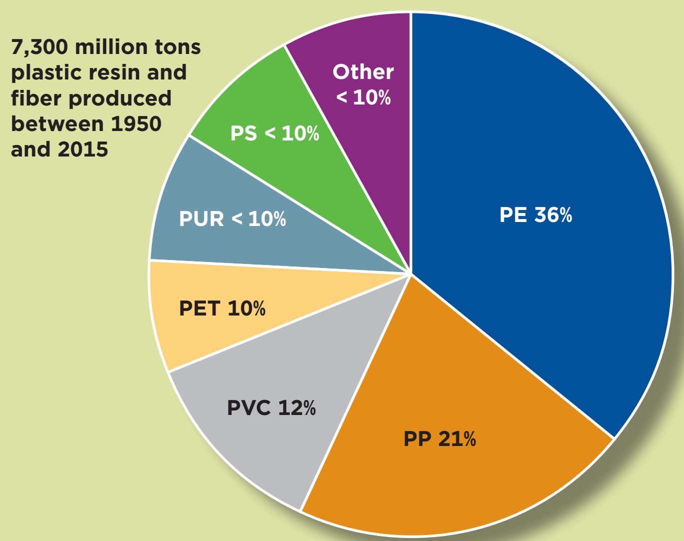
PP accounts for 21 percent of plastic produced.[31] PP is used for food packaging, snack and candy wrapping, and microwavable containers, among other uses.[32] Similar to PE, packaging represents the largest single-use category for polypropylene.[33]

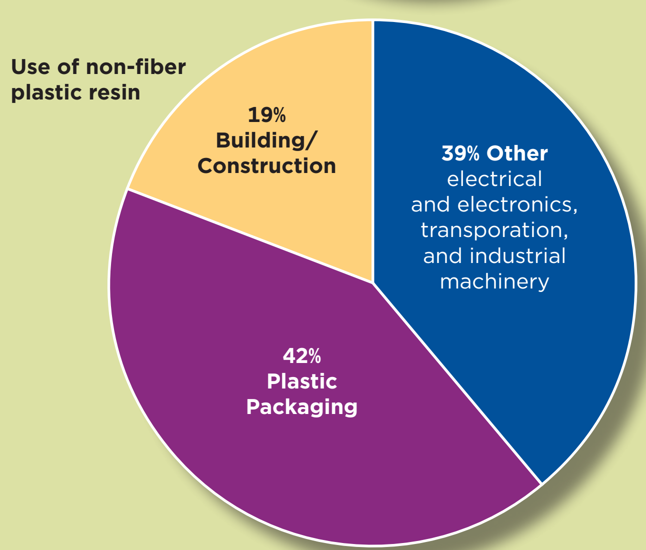
PVC accounts for 11.8 percent of plastic produced.[34] While it is used in packaging, PVC is primarily used as a building and construction material, and it is found in pipes, window frames, and floor and wall coverings, among other uses.[35]

PET accounts for 10.2 percent of plastic produced. PET is nearly exclusively used for plastic packaging, particularly in water bottles, soft drinks, and cleaning products.[36]

FIGURE 4

Common Plastics and their Uses





Source: Roland Geyer, Jenna R. Jambeck and Kara Lavender, Law, Production, use, and fate of all plastics ever made.

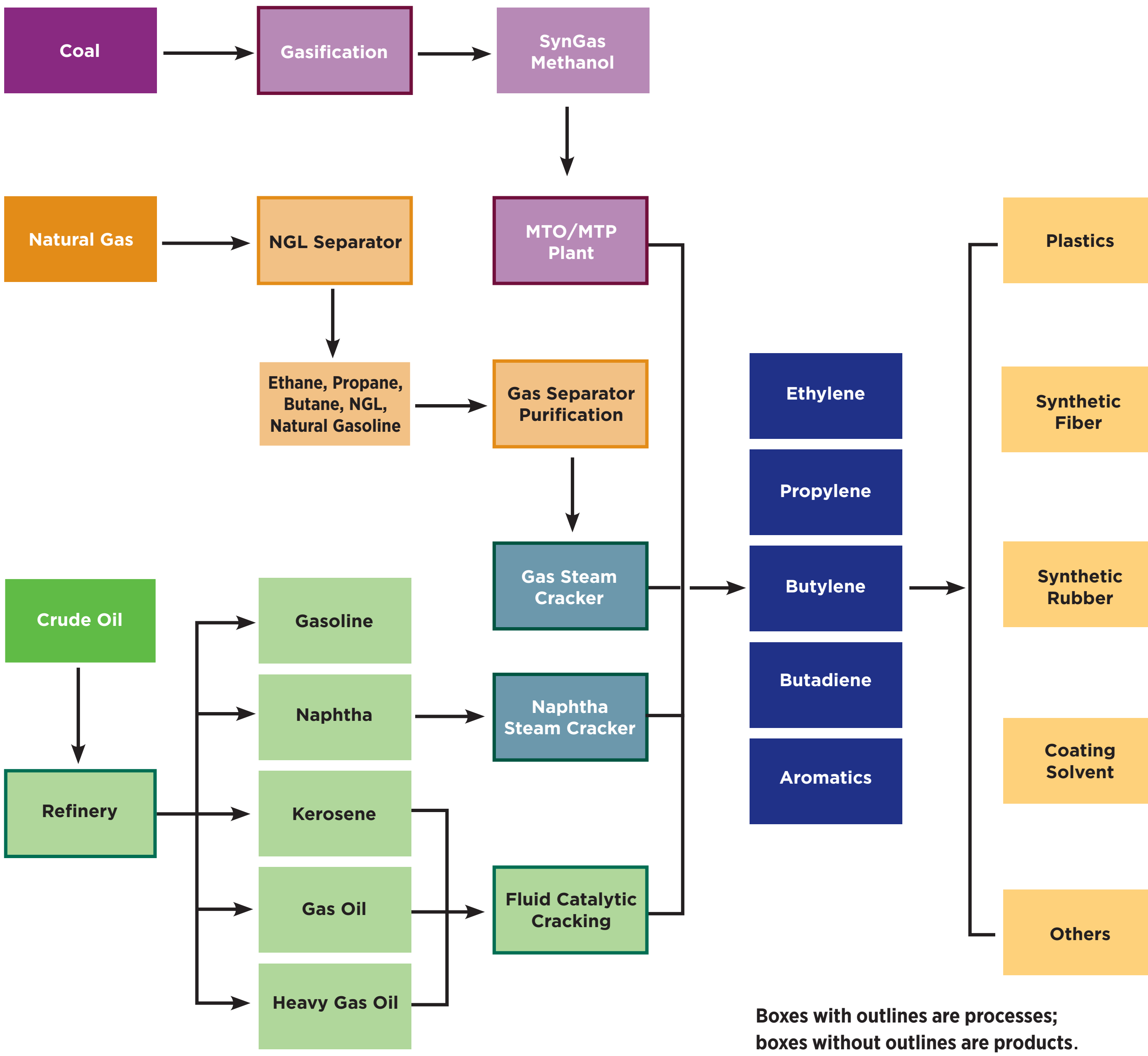
Finally, PS accounts for 7.6 percent of plastic produced. Polystyrene is used for products like glasses frames and cups. It is more familiar in its expanded form, expanded polystyrene (EPS), commonly misidentified as the brand name Styrofoam, which is used for items such as cups, food trays, and cushioning material.[37]

The Growth of Petrochemical Production

Analyses of the plastic and petrochemical industries are largely consistent in forecasting significant growth in both production and consumption of plastic over the next several decades. WEF predicts growth in plastic production of 3.5–3.8 percent per year through 2050.[38] Material Economics projects plastic production to more than double, from just over 320 million Mt per year in 2015 to over 800 million Mt per year by 2050.[39] IEA predicts slightly slower growth, but still projects a nearly 70 percent increase in key thermoplastic production between 2017 and 2050.[40] Consistent with the growth in plastic production, estimates from Mitsubishi Chemical Techno-Research project growth in the production of ethylene and propylene, the key feedstocks for the main thermoplastics, of 2.6 percent and 4.0 percent per year, respectively, through 2025.[41]

FIGURE 5

Petrochemical Products from Various Feedstocks



Source: Presentation, Mitsubishi Chemical Techno-Research, Global Supply and Demand of Petrochemical Products relied on LPG as Feedstock (Mar. 7, 2017) (on file with authors).

These projections not only forecast an impending acceleration of plastic production and waste, but also underscore the importance of growing plastic production as a driver of increased fossil fuel demand. According to WEF, plastic production accounts for 4–8 percent of global oil consumption annually, with roughly half used for material feedstock and half used for energy in the production process.[42] WEF estimates that, if growth trends continue, plastic will account for 20 percent of global oil consumption by 2050.[43] IEA's *The Future of Petrochemicals* report predicts that petrochemicals will account for more than a third of oil production growth through 2030 and more than half of oil production growth through 2050.[44]

If growth trends continue, plastic will account for 20 percent of global oil consumption by 2050.

BOX 3

The Truth about Bioplastic

Bioplastic—or biopolymers—is distinct from conventional plastic because it is made from renewable plant feedstocks such as corn, cassava, sugar beet, or sugar cane and not petrochemicals. Some products labeled as bioplastic contain a combination of plant-based and petrochemical feedstocks. Bioplastic can be as versatile as conventional plastic and is used to manufacture a variety of commercial products. Food-packaging uses include coffee cups, bottles, plates, cutlery, and vegetable bags; medical applications include surgical sutures, implants, and fracture fixation; other commercial applications include fabrics. Bioplastic includes polylactic acid (PLA), plant-derived PET, and polyhydroxyalkanoate (PHA) and can be mixtures of biopolymers, petrochemical-derived plastic, and fibers.

Bioplastic is not inherently biodegradable. The material used in plant-based PET is indistinguishable from its petrochemical equivalent. Plant-based PET, like petrochemical PET, will not decompose, but it can be recycled with conventional PET. Plant-derived PET thus has the same environmental impact as conventional plastic through its use and end of life. PLA is not suitable for home composting; biodegradation requires an industrial composting process that uses high temperatures (over 58˚C) and 50 percent relative humidity (most home composters operate at less than 60˚C and only rarely reach temperatures greater than this).

Pure bioplastic will release carbon dioxide (or methane) and water when it breaks down. However, if additives or toxins have been added during the manufacturing process, as is generally the case, these may be released during degradation. As with fossil-fuel-based plastic, chemicals may be added to a bioplastic to add strength, prevent wrinkling, or confer breathability. Further research and lifecycle analyses will help to understand the role and impacts of different bioplastics.

Plastic production is expected to grow for decades, and those projections extend further into the future than current plans to construct new petrochemical and plastic production facilities. Current plans for rapid expansion of production capacity are concentrated in the United States, China, and the Middle East, but also include expansions of petrochemical capacity in Europe and South America.

As a result of the shale gas boom in the United States, firms are investing heavily in new production capacity near shale formations. As of September 2018, projected investments in US petrochemical buildout linked to fracked shale gas amounted to over $202 billion for 333 new facilities or expansion projects.[45]

The fracking boom in the United States has led suppliers to seek long-term supply contracts and export oversupplied gas. Liquefied natural gas (LNG) facilities—and the pipelines, coastal terminals, and ships that service them—have accordingly become a growing component of fracking infrastructure to support these efforts.

This internationalization of the fracking boom has already started and is set to accelerate. In Argentina's Vaca Muerta region, oil, gas, and petrochemical companies are working to open the second-largest fracking frontier on the planet and attract major petrochemical investments to exploit the fracked gas. In July 2017, the United Kingdom received its first delivery of LNG from the Sabine Pass export terminal in the US state of Louisiana. The Cove Point LNG export facility in Maryland is now a point of transport for Marcellus Shale gas destined for Japan and India. As of the drafting of this report, five additional LNG export terminals are in the planning stages in the United States.[46]

GREENHOUSE GAS EMISSIONS FROM OIL AND GAS FEEDSTOCKS

The extraction and transport analysis in this report focuses primarily on emissions from the

US natural gas sector. This focus ensured that a robust profile of emissions could be produced, whereas limitations in data access and variability in regional emissions data would make such global measurements extremely difficult. Nonetheless, a description of the global oil market and its emissions is warranted to provide a rough estimate of the scale of emissions from oil production, as well as an understanding of the limitations in constructing emissions analyses.

The CO_2e emissions per barrel of oil produced varies greatly between sources of oil. According to a 2015 report from the Carnegie Endowment for International Peace, the carbon intensity of oil can vary by over 80 percent per barrel between the lowest- and highest-emitting oils.[47] A recent analysis of nearly 9,000 oil fields determined a weighted-average carbon intensity for "well-to-refinery" oil production and concluded that global well-to-refinery emissions in 2015 were approximately 1.7 Gt CO_2e.[48] Apportioned for the approximately four percent of oil used as chemical feedstock for plastic,[49] an estimate of 68 million Mt CO_2e can be produced for the contribution of emissions from oil production to plastic production in 2015.

This estimate has significant limitations, however. While it is true that approximately four percent of oil is used as material feedstock for plastic production, that contribution is not distributed evenly. The carbon intensity of the specific oil sourced will affect the carbon intensity of the subsequent plastic produced, and as noted earlier, that carbon intensity can vary greatly. Moreover, because crude oil is widely traded, plastic production and oil production are not as geographically tied as is the production of plastic from natural gas. Nonetheless, while this estimate should not be relied on for formal greenhouse gas accounting, it demonstrates the scale of emissions from plastic production.

After extraction and transportation, oil is refined. The refining process produces naphtha, which can then be cracked to produce olefins for plastic production, and may also directly produce olefins through the fluid catalytic cracking of lighter elements in the oil. Global emissions from steam cracking for both ethane and naphtha are addressed in the next section.

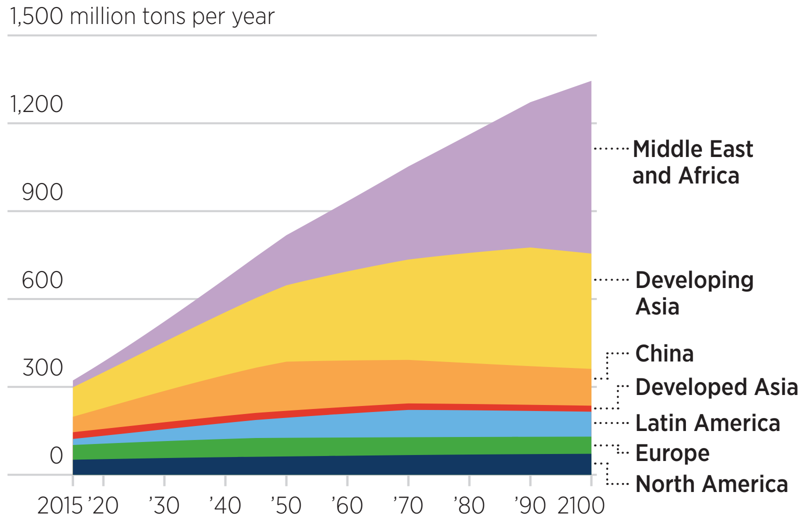
Calculating the exact greenhouse gas emissions from oil refining is challenging, but estimates may be made. One from Moody's places greenhouse

FIGURE 6

Plastic Production Will Increase Significantly

Projections based on business-as-usual growth predict markedly increased plastic use through 2100.

Plastics Demand by Region, 2015 to 2100



Source: Material Economics, The Circular Economy (2018).

BOX 4

Coal-to-Chemicals and Greenhouse Gas Emissions

It is possible to make olefins, the base chemicals for plastic production, from coal feedstocks. This process is sometimes called coal-to-olefins, coal-to-chemical, or methanol-to-olefins (as methanol is often made from coal feedstocks). This process is typically not cost competitive with plastic production from oil or gas feedstocks and is only used in China.

Converting coal into methanol and subsequently converting methanol into olefins is an extremely energy-, water-, and emissions-intense process. Ethane and naphtha cracking release 1.0–1.2 and 1.6–1.8 Mt CO_2e per Mt olefin produced, respectively. According to an estimate from HSBC Bank, coal-to-olefins processes, in contrast, emit 7.1–10.6 Mt CO_2 per Mt of olefin produced.[50] It is unsurprising, then, that Olivier Thorel, an executive at Shell Chemicals, described the process as "massive CO_2 machines that make chemicals as a sidestream."[51]

The future of the coal-to-olefins process is not clear. Massive investments in new coal-to-olefins capacity have been announced, although competing shipments of US natural gas and naphtha feedstocks may affect those plans. Either way, this form of producing plastic is a profound climate problem above and beyond the already problematic lifecycle of plastic produced from oil or gas. From a climate, energy-use, and water-use perspective, preventing the construction of additional coal-to-olefins production plants should be a high priority.

gas emissions from oil refining at approximately one Gt CO_2e per year.[52] This appears consistent with other estimates measuring the carbon intensity of refining or the emissions from refining in one region.[53] Applying the same four percent attribution ratio as above, emissions of approximately 40 million Mt CO_2e per year may be applied to plastic production.

This report estimates that 12.5–13.5 million Mt CO_2e are emitted per year by the extraction and transportation of natural gas in the United States for the creation of plastic feedstocks.

Again, this estimate is subject to significant uncertainty. Emissions vary by refinery and kind of oil refined, and it is beyond the scope of this report to try to trace emissions with that degree of specificity. Still, it is possible to produce a reasonably reliable present estimate of emissions from oil production and refining attributable to plastic production, at 108 million Mt CO_2e per year. Conservative assumptions built into the estimates here suggest no reason to believe the actual number is materially smaller; to the contrary, the actual number may be considerably larger.

Additional emissions from natural gas extraction and transformation in the Middle East, which primarily uses ethane for plastic production, are omitted from this analysis due to the inaccessibility of adequate data. Nonetheless, those emissions are not insignificant and should be understood as an additional element of the greenhouse gas impact of plastic production.

The next several sections identify and quantify the various sources of emissions from the natural gas production and transportation process in the United States and apportion those emissions to plastic production.

NATURAL GAS IN THE UNITED STATES

Plastic can be made from a variety of hydrocarbon feedstocks,[54] but one of the principal raw materials begins with ethane gas that produces ethylene through steam cracking.[55] After methane, ethane is usually the most common component of natural gas. It is considered a natural gas liquid; natural gas high in NGLs is called "wet gas." According to IEA, natural gas in the US accounts for around 40 percent of global capacity to produce low-cost ethane, and the fracking boom in the United States led to increases in the US share of ethane-based chemical exports globally.[56]

Although Saudi Arabia and Iran are significant producers of petrochemicals sourced from ethane, there is not much publicly available information from those and other Middle Eastern countries. In contrast, the available information from the US shale gas boom provides a useful look into the greenhouse gas emissions from the first stages of the plastic lifecycle.[57]

The oil and gas industry is the largest industrial source of methane emissions, according to the USEPA.[58] Estimating the portion of greenhouse gas emissions from the gas industry attributable to the production of plastic requires making several assumptions due to industry variability, demand-side fluctuations, and numerous data gaps. However, because approximately 4.2 percent of the natural gas stream is composed of ethane, and 44 percent of ethane is used for petrochemical production, 1.8 percent of emissions from the natural gas production process will be applied to the plastic lifecycle. This report estimates that 9.5-10.5 million Mt CO_2e are emitted per year by the extraction and transportation of natural gas in the United States for the creation of plastic feedstocks.

Ethane Production Estimates

In 2015, 790,968 active oil and gas wells in the US produced over 32.9 trillion cubic feet of natural gas. Some of the ethane from the natural gas remains in the natural gas stream to be burned by industrial, commercial, and residential consumers in a process known as ethane rejection.[59] This practice is likely to increase as new pipelines and crackers come online and more ethane can be used.

It is impossible to say at this time exactly how much ethane comes out of the ground in the United States because of ethane rejection and the high variability of ethane in different oil and gas formations.[60] Union Gas, a supplier that receives gas from Canadian and American wells, however, indicates that ethane comprises between 1.5 and nine percent of natural gas, with an average of 4.2 percent.[61] Applying that figure to total gas production results in an estimate of around 1.34 trillion cubic feet of ethane (or 934 million 42-gallon barrels) produced in the United States in 2015.[62]

© Garth Lenz/ILCP

The amount of NGLs produced at gas facilities in the United States has nearly doubled to more than 1.2 billion barrels in the ten years between 2005 and 2015, mainly due to large increases in production from shale gas and tight oil formations.[63] Ethane is the most common of these NGLs, accounting for 412 million barrels in 2015.[64] Using the Union Gas estimate of natural gas containing 4.2 percent ethane,[65] about 44 percent of the ethane produced is used as a plastic feedstock, totaling 589.6 million cubic feet (MMcf) of used ethane—with the balance rejected into the natural gas stream, vented, flared, or wasted in some other fashion.

Globally, 134 million Mt of ethylene were produced in 2014, including 25 million Mt in the United States.[66] Propylene, the second most common petrochemical feedstock after ethylene, had an estimated production of 89 million Mt in 2014 and is the source of polypropylene plastic.[67] Such plastic is co-produced at some petrochemical cracker facilities, along with smaller amounts of polybutylene from butane feedstocks.[68]

As noted above, this report apportions just 1.8 percent of greenhouse gas emissions from natural gas production to the development of plastic.

As new NGL pipelines and facilities are built, however, this percentage is expected to rise, as less ethane is rejected into the natural gas stream, flared, or vented. Additionally, many industry analysts[69] consider the development of NGLs to be a driving force in the extraction industry. High production values in recent years have meant that natural gas prices remain low[70] as supplies remain strong. Now, NGL prices are rebounding,[71] making production more profitable.

GREENHOUSE GASES FROM NATURAL GAS EXTRACTION

Estimating the greenhouse gas footprint of the natural gas industry is a complex process, with many data gaps. The USEPA's 2017 report *Inventory of US Greenhouse Gas Emissions and Sinks* (hereinafter *Inventory of US Greenhouse Gas*) provides some clues, including estimates of CO_2e from the production phase of oil and gas. The report estimates that 204.8 million Mt CO_2e were emitted into the atmosphere from natural gas systems in 2015.[72] These emissions are largely methane and include emissions from venting, flaring, leaking tanks and pipelines, gas engines, and other sources.[73] Sixty-six percent of these emissions occurred in the field production stage, followed by transmission and storage, which accounted for 21 percent of emissions, and processing and distribution, which produced roughly seven percent of total emissions.[74]

Applying the 1.8 percent attribution factor, 3.69 million Mt CO_2e can be applied to the production of plastic. However, as will be detailed in this section, this estimate likely significantly underestimates the greenhouse gas emissions from natural gas production and transportation—and therefore the climate impact of plastic as well.

Estimating the greenhouse gas footprint of the natural gas industry is a complex process, with many data gaps. In 2015, 204.8 million Mt CO_2e were emitted from natural gas systems. These emissions are largely methane and include emissions from venting, flaring, leaking tanks and pipelines, gas engines, and other sources.

In the United States, oil and gas drilling began in 1859[75] using conventional drilling, which consists of drilling a vertical well.[76] This process made oil and gas extraction relatively easy because tapping shallow producing fields allowed the product to be either pumped or brought to the surface under its own pressure.[77] Later processes introduced unconventional drilling, in which a well is drilled vertically and then horizontally for more than two miles.

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Some studies have estimated the amount of methane lost from a shale gas well (barring any accidents or emergency venting) to be between 3.6 and 7.9 percent of its total production, which is much higher than conventional wells.[78] A recent study by Robert Howarth using satellite data estimates that even more methane is released from well development to delivery of gas: 12 percent of total production.[79] These varied estimates and the numerous data gaps demonstrate the challenge of assessing the greenhouse gas emissions from natural gas extraction. In the US, the extraction process is regulated at the state level, so reporting requirements for drilling companies vary significantly, if they exist at all. There are also no national reporting requirements for greenhouse gas emissions from this industry. In fact, in 2017, the USEPA removed its request to existing oil and gas operations for information about oil and gas equipment and emissions.[80] Requiring the industry to report greenhouse gases to states and/or the USEPA would help overcome this significant data gap.

Because of these data gaps, greenhouse gas emissions from the oil and gas industry can be estimated by looking instead at emissions sources, including those assessed in *Inventory of US Greenhouse Gas*.

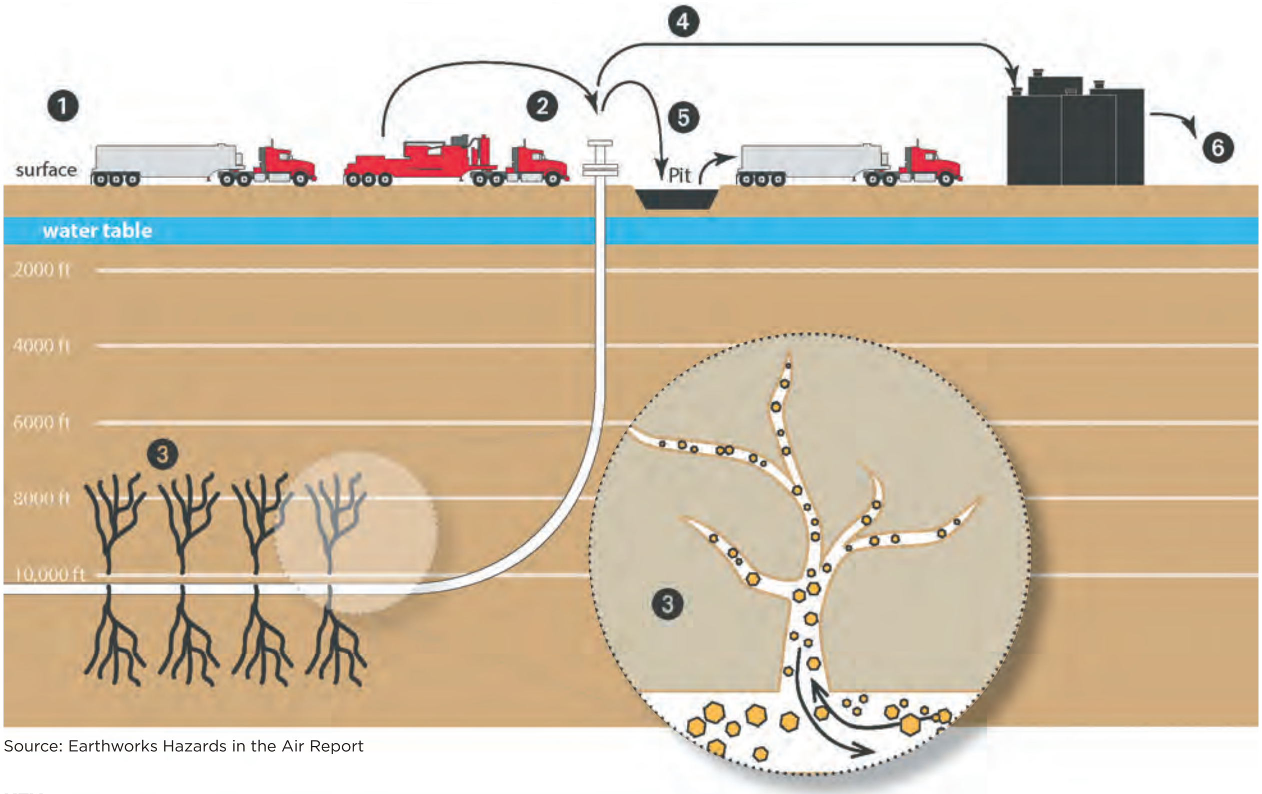
HYDRAULIC FRACTURING

The advent of new hydraulic fracturing (fracking) technologies at the turn of the 21st century enabled access to natural gas reserves that were previously unavailable for exploitation. Together, unconventional drilling and hydraulic fracturing have led to a massive oil and gas boom in recent years, which has, in turn, fueled a plastic production boom.[81]

Fracking is a pressurized process in which underground rock formations (shale) are cracked, or fracked, to release trapped oil and gas. Drilling a natural gas well today involves two key steps: directional drilling (drilling vertically into the ground, then turning the well 90 degrees to access certain hydrocarbon-containing formations) and then stimulating the formation using a mixture of chemicals, sand, and fresh water to prop open cracked shale rock. This causes oil and gas to flow out of the drilled well. One study of five unconventional wells from 2011 estimated between 0.6 and 3.2 percent methane was emitted as a proportion of lifetime production. These estimates do not include accidents or emergency venting.[82]

FIGURE 7

Unconventional Oil and Gas Production



Source: Earthworks Hazards in the Air Report

KEY

1. Water, sand, and chemicals are hauled to the well pad
2. Well pad is prepared, drilled, and fracked
3. Pressurized mixture causes the shale to crack, oil and gas to flow into the well
4. Active extraction of oil, gas, and waste fluids
5. Transmission, storage, and distribution of oil and gas
6. Processed water, oil, and gas are hauled to treatment for use

Significant greenhouse gases can be emitted during horizontal drilling due to the extreme distances underground that wells are being drilled today. Some wells have a total bore hole length of more than 5.2 miles per well, including horizontal portions that exceed 3.7 miles. The record for longest total well is broken every year.[83]

In 2010, the oil and gas industry drilled a cumulative distance of 45,312 miles of vertical and lateral well bores.[84] Drill site operators use a variety of heavy equipment, running either on diesel, natural gas, or electricity. One of the key pieces of equipment is the drilling rig, which comes in various sizes. Rigs capable of drilling very long laterals in a deep formation are enormous and involve multiple heavy machines.[85] Despite significant fuel consumption and attendant emissions from its operation, much of this equipment is not covered by air emissions regulations and accordingly its precise emissions, while likely significant, are not publicly reported.[86]

Fracking involves injecting water and chemicals into the well bore at very high pressures, to fracture the shale or other tight formation rock, along with proppants (usually sand) to keep those fissures open, allowing the hydrocarbons to escape. The process has been in use for more than 60 years, and it is now used in the majority of wells in the United States. In shale and other tight formations, the fluid volumes injected into the well for hydraulic fracturing are orders of magnitude above what are used in conventional oil and gas drilling operations. According to FracFocus, an industry registry site, in 2015, wells were reported to average nearly 5.5 million gallons of water injected per tap, a figure that increased to over 9.5 million gallons in 2017.[87] Many conventional wells are stimulated with much less hydraulic fracturing fluid, between 10,000 and 300,000 gallons.[88]

These water volumes impact greenhouse gas emissions for a number of reasons. Not only must the water be sourced and transported to the site (as discussed below), but the engines used to pressurize and inject the fluids and proppants also emit greenhouse gases. The hydraulic fracturing stage of the operation often requires dozens of frac pumps,[89] each of which may run on 2,500-horsepower engines.[90] Additional on-site equipment must mix the hydraulic fracturing chemicals.

Some states are moving away from open-air impoundments to more tightly controlled storage containers, which could reduce greenhouse gas emissions from this component of the oil and gas drilling process or transfer the burden to storage tanks.

Lacking specific details on the amount and type of fuel used to operate this machinery industry-wide, the present report relies on the assumption that the petroleum and natural gas sections of USEPA's *Inventory of US Greenhouse Gas* report adequately account for these greenhouse gas emissions. As noted above, however, the lack of emissions certifications for key pieces of heavy equipment make it more likely than not that emissions from fracking operations are underestimated.

BOX 5

Storage and Transmission Systems

The natural gas system in the United States includes hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. According to US Central Intelligence Agency data, in 2013 the United States had more miles of pipelines than any other country, with 1,232,999 miles in natural gas transport and 149,570 miles in petroleum products. The next closest countries were Russia (101,825 miles) and Canada (62,137 miles).[91] Pipeline data from the Pipeline and Hazardous Materials Safety Administration notes more than 2.5 million miles of distribution and transmission pipelines for natural gas, and the associated number of known compressor station facilities exceeds 10,000, significantly more than the "hundreds" cited in the *Inventory of US Greenhouse Gas* report.[92] It is therefore likely that the greenhouse gas emissions of natural gas storage and transmission systems are significantly under-calculated for 2015. The USEPA should re-examine these figures in subsequent reports.

When wastewater is temporarily stored in open impoundments on site, these ponds emit a number of volatile organic compounds, including methane. There is insufficient data to adequately estimate the total volume of liquids in these impoundments that off-gas into the atmosphere, and thus it is impossible to measure the impoundments' greenhouse gas contributions. Some states are moving away from open-air impoundments to more tightly controlled storage containers, which could reduce greenhouse gas emissions from this component of the oil and gas drilling process or transfer the burden to storage tanks. These large wastewater volumes must be transported off site for waste disposal after hydraulic fracturing is completed and gas production begins.

Venting and Flaring

As more fluid is injected for well stimulation, greater volumes of flowback return to the surface. Not all of the hydrocarbons produced by oil and gas operators enter the production stream. For a variety of reasons, including natural gas production that exceeds the capacity of pipelines and fractionators in predominately oil-producing regions and the periodic spikes in pressure in the fracking process, large quantities of gas are routinely emitted into the atmosphere (venting) or intentionally burned (flaring).[93] According to the Energy Information Administration (EIA), 289.5 billion cubic feet of natural gas, about 0.9 percent of total gas produced,[94] was vented or flared in 2015.[95]

Given that 53 Kg CO_2 are released from the combustion of one million British thermal units of natural gas, flaring this volume of natural gas would release 15.9 million Mt CO_2 into the atmosphere. This figure excludes venting, when natural gas is emitted but not combusted. In USEPA's *Inventory of US Greenhouse Gas* report, associated gas venting and flaring is listed at 3.7 million Mt CO_2e for petroleum systems. However, the report includes flaring from all onshore oil and gas production in the natural gas systems section,[96] where figures for flaring at the wellhead are not delineated from the broader category of field production emissions from the natural gas systems. Because of this, and because the percentage of gas vented instead of flared does not appear in the EIA flaring data, it is not possible to assess whether the USEPA's *Inventory of US Greenhouse Gas* report adequately represents the atmospheric carbon impacts of venting and flaring in 2015. More detailed data from both EIA and USEPA would be helpful for greater precision.

Raw natural gas is often not ready to be pressurized and distributed directly into the pipeline network. Prior to that process, and dependent on the formation being accessed, the raw gas must first be processed to remove other hydrocarbons (such as pentane and butane) and sulfur gases.[97]

Leaking Tanks and Pipelines

After a well is completed, it can still emit greenhouse gases both intentionally and unintentionally. Pneumatic pumps and dehydrators are the major sources of leakage, though leaks can also occur from the site's meters and vapor recovery units.[98] Storage tanks, a familiar sight on the oil and gas landscape, typically contain raw and refined liquid petroleum products and associated liquid waste products. USEPA's *Inventory of US Greenhouse Gas* estimates that emissions from natural gas systems, including pipeline emissions, were an estimated 33.7 million Mt CO_2e for transmission and storage in 2015.[99] The discussion that follows examines whether and to what extent these emissions estimates are complete.

Pipeline and Hazardous Materials Safety Administration (PHMSA) reports indicate that pipeline system leaks are rather commonplace, with 585 known leaks in transmission line systems and 25 leaks in gathering line systems awaiting repair in March 2019.[100] Volumes of escaped gases are not tracked in this context, however, so the CO_2e of these leaks cannot be calculated. Some studies have looked into pipeline emissions, but the estimates vary substantially. Globally, a review of previous research suggested that 2.5 to ten percent of the total amount of methane pumped through pipelines leaks out of the system.[101] The upper level is due in large part to leaking infrastructure in Russia, but significant leakage rates have been documented in other countries. In the United Kingdom, soil gas measurements of methane from high-pressure gas pipelines indicated a total flux of 62,600 Mt per year, or 2.9 percent of the country's total annual methane emissions.[102] In the US, a direct monitoring study on Texas pipeline emissions indicated leakage rates between 2.3 and 4.9 percent.[103] If this figure is applied to the 28.8 trillion cubic feet of marked gas in the US in 2015, the amount of gas leaked would be between 661.8 billion cubic feet and 1.4 trillion cubic feet of methane released in pipeline leaks, or between 36 and 77 million Mt CO_2e.[104] The proportion of this attributable to plastic would be between 648,000 Mt and 1.4 million Mt. The industry should make additional research into the quantity of gas released in pipeline leaks a priority.

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TRANSPORT

The considerable use of trucks to service well sites is another source of greenhouse gases in oil and gas extraction. Thousands of trucks of various sizes and capacities emit greenhouse gases to both haul water and dispose of waste.

Water Hauling

If temporary water pipelines are not constructed, water hauling is a major source of truck traffic. Average water use per injection for new wells in 2015 was approximately 5.5 million gallons.[105]

Due to the varied sizes of water hauling trucks, estimates of the number of trucks required for high-volume hydraulic fracturing operations vary significantly. One source estimates 320 trucks would be required to supply two million gallons of water, with up to 1,440 trucks needed for nine million gallons. This works out to 6,250 gallons per truck, meaning that 5.5 million gallons for stimulating one well for one injection would require 846 trips.[106]

While 6,250-gallon tankers exist, 4,000-gallon water haulers are more typical.[107] Using 4,000-gallon tankers would require 1,375 trips for a 5.5-million-gallon fracking operation. These trip calculations assume each truck must make a round trip from its water source.

Waste Disposal

Waste disposal, too, varies tremendously depending on the target formation and the amount of fluid injected into a well. A 2016 analysis from Duke University calculated 449,000-3.8 million gallons of liquid waste flowback during the life of a well in various shale plays around the United States.[108] That would require an additional 112-950 truck trips to dispose of the brine and flowback fluid. There are also a number of other waste streams to consider, including drill cuttings and drilling mud, spent lubricants and chemical containers, and earth that has been contaminated on site.[109]

Other Traffic

Trucks carrying chemicals, proppant, and equipment must also be taken to and from the site.[110] Workers, contractors, and inspectors must access the well site on a regular basis, as well. One estimate from 2011 puts the total number of truck trips accessing a horizontal well site at 3,950 heavy-duty trucks and 2,840 light trucks, totaling 6,790 trips per injection.[111] Since 2011, extraction techniques have become substantially more intensive, meaning that more recent wells require transporting even more chemicals, equipment, water, and waste.

Calculating the greenhouse gas emissions of all this traffic conclusively is difficult due to variability. However, using estimates of the CO_2 emissions of heavy-duty trucks based on Mt-miles—the product of Mt hauled multiplied by miles driven—multiplied by average freight emissions at 161.8 grams CO_2 provides a ballpark estimate. Dividing by 1,000 yields results in kilograms.

Light-duty trucks are calculated based on average fuel efficiency. For this analysis, the Ford F-250 will represent an average between vehicles used by workers to access rugged well sites, as well as the delivery of smaller items to the site that would not require heavy-duty delivery. Real-world analysis of the 2015 model of Ford F-250s average 13.7 miles per gallon. While some of these lighter-duty vehicles would likely use diesel, which emits 10,180 grams of CO_2 per gallon, this report makes the calculation with gasoline (8,887 grams) for a more conservative estimate.

Given the rapid and continuing growth of the fracking boom and associated transport activity, the 2011 estimate of 3,950 heavy-duty trucks and 2,840 light trucks does not reflect the dramatic increase in water, waste, sand, and chemicals associated with unconventional drilling in more recent years. Accordingly, any estimate based on these figures will almost certainly understate the current scale of transport-related emissions. In the absence of more current figures, however, this report incorporates the 2011 numbers to calculate a very conservative baseline.

The total emissions from trucks servicing a single unconventional well in Pennsylvania is estimated between 708–3,728 Mt CO_2, depending on the average round-trip distance. One fundamental variable to calculate the emissions related to truck traffic is the number of unconventional wells drilled in a given year. In the early days of fracking the Marcellus Shale formation, the growth rate in wells drilled per year was exponential. However, as of publication, this peaked in 2011 with 1,958 wells, before falling to barely one quarter that figure in 2016.[112]

The cumulative CO_2 emissions from trucks servicing unconventional oil and gas wells in Pennsylvania are therefore likely to be between 8.1-40.5 million Mt, depending on the distances driven. In 2015, the CO_2e emissions are between 555,000-2,774,000 Mt. It is worth noting that the 4.8 trillion cubic feet produced in Pennsylvania in 2015 represented 16.7 percent of the natural gas in the United States that year. If the state is representative of truck traffic in other regions, then the national figure of CO_2 emitted in 2015 by servicing trucks would have been between 3.2–16.4 million Mt, a figure not accounted for in *Inventory of US Greenhouse Gas.* Between 57,000–295,000 Mt CO_2e of these emissions would be attributable to plastic.

The considerable use of trucks to service well sites is another source of greenhouse gases in oil and gas extraction. Thousands of trucks of various sizes and capacities emit greenhouse gases to both haul water and dispose of waste.

PIPELINE CONSTRUCTION AND COMPRESSOR STATIONS

Pipeline construction is an intensive process. US federal pipeline safety regulator PHMSA estimates that there are more than 2.5 million miles of natural gas pipelines (excluding gathering lines) and more than 68,000 additional miles of natural gas liquid pipelines in the United States. In addition to their construction, pipelines require significant infrastructure to keep running, in particular compressor stations and metering stations.

The National Emissions Inventory, compiled by the USEPA, maintains a detailed list of emissions from point sources such as compressor and metering stations. In a significant omission, however, CO_2, methane, and other greenhouse gases are not included in the inventory for these sources, making a comprehensive evaluation of the greenhouse gas contribution of these facilities using the NEI difficult.

Replace first sentence with: Federal Energy Regulatory Commission (FERC) Environmental Impact Statements outline the potential greenhouse gas impacts of recently proposed pipeline projects.[113] For the 600-mile Atlantic Coast pipeline system stretching from North Carolina to West Virginia, an estimated one million Mt CO_2 were released during the construction phase of the project, plus an additional 973,865 Mt per year between seven associated compressor stations and 248,145 Mt from seven metering stations. In comparison, FERC documents suggest the that construction emissions for the Sabal Trail project, spanning 515 miles from Alabama to Florida, will be 200,215 Mt CO_2e. Operating emissions, blowdowns, and leaks are expected to contribute 31,104 Mt CO_2e annually. Five compressors are associated with the project, contributing 858,030 Mt per year, along with one metering station, adding 7,985 Mt.[114] The 303-mile Mountain Valley Pipeline, running from Virginia to West Virginia, is expected to generate 877,620 Mt of greenhouse gas emissions during construction, followed by 673,621 Mt annually from three compressors. Assuming these compressors are representative, these measurements suggest an average of 167,034 Mt CO_2e per year per compressor station.[115]

Annual emissions from natural gas compressor stations in the United States are almost certainly greater than 256 million Mt CO_2e, 4.6 million of which are applicable to plastic production.

Between the three projects, there are over two million Mt of greenhouse gas emissions from the construction of 1,418 miles of pipelines, along with 2.5 million Mt from 15 compressor stations and 2.856 million Mt from eight metering stations. One of the three includes an annual figure of 31,104 Mt from various sources. The average per-mile contribution annually includes 1,469 Mt for construction, 1,767 Mt from associated compressors, 181 Mt from metering stations, and 22 Mt from operation, leaks, and blowdowns. Based on this data, a compressor station is needed every 95 miles on average, and a metering station is required every 177 miles.[116]

Pipeline construction is booming, a trend that is expected to continue as more midstream infrastructure comes online. According to data from PHMSA, an average of 14,127 miles of pipeline were installed between 2000 and 2009, compared to 35,436 miles per year in the current decade.[117] Using the figures above as a guide, this calculates to over 52 million Mt CO_2e for pipeline construction per year in the current decade, in addition to bringing 362 compressors (over 60 million Mt annually) and 200 metering stations (over six million Mt annually) online every year. Collectively, this amounts to over 118 million Mt CO_2e emitted per year, of which 2.1 million Mt are attributable to plastic.

The 2014 version of the NEI includes emissions data for 1,532 compressor stations across the United States.[118] If the data from the new compressors are representative, this would indicate a baseline of nearly 256 million Mt CO_2e per year. This is similar to the 1,367 compressor stations in a dataset published by the US Department of Homeland Security (DHS). However, both of these are likely missing large numbers of compressor stations associated with gathering lines. The Oil & Gas Threat Map, a project of Earthworks, Clean Air Task Force, and FracTracker Alliance, identified 10,472 compressor stations, clustered in oil-and-gas-producing regions. These stations do not overlap significantly with the compressors reported by DHS, which are spread throughout long distribution pipeline networks. The Oil & Gas Threat Map compressor dataset is also likely to be incomplete, as 6,486 of the facilities (62 percent) are in the state of Louisiana alone. While Louisiana is a major oil-and-gas-producing area, it is not the biggest, and compressors in other states are likely to be significantly underrepresented.

The NEI data has some overlap with the Oil & Gas Threat Map and DHS maps. While it is incomplete in scope, the NEI data has some dense clusters of gathering line compressors in geographies not covered by the Oil & Gas Threat Map, notably in Kansas and southern Appalachia. The lack of a comprehensive dataset of compressor stations in the United States is a significant data gap for understanding the aggregate greenhouse gas emissions from this segment of the supply chain for natural gas and, accordingly, for plastic.

Applying the average calculated above to the compressor stations included in the NEI dataset results in annual emissions of 256 million Mt CO_2e, with 4.6 million Mt attributable to plastic. This figure, however, fails to consider the majority of compressor stations as indicated in the Oil & Gas Threat Map. Those stations in the Oil & Gas Threat Map likely have smaller per-station emissions, and the emissions average calculated above cannot reliably be applied to those stations. As such, annual emissions from natural gas compressor stations in the United States are almost certainly greater than 256 million Mt CO_2e, 4.6 million of which are applicable to plastic production.

Land Disturbance

Oil and gas extraction, pipelines, and processing facilities inherently require intensive use of the landscape. This is especially true for modern, industrial-scale unconventional drilling operations. This land disturbance impacts the industry's greenhouse gas footprint.

Based on analysis conducted in 2010 and 2011 with respect to fracking operations in Pennsylvania, the Nature Conservancy estimated that while a Marcellus Shale well pad might only measure three acres on average, it also requires an additional 25 acres of land disturbance for related infrastructure, or 28 acres including gathering lines to take the gas to processing facilities, the construction of access roads, water impoundments, and related infrastructure.[119] Gathering pipelines require the greatest proportion of ground clearing, averaging 19 acres per site, assuming the gathering lines average 3.1 miles in length and include a 50-foot right of way.

Assessing the total impact of land-clearing activities related to oil and gas extraction is impeded by lack of clarity around which oil and gas wells are on multi-acre pads and how many are conventional operations, which may involve a cleared area of a quarter acre or less, not counting gathering line routes. There are now some well pads with 30 or more wells, although this is relatively rare, and the pad size in those cases are closer to ten acres than the three acres calculated by the Nature Conservancy.[120]

A recent report looked at the land footprint of natural gas extraction from more than a half million producing gas wells in 2015, reasoning that the average between conventional and unconventional well pad construction would be five wells on a five-acre site, or an acre per well.[121] This figure did not include gathering lines. If the Nature Conservancy's estimate of clearing 19 acres of gathering line per well site can be extrapolated across the United States, gathering lines would account for 2,110,383 acres of cleared land connecting 111,073 drilling sites, and the combined gathering line and well pad area would include 2,665,747 acres of cleared land.

These calculations are subject to a number of assumptions, and a comprehensive study on the footprint of oil and gas extraction and transmission operations would increase confidence in these findings substantially.

The estimated 28 total acres of land disturbance for unconventional oil and gas well pads, including the associated gathering lines, is only a small portion of the overall land disturbed. Distribution pipelines are the single largest cause of ground

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disturbance in oil and gas extraction processes. PHMSA estimates there are 2.7 million miles of gas- and petroleum-related pipelines in the United States, not counting gathering lines.[122] The width of a typical pipeline right of way is 50–100 feet, and 50 feet is more common for a permanent easement.[123] At that width, a pipeline would disturb 6.06 acres per linear mile,[124] meaning the aggregate disturbance would be 16.6 million acres, an area slightly larger than the combined size of West Virginia and Rhode Island.[125]

The greenhouse gas contribution of that cleared land can be considerable, depending on the vegetation profile of the land in question. The focus here will be on forested land, which represents about 33 percent of land cover in the US.[126] The average forested land in the United States contains 158,000 pounds of organic carbon per acre,[127] which when disturbed will mostly be released into the atmosphere as 263 Mt CO_2 per acre.[128] In addition to this one-time release of carbon, most of this land would need to remain free from tree growth for the duration of the pipeline's existence, and would therefore cease absorbing carbon[129] from the atmosphere on a continuing basis. In 2015, US forests removed 778.7 million Mt CO_2e[130] from an inventory of 766 million forested acres,[131] or about 1.02 Mt CO_2e removal per acre per year.

In total, approximately 19.2 million acres of land have been cleared for oil and gas development in the United States. Assuming that a third of this land impacted is forested, this amounts to a one-time release of 1.686 billion Mt CO_2 into the atmosphere, along with the removal of 6.5 million Mt of carbon sink capacity on an annual basis. Recognizing that this land disturbance reflects a wide array of oil and gas development and distribution infrastructure developed over the course of many decades, it is neither feasible nor appropriate to apportion the emissions from historic land disturbance to recent or ongoing plastic production. It is nonetheless important to acknowledge the scale of emissions from a source that receives little attention. New pipelines associated with natural gas production are actively being constructed or proposed, and still more expansions are projected in the years to come. As discussed more fully later, these pipelines are increasingly driven not only by demand for natural gas in energy production, but by the rapid expansion of infrastructure for the production and export of plastic, plastic resins, and plastic feedstocks.

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As mentioned above, PHMSA data indicate an average of 6,194 miles of pipelines built per year in the current decade, resulting in an estimated 37,573 new acres cleared, of which 12,512 were likely forested. This means the eventual release of 3.3 million Mt CO_2 into the atmosphere from land-disturbing activities in 2015, plus the permanent loss of forest carbon sinks capable of absorbing 13,000 Mt CO_2 per year. With respect to plastic, this would yield an estimated contribution of 59,461 Mt of new carbon in 2015 and a failure to remove existing carbon due to land clearing associated with oil and gas development.

NATURAL GAS STORAGE AND DISPOSAL

Natural gas storage (temporary) and waste disposal sites (permanent) are two often overlooked areas in accounting for the oil and gas industry's emissions footprint. Accidents, leaks, and unplanned releases are difficult to quantify but still significant sources of emissions for the industry. The high-profile example of Aliso Canyon can serve as a case study.

In October 2015, a gas leak was noticed in one of 115 wells servicing Aliso Canyon,[132] an enormous gas storage facility in the Los Angeles, California, area. By the following February, when the leak was finally sealed, an estimated 90,300–108,950 Mt of methane had been released into the atmosphere.[133] This range corresponds to 2.53–3.05 million Mt CO_2e. This single emissions event released more than one percent of the total emissions from natural gas systems reported by the USEPA in 2015.

The Aliso Canyon accident was the largest natural gas leak in US history. While this release was unique in its scale, releases of this kind happen with alarming frequency across the oil, gas, and petrochemical industries. Additional high-profile accidents, including those in Crosby and Deer Park, Texas,[134] are drawing attention to sudden, accidental, and unaccounted for releases of greenhouse gases that exceed permissible amounts of emissions under the permits filed with regulators and further distort the total amount of emissions released in petrochemical processes. Smaller accidents, leaks, and unplanned releases remain harder still to document and quantify.

GAS PROCESSING

Natural gas and crude oil are rarely useable without some degree of processing. Natural gas is processed and separated into methane gas and natural gas liquids like ethane, propane, butane, condensate, and gasoline at natural gas plants and fractionators. Oil is processed into products such as gasoline, jet fuel, lubricants, and naphtha at petroleum refineries. This section focuses on emissions from natural gas processing plants.

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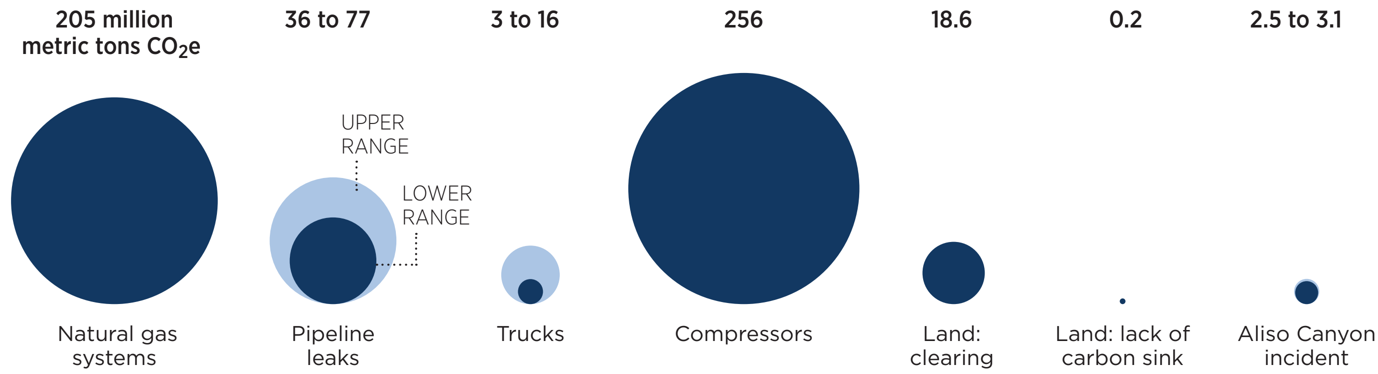
The USEPA requires gas processing plants to measure and report greenhouse gas emissions if they process at least 25 MMcf of gas per day. In 2015, 467 gas processing plants reported releasing 59 million Mt CO_2e (roughly 55 million Mt CO_2 and 4.08 million Mt methane as CO_2e). A large share of these emissions were from fossil fuel combustion, while the rest were from processes that include acid gas removal units, other flare stacks, compressors, blowdown vent stacks, dehydrators, and equipment leaks.[135]

One industry analysis reviewed emissions intensity—the amount of CO_2e released for each MMcf of gas processed—at ten plants based on natural gas throughput and greenhouse gas emissions from 2012. Emissions rates ranged from 0.616-3.387 Mt CO_2e per MMcf processed, with an average of 1.668 Mt per MMcf and a median of 1.546 Mt per MMcf. Emissions intensities based on NGL production ranged between roughly 0.01 to just over 0.07 Mt per gallon.[136]

Facilities that start up, shut down, or malfunction unexpectedly may emit more greenhouse gases than a plant that is operating safely and efficiently. For instance, in 2014, DCP Midstream's Goldsmith gas plant in Ector County, Texas, reported processing an average of 60 MMcf of gas and releasing 239 million Mt CO_2e, meaning that it released 10.9 Mt CO_2e per MMcf of gas processed.[137] That year, the plant also reported unauthorized emissions from one startup event, two maintenance events, and 99 other emissions events to the Texas Commission on Environmental Quality.[138] These unplanned emissions events suggest operational problems at the plant, and they often result in higher emissions due to leaks and/or increases in venting and flaring. Preventing and avoiding unplanned emissions events can reduce greenhouse gas emissions and emissions of other

FIGURE 8

Emissions Associated with Petroleum Extraction



Source: Calculations by FracTracker Alliance.

dangerous pollutants, but in the absence of better controls, these incidents provide an additional and unpredictable source of greenhouse gas impacts from the plastic lifecycle.

CASE STUDY: PENNSYLVANIA

As noted throughout this chapter, sources of detailed and reliable emissions data are lacking at the national and global level for many important links in the supply chain for oil, gas, natural gas liquids, and plastic. Because the oil and gas industry is regulated state by state, much of this data is published at the state level. For some producing states, regulations and emissions data are as or more limited than data from federal sources. Pennsylvania releases more comprehensive oil and gas data than most and therefore serves as a good example for understanding the industry's carbon impacts.[139] Accordingly, this data can shed additional light on the nature and scale of potential emissions from this sector.

Wells and Production

According to EIA, Pennsylvania produced 4.81 trillion cubic feet of natural gas in 2015, ranking second only to Texas in total quantity of gas.[140] Pennsylvania also ranked second to Texas in the number of producing gas wells that year, with 70,051 wells.[141] Records from the Pennsylvania Department of Environmental Protection are different, although in the same ballpark. Total gas production for the year is listed at 4.77 trillion cubic feet from 79,216 producing wells.

From the numbers, it is clear that the vast majority of production comes from a limited number of unconventional wells. Accounting for just nine percent of the state's producing well inventory, unconventional wells produce over 96 percent of Pennsylvania's natural gas.[142] The average unconventional well produced 277 times the amount of gas as its conventional counterpart in 2015.[143] As a result, it is safe to extrapolate that unconventional drilling from formations such as the Marcellus Shale is the largest contributor to Pennsylvania's gas extraction industry.

Water, Proppant, and Chemical Usage

Unconventional well operators in Pennsylvania are required to submit information to the national registry known as FracFocus about the quantity of materials injected into the well bore during the hydraulic fracturing stage of operations.[144] Reports have been submitted for 932 wells in Pennsylvania in 2015,[145] in which fracking operations used a total of 8.5 billion gallons of water, averaging about 9.15 million gallons of water per well. An unknown quantity of the water may have been piped into the well pads, but if it were all trucked to the well site, it would have required 2,132,051 water haulers with a 4,000-gallon capacity.

The same source also reports on the ingredient mass (excluding water) injected into the well.[146] The most common ingredient is fine sand (e.g. frac sand) mined in the upper Midwest, which props open the shale fractures. Other ingredients include chemicals that are designed to increase production and eliminate problems in the well bore. These arrive via intermodal routes that may include trucks, rail, and river barges, with trucks required to bring the material the final distance to the well site. Pennsylvania wells completed in 2015 used nearly 28.5 million Mt of these materials,[147] which would require 994,415 trucks hauling loads of 28.75 Mt of material. Some wells reported the use of water but no amount of sand or chemicals.[148]

Waste

According to the self-reported data that oil and gas operators submitted to the Pennsylvania Department of Environmental Protection, 49,397,351 barrels (2.1 billion gallons) of liquid waste were produced from oil and gas wells in the state in 2015, along with 1,117,351 tons of solid waste.[149] Hauling that waste would require nearly 519,000 full, 4,000-gallon liquid waste haulers.[150] For solid waste, the amount of waste that can be carried depends significantly on local roads, as some roads and overpasses have weight restrictions that are more stringent than Pennsylvania's statewide gross weight limit of 40 tons.[151] The weight of a large, empty dump truck is variable, but weights ranging from 11.25–13.5 tons are common.[152] This makes 28.75 tons an extremely heavy load, and the solid waste generated in Pennsylvania in 2015 would require a minimum of 38,865 trucks of this capacity.[153]

The principal source of greenhouse gases for injection wells is traffic to and from the site. A paper by Chesapeake Energy discussed the idea of treating and reusing deep formation brines produced in Pennsylvania in other oil and gas wells, indicating that the process would save 52,500 road miles of transportation of waste to distant injection wells per production well drilled. According to their calculations, this would save 88 Mt CO_2 emissions per well.[154] Using, as a point of comparison, Duke University's high-end figure of 3.8 million gallons of flowback per unconventional well and using 4,000-gallon trucks generates an estimate of 950 trucks travelling an average round trip of 55 miles, the truck mileage estimates presented in the present report are reasonable.

Land Use

Using the figure of 28 acres of impact per well pad, including access roads, impoundments, gathering lines, and staging areas, Pennsylvania's unconventional wells are situated on 3,715 well pads, meaning the total disturbed area would be 104,020 acres. In addition, Pennsylvania has 91,302 miles of oil and gas pipelines according to PHMSA, excluding gathering lines, which are calculated above. With a 50-foot right of way, the disturbed area for pipelines is an additional 553,290 acres.

According to research from Pennsylvania State University, forests cover approximately 59 percent of land area in Pennsylvania.[155] It is likely that the areas in which unconventional oil and gas are

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TABLE 2

Pennsylvania Production Figures, 2015

Category	Conventional	Unconventional	All Wells
Production (Mcf)	169,695,753	4,600,905,454	4,770,601,207
Well Count	72,147	7,069	79,216
Average Production (Mcf/Well)	2,352	650,857	2,142

Source: Pennsylvania Department of Environmental Protection.

TABLE 3

Ingredients Injected into Pennsylvania Gas Wells by Mass and Volume

Item	Ingredient Mass (pounds)	Water Volume (gallons)
Sum of Values	57,178,881,364	8,528,204,586
Count of Wells	630	932
Average Values per Well	90,760,129	9,150,434

Source: Pennsylvania Department of Environmental Protection.

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developed are at least this forested, as they avoid urban and suburban Philadelphia, most of the urban and suburban Pittsburgh region, and significant portions of farmland in the south-central part of the state. Therefore, it is reasonable to assume that about 387,813 of the 657,310 acres impacted by unconventional oil and gas and pipelines in the state were originally forested.

This works against the natural role of the forest as a carbon sink. Nationally, forests store about 14 percent of all carbon emissions, and forested land in the US stores an average of 71.7 Mt of organic carbon per acre, so this is an important function. This would mean a disruption of 27.8 million Mt of organic carbon in Pennsylvania's forests. Forests in the state absorb an average of 528 kg of carbon per acre per year, meaning that the carbon sink in the state has been reduced by a total capacity of 451,414 Mt per year.

Projected Buildout

Public statements by industry and governmental sources alike project continued buildout in the Marcellus shale region over the next three decades. The EIA projects that Appalachian natural gas production will see an increase of more than 350 percent from 2013 to 2040. Specifically, NGL production is projected to increase over 700 percent by 2023 compared to 2013 figures.[156]

In line with those projections, the CNA Corporation forecasts 47,600 additional wells drilled from 2015 to 2045, in the Marcellus Shale formation in Pennsylvania.[157] Cumulatively, this buildout would require 583 billion gallons of fresh water and 386 million tons of sand, based on a 2018 analysis of 2017 data.[158] According to a 2011 estimate of 6,790 truck trips per well, the cumulative requirement would exceed 323 million truck trips.[159] These wells would produce an estimated 1.7 billion gallons of liquid waste and 588,000 tons of solid waste. Between existing, proposed, and projected well pads and pipelines, the total area impacted by oil and gas extraction and midstream operations would approach 800,000 acres.

Reducing Emissions

Some USEPA estimates project that up to 90 percent of methane emissions could be reduced

per unconventional well using technologies associated with reduced emissions (reduced emissions technologies, or RECs), also known as “reduced flaring completions” or “green completions.”[160] RECs include sand traps, separators, portable compressors, membrane acid gas removal units, and desiccant dehydrators. For wells that require fracking, RECs may be a viable way to recover natural gas and condensate during well completion, since operators can offset the costs by selling the captured gas. However, RECs cannot be conducted without access to pipelines prior to well completion, which is not always possible for exploratory wells or in newly developed extraction areas.[161] If pipelines are not available to direct the processed gases, flare tanks can be used to combust the waste gases and can be transported from site to site.[162] RECs are currently required for new or modified wells, but not existing ones.

Beyond fracking bans and other measures to limit production, one of the best ways to reduce emissions from the extraction and transport of natural gas products is to detect the sources of leaks and unnecessary releases. However, in September 2018, the Trump administration proposed weakening two rules that require companies to test for and repair methane leaks, among other measures, on federal lands via a finalized rule[163] from the US Department of Interior and on private lands through a USEPA amendment.[164] Some estimates suggest that because of the USEPA’s proposed rule change, methane emissions could increase by a total of 344.73 Mt over USEPA’s baseline, between 2019 and 2025.[165] The Department of Interior’s rule change is currently being contested in court, and the public comment period for the USEPA’s amendment ended in October 2018. Considering the already detrimental greenhouse gas contributions from the industry, these rule changes will only serve to increase emissions.

Beyond fracking bans and other measures to limit production, one of the best ways to reduce emissions from the extraction and transport of natural gas products is to detect the sources of leaks and unnecessary releases. However, in September 2018, the Trump administration proposed weakening two rules that require companies to test for and repair methane leaks.

EXTRACTION AND TRANSPORT EMISSIONS GAPS

Inventory of US Greenhouse Gas cites substantial greenhouse gas emissions from the oil and gas industry, with natural gas systems ranking second on the report for methane emissions and fourth among all categories for CO_2 emissions.

However, the lifecycle greenhouse gas impact of oil and gas development associated with the plastic industry remains inadequately documented and poorly understood. There are instances where there is little data, such as total emissions from machinery at the well site. There are also items that seem to underrepresent other known sources of data, including the total mileage of the US pipeline system and the number of compressor stations. Finally, there are impacts that are not considered at all, including truck traffic and other intermodal transportation requirements, as well as the effects of land clearing for wells, pipelines, and related infrastructure on releasing carbon into the atmosphere and hindering the forest’s ability to act as a carbon sink.

Taken together, the total greenhouse gas impact of oil and gas extraction substantially exceeds the already alarming totals in *Inventory of US Greenhouse Gas*. Meaningful reductions in greenhouse gas emissions are unlikely to happen without making significant reductions in these massive industries, which are just the first steps in plastic production.

CHAPTER FIVE

Refining and Manufacture

The majority of research estimating greenhouse gas emissions has primarily focused on indirect and direct emissions from the point of plastic manufacturing onward.[166] This includes emissions from cracking natural gas and petroleum-based feedstocks like ethane, propane, and naphtha into ethylene, propylene, and other monomers. With further processing and the addition of catalysts, the bulk of these monomers are converted into plastics like PE, PP, and PS, which are pelletized and sold as resins. Petrochemical and resin manufacturing capacity is currently expanding globally, with a wave of new or expanded capacity slated to come online between 2019 and 2023.

This chapter does not attempt to provide a firm estimate for all emissions from the production and manufacture of plastic. The diversity of processes and their emissions profiles makes such estimates extremely difficult. Rather, this section does five things. First, it explains the challenges of making such estimates and outlines the major sources of greenhouse gas emissions from the various stages of plastic production and manufacture. Second, using United States ethylene production as a case study, it tabulates current and future US emissions from this major source of emissions that is expected to increase significantly in the next several years. Third, this chapter provides current and future global estimates for emissions from the cracking process as applicable to the production of ethylene. Fourth, it compares existing cradle-to-resin lifecycle estimates for emissions intensity, noting where emissions may be undercounted. Finally, this section provides recommendations for reducing greenhouse gas emissions from plastic production and manufacture.

CHALLENGES OF CALCULATING EMISSIONS FROM REFINING AND MANUFACTURE

Emissions from the refining and manufacturing stage of the plastic lifecycle are considered industrial emissions. While overall sectoral emissions are reasonably well understood and quantified, apportioning those emissions to the refining and manufacture of plastic presents challenges.

Industrial sources accounted for 15.4 Gt of CO_2e emissions, or 32 percent of global CO_2e emissions, in 2010.[167] Industry emissions were calculated based on direct energy-related emissions, indirect emissions from electricity and heat, process CO_2 emissions, emissions of non-CO_2 greenhouse gases, and direct emissions from waste and wastewater. Manufacturing accounts for roughly 98 percent of total direct CO_2e emissions from the industrial sector, with most of these emissions arising from the chemical reactions and fossil fuel combustion needed to produce the intense heat needed for these reactions.[168] These emissions are dominated by a handful of energy-intensive, high-emitting industries, including chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminum.[169] The chemical sector is second only to steel among industrial emissions sources, accounting for 15 percent of all direct emissions from industrial sources[170] and 1.5 Gt CO_2e emissions in 2010.[171]

As the IPCC notes, calculating emissions from the chemical sector poses significant "methodological and data collection challenges."[172] It recognizes, however, that greenhouse gas emissions from chemical production are dominated by a small number of key outputs.[173] Of the five key chemical outputs identified by IPCC, three

Opposite: © Carroll Muffett/CIEL

(ethylene, adipic acid, and caprolactam) are used primarily in the production of plastic and synthetic fibers. Ammonia and nitric acid are used principally for fertilizer production, with about five percent of ammonia also used in synthetic fibers.[174]

The myriad industrial processes and pathways from which fossil fuels become plastic, and the number of stages of such production, make specific attribution of industrial emissions of greenhouse gases to plastic production extremely difficult.

In addition to direct emissions from chemical processes, chemical manufacturing is profoundly energy intensive, and the production of plastic feedstocks and resins is the most energy-intensive sub-sector of the chemical industry. As the IPCC notes, "[s]team cracking for the production of light olefins such as ethylene and propylene is the most energy consuming process in the chemical industry."[175]

Even when only process and indirect-energy emissions are considered, calculating emissions from plastic production poses unique challenges because of the heavy integration between the production of plastic monomers and resins, and the production and combustion of the fossil fuels that provide both the primary feedstocks and energy source for plastic production. For example, a 2008 analysis of energy use in the petrochemical sector noted that basic chemicals and plastic resins accounted for 60 percent and more than 20 percent, respectively, of all energy expenditures in the chemicals industry.[176] The largest market for basic chemicals themselves is plastic production.

In the United States, for example, 70 percent of all petrochemicals become plastic resins, synthetic rubber, or manufactured fibers.[177] Indeed, as noted in a 2008 report by Lawrence Berkeley National Laboratories, emissions calculations for plastic are further complicated because the two most important of these basic chemicals, ethylene and propylene, are classified as energy products (rather than chemicals) under some, but not all, classification schemes.[178] A more recent analysis by the American Chemistry Council reported that 77 percent of all energy consumed by the chemistry sector was used in the manufacture of petrochemicals or plastic.[179]

The myriad industrial processes and pathways from which fossil fuels become plastic, and the number of stages of such production, make specific attribution of industrial emissions of greenhouse gases to plastic production extremely difficult. Despite these challenges, this chapter attempts to identify and, where possible, quantify the major sources of greenhouse gas emissions in the refining and manufacture stages of the plastic lifecycle.

EMISSIONS SOURCES

Known and quantifiable emissions from plastic production and manufacture are mostly direct, meaning they are owned or controlled by the manufacturing facilities themselves. Studies that evaluate greenhouse gas emissions from petrochemical production typically group emissions into two source categories: those from fuel combustion and those from manufacturing processes (process emissions).[180] Emissions from fuel combustion include those from burning natural gas, oil, coal, or other fuels for the purpose of providing power or heat for industrial processes. Process emissions include emissions that occur when natural gas liquids and other petrochemical feedstocks are converted into usable products, like ethylene, propylene, and plastic resins. Fuel combustion accounts for the bulk of emissions. For instance, according to the International Energy Agency, 85 percent of the global petrochemical industry's carbon dioxide emissions come from fuel combustion, while 15 percent comes from processes.[181]

Direct greenhouse gas emissions from petrochemical and resin manufacturers typically depend on facility efficiency, configuration, and age, the desired end product or product mix, preferred feedstocks, fuel sources, and regulatory constraints and compliance (such as emissions limits, requirements for emissions control technologies or practices, and enforcement). Some of these emissions are relatively straightforward to quantify, while others are more difficult or involve greater uncertainty. For instance, emissions that occur during routine operations or where permits require monitoring are usually easier to quantify, while direct emissions from accidents, malfunctions, and leaks involve more speculation.

Industrial expansions have already and will continue to release greenhouse gases during construction, modification, or expansion of manufacturing plants, as these projects can take several years to complete due to their enormous complexity, size, and cost. However, the greenhouse gas impact from this industrial buildout is also difficult to accurately quantify without policies that require robust emissions accounting and environmental impact assessments. New and expanded ethane crackers and resin manufacturing plants in the United States are not required to estimate construction emissions to obtain an air permit.

The transportation of intermediate and final products, and the associated infrastructure expansion to get those products to new markets, also result in greenhouse gas emissions.

Some indirect emissions associated with petrochemical and resin manufacturing stem from displaced land use, like deforestation or filling wetlands, which accompanies both new construction and expansion projects that are often massive in order to provide economies of scale. Other indirect emissions come from the generation and use of co-products that are not typically considered part of the plastic lifecycle, like residual fuel or coke from oil refineries that also crack naphtha into ethylene and other products. Indirect emissions can also result from downstream market changes that reinforce dependency on fossil fuels—like cheap plastic pricing other packaging materials out of the market, though these are difficult to estimate.[182]

STEAM CRACKING

Ethylene cracking, or steam cracking, is by far the largest direct source of emissions at this stage in the plastic lifecycle. Steam cracking is a multi-step, energy-intensive process. It involves sending feedstocks like ethane or naphtha through steam cracker furnaces, where it is heated to between 750°C and 1,100°C and mixed with steam to split the feedstock into smaller hydrocarbon molecules. Chemical reactions occur before the output from this step is sent to quenching and heat recovery, where products are partially condensed, and steam and pyrolysis gas are recovered. From there, products are compressed to around 3,500 kilopascals (kPa) (for comparison, a car tire requires between 196 and 234 kPa) and acid gas, CO_2, and water are removed. Next, the cracked gas is refrigerated and molecules of different weights are separated, through a process called fractionation, into salable products like ethylene, propylene, butadiene, hydrogen, and benzene and other aromatics.[183]

The first step in this process—heating and providing steam for the steam cracker furnaces—is the largest source of emissions in steam cracking because of the huge amount of energy it requires. For example, emissions from steam crackers often account for two-thirds of the greenhouse gas emissions associated with newly permitted ethylene manufacturing units in the United States. Five recently permitted cracking furnaces at a new ethylene unit at Occidental Chemical Corporation's Ingleside, Texas, plant account for 62 percent of the 474,976 tons of CO_2e per year that the facility is authorized to release under the Clean Air Act. A new, larger ethylene facility at ExxonMobil's Baytown, Texas, olefin plant runs

BOX 6

Pennsylvania Production Case Study

Recent developments in the US state of Pennsylvania provide a useful snapshot of these dynamics and the variety of emissions sources.

Ethane and natural gas liquids fracked from the Marcellus and Utica Shale formations in Pennsylvania are fueling the construction of a major new Shell ethane cracker in Beaver County, Pennsylvania, where they are cracked into ethylene to be exported for use in plastic production. The construction and operation of infrastructure required to support this new trade route has a significant environmental and climate impact.[184] Exporting ethane and propane from the Marcellus formation involved reconfiguring an idled refinery outside of Philadelphia into an export terminal for natural gas liquids (now called the Marcus Hook Industrial Complex), constructing the Mariner East pipeline(s) and associated compressor stations to carry fracked gas across Pennsylvania,[185] constructing and operating seven 180-240-meter-long "Dragon" ships that carry 800,000 Mt of ethane per year across the Atlantic Ocean,[186] and upgrading and operating two INEOS petrochemical facilities in Grangemouth, Scotland, and Rafnes, Norway, which collectively released 967,093 Mt CO_2 in 2016.

Ethylene and petrochemicals from these facilities are used as feedstocks to manufacture plastic on site and elsewhere in Europe. Sunoco, the operator of the Marcus Hook Industrial Complex and Mariner East pipeline, is currently trying to complete construction of an additional pipeline alongside the original Mariner East pipeline called Mariner East II, and has plans to add a third called Mariner East 2x.[187] This new pipeline project has already violated environmental laws, and Sunoco has been required to pay millions of dollars in civil penalties assessed by the Pennsylvania Department of Environmental Protection.[188]

eight steam cracker furnaces that account for 67 percent of the facility's 1.45 million tons authorized for its annual CO_2e emissions.[189] The emissions estimates are based on maximum annual permit limits that are set with the assumption that facilities will use the best available (and affordable) emissions-control technologies and practices to keep emissions "low."

Naphtha cracking is more energy intensive than ethane cracking, which results in more greenhouse gas emissions. It requires higher temperatures compared to ethane and propane, though the process generates more opportunities to recover steam that can be used as a heat source in other processes or recycled.

Emissions from steam cracking are generally higher when naphtha, instead of ethane, is used as a primary feedstock. Most ethylene crackers in the US and the Middle East use ethane as the primary feedstock, while those in Western Europe, Japan, and China use naphtha.[190] Naphtha cracking is more energy intensive than ethane cracking, which results in more greenhouse gas emissions. It requires higher temperatures compared to ethane and propane, though the process generates more opportunities to recover steam that can be used as a heat source in other processes or recycled.[191]

TABLE 4

Estimated Annual Global CO_2 Emissions from Steam Cracking, 2015–2030

	2015	2030
Global ethylene capacity (million Mt per year)	143.8	191.2–195.5
Feedstock mix	35% ethane, 47% naphtha, 18% other	38.5% ethane, 44% naphtha, 17.5% other
Feedstock-based emission factors (Mt CO_2/Mt ethylene)	1–1.2 (ethane) 1.6–1.8 (naphtha) 1 (other)*	
Estimated CO_2 emissions from global steam cracking (million Mt per year)	184.3–213.0	241.7–286.2
Coal-plant equivalency	45–52	59–69

Note: Baseline feedstock mix is for 2017, and future feedstock mix is estimated for 2027. Coal plant equivalency assumes a new base-load coal plant running at all times emits 4.13 million Mt of CO_2e per year.

Sources: Philip Reeder, *Analysis: Naphtha's Challenge in the Age of Petrochemical Feedstock Boom*, S&P Global Platts (Mar. 15, 2018, 2:04 AM), https://www.spglobal.com/platts/en/market-insights/latest-news/petrochemicals/031518-analysis-naphthas-challenge-in-the-age-of-petrochemical-feedstock-boom; Oil & Gas Journal, Special Report: International Survey of Ethylene from Steam Crackers (2015), https://www.ogj.com/content/dam/ogj/print-articles/volume-113/jul-6/International-survey-of-ethylene-from-steam-crackers--2015.pdf; Tao Ren et al., *Olefins from Conventional and Heavy Feedstocks: Energy Use in Steam Cracking and Alternative Processes*, 31 Energy 425 (2006), https://www.researchgate.net/publication/222578401_Olefins_from_conventional_and_heavy_feedstocks_Energy_use_in_steam_cracking_and_alternative_processes.

According to one estimate, ethane cracking generates 1-1.2 Mt CO_2 per Mt ethylene produced, while naphtha cracking generates 1.8-2 Mt CO_2 per Mt ethylene or 1.6–1.8 Mt CO_2 per Mt high-value chemicals (other than ethylene).[192] This suggests that naphtha cracking generates 73 percent more CO_2 per Mt of ethylene than ethane cracking.[193]

In 2017, 47 percent of the world's ethylene was manufactured using naphtha, 35 percent from ethane, and 17 percent from other feedstocks.[194] This mix is expected to shift by 2027 to 44 percent naphtha and 38.5 percent ethane.[195] Total global ethylene production capacity was 143.7 million Mt in 2015.[196] Capacity is expected to increase by 33-36 percent by 2030, to between 191 million Mt and 195 million Mt per year. Potential CO_2 emissions are between 241.7 and 286.2 million Mt per year by 2030, a growth of up to 34 percent in 15 years.

CASE STUDY: GREENHOUSE GAS EMISSIONS FROM US ETHYLENE PRODUCTION AND PROJECTED EXPANSIONS

In 2015, 28 industrial facilities in the US were home to ethylene crackers, according to Oil and Gas Journal's International Survey of Ethylene from Steam Crackers. These facilities were capable of producing 28.4 million Mt of ethylene per year. Six of the 28 primarily used naphtha as a feedstock, accounting for about 20 percent of capacity.[197] The remainder relied on mixtures of ethane, propane, and butane, with one facility relying on 100 percent refinery gas.

These industrial facilities reported emitting a total of 53 million Mt CO_2e in 2015 to the USEPA's Greenhouse Gas Reporting Program.[198] Only 24 of the 28 facilities reported enough information to determine the portion of emissions that could be attributed to ethylene production: 17.5 million Mt CO_2e per year, or one third of their total reported emissions. Emission rates varied between 0.03 to 1.88 Mt CO_2e per Mt of ethylene capacity, with an average of 0.74 Mt CO_2e per Mt of ethylene capacity.

US ethylene capacity is expected to grow rapidly over the next several years. Twelve cracker projects

TABLE 5

Greenhouse Gas Emissions from US Ethylene Producers

Plant (location)	2015 Capacity (Mt per year)	Feedstock Mix	Total CO_2e Emissions Reported (Mt)	% from Ethane Cracking	Emissions Rate (CO_2e from ethylene/ ethylene capacity)
BASF Fina Petrochemicals (Port Arthur, TX)	860,000	Naphtha (100%)	1,659,452	97%	1.88
Chevron Phillips Chemical (Cedar Bayou, TX)	835,000	Ethane (30%), Propane (20%), Butane (25%), Naphtha (25%)	1,031,152	90%	1.1
Chevron Phillips Chemical (Port Arthur, TX)	855,000	Ethane (80%), Propane (15%), Butane (5%)	784,276	72%	0.66
Chevron Phillips Chemical (Sweeny, TX)	1,950,113	Not reported	1,411,258	96%	0.69
Dow Chemical (Freeport, TX)	1,640,000	LHC 7: Ethane (50%), Propane (50%) LHC 8: Ethane (10%), Propane (20%), Naphtha (70%)	2,656,304	N/A	N/A
Dow Chemical (Plaquemine, LA)	1,260,000	LHC 2: Ethane (75%), Propane (25%) LHC 3: Propane (70%), Butane (10%), Naphtha (20%)	2,318,118	58%	1.07
Dow Chemical (Taft, LA)	1,000,000	Unit 1: Ethane (20%), Propane (40%), Naphtha (40%) Unit 2: Not reported	2,343,557	44%	1.03
DuPont (Orange, TX)	680,000	Ethane (100%)	993,914	17%	0.25
Eastman Chemical (Longview, TX)	781,000	Ethane (25%), Propane (67%), Butane (7%), Naphtha (1%)	2,262,549	32%	0.93
Equistar Chemicals (LyondellBasell) (Channelview, TX)	1,750,000	Ethane (5%), Naphtha (95%)	1,886,325	71%	0.76
Equistar Chemicals (LyondellBasell) (Clinton, IA)	476,000	Ethane (80%), Propane (20%)	421,998	43%	0.39
Equistar Chemicals (LyondellBasell) (Corpus Christi, TX)	771,000	Ethane (10%), Propane (30%), Naphtha (60%)	1,170,011	58%	0.88
Equistar Chemicals (LyondellBasell) (LaPorte, TX)	1,189,000	Ethane (60%), Propane (20%), Naphtha (20%)	1,113,490	94%	0.88
Equistar Chemicals (LyondellBasell) (Morris, IL)	550,000	Ethane (80%), Propane (20%)	391,192	79%	0.56
ExxonMobil Chemical (Baton Rouge, LA)	1,000,000	Ethane (9%), Propane (8%), Butane (8%), Naphtha (25%), Gas Oil (25%), Other-Residue (25%)	4,425,161	15%	0.65
ExxonMobil Chemical (Baytown, TX)	2,200,000	Ethane (58%), Propane (8%), Butane (9%), Naphtha (25%)	7,797,812	3%	0.08
ExxonMobil Chemical (Beaumont, TX)	900,000	Ethane (8%), Propane (8%), Butane (9%), Naphtha (75%)	4,708,198	9%	0.47
Flint Hills (Port Arthur, TX)	634,921	Naphtha (60%), Other-LPG (40%)	783,141	53%	0.66
Formosa Plastics (Point Comfort, TX)	1,541,000	Ethane (45%), Propane (15%), Naphtha (40%)	3,721,786	41%	0.99
Huntsman (Port Neches, TX)	180,000	Not reported	902,951	18%	0.89
INEOS Olefins and Polymers USA (Chocolate Bayou, TX)	1,752,000	Ethane (50%), Propane (35%), Naphtha (15%)	2,296,932	53%	0.70

(CONTINUED)

TABLE 5 (CONTINUED)

Greenhouse Gas Emissions from US Ethylene Producers

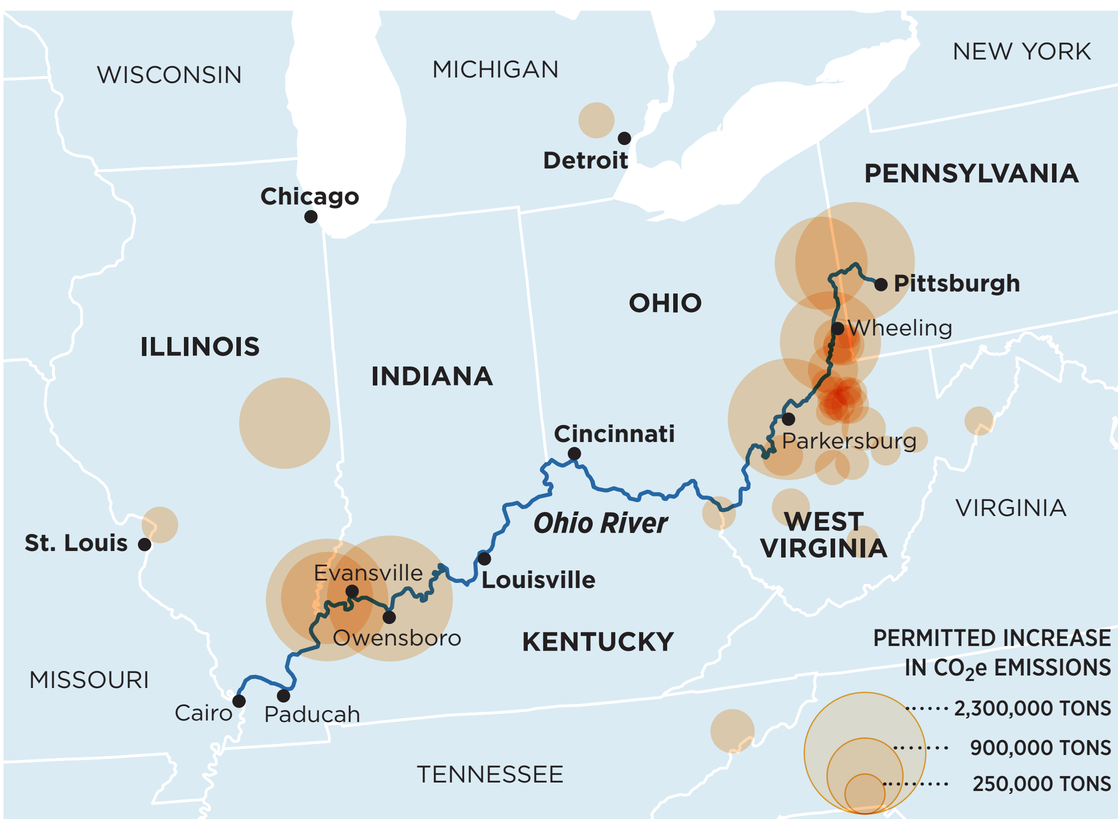
Plant (location)	2015 Capacity (Mt per year)	Feedstock mix	Total CO_2e Emissions Reported (Mt)	% from Ethane Cracking	Emission Rate (CO_2e from ethylene/ ethylene capacity)
Javelina (Corpus Christi, TX)	151,000	Other-Ref. Gas (100%)	35,393	N/A	N/A
Sasol (Lake Charles, LA)	471,655	Ethane (100%)	636,129	N/A	N/A
Shell Chemicals (Deer Park, TX)	1,179,138	Not reported	3,336,201	25%	0.71
Shell Chemicals Ltd. (Norco, LA)	1,451,247	Ethane (5%), Naphtha (35%), Gas Oil (60%)	2,337,013	26%	0.41
Westlake Petrochemicals (Calvert City, KY)	285,714	Ethane (100%)	373,022	2%	0.03
Westlake Petrochemicals (Sulphur, LA)	1,197,844	Unit 1: Ethane (100%) Unit 2: Ethane (70%), Propane (30%)	857,886	22%	0.16
Williams Olefins (Geismar, LA)	884,354	Ethane (92%), Propane (8%)	347,774	N/A	N/A

Source: USEPA Permits.

FIGURE 9

Planned Petrochemical Production Buildout in the Ohio River Valley

Of 128 existing or potential facilities that are part of a vast buildout of the petroleum and petrochemical industry in the Ohio River Valley, 38 have data available on permitted emissions increases. Shown below, these increases would add 21,866,924 tons per year of CO_2e emissions.



Sources: Proprietary databases and reports from industry and trade press, and datasets maintained by environmental advocacy groups.

are already underway to expand US capacity by at least 13.6 million Mt per year (see Table 6). Six of the 12 projects also involve expanding capacity of other downstream products, like PVC and PE. All but one of these projects (PTT Global Chemical America) have been authorized to begin construction under the Clean Air Act. These projects have the potential to directly emit a total of 21.2 million Mt CO_2e per year.[199] The majority of these new cracker projects are being built along the Gulf Coast of Texas and Louisiana, which is already a major global petrochemical hub. Two of the new projects are located near the Marcellus shale formation in Pennsylvania and Ohio, where the fracking boom is fueling industry plans to create a major new petrochemical hub in the region.[200]

BOX 7

Manufacturing Emissions Daily

The US Department of Energy's National Renewable Energy Laboratory estimated that daily CO_2e emissions from the average petrochemical manufacturing facility were about 1,252 Mt per day in 2014, and 643 Mt per day for plastic manufacturing. Petrochemical manufacturing required average process heat temperatures of 875°C, while plastic material and resin manufacturing required temperatures of 291°C.[201] In total for 2014, 35 petrochemical (ethylene) facilities released 43,806 Mt per day, and 72 plastic manufacturing facilities released 46,324 Mt CO_2 per day.[202]

TABLE 6

US Ethylene Expansions and Potential Emissions Increases

Company (Location)	2015 Ethylene Capacity (Mt/year)	2015 GHG Emissions (tons CO_2e)	New Capacity (Mt ethylene/year, other products specified)	Potential CO_2e Increase (tons/year)
OxyChem/Mexichem (Ingleside, TX)	N/A	N/A	544,000	474,976
Dow Chemical (Freeport, TX)	666,800	2,928,091	1,500,000	2,942,218
ExxonMobil Chemical (Baytown, TX)	2,200,000	8,596,932	1,500,000	1,453,293
Chevron Phillips Chemical (Cedar Bayou, TX)	835,000	1,137,171	1,500,000	1,615,000
Formosa Plastics (Point Comfort, TX)	1,541,000	4,103,006	1,250,000	3,868,872
Sasol (Lake Charles, LA)	471,655	701,239	1,600,000 LDPE: 450,000 LLDPE: 450,000 EO/EG: 300,000 Ethoxylates and detergent alcohols: 300,000	3,955,120
Westlake (Axiall)/Lotte (St. Charles, LA)	N/A	N/A	1,000,000 MEG: 771,617	1,155,059
Shintech (Plaquemine, LA)	N/A	N/A	500,000 PVC: 407,500 Caustic Soda: 800,000 Chlorine: 700,000 Vinyl chloride monomer: 1,200,000 Ethylene dichloride: 750,000	1,403,807
Shell (Monaca, PA)	N/A	N/A	1,500,000 HDPE/LLDPE: 1,100,000 HDPE: 500,000	2,248,293
Total/Borealis/Nova (Port Arthur, TX)	N/A	N/A	1,000,000	1,396,476
PTT Global Chemicals America (Dilles Bottom, OH)	N/A	N/A	1,500,000 HDPE: 650,000 LLDPE: 900,000	1,764,765
Exxon/SABIC (Gregory, TX)	N/A	N/A	1,800,000 PE: 1,300,000 MEG: TBD	2,933,595
Total			**13,694,000 (Ethylene only)**	**23,446,709**

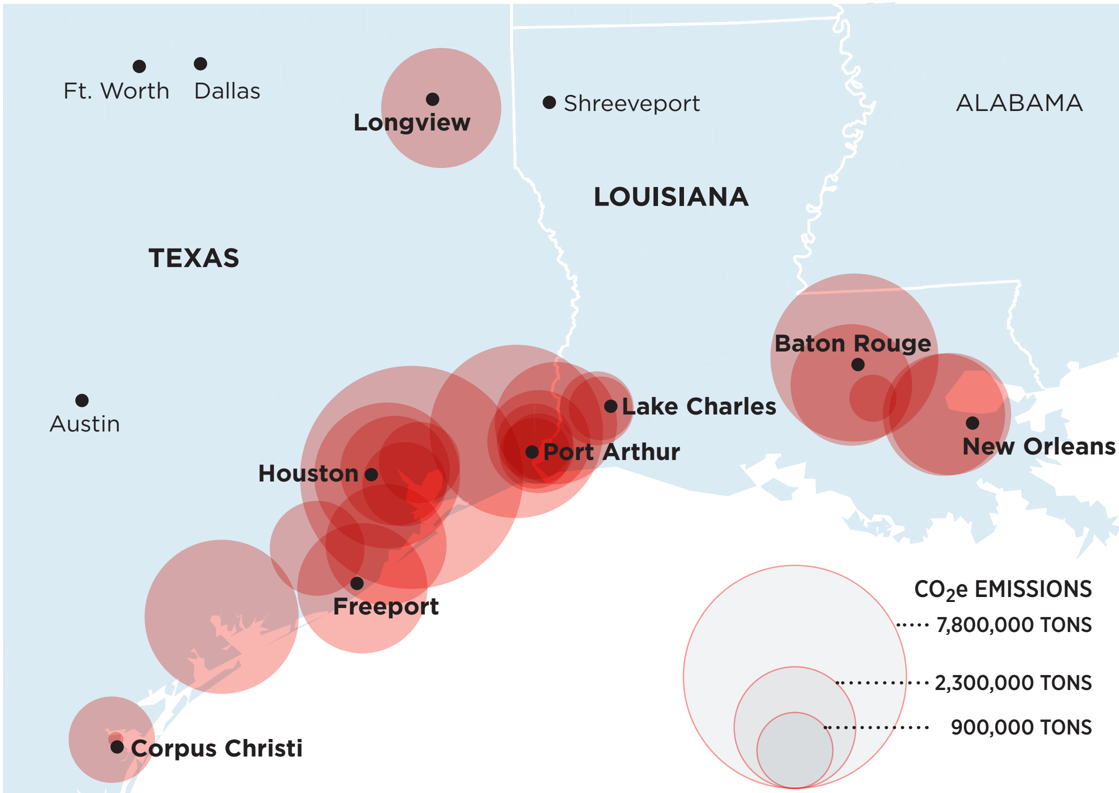
Note: CO_2e increases are from permits and permit applications, which were calculated using AR4 global warming potentials, not AR5. They are also in US short tons, not metric tons.

Sources: USEPA permits; Insights from *First Wave of US Ethylene Projects Drive Second Wave Decisions*, Petrochemical Update (May 5, 2017), http://analysis.petchem-update.com/engineering-and-construction/insights-first-wave-us-ethylene-projects-drive-second-wave-decisions.

FIGURE 10

Emissions from US Gulf Coast Petrochemical Plants that Produce Ethylene

The US had 28 industrial facilities with ethylene crackers in 2015, capable of producing 28.4 million metric tons of ethylene a year. These sites reported total emisions of 53 million metric tons of CO_2e in 2015, though many make of a range of products, so not all of those emissions can be attributed to steam cracking. All but three of these sites were near the Gulf Coast.



Sources: Oil & Gas Journal, Special Report: International Survey of Ethylene from Steam Crackers (2015), https://www.ogj.com/content/dam/ogj/print-articles/volume-113/jul-6/International-survey-of-ethylene-from-steam-crackers--2015.pdf; US EPA, Greenhouse Gas Reporting Program (2015).

RESIN MANUFACTURING

Resin manufacturing processes and energy requirements vary by product and so do their emissions. Certain types of plastic—such as PS and PET—are more energy intensive to produce than others—such as LLDPE, LDPE, HDPE, and PP—because of the additives or catalysts needed in the manufacturing process. Like in cracking, emissions and energy requirements vary by production method and efficiency, as well as plant age and the types of emissions controls used. Growth in US ethylene is fueling an increase in polyethylene production, which is expected to increase from 17 million Mt in 2015 to 23 million Mt (a 35-percent increase) by 2020.[203] US PET production was three million Mt in 2012, with increases expected as a new plant in Corpus Christi, Texas, will add another 1.1 million Mt per year when constructed.

LDPE requires compression to 100-300 megapascals, interstage cooling, and reactor temperatures between 130°C and 330°C. Some process heat can be collected and reused. PET, in contrast, requires additional inputs and energy to produce. Its building blocks are ethylene glycol and terephthalic acid. The former is created from ethylene, and the latter is produced from xylene, hydrogen, and acetic acid. Two processes can be used to create PET: esterification and trans-esterification. Each process relies on ethylene glycol but different forms of terephthalic acid (purified or dimethyl) and it yields either water or methanol as a byproduct. Polymerization is a two-step reaction that requires temperatures of 260°C and 260-300°C.[204]

Existing Cradle-to-Resin Lifecycle Analysis Estimates

As noted in Chapter 3, the most recent research into cradle-to-resin greenhouse gas emissions for plastic are modeled on emissions factors prepared by Franklin Associates in 2011.[205] Table 7 shows annual greenhouse gas emissions estimates based on 2015 North American resin production, scaled up by 33–36 percent through 2030, holding all else equal. Using these CO_2e emission rates, the production of 38 million Mt of the seven most common plastic resins likely resulted in the release of 67.9 million Mt of greenhouse gases in 2015, including emissions from oil and natural gas extraction. This is roughly the equivalent of 15 five-hundred-megawatt coal plants running around the clock for a full year. By 2030, total annual greenhouse gas emissions could expand to as much as 92.4 million Mt, or the equivalent of 20 five-hundred-megawatt coal plants.[206] As detailed above, these estimates likely underestimate the actual greenhouse gases emitted in 2015. They do not include any indirect emissions, direct emissions associated with plant leaks and malfunctions, or other situations in which emissions may be higher than normal, such as natural disasters.

Opportunities to Reduce Emissions from Plastic Production

Several studies have examined ways to reduce greenhouse gas emissions during this step in the process. Posen et al. argue that manufacturing plants could source their energy from renewable sources where possible and reduce overall greenhouse gas emissions by 50–75 percent at a cost of $85 per Mt of plastic. They could also transition to using bio-based feedstocks, which, in the case of corn-based plastic, could reduce emissions by 25 percent at a cost of $3,000 per Mt of plastic.[207]

These are, at best, incomplete solutions. For example, a 2018 analysis by Material Economics suggested that even powering plastic production with 100 percent zero-carbon energy sources would reduce overall emissions by only half.[208]

A 2018 analysis by Material Economics suggested that even powering plastic production with 100 percent zero-carbon energy sources would reduce overall emissions by only half.

IEA makes several broad policy recommendations that might reduce greenhouse gas emissions from petrochemical manufacturing in the long term, assuming that production does not increase from current levels. These include: directly stimulating research and development of sustainable production and methods for limiting risks; establishing and extending plant-level benchmarking, including parameters like energy efficiency and CO_2 emissions; creating policies that reduce CO_2 emissions; setting stringent air quality standards; and structuring fuel and feedstock subsidies so that they do not inhibit the use of more sustainable alternatives to fossil fuels and feedstocks. Under the best-case scenario outlined by the IEA, reducing greenhouse gases in the long term will also involve increased recycling rates to reduce demand for primary chemicals and feedstocks. Companies will also have to shift to lighter feedstocks and improve energy efficiency by using new technologies

TABLE 7

Cradle-to-Resin Greenhouse Gas Emissions Estimates Based on US Resin Production

Resin	Mean Emissions Factor (unit CO_2e/ unit plastic/year)	North American Production (million metric tons, 2015)	2015 CO_2e Emissions (million metric tons, 2015)	Assuming 33–36% Production increase (million metric tons per year by 2030)
Polystyrene (PS)	3.1	2	6.2	8.2–8.4
Polyethylene Terephthalate (PET)*	2.4	2.8*	6.7	8.9–9.1
Polyvinyl Chloride (PVC)	2.2	6.7	14.7	19.6–20.0
Low-Density Polyethylene (LDPE)	1.8	3.2	5.8	7.7–7.8
Linear Low-Density Polyethylene (LLDPE)	1.5	6.6	9.9	13.2–13.5
High-Density Polyethylene (HDPE)	1.5	8.6	12.9	17.2–17.5
Polypropylene (PP)	1.5	7.8	11.6	15.6–15.9
Total		**38**	**67.9**	**90.3-92.4**

* PET production is from 2012

Source: Daniel Posen et al., *Greenhouse Gas Mitigation for U.S. Plastics Production: Energy First, Feedstocks Later,* 12(3) *Envtl Res. Letters* (Mar. 16, 2017), *https://iopscience.iop.org/article/10.1088/1748-9326/aa60a7/pdf.*

© Carroll Muffett/CIEL

like naphtha catalytic cracking, which requires less naphtha than steam cracking.[209]

IEA also suggests that further integration of petrochemical and plastic manufacturing within existing natural gas, oil, and fossil fuel industries would improve efficiency and allow expanded use of carbon capture, usage, and storage (CCUS) technologies.[210] However, CCUS technologies impose significant energy penalties that limit the emissions reduction benefits. Moreover, the most economic uses of carbon capture are likely to result in increased production of oil or combustible fuels that exacerbate emissions.[211] Finally, developing and deploying CCUS projects at scale will require significant new investments in long-lived fossil fuel infrastructure, which is incompatible with the rapid phaseout of fossil fuels required to keep climate change to below 1.5°C of temperature rise.[212]

PLASTIC PRODUCT MANUFACTURING

The plastic manufacturing process is the stage in the lifecycle in which a thermoplastic or resin in pellet form undergoes a series of molding processes to create final products, like single-use containers for fast-moving, consumer-facing brands. For the key plastic manufacturing processes, emissions are released as part of the direct emissions from processing, as well as the indirect emissions from processes that contribute to finished polymers, including PE, PP, and PS.

Plastic packaging represents 40 percent of total production of plastic products.[213] Plastic packaging is typically single-use, ubiquitous, and extremely difficult to recycle. Bottles, bags, wraps, and films comprise the largest packaging segments by revenue.[214] According to the United Nations Environment Programme (UNEP), the negative impacts of plastic packaging are estimated at $40 billion and expected to increase with significantly expanded production under a business-as-usual scenario.[215]

Recommendations for Reducing Emissions in Plastic Manufacturing

Proponents of the circular economy advocate for developing business models and industry structures to greatly increase the usable lifespan of products and materials, dramatically reduce material production and the consumption of raw materials, and reduce the greenhouse gas emissions that arise from unnecessary production, consumption, and waste disposal.[216] For the manufacturing of plastic, this includes policies and initiatives that address:

Materials Reduction: Curtail and reduce the unnecessary or excessive use of materials, through changes in processes, products, or behaviors. In the plastic context, this would include initiatives to ban or curtail the use of non-essential plastic, including single-use disposable plastic commonly found in packaging, food and beverage service, and fast-moving consumer goods.

Materials Recirculation: Develop the policies, technologies, and systems necessary to reduce waste and decrease reliance on virgin materials by ensuring products are designed and managed throughout their lifecycles for reuse and continual recycling (rather than downcycling). These processes include setting and reinforcing standards to regulate waste and improving the design and end-of-life handling of products. At present, strategies for materials recirculation face significant systemic challenges, which are discussed in Chapter 6. Accordingly, simple pledges to increase recycling rates, even dramatically, are unlikely to address either the material or the climate impacts of growing plastic production.

Product Material Efficiencies: Ensure greater use for materials and incentivize reuse and recycling through target initiatives intended to improve product materials through greater transparency, technology, and information.

Circular Business Models: Stimulate reuse as a way to support fewer products for the same benefit, service, or output. Developing business models that increase use while prolonging the lifetime of materials-intensive assets could reduce emissions by 62 million Mt CO_2 per year. [217]

These processes include adopting greater energy efficiency technologies in the manufacturing process, improving design and management of raw materials, and fostering greater use and reuse by the largest consumer-facing producers. Reducing waste in production, extending the lifetime of products, and deploying new business models could produce rapid and significant improvements in both waste streams and greenhouse gas emissions. Adopting circular economy strategies alone, however, is unlikely to outpace the scale and rate of petrochemical infrastructure expansion. For example, the American Chemistry Council is also ostensibly embracing the circular economy approach by making statements that resin producers aim to recycle or recover 100 percent of plastic packaging by 2040.[218] Such statements obscure the fact that the intended path towards achieving such goals include accelerating plastic production that would be "balanced out" by dramatically increasing incineration, as a form of plastic "recovery."

On average, the production of one ton of plastic resin will emit 1.89 Mt CO_2e. When the differing emission profiles in the US and Europe are taken into account, producing a ton of PE will release 1.675 Mt CO_2e; PP, 1.55 Mt; PET, 2.275 Mt; PVC, 2.095 Mt; and PS, 3.2 Mt.

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CHAPTER SIX

Plastic Waste Management

"END OF LIFE" IS NOT END OF IMPACT

As previous chapters demonstrate, the direct and indirect greenhouse gas emissions from plastic production, transport, refining, and manufacture are significant. Yet the climate impact of plastic does not end after the plastic has been used and is discarded. Depending on how it is handled, plastic can pose just as significant a threat to the climate when it reaches the waste phase of its lifecycle. For most materials, this stage is often referred to as "end of life." In truth, because plastic continues to pollute long after its useful "life" is over, there is increasing understanding that there is no such thing as an "end of life" for plastic.

This chapter aims to shed light on the climate impact of plastic after it is used, examining direct and indirect greenhouse gas emissions and emissions offsets at the disposal stage of the plastic lifecycle. As no contemporary research provides quantitative estimates for greenhouse gas emissions from different plastic waste management methods, Sound Resource Management Group undertook modeling and data analysis specifically for this report. The analysis provides the current status and future prospects of greenhouse gas emissions from incineration, disposal at landfills, and recycling, based on existing estimates of worldwide plastic generation and disposal. The scope of this analysis is adjusted to plastic packaging, due to the lack of data on the composition of all plastic waste at a global level. A detailed description of the research methodology and relevant sources are online at *http://www.no-burn.org/plastic-climate-appendix*.

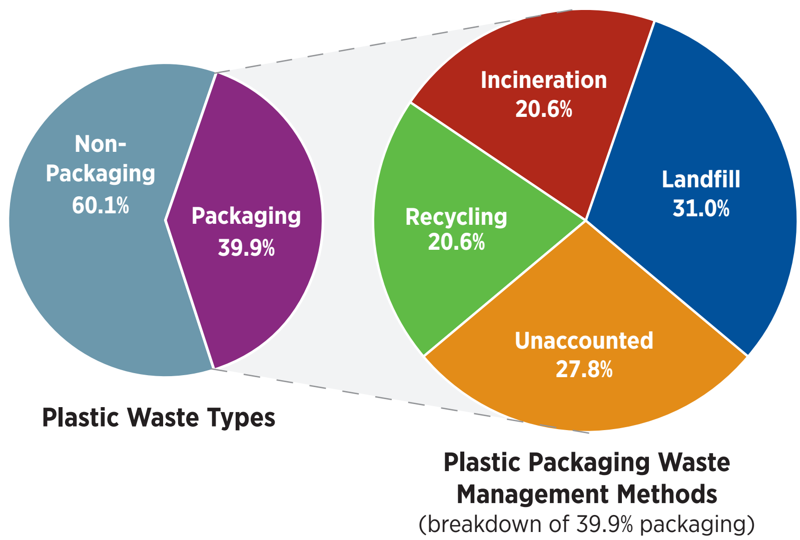
Known Paths of Plastic Waste

While some plastic can be recycled, doing so involves many steps that require separate collection, long-distance transportation, processing, and re-manufacture. The high costs of these steps, the low commercial value of recycled plastic, and the low cost of virgin material mean that plastic recycling is rarely profitable and requires considerable government subsidies. Due to these limitations, only nine percent of all plastic ever discarded since 1950 has been recycled, while another 12 percent has been incinerated.[219] The remaining plastic has been buried or ended up in open yards for burning and dumping, in oceans and other waterways, and scattered across human and natural landscapes worldwide.

Regardless of disposal method, all discarded plastic represents a danger to human health and the environment. Whenever plastic is burned, it emits greenhouse gases, principally CO_2. Plastic

FIGURE 11

Global Plastic Packaging Waste Management, 2015



Opposite: © Claire Mortimer/Greenpeace

FIGURE 12

Generation, Recycling, and Disposal of Plastic in the US, 2015

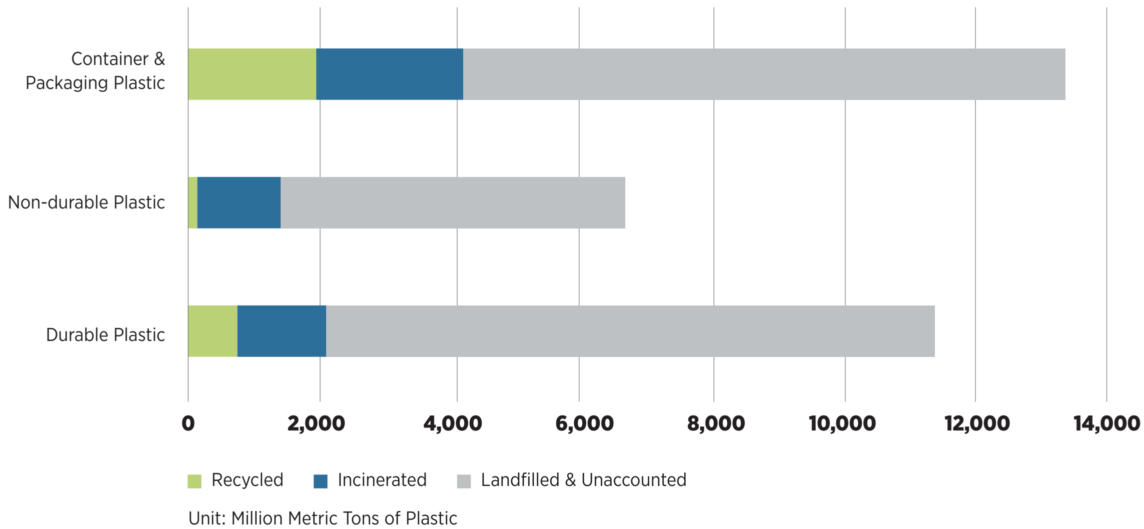


TABLE 8

1960–2015 Data on Plastics in MSW by Weight (in thousands of US tons)

Management Pathway	1960	1970	1980	1990	2000	2005	2010	2014	2015
Generation	390	2,900	6,830	17,130	25,550	29,380	31,400	33,390	34,500
Recycled	—	—	20	370	1,480	1,780	2,500	3,190	3,140
Composted	—	—	—	—	—	—	—	—	—
Combustion with Energy Recovery	—	—	140	2,980	4,120	4,330	4,530	5,010	5,350
Landfilled	390	2,900	6,670	13,780	19,950	23,270	24,370	25,190	26,010

Sources: American Chemistry Council and the National Association for PET Container Resources. A dash in the table means that data is not available.

also contains hazardous chemicals in the form of additives that are released into the environment. Concentrations and quantities of these pollutants vary depending on how plastic waste is handled. The human health impacts of plastic incineration are reviewed in greater detail in the companion report *Plastic & Health: The Hidden Costs of a Plastic Planet.*

In the US, plastic waste in municipal solid waste (MSW) streams is managed by recycling, landfilling, and burning in waste-to-energy facilities. Plastic waste managed in MSW amounted to 34.5 million tons in 2015, comprising about 13 percent of total MSW generated that year.[220] As indicated by the estimates from USEPA for 2015 shown in Figure 12,[221] landfilling was the primary handling method for plastic waste, accounting for 75.4 percent. The remainder was either incinerated (15.5 percent) or recycled (9.1 percent). For non-durable and container/packaging plastic, the proportion incinerated was greater than for durable plastic.

An unknown amount of plastic packaging waste in the United States is mismanaged, primarily via littering and open burning.[222] The mismanagement rate is relatively low, compared to other countries with lower waste collection and processing capacity, which often leads to an assumption that low-income countries are responsible for unmanaged waste leaking into oceans and lands. However, high per-capita waste generation and large coastal populations result in a large mass of uncontrolled plastic waste even when rates of mismanagement are low, as shown in one study that estimated that the US is among the major contributors to plastic ocean leakage.[223]

Plastic Packaging Waste

Plastic packaging represents 40 percent of total production of plastic products.[224] Packaging is one of the most problematic types of plastic waste, as it is typically designed for single use, ubiquitous in trash, and extremely difficult to recycle. A constant increase in the use of flexible and multi-layered packaging has been adding challenges to collection, separation, and recycling. Figure 10 on page 55 shows current plastic packaging waste management methods in use worldwide. While 40 percent of plastic packaging waste is disposed of at sanitary landfills, 14 percent goes to incineration facilities, and only 14 percent was collected for recycling, 12 percent of which failed to be recycled into the same or similar quality of the original form.[225] The remaining 32 percent follows other pathways, including open dumping, open burning, and uncontrolled release onto land and into water.[226]

In Europe, efforts to divert plastic packaging waste from landfills have accelerated over the past decade, showing an increase in recycling and incineration with energy recovery.[227] The trend is more distinct among countries that implement bans on landfilling recyclable waste, most of which tend to heavily rely on waste incineration with energy recovery.[228] In the following sections, the climate impact of growing dependence on waste incineration is examined under a series of possible future scenarios.

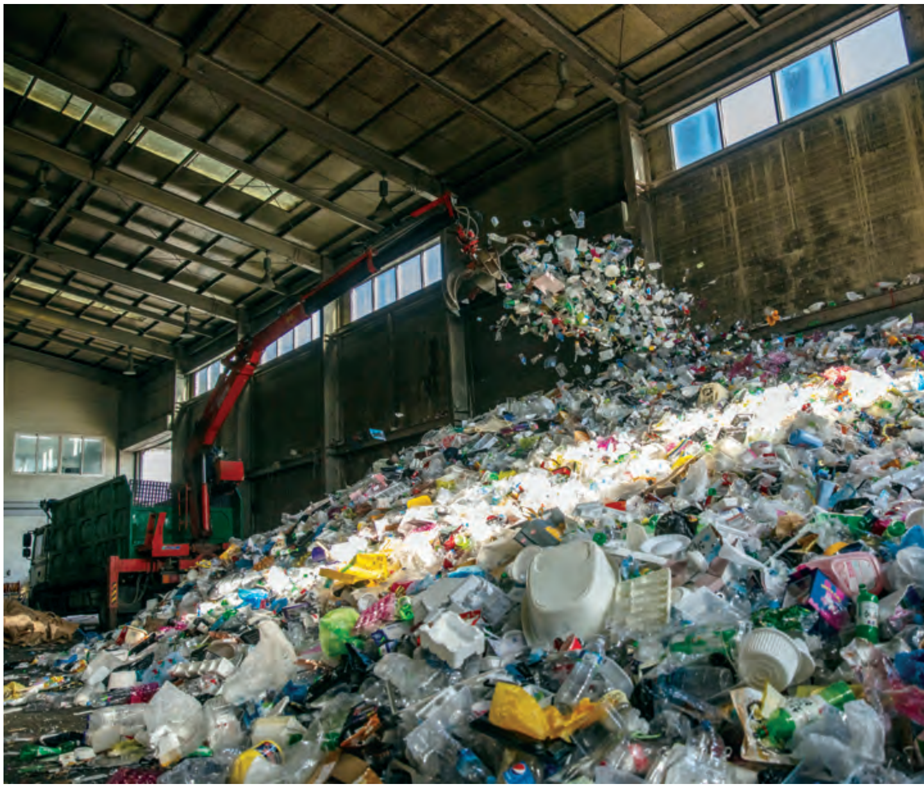
GREENHOUSE GAS EMISSIONS FROM PLASTIC WASTE DISPOSAL

There are several ways of managing plastic waste, each of which has clear implications for the climate. As stated earlier, this analysis compares greenhouse gas emissions from recycling, landfilling, and incineration with energy recovery, based on the data available for plastic packaging waste. Key parameters and estimates factored into this analysis include annual plastic production in 2015, plastic packaging portion of total plastic production (39.9 percent in 2015), polymeric composition, and combustible carbon content plastic packaging, which enable estimating of carbon emissions from power generation and potential emissions offsets though energy recovery. Indirect greenhouse gas emissions from energy use for materials handling and waste collection were calculated to quantify the climate impact of plastic waste throughout the disposal process. In order to estimate net greenhouse gas emissions from plastic recycling, emissions offsets from replacing virgin material production with recycled content were calculated. For estimates of greenhouse gas emissions offsets resulting from energy recovery, the analysis applies a conservative estimate from the EIA of the current and future ratios of natural gas and renewable energy in the energy mix. Detailed references and assumptions are available at: *http://www.no-burn.org/plastic-climate-appendix*.

As shown in Figure 13, incineration, including waste-to-energy, creates the most CO_2 emissions among the plastic waste management methods. Waste collection, hauling, and processing also create climate-changing greenhouse gas emissions, mainly due to energy use. These various waste management methods are discussed in more detail in the following sections, beginning with the most intensive emissions-producing processes first.

Waste Incineration and Waste-to-Energy

Incineration is often thought of as an easy answer to large-scale, land-based plastic pollution. Frequently touted for its ability to turn waste to energy, incineration converts waste into air pollutants, bottom ash, fly ash, combustion gases, wastewater, wastewater treatment sludge, and heat by burning. In urban areas, incineration of waste occurs at waste-to-energy (WTE) facilities and other industrial facilities, including utility



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boilers, paper mills, and cement kilns, in which collected wastes are burned with coal or biomass in a process known as co-incineration.

As Figure 13 depicts, one Mt of plastic burned results in 0.9 Mt of net CO_2e emissions, even after taking into account the electricity generated by the combustion process. On average, one Mt of plastic packaging contains 79 percent combustible carbon content,[229] which would release 790 kg of carbon, or about 2.9 Mt of CO_2, into the atmosphere.[230] The USEPA recognizes that net greenhouse gas emissions can be reduced through energy recovery by offsetting the need for energy from fossil sources. Accordingly, USEPA's analysis quantified the power generation potential for plastic packaging burned in MSW in a WTE facility by multiplying average energy content of plastic packaging waste by an average electricity output efficiency for WTE incinerators of 17.8 percent.[231] The estimated power generation potential of less than 2,000 kilowatt hours (kWh) per Mt was further converted to natural gas and renewable energy offsets based on EIA estimates for worldwide electricity generation, to reach a conclusion that incineration of plastic packaging waste will still result in 0.9 Mt of CO_2e emissions, even when two Mt of CO_2e can be offset by energy recovery.

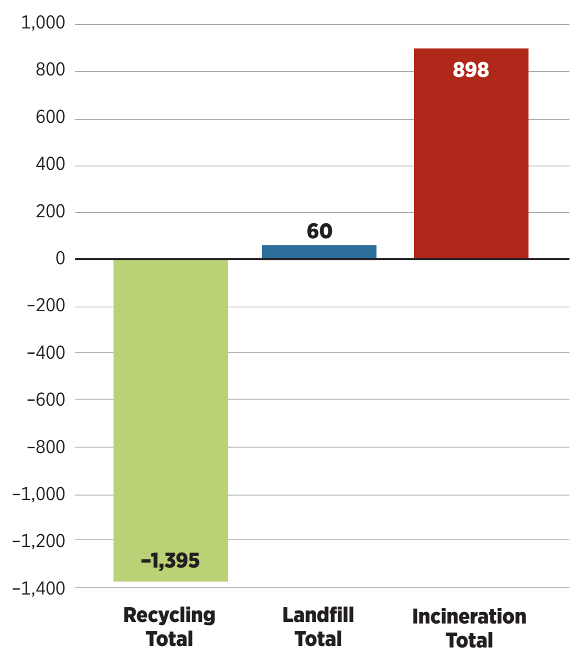
The greenhouse gas emissions offset potential can vary depending on a number of factors, including the type of energy used in the incinerators and the composition of waste feedstock that is burned. When municipal solid waste is too low in calorific value and/or too high in moisture content, additional fossil fuels are required to sustain the combustion. For example, in China, the ratio of coal in the fuel used in MSW incinerators is as high as 50-70 percent due to the large portion of organic waste.[232]

According to our analysis, net greenhouse gas emissions attributable to the incineration of plastic packaging are estimated to be 16 million Mt in 2015. These figures are based on the estimated amount of plastic packaging waste (40 percent of all plastic waste) collected for management (64 percent); thus, it reflects only 25 percent of all plastic waste. For a broader plastic waste stream, including plastic packaging and non-packaging plastic waste, USEPA reported that waste incineration released 11 million Mt CO_2e in the US, more than half of which came from plastic waste (5.9 million Mt) in 2015.[233] The climate impact of plastic waste incineration in the US is equivalent to 1.26 million passenger vehicles driven for one year, or more than half a billion gallons of gasoline consumed.[234]

When plastic packaging waste commingled in MSW is burned in a WTE incinerator, the generated electricity replaces power generated from other

FIGURE 13
Climate Impacts of Plastic Packaging Waste Disposal Options (kg CO_2e/metric ton)

Activities/Processes	Recycling	Landfill	Incineration
Collection/Self-Haul	45	35	35
Material Handling	650	25	38
Virgin Material Offset	−2,090		
Biodegradation		0	
Incineration			2,894
With Energy Recovery			
Natural Gas Offsets			−2,040
Renewable Energy Offsets			−30
Total	**−1,395**	**60**	**898**



Note: This analysis assumes that all incineration is conducted with energy recovery, as exact data on the ratio of incineration without energy recovery is currently not available. While incineration without energy recovery does exist, it results in 2,894 kg CO_2e of greenhouse gases per Mt of plastic burned, which is the same as open burning. US EIA, International Energy Outlook, 2017 (data for 2015) estimates that renewable energy accounted for 17 percent of worldwide electricity generation in 2015.

Source: Sound Resource Management Group, Inc provided this analysis based on the sources available at *https://www.no-burn.org/plastic-climate-appendix*.

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fuels. In many cases, this will be natural gas because natural gas turbines are often used for peaking power on electrical power grids, or are often the type of energy used in power generation facilities that are the next in line for construction. To an ever greater degree, new power production also comes from renewable solar or wind energy facilities. According to the EIA, in 2015, natural gas combustion produced almost five times as much electricity worldwide as did renewable solar, wind, and geothermal energy.[235] This ratio was used to calculate the WTE greenhouse gas offsets for natural gas and renewable solar. Those calculations also take into account the relative fossil carbon footprints of electricity generated from renewable solar, natural gas, and packaging plastic waste.[236] As the proportion of renewable energy in the energy mix continues to grow over the coming decades, the net emissions from incinerating plastic will increase as electricity production will be less dependent on fossil fuels, resulting in smaller emissions offsets. An analysis of lifecycle plastic emissions in Europe undertaken by Material Economics concluded that, as this energy transition occurs,

In 2015, USEPA reported plastic waste incineration released 5.9 million Mt CO_2e. As the energy transition occurs, the incineration of plastic waste will become one of the largest sources of fossil fuel emissions in Europe's energy sector.

the incineration of plastic waste will become one of the largest sources of fossil fuel emissions in Europe's energy sector.

The climate impact of plastic waste management will increase even more dramatically if industry's plans to increase incineration and expand petrochemical buildout by 2030 and 2050 come to fruition. The continuing decarbonization of the energy mix will also result in an increase in the proportion of net greenhouse gas emissions from the incineration of plastic packaging. As a result, greenhouse gas emissions from plastic packaging waste are projected to reach 84 million Mt and 309 million Mt by 2030 and 2050, respectively. (See Figure 14.)

BOX 8

Future Scenarios of Greenhouse Gas Emissions from Plastic Packaging Waste Incineration with Energy Recovery

THE INDUSTRIAL OUTLOOK

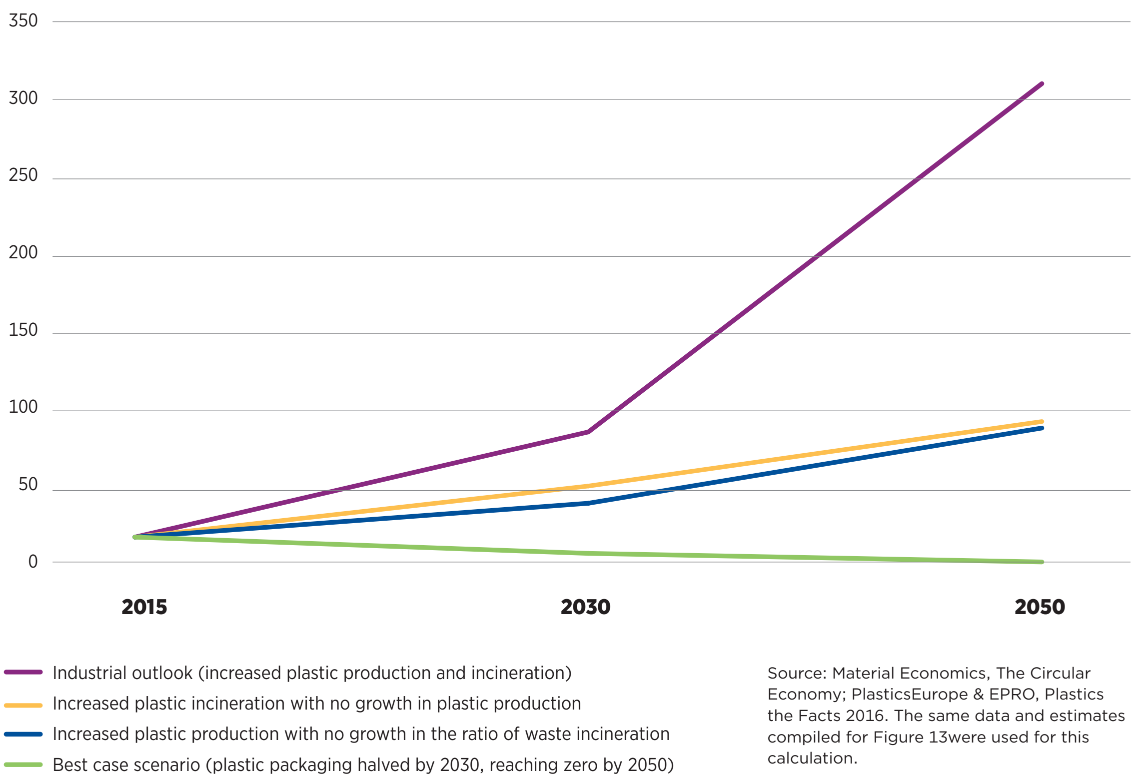
This scenario factors in the growth in plastic packaging production and the expansion of incineration capacity based on industry projections. According to several sources, plastic packaging production is expected to nearly double by 2030 or 2035 and nearly quadruple by 2050.[237] The present analysis estimates that this growth would increase plastic packaging waste from 128 million Mt in 2015 to 219 million Mt by 2030 and 435 million Mt by 2050. Greenhouse gas emissions from incineration of plastic packaging waste would grow correspondingly to 84 million metric tons by 2030 and 309 million metric tons by 2050. The faster growth in carbon emissions relative to plastic packaging waste is due entirely to faster growth in electricity generated from solar, wind, and geothermal energy versus natural gas and the corresponding fall in the carbon offsets for WTE, which was applied to all of the following cases.

INCREASED INCINERATION WITH NO GROWTH IN PLASTIC PRODUCTION

A recent study on world energy resources by the World Energy Council projected a greater than ten percent compound annual growth rate for waste-to-energy incineration between 2015 and 2025.[238] Assuming that WTE grows at above ten percent through 2030, WTE incineration would increase to 31 percent of treatment for all plastic packaging waste by 2030. Extending this scenario to 2050 assumes a somewhat slower growth of WTE after 2030, in which case 50 percent of plastic packaging waste is managed by WTE by 2050. This case shows that greenhouse gas emissions from

FIGURE 14

Future Scenarios of Greenhouse Gas Emissions from Plastic Packaging Waste Incineration with Energy Recovery



Unit: Million Mt CO_2e/year

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016. The same data and estimates compiled for Figure 13were used for this calculation.

plastic incineration would increase to 49 million Mt by 2030 and 91 million Mt by 2050, even when the total amount of plastic produced stays at the current level.

INCREASED PLASTIC PRODUCTION WITH SIMILAR INCINERATION RATE

Greenhouse gas emissions from plastic incineration would grow at a similar rate as the previous case if plastic production increases in line with industry projections, along with a slower growth of WTE. The present analysis assumes that the ratio of waste incineration as a waste management method will remain at 14 percent, which means WTE facilities expand proportionately to the growth rate of plastic production; this is less growth than the "industrial outlook" scenario. In this scenario, greenhouse gas emissions from plastic incineration will increase to 38 million Mt by 2030 and 87 million Mt by 2050.

THE BEST-CASE SCENARIO WITH SIGNIFICANT DECREASE IN PLASTIC PRODUCTION AND INCINERATION

These projections also include a best-case scenario for a future in which the use of plastic packaging is cut in half by 2030 and reaches zero by 2050, ultimately resulting in zero emissions from incineration of plastic packaging. The greenhouse gas emissions from this scenario would be as low as six million Mt by 2030 and zero by 2050. This last set of projections are guided by targets set as part of the New Plastics Economy Global Commitment—which was signed by more than 290 companies to eliminate problematic or unnecessary plastic packaging by 2025[239]—and Break Free From Plastic's goal of drastically eliminating all non-essential uses of plastic by 2035, following a peak of plastic packaging and other single-use disposable applications in 2025.[240]

BOX 9

Future Outlook on the US Energy Grid and the Implications on Greenhouse Gas Emissions Offsets

Electricity generation methods gradually evolve. That is, based on US Energy Information Administration projections for worldwide electricity generation through 2040,[241] the relative amounts of electricity produced from renewable solar, wind, and geothermal energy will rise relative to electricity production from natural gas. Currently, natural gas fuel generates 4.9 times as much electricity as the aforementioned renewables. In a conservative manner, EIA projects that this ratio will decrease to 2.1 by 2030 and continue decreasing at a slower rate through 2040. Assuming this slowdown continues, by 2050 natural gas would generate only 150 percent more electricity than the three renewables. This decreases the energy offset for waste-to-energy incineration of plastic packaging wastes, lowering the natural gas and renewables weighted average offset from 2,070 kg CO_2e per Mt of incinerated plastic in 2015 to 1,728 kg CO_2e by 2030 and 1,545 kg CO_2e by 2050.

In a future with 100 percent renewable electricity, there would be almost no carbon offsets for WTE electricity generation from burning plastic packaging waste. Even at present, carbon emissions per kilowatt generated from WTE incineration of plastic waste are not low enough to beat natural gas carbon emissions per kilowatt hour. That is, WTE incineration of plastic packaging waste is over 20 percent higher in carbon emissions per kilowatt hour than natural gas. Compared to renewables, the carbon emissions from WTE are greater by an order of magnitude. For example, solar electricity is almost 17 times more efficient than WTE incineration of plastic packaging waste for generating electricity. Thus, as electricity supplied to the power grid by renewables increases relative to natural-gas-fueled power, the net emissions from WTE incineration of plastic packaging increases from about 900 kg CO_2e per Mt of incinerated plastic at present to over 1,400 kg CO_2e per Mt of incinerated plastic by 2050.

It is likely that the net emissions from WTE will be significantly greater because the offsets of natural gas are almost certainly overestimated. Over the last decade or more, renewable energy deployments have routinely and substantially exceeded long-term forecasts by both EIA and IEA.[242] This trend has continued in recent years, suggesting that the proportion of fossil fuels in the global energy mix may decline much faster than EIA estimates. Moreover, as noted in the introduction to this report, the IPCC warns that global net emissions of CO_2 must fall to zero by 2050. The IPCC noted that achieving this goal will require the near complete elimination of fossil fuels from energy production and a transition to a renewable energy economy in the coming decades.[243]

BOX 10

Unknown Climate Impact of Plastic-to-Fuel

Gasification, pyrolysis, and plasma arc are other forms of waste incineration, which convert waste into synthetic gas or oils through combustion or other thermal processing. Plastic-to-fuel is a common name for these undefined technologies, which aim to convert all carbon-based materials into energy.[244] Studies sponsored by the American Chemistry Council argue that there are energy and environmental benefits associated with producing high-quality fuels in this manner.[245] Despite aggressive public relations campaigns and construction attempts, there are few facilities successfully operating on a commercial scale. Industry has recorded years of delays and high-profile failures due to operational inexperience, high costs, lack of financing, and environmental concerns around the globe.[246] Due to a lack of empirical data from commercial operations, the greenhouse gas emissions remain unquantified. The fuel produced through this technology is yet another fossil fuel, and the industry will need to prove self-claimed climate benefits by measuring indirect emissions from energy use and the emissions from burning final fuel products, as well as direct greenhouse gas emissions from the combustion process.

Landfilling

In this analysis, landfills refer to sanitary landfills that typically use a clay and/or plastic liner to isolate waste from groundwater and add a daily covering of soil to reduce the waste's exposure to air. Greenhouse gas emissions from landfills are mainly derived from organic waste, such as discarded food, yard trimmings, paper, and wood as they decompose. Landfill wastes of fossil origin have not been documented to emit greenhouse gases, nor are they counted as a carbon sink. Therefore, emissions related to landfilling plastic packaging result primarily from the fossil fuel use associated with the sorting and handling of the wastes prior to landfilling and the transportation of the waste from the collection point to the landfill. This does not exclude the possibility of greenhouse gas emissions from fires in the landfills, however, as an average of 8,300 fires are reported from landfills in the US alone each year.[247]

While landfilling poses significant environmental health risks due to toxic substances leaching into soil and waterways and its emissions from biogenic waste degradation, landfilling plastic waste has lower climate impacts than incineration, as shown in Figure 13. In some cases, landfilling—or dumping waste in an open yard—may be the only option for waste management when there is

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no collection system and no proper material recovery infrastructure in place. However, landfills produce acids by decomposing organics and leach heavy metals out of plastic into the groundwater and therefore cannot be viewed as a long-term solution for plastic waste management.[248]

Recycling

Plastic recycling refers to physical processes that recover materials without altering the molecular structure of the polymers. As Figure 13 demonstrates, plastic recycling has outstanding greenhouse gas benefits compared to other existing waste disposal methods. Making new products from recycled plastic packaging materials is more than three times more efficient in terms of greenhouse gas emissions than manufacturing those same products with virgin raw materials, mainly because of the energy savings in recycled versus virgin-content product manufacturing. For the 3.17 Mt of plastic waste recycled in the US in 2014, USEPA estimates 3.2 million Mt of CO_2e savings, which is equivalent to 670,000 less cars on the road over the course of a year.[249] Recycling a metric ton of plastic packaging into new products conserves almost 1.4 Mt CO_2e.

Theoretically, increased recycling results in negative greenhouse gas emissions by reducing raw material extraction and avoiding emissions from manufacturing an equivalent amount of material from virgin inputs. Emissions per ton of virgin plastic produced are estimated to be 3.6 times higher compared to recycling as of 2017.[250] This gap is estimated to widen to as much as 48 times higher by 2050, as efficiency in both plastic production and recycling improves.[251]

In reality, only a fraction of "recyclable" used plastic is recycled into the products for which they were originally produced, even in the case of the most readily recyclable plastic such as PET and HDPE.[252] The challenges are due to colorants, additives, and fillers used during plastic production, contamination from consumer use, and yield losses during the recycling process.[253] The low price of overproduced virgin plastic further limits the recyclability of plastic by lowering the economic value of recycled plastic and hindering investments in proper infrastructure and markets.[254] Even if plastic were recycled despite all the barriers above, each cycle of the recycling process shortens the length of polymer chains, resulting in quality loss and, eventually, the need to dispose of the material.[255] Lower-grade plastic waste, including post-consumer and multi-layered plastic packaging is particularly difficult to separate and process, which explains why the major plastic-consuming nations in Europe and North America have relied on international trade for plastic recycling, rather than processing plastic scrap at their own labor and environmental cost.[256]

With these limitations, recycling alone will not reduce greenhouse gas emissions from the plastic lifecycle commensurate with the reductions necessary to meet the Paris Agreement. Nevertheless,

BOX 11

Opportunities and Threats of China's Waste Import Ban

In January 2018, the Chinese government banned the import of waste to stop the overwhelming flow of low-grade plastic scrap being shipped to China from the Global North.[257] This ban has had a significant impact throughout the world and highlighted the urgent need to reshape local recycling systems and global policies on plastic production and disposal. The new waste policy bans imports of 24 types of solid waste, including post-consumer plastic, and strengthens contamination control rules for recyclables, rendering much plastic scrap sub-standard.

Local recycling systems, as well as the global recycling trade, have experienced upheaval since the ban was implemented, especially in countries that relied heavily on exporting low-grade plastic scrap for processing. In the United States, facilities in Arizona, Arkansas, Colorado, Hawaii, Maryland, Missouri, and New Jersey reported that they have stopped accepting mixed plastic scrap or have restricted collection to certain types of plastic (mostly PET and HDPE).[258] Scheduled shipments have been held, and material recovery facilities are stockpiling collected waste in many places. Instead of using the ban as an opportunity to consider building a domestically sustained recycling system and working to phase out single-use plastic and plastic packaging, many cities are exploring alternative destinations that can accommodate their waste, which prompted Vietnam, Thailand, and Malaysia to announce their own restrictions on plastic scrap imports.[259] Waste incineration has also been an option for some cities in the US, sparking community organizing against sending recyclables to incinerators.[260] Furthermore, communities are actively guiding cities to respond to the current disruption in domestic plastic recycling with zero-waste approaches focused on reduce and reuse. One example is an ordinance that was recently passed by the City Council of Berkeley, California, to curb disposable foodware.[261]

many studies continue to rely on plastic recycling as a primary solution to the plastic crisis. The Material Economics report states that the ideal scenario for plastic waste management in 2050 can be achieved by increasing plastic recycling capacity by 4.6 times, enabled by a collection rate of 85 percent for the five most common types of plastic, along with a six percent increase of waste-to-energy and more reuse practices. A recent report published by the Organisation for Economic Co-operation and Development and IEA also projects a 65 percent increase in production of recycled plastic compared to the baseline scenario by 2030 and an increase of more than double by 2050.[263]

BOX 12

Plastic Chemical Recycling: A False Solution to the Plastic Waste Crisis

Chemical recycling is a process that chemically transforms materials into their basic components with the purpose of reproducing the same material. While thermochemical and catalytic conversion technologies have been developed for some waste plastic, it is hard to estimate the greenhouse gas emissions associated with the use of high-temperature treatment and plastic solvents. In addition, the plastic industry often conflates chemical recycling with plastic-to-fuel technologies under the guise of terms like "plastic recovery."

For example, in May 2018, the American Chemistry Council announced a plan to ensure 100 percent of plastic packaging would be reused, recycled, or recovered by 2040, with an interim goal of making plastic packaging recyclable or recoverable by 2030.[262] This pledge, while appearing to be a step toward sustainability at face value, raises more questions than answers. The American Chemistry Council's plan to recover plastic includes a variety of technologies, such as pyrolysis, gasification, and other plastic-to-fuel systems (see Box 10: Unknown Climate Impact of Plastic-to-Fuel). Since this technology is relatively new and commercial operations are extremely limited, the greenhouse gas emissions impact of this form of plastic recycling remains unknown. In addition to unanswered questions about the feasibility of these techno-fixes, managing plastic waste through energy-intensive thermal processing to produce more oil and gas is hardly a solution that fits into a circular economy, and it does not recover materials to their original form. Furthermore, as the volume of unrecyclable plastic grows, a timeline much shorter than 2040 is needed to immediately curb plastic pollution.

Other Known Unknowns

The analysis above only covers plastic packaging that is collected for management, leaving the climate impact of almost one-third of world plastic packaging undefined. There are several possibilities for the unmanaged 32 percent of plastic packaging, including open burning, open dumping, and littering, which are more prevalent in rural areas or places with less developed waste management infrastructure.

Open burning, a practice of burning unwanted combustible materials in nature or in open dumps, has severe climate and health impacts because it is undertaken in the absence of air pollution controls and because it generally occurs at much lower temperatures compared to closed combustion environments.[264] Plastic packaging burned in the open releases 2.9 Mt CO_2e of greenhouse gases into air per ton of plastic packaging.

The climate impact of dumping waste into an open hole in the ground (open dumps) without extra effort to compact or cover it up is less defined. As discussed in Chapter 7, degrading plastic exposed to sunlight in terrestrial environments may off-gas greenhouse gases at a higher rate than plastic at the ocean's surface. Consistent with these findings, research conducted in 2018 showed that plastic packaging waste in open dumps or littered onto land or in water emits greenhouse gases over time due to exposure to ambient solar radiation.[265] However, as the annual rate and magnitude of these releases have not as yet been well researched, this study does not include an estimate for these greenhouse gas emissions.

Despite evident data gaps with respect to many of these disposal pathways, exploring a range of added greenhouse gas emissions from the unmanaged portion can cast light on the full scope of threats caused by plastic packaging waste. The climate impact of unmanaged plastic waste largely depends on the proportion that is burned, which can result in 118 million Mt of additional emissions in the case of 100 percent open burning of all unmanaged plastic packaging waste. On the other end of the range, a case of 100 percent littering or open dumping will result in slow but potentially continuous greenhouse gas emissions, and contribute to other areas of environmental concern.

AN ALTERNATIVE PATH: ZERO WASTE

The industry's plans to massively expand the petrochemical buildout and increasingly rely on incinerators are incompatible with the urgent need for dramatic global reductions in greenhouse gas emissions. Fortunately, burning waste is not the only path forward, and the zero-waste approach is gaining traction. Zero waste refers to a systemic approach to waste prevention and reduction. Key components of this approach include decentralized separated collection, sorting and reuse of waste, and an iterative evaluation process that enables communities to assess the waste stream and implement policies to reduce the production and consumption of materials that are hard to recover, such as bans on single-use plastic items. Zero-waste systems aim to return all materials to the community as a resource without being processed in incinerators or landfilled.

The climate benefits of zero waste are clear: non-essential plastic packaging would be eliminated entirely,[266] resulting in no emissions from downstream waste management. The following section outlines three recommendations for alternative zero-waste implementation as part of climate change mitigation strategies.

Use Less Plastic

Plastic packaging, which continues to be produced, used, and discarded at alarming rates, already outpaces all existing waste processing methods due to the unprecedented amount produced, its complex multi-layer construction, and consumer use contamination. Due to the limitations of plastic recycling, phasing out plastic packaging must be prioritized to prevent today's substitution from becoming tomorrow's problems.[267] A boom of investment in the construction and expansion of plastic recycling infrastructure could unintentionally sustain a single-use, linear economy by providing downstream measures to deal with current or even increased plastic production and use. Plastic recycling should, therefore, only be used as a bridge to greater plastic reduction, and as the production of plastic decreases over time, so too should recycling. The highest priority should be developing zero-waste systems where all materials are produced and consumed respon-sibly within ecological limits.

Waste prevention coupled with reduced plastic production is by far the most effective way to reduce greenhouse gas emissions from plastic waste.[268] Source reduction—the waste industry term for less production and consumption—greatly contributes to reducing greenhouse gas emissions from raw material acquisition and manufacturing, resulting in no emissions from waste management.

Plastic packaging, which continues to be produced, used, and discarded at alarming rates, already outpaces all existing waste processing methods due to the unprecedented amount produced, its complex multi-layer construction, and consumer use contamination.

Source reduction avoids greenhouse gas emissions throughout the lifecycle. The USEPA has examined the greenhouse gas benefits of halving the annual generation of plastic packaging in 2006. If, instead of producing 14 million Mt of plastic packaging, only seven million Mt had been produced, 14.85 million Mt CO_2e could have been avoided.[269]

Another USEPA study compared the climate change benefits of different waste management methods, including waste prevention, recycling, composting, incineration, and landfilling, through an investigation of 16 types of waste materials, including three types of plastic (HDPE, LDPE, and PET).[270] Waste prevention showed the biggest climate benefits, with 18 million Mt of CO_2e reduction if waste generation dropped to 1990 levels. The study also concluded that source reduction and recycling result in negative net greenhouse gas emissions, while combustion adds to the climate burden by increasing emissions.[271]

It is important to note that source reduction often refers not only to replacing plastic packaging with reusable and refill-friendly alternatives, but also to substituting plastic with other materials to serve the same function. While the former addresses the root causes of the current waste crisis, the latter continues the reliance on disposable items, lightweight plastic, and bioplastic. Continued use of single-use products that are outside a closed-loop system for their end-of-life phase perpetuates a linear, throw-away economy by providing the means to sustain current production and consumption patterns and undermining the transformation needed in plastic production and consumption systems as a whole. In this regard, effective strategies for plastic source reduction are those that use reusable and refill-friendly alternatives in order to avoid waste generation in the first place.

Phase Out Waste Incineration

As this chapter suggests, incineration is the primary source of greenhouse gas emissions from the management of plastic waste. As reliance on incineration grows, so do emissions from plastic waste. Even when waste incinerators generate electricity that might otherwise have been generated by burning natural gas, incineration still consumes more energy, resulting in greater greenhouse gas emissions compared to other management options.[272] Moreover, the offset greenhouse gas emissions will decrease over time as fossil fuels for electricity generation are phased out. As this energy mix shifts to incorporate more renewable sources, using plastic incineration for energy production will become a much greater percentage of net CO_2 emissions from the energy sector.[273]

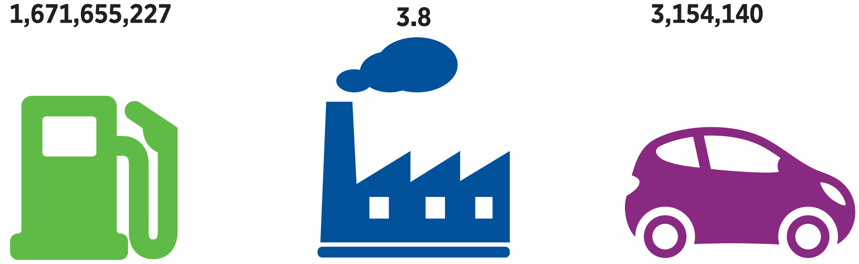
In Europe, the total greenhouse gas emissions from plastic—estimated at 132 Mt in 2017—and an additional 90 Mt of CO_2 will be released each year based on the current trend of increased incineration in the region.[274] This projection highlights the urgent need to end the use of incineration as a waste management strategy. This conclusion runs counter to the dangerous trend of new and expanded investments in incineration in Asia, Latin America, and Africa.

The climate impacts of using waste-to-energy incineration for municipal solid waste do not end with increased greenhouse gas emissions from the incineration of plastic. In municipal solid waste incinerators, mixed plastic is treated with food waste that is high in water content, resulting in energy loss and thus higher greenhouse gas emissions.[275] Waste incineration also has many other drawbacks. Evidence demonstrates significant acute and residual environmental health risks related to incineration. High construction and maintenance costs leave nearby communities indebted. Incinerators experience a lock-in effect, creating a constant demand for feedstock for facilities to stay operational. Significantly, incineration facilities are disproportionately located near communities of color and low-income and marginalized communities. Experience demonstrates that such communities often lack both the necessary resources and meaningful opportunities to challenge these siting decisions, even when the projects involved are likely to negatively impact their environment and health.[276]

Increasingly, policy directives are acknowledging the dangers of waste incineration. In 2017, the European Commission released a communication on the role of WTE in the circular economy that recommended introducing measures to phase out landfilling and other forms of residual waste treatment, including incineration, pyrolysis, gasification, and plasma processes.[277] It also recommended providing economic incentives and co-financing for waste prevention, reuse, and recycling performance. Similarly, the New Plastics Economy Global Commitment explicitly excludes waste incineration by stating, “No plastic should

FIGURE 15

Annual Greenhouse Gas Benefit of 50% Source Reduction of Plastic Packaging Products in MSW in 2006



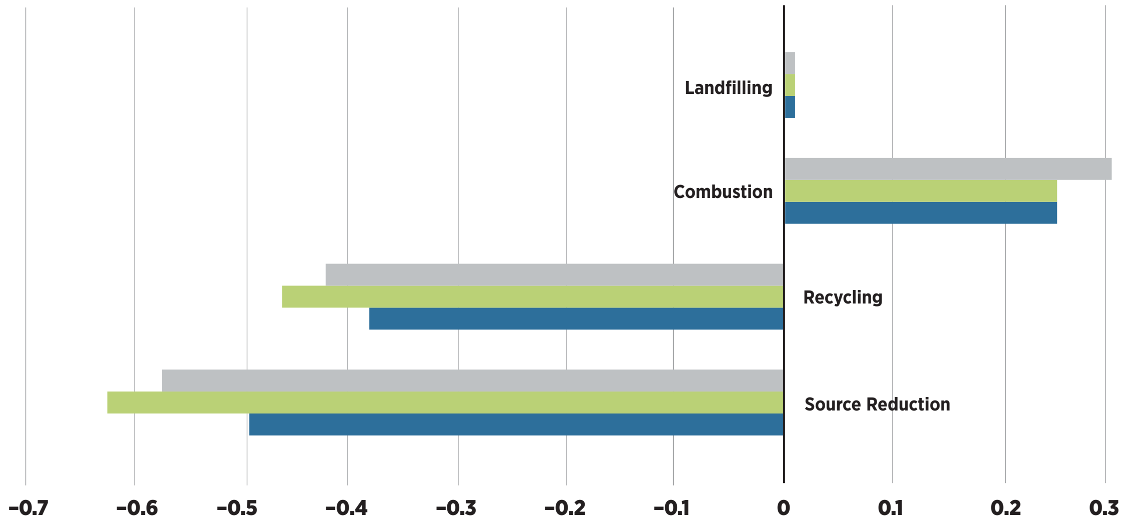
1,671,655,227	3.8	3,154,140
gallons of gasoline consumed	coal-fired power plants in one year	passenger vehicles driven for one year

Greenhouse gas impact of 50% source reduction in the US = 14,856,000 Mt CO_2e saved

Source: U.S. EPA (2009). Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. *https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator*.

FIGURE 16

Net Greenhouse Gas Emissions from Source Reduction and MSW Management Options



Polyethylene terephthalate (PET) Low-density polyethylene (LDPE) High-density polyethylene (HDPE)

Unit: Mt CO_2e/ton

Source: U.S. EPA (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks Report.* Third edition.

end up in the environment. Landfill, incineration, and waste-to-energy are not part of the circular economy target state."[278] In 2017, 250 mayors across the United States unanimously agreed to a resolution on transitioning to 100 percent renewable energy, affirming that waste-to-energy must not be classified nor subsidized as a renewable energy.[279] At a global level, the C40 Cities' Advancing Towards Zero Waste Declaration is another good example of cities pledging to tackle the waste crisis at the source, by reducing municipal solid waste generation per capita by at least 15 percent by 2030 compared to 2015, reducing the amount of municipal solid waste disposed to landfill and incineration by at least 50 percent on the same timeline, and increasing the diversion rate away from landfill and incineration to at least 70 percent.[280]

Maximize Reuse and Recyclability for Other Waste Streams

In addition to calling for an end to incineration and the elimination of single-use plastic packaging, zero waste has the added benefit of identifying the best use for all waste streams, not just plastic. This is achieved by careful separation of waste streams at the source, such as a household or business. Separated streams of food waste and other organic compounds can be used for composting or anaerobic digestion, which can lower greenhouse gas emissions from biogenic waste by diverting it from landfills.[281] Non-organic waste streams have considerable value when recycled, reused, or otherwise redeployed back into a circular economy, and such measures can further reduce greenhouse gas emissions by reducing the need for extracting virgin materials. The elimination of single-use plastic packaging augments recycling efforts by increasing the quality of recycled waste streams, which are currently contaminated with unrecyclable plastic waste. In addition, contaminated mixed waste creates the perception of a much greater stream of residual waste than actually exists, thereby artificially increasing the perceived demand for industrial-scale waste management solutions like incineration.

In addition to calling for an end to incineration and the elimination of single-use plastic packaging, zero waste has the added benefit of identifying the best use for all waste streams, not just plastic. This is achieved by careful separation of waste streams at the source, such as a household or business.

CHAPTER SEVEN

Plastic in the Environment

As the preceding chapter suggests, the greenhouse gas impacts of plastic do not stop when plastic is discarded. For the majority of all plastic ever made, its use and disposal is only the first and shortest phase of a lifecycle that will span centuries or more. Notwithstanding the significant role of plastic in the global economy, in global waste streams, and to the global climate, this report demonstrates that climate impacts from the plastic lifecycle remain poorly quantified and poorly understood. The least studied and, as yet, least understood of these impacts arise once plastic has been released into the environment, starting as pre- and post-consumer waste contaminating urban streets, farmlands, landfills, natural areas, coastal zones, and waterways, and making their way via freshwater rivers and streams to the ocean.

The relatively modest amount of climate-relevant research to date has focused primarily on the impacts of plastic and microplastic within oceanic environments and aquatic ecosystems. This chapter provides a brief introduction to that research. It briefly reviews emerging evidence of the various pathways through which climate impacts are or may be occurring. It acknowledges the significant data gaps and uncertainties with respect to those pathways. Lastly, it highlights the potentially profound risks should those gaps remain unfilled.

PLASTIC IN THE OCEAN

Until recently, the science of plastic pollution in the ocean has focused on its global abundance, distribution, and evidence of ecological harm. Anecdotal reports of plastic being ingested by sea turtles appeared soon after plastic production began expanding in the 1950s, and by the 1960s, researchers had documented plastic in the stomachs of sea birds.[282] Significant amounts of plastic debris were also reported in the proceedings of a workshop on oil pollution convened by the US National Academy of Sciences in 1973, including reports that plastic debris was aggregating other toxics and being routinely ingested by ocean wildlife.[283] A second workshop held the same year on potential ocean pollutants identified similar concerns with the potential impacts of plastic in the environment.[284]

A team led by Sarah-Jeanne Royer of the University of Hawaii released a study documenting that the growing volume of plastic accumulating in the environment may be contributing to climate change.

The first targeted research into the environmental impacts of ocean plastic began in 1972 when EJ Carpenter and KL Smith documented plastic floating on the Sargasso Sea surface.[285] By the early 1980s, the issue began to attract growing attention and more targeted research.[286]

To date, research on marine plastic pollution has reached three main conclusions. First, plastic breaks into smaller pieces that can now be found in the most far-flung corners of the globe, including the deepest area of the ocean. Second, attached to these plastic pieces are a mix of toxic chemicals that are harmful to humans and animals, known as persistent organic pollutants. Third, and finally, plastic harms aquatic animals through entanglement and ingestion at all levels of the food chain, and humans in turn ingest plastic through a variety of pathways.[287]

In August 2018, a team led by Sarah-Jeanne Royer of the University of Hawaii released a study documenting that the growing volume of plastic

Opposite: © Sarah-Jeanne Royer

accumulating in the environment may be contributing to climate change.[288] These impacts are a result of the exposure of plastic to solar radiation and the slow breakdown, or degradation, of plastic in the environment.

The degradation and breakdown of plastic represents a previously unrecognized source of greenhouse gases that are expected to increase, especially as more plastic is produced and accumulates in the environment.

Plastic degradation induces a chemical change that reduces the molecular weight of the polymer.[289] Degradation begins from the moment plastic is exposed to ambient conditions. With time, the polymer weakens and often becomes brittle, breaking down into smaller particles. In the ocean, weathering processes such as biodegradation, thermo-oxidative degradation, thermal degradation, hydrolysis, and solar radiation contribute to this breakdown.[290] Plastic photodegradation (exposure to light) is of particular interest to this report because it triggers the production of greenhouse gases.[291] This unexpected discovery shows that the degradation and breakdown of plastic represents a previously unrecognized source of greenhouse gases that are expected to increase, especially as more plastic is produced and accumulated in the environment.

Royer's study also revealed that among the common types of plastic used worldwide, low-density polyethylene, the most prevalent plastic discarded in the ocean today, releases methane, ethylene (C_2H_4), ethane, and propylene at the highest rate. The results further showed that, as the surface area of plastic increases due to weathering and breakdown in the ocean, there is a tremendous increase in methane and ethylene off-gassing. For example, LDPE powder off-gases methane 488 times more rapidly than when the same weight of LDPE is in pellet form. Finally, the study demonstrated that plastic exposed directly to sunlight (not submerged in water) produces even more of the gases. LDPE releases approximately two times more methane and 76 times more ethylene when exposed to air than when incubated in water. This indicates that the plastic in oceans and terrestrial environments contributes to the greenhouse gas impacts of the plastic lifecycle, though it is often overlooked. The results even indicate that, once initiated, the production of hydrocarbon gases continues in the absence of sunlight. While the quantity of emissions of individual plastic particles is small, these emissions continue indefinitely as the plastic continues to break down, exposing yet more surface area to reactive processes. These emissions will continue to grow as the volume of plastic in the oceans and in the terrestrial environment increases.[292]

Another potential indirect greenhouse gas effect of ocean plastic has only recently begun to emerge in the scientific literature. While the data remain too preliminary to draw broad conclusions, that research is presented here to explore the potential impact plastic may have on the health of planktonic organisms that form the foundation of oceanic food chains. These planktonic communities, made up of phytoplankton and zooplankton, also play an essential role in the ocean's carbon cycle, capturing carbon dioxide at the surface and transporting the carbon to the deep oceans, where it is sequestered away from the atmosphere for centuries. As discussed fully below, there is growing evidence that these plankton—like other marine species—are ingesting ever greater quantities of microplastic debris with potentially significant impacts on their metabolism, reproductive success, and mortality rates.[293] This raises significant questions about the impact that microplastics may have on the ocean's ability to store and absorb atmospheric CO_2 and other greenhouse gases. Earth's oceans provide the largest single natural sink for anthropogenic greenhouse gases, in the absence of which the climate impacts of fossil fuel combustion would be significantly greater. Since the industrial era, the oceans have absorbed 30-50 percent of atmospheric anthropogenic CO_2.[294] Disruptions to the ocean's ability to absorb CO_2 could have a massive impact on increased atmospheric buildup of CO_2 and other harmful gases that had been previously absorbed by phytoplankton.

GREENHOUSE GAS EMISSIONS FROM PLASTIC: HAWAII CASE STUDY

The study by Royer et al. was the first to examine greenhouse gas emissions from plastic under natural conditions in oceanic and terrestrial environments, and it tested some of the most commonly used types of plastic, such as PP, PS, HDPE, and LDPE from both virgin plastic and ocean plastic sources.[295] The experiments detected ongoing emissions of methane and ethylene.

In stations set up on the roof of the laboratory facility, Royer's team conducted two long-term experiments incubating virgin LDPE and aged LDPE collected from Station ALOHA in the North Pacific Subtropical Gyre. Plastic was exposed to ambient sunlight in extremely pure water for several months to measure hydrocarbon off-gassing. Both aged plastic collected at the sea surface and virgin plastic were tested to determine their emissions rates for a period of 212 days and 152 days, respectively. Other experiments also evaluated the effect of plastic density and fragment morphology (pellets, flakes, and powder) on the production of greenhouse gases. Finally, the study tested how differences in the medium, either air or water, affected greenhouse gas emissions.[296]

Royer et al. discovered that exposure to ambient sunlight caused the seven most commonly used kinds of plastic to produce measurable amounts of both methane and ethylene. Methane emissions ranged from 10-4100 pmol per gram per day. Ethylene emissions ranged from approximately 20–5100 pmol per gram per day.[297] Royer suggests that the higher rate of off-gassing from LDPE, which is incorporated in a wide variety of plastic products including plastic bags, shrink wraps and films, plastic coatings for paper milk cartons and beverage cups, container lids, and squeezable bottles for soaps, shampoos, and condiments, among many other uses, may be due to its weak polymer structure and more exposed hydrocarbon branches.

Virgin vs. Aged Plastic

Before they are reshaped into bottles, bags, and other plastic products, plastic resins are produced and transported as virgin plastic pellets, also known as nurdles. These pellets can and do escape into the environment from sewer drains and discharge pipes at plastic plants, from leakage and spills from trucks and rail cars transporting virgin pellets, and from cargo vessels and containers that transport virgin plastic around the world. They are among the most common forms of

plastic pollution worldwide. In Royer's experiments, greenhouse gas emissions from these virgin plastic pellets increased over time while aged-plastic emissions remained constant. With the exception of methane, emissions of greenhouse gases from virgin plastic pellets were higher than emissions from aged plastic. This is likely due to the presence of ultra-violet (UV)-resistant plasticizers that are often added to plastic products to counteract the effects of UV radiation and slow down the degradation processes, and are not found in virgin plastic.[298]

Physical Features

The morphology of plastic also affected the degree to which it emitted greenhouse gases. As plastic cracks, fractures, and breaks, the surface area increases, increasing the total surface available for photodegradation. The production rates of greenhouse gases increase progressively as the plastic breaks down into smaller and smaller pieces with greater surface area. Royer et al. discovered that as the surface area of plastic increases due to weathering and degradation in the ocean, more and more greenhouse gases will be produced for the same amount of plastic over time.[299]

Royer et al. also found that both virgin and aged plastic continue to emit greenhouse gases to the environment (both in air and submerged in seawater) for an undetermined and potentially indefinite period. This could be attributed to photodegradation fragmenting plastic into progressively smaller fragments, microplastic (less than 5 mm) and nanoplastic[300] (less than 100 nm). Moreover, and as discussed further below, the continuous decline in the size of plastic particles makes them more easily absorbed or ingested by even smaller organisms, thus increasing their bioavailability and potential impact across ecosystems.

ESTIMATING DIRECT GREENHOUSE GAS EMISSIONS FROM OCEAN PLASTIC

Building on the emissions rates found by Royer et al. for LDPE and other plastic resins, it is feasible to produce a very preliminary estimate of the annual rate of greenhouse gas emissions from ocean plastic using a standing stock of sea surface microplastic[301] and the emissions rate of LDPE powder.[302] As discussed fully below, this estimate has significant limitations and uncertainties. Accordingly, it is presented here for discussion purposes but is not incorporated into the global estimates of lifecycle emissions presented elsewhere in this report.

The first global estimate of microplastic found at the sea surface was published in 2014 by 5Gyres, in which Eriksen et al. estimated that 5.25 trillion microplastic particles, equivalent to 66,100 Mt of particles, were floating at the sea surface.[303] However, standardized prediction models of global mass estimates done by Erik van Sebille et al. in 2015 estimated that the amount of small floating microplastic debris is substantially greater than previously published.[304] Estimates showed that the standing stock of microplastic concentrated at the sea surface in 2014 ranged from 15 to 51 trillion particles, weighing between 93,000–236,000 Mt.[305] Significantly, this estimate was equivalent to just one percent of the global plastic waste estimated to enter the oceans in the year 2010 alone, and a far smaller fraction of the plastic discharged into the oceans over the past seven decades. Two other standing stock estimates were calculated in the same study. The total microplastic count and mass patterns were similar across all three models, with higher amounts in the subtropical regions and lower amounts in the tropical and high-latitude regions.

According to Royer et al., the highest gas-producing plastic (LPDE in powder format) produced methane at a rate of 55 nmol per gram per day.[306] Using the estimated 236,000 Mt of standing stock of sea surface microplastic pollution from the 2015 van Sebille model, there is an annual emissions rate of 4.74 x 1015 nmol per year. This totals an annual methane production of 76 Mt from the standing stock of plastic at the sea surface. Applying the 100-year global warming potential of methane yields annual greenhouse gas emissions of 2,129 Mt CO_2e.

Royer et al. also determined a rate for ethylene in LDPE powder form.[307] Doing the same calculation for ethylene equates to 51 Mt of annual ethylene production.

Given the challenges mentioned above for the collection of data on greenhouse gas emissions rates for all ocean plastic, preliminary estimates for both methane and ethylene emissions assume that both the rate and amount at which plastic is input into the ocean remains constant. With a 33-36 percent predicted increase in plastic production by 2025, the amount of methane emissions produced from sea surface ocean plastic would be 101-103 Mt per year if no mitigation efforts were implemented to stop leakage from land. For ethylene, this would amount to 68–70 Mt per year.

It is important to note the multiple and significant limitations of these estimates. For example, these estimates are based on Royer et al. emissions rates for methane and ethylene for microplastic particles exposed to UV radiation at the sea surface in a tropical environment. Thus, they do not encompass all possible emissions rates for plastic slightly submerged in the water column and for different levels of plastic degradation. In addition, these calculations only consider the highest hydrocarbon-gas-producing plastic type, LDPE in powder form, to represent the entire floating microplastic debris standing stock, since polyethylene accounts for most of the plastic found in the environment.[308] Van Sebille's 2015 global stock estimate of 236,000 Mt does not evaluate the standing stock of plastic by resin type.

There is still a considerable amount that is not known about the greenhouse gas emissions of plastic in the environment. The fact that the age and treatment of plastic are typically unknown at the time of collection also affects emissions estimates. Annual estimates only consider the tiny fraction of ocean plastic found at the surface and do not consider emissions from the "missing plastic" in the water column, on the seafloor, stranded on coastlines, or in larger debris, like fishing gear. Van Sebille et al. highlight the difference between annual inputs, which are calculated based on all plastic types, and standing stock estimates, which are based on sea surface microplastic, mostly PP and PE.[309]

There is still a considerable amount that is not known about the greenhouse gas emissions of plastic in the environment. Annual estimates only consider the tiny fraction of ocean plastic found at the surface and do not consider emissions from the "missing plastic" in the water column, on the seafloor, stranded on coastlines, or in larger debris, like fishing gear.

Another missing variable involves ocean plastic removal rates, which are not yet fully understood[310] and can skew emissions rate estimates. Stranding and eventual sinking of floating plastic likely accounts for the bulk of surface removal. Also, ingestion by animals, transportation to land and regurgitation, and fecal pellets sinking to the seafloor[311] may also skew estimated emissions rates.

Finally, and more significantly from the perspective of assessing the global impacts of plastic pollution, Royer et al. conclude that more gases are emitted by plastic when it is exposed to air than when it is in submerged in water. LDPE plastic produced 76 times more ethylene and 2.3 times more methane in air than in water. The difference in emissions rates for plastic in water compared to plastic exposed to air is partly due to temperature and heat buildup, resulting in the plastic material reaching a temperature higher than the surrounding medium.[312] This suggests the need for additional research into the scale of emissions from plastic exposed to greater ambient temperatures—including not only plastic floating on the surface, but the massive quantities of plastic accumulated on coastlines, beaches, and riverbanks, as well as the still poorly estimated quantities of plastic disintegrating in terrestrial environments around the world. Any estimation of the greenhouse gas impact of plastic waste must ultimately take into account not only the immense volume of plastic pollution found worldwide, but the diverse environments in which that plastic pollution occurs.

Compared to the millions of tons of emissions from other links in the plastic lifecycle, and the billions of tons in which the global carbon budget is measured, the methane production rates calculated by Royer et al. may appear comparatively modest. Royer's team drew a similar conclusion, at least with respect to methane.[313] As Royer observed, however, as plastic production increases and the volumes of mismanaged waste entering oceans increases,[314] methane emissions from degrading plastic will likely also increase and may warrant increased concern. Future studies are needed to address the role of plastic off-gassing methane, ethylene, and other greenhouse gases.

POTENTIAL IMPACT OF MICROPLASTIC ON THE OCEANIC CARBON SINK

The preceding discussion addresses the direct emissions of greenhouse gases from oceanic plastic pollution. In addition to these direct climate impacts, emerging but still preliminary evidence suggests that plastic pollution may be having a less direct but ultimately greater role in climate change through its impact on the species that form the foundation of oceanic food chains and provide the biological carbon pump that sequesters carbon in the deep oceans.

The impacts of ocean plastic on ecosystems that are directly responsible for the ocean's CO_2 gas exchange cycle may be indirectly causing more atmospheric greenhouse gas emissions.

The world's oceans provide the largest natural sink for anthropogenic greenhouse gases. Since the dawn of the industrial era in the late 18th century, the oceans have absorbed 30–50 percent of atmospheric anthropogenic CO_2.[315] The impacts of ocean plastic on ecosystems that are directly responsible for the ocean's CO_2 gas exchange cycle may be indirectly causing more atmospheric greenhouse gas emissions.

These impacts may occur through four distinct but interconnected pathways. First, emerging evidence indicates that microplastic particles can affect the phytoplankton whose photosynthesis absorbs (or "fixes") nearly half of the CO_2 that is released into the earth's atmosphere.[316] Oceanic primary production (the first step in the food chain) accounts for up to 80 percent of the planet's total oxygen production.[317] Phytoplankton are the ocean's main primary producers, taking CO_2 from the atmosphere and water from the ocean and using photosynthesis to produce carbohydrates, but laboratory experiments have shown that microplastic exposure can be toxic to phytoplankton. The smaller the microplastic size, the greater its toxicity.[318] A study released in 2018 found that this toxicity is able to disrupt phytoplankton feeding, reproduction, physical ingestion, and metabolism, among other impacts. In one laboratory study, microplastic reduced the rates of photosynthesis of contaminated phytoplankton by 45 percent.[319] These impacts have real-world implications beyond the laboratory. Research demonstrates that phytoplankton readily integrate with and form aggregates with microplastic particles when they are present in water.[320] It is thus possible that ocean plastic is affecting the metabolism, survival, and reproduction of the organisms responsible for the base of oceanic food chains, and indirectly influencing the ocean-atmosphere gas exchange process. However, more studies are needed to determine how exactly plastic affects the ocean's biological carbon pump through primary production.

Plastic not only affects the phytoplankton cells that absorb CO_2 from the ocean's surface, but it may also be harming the zooplankton (microscopic animals) that transport that carbon to the deep oceans. Just as phytoplankton are the primary fixers of carbon in ocean ecosystems, zooplankton are the first and most important consumers of phytoplankton. More importantly from the climate perspective, zooplankton are instrumental in taking the carbon fixed by the phytoplankton and transporting it to the deep ocean in the form of fecal pellets. Without this critical step in the process, the CO_2 fixed by the phytoplankton would quickly re-enter the surface waters and the atmosphere.

Changes to this segment of the food chain (phytoplankton and zooplankton) may thus affect the ocean's ability to absorb and store CO_2. Figure 17 illustrates the role of plankton in carbon transportation between the atmosphere and the ocean.

Copepods are the most common types of zooplankton. The copepod Calanus helgolandicus is a keystone species in Europe and the Northeast Atlantic, making up 90 percent of all mesozooplankton biomass.[321] In a 2015 study led by Matthew Cole of Plymouth Marine Laboratories, researchers demonstrated that microplastic exposure negatively affected the metabolism and health of copepods in at least three distinct ways. First, copepods that ingested plastic reduced

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their feeding rates by 40 percent. Second, with exposure to microplastic over time, copepod eggs became smaller and were less likely to hatch. Third, exposure to microplastic increased overall mortality among contaminated copepods.[322] As a result, Cole et al. concluded that, over time, growing exposures to microplastic could lead to significant reductions in the amount of carbon biomass ingested by zooplankton.[323] Put more simply, zooplankton might ingest less and less of the anthropogenic carbon being fixed by the ocean's phytoplankton—even as those phytoplankton themselves are fixing carbon less efficiently because of exposure to toxic microplastic.

While the research by Cole et al. focused on the North Atlantic Ocean, the ingestion of plastic by zooplankton is a global phenomenon. A 2015 study in the Northeastern Pacific Ocean off the Pacific coast of North America found microplastic was ingested by both copepods and euphasids, indicating that even species at the lowest levels of the oceans' food chain were mistaking plastic for food.[324] A separate study published in 2016 by researchers with the Ocean University of China reached similar results, finding that microplastic affected both the growth of microalgae and the efficiency of photosynthesis.[325] Sampling conducted in the Baltic Sea found microplastic ingestion by every taxon of zooplankton studied, including mysid shrimp, copepods, rotiferans, and polychaete worm larvae, among others.[326] It also demonstrated that microplastic can be transferred from smaller to larger zooplankton when bigger plankton species eat smaller ones. The ingestion of microplastic has also been documented for multiple taxa of zooplankton in the Indian Ocean off the coast of Kenya,[327] and in 11 separate zooplankton taxa in the Yellow Sea off the coast of China.[328]

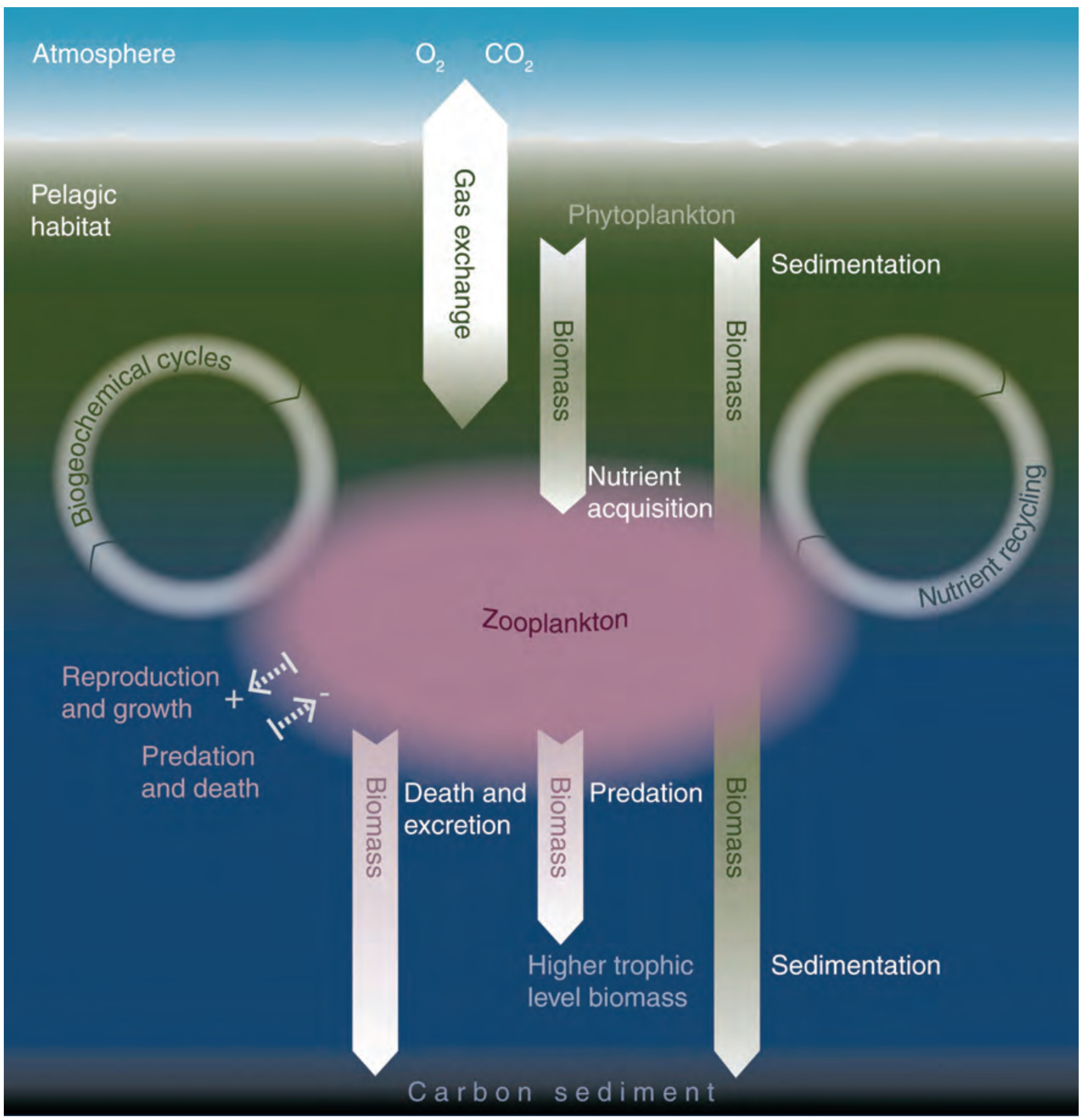
It is likely that microplastic affects the many and varied taxa of zooplankton in different ways, and that some taxa will be less affected than others. For example, a study of the Pacific Oyster, Crassostrea gigas, did not find any impacts to its development or feeding capacity from exposure to polystyrene microplastic.[329] Clearly, additional research is needed to understand the potential scale and scope of the problem. Given the critical importance of the ocean carbon sink to the global climate, however, the potential of microplastic pollution to affect both the fixing of CO_2 by phytoplankton and its transport to the deep ocean by zooplankton should be a cause of significant concern and immediate and significant research.

This raises a third route through which microplastic has the potential to affect the ocean's biological carbon pump. When zooplankton ingest phytoplankton, the carbon they absorb is then transported to the deep ocean in fecal pellets—a major constituent of marine snow. The fecal pellets slowly descend to deep water, where they are deposited in the muck on the ocean floor. Studies have documented that microplastic is transported below the surface in zooplankton fecal pellets.[330] However, when fecal pellets are contaminated by microplastic, they sink more slowly and break up more readily than uncontaminated pellets,[331] thus reducing the proportion of the carbon that reaches the deep sea to be sequestered.

Fourth, and finally, it is important to consider the fate and impact of the plastic that does reach the deep sea. The sea surface is not the end point for plastic in the oceans. Sea surface estimates only account for approximately one percent of the estimated millions of Mt of plastic waste created on land.[332] These low estimates have led scientists to explore plastic sinking mechanisms.[333] Plastic's

FIGURE 17

Carbon Transportation Processes Between Phytoplankton and Zooplankton



Source: Andrew Brierley, *Plankton*, 27 Current Biology R478 (2017), *https://www.sciencedirect.com/science/article/piiS0960982217302154*. Image by Steve Smart.

ability to sink relates to its density (if greater than water) and biofouling (accumulative buildup of organic matter and organisms).[334] For example, microplastic sticks to algal species (phytoplankton aggregates) that travel down into the water column, which may partially explain why the sea floor has become a major sink for microplastic.[335] The presence of microplastic on the sea floor may also be affecting the ocean's carbon stocks.[336] Their behavior and impact in deep ocean environments remains largely unknown.

REDUCING THE CLIMATE IMPACT OF PLASTIC IN THE ENVIRONMENT

As the research by Royer et al. suggests, the sources and scale of climate impacts from plastic in the environment are only beginning to be identified and investigated. Technological improvements in satellites, hyperspectral imagery, and drones can help provide better estimates of all ocean plastic greenhouse gas emissions, especially those carried back to shorelines and on land.[337] Terrestrial sources of plastic waste and ocean plastic returned to land are likely bigger emitters since they are exposed to more ambient conditions (sunlight and air) and thermal loading that exacerbates greenhouse gas release.

If waste management is not improved by 2025, plastic inputs into the ocean will increase by an order of magnitude,[338] regardless of the increased production rate. Irrespective of improvements to waste management, the problem of greenhouse gas emissions from the plastic lifecycle cannot be solved downstream. For example, recycling ocean plastic is not a viable solution to plastic-related greenhouse emissions or to pervasive and growing plastic pollution throughout the environment. A recent study looked at the recyclability of four types of plastic after being exposed to UV radiation in the ocean. All plastic types in this study presented damage to their thermal and mechanical properties, making mechanical recycling unfeasible.[339]

Reducing sources of plastic entering the oceans and waterways must be an urgent area of focus. Rivers are one entry point (1.15-2.41 million Mt per year); most of the top 20 most polluted rivers are located in Asia and represented 67 percent of this rate.[340] It must be stressed that the transportation of ocean plastic via river systems remains largely understudied, and further monitoring of plastic pollution is required. Studies looking at how, where, and what type of plastic pollution is entering these rivers are needed.

Yet these solutions address the plastic problem only after the plastic has been created, disposed of, and turned into waste. Unless the growth of plastic production and disposal is reversed, such end-of-life efforts to manage plastic will be confronted with ever greater flows of pollution to be managed. The most effective way to stem this rising tide of plastic in the environment is to dramatically reduce the amount of plastic being produced and discarded.

Shifting to a circular economy from the current linear economy can introduce potential solutions to the plastic pollution problem in all types of environments, including oceanic and terrestrial environments. Where circularity isn't possible, replacement with natural-based products for plastic can help. However, bioplastic is not necessarily biodegradable (see Box 3). 5Gyres' Better Alternatives Now (BAN List) 2.0 demonstrated how some products are only biodegradable in industrial systems and not in natural environments.

Plastic reduction and reuse, part of zero-waste living, is a growing trend worldwide. Ending the production of new plastic is the most reliable way to reduce the generation of microplastic in general.

There is also a need to improve product design and packaging to aid the recovery of plastic. This can occur by implementing extended producer responsibility, making producers legally and financially responsible for their products' environmental impacts.[341] However, improvements to economic models and logistical aspects of extended producer responsibility are still needed.

Scaling zero-waste strategies is the solution that best leads to a circular economy. Plastic reduction and reuse, part of zero-waste living, is a growing trend worldwide and, in some cases, is helping remove ocean plastic pollution. For example, lost or discarded fishing gear is being transformed—or upcycled—into sunglasses and skateboards. Ending the production of new plastic is the most reliable way to reduce the generation of microplastic in general.[342] Collectively, all these steps reduce the leakage of plastic into both terrestrial and aquatic environments, which is the most efficient way to reduce microplastic in the environment and prevent its associated greenhouse gas emissions.

CHAPTER EIGHT

Findings and Recommendations

PLASTIC & CUMULATIVE GREENHOUSE GAS EMISSIONS

The cumulative emissions from the plastic lifecycle illustrate the degree to which increased plastic production is inconsistent with the immediate need to rapidly reduce global greenhouse gas emissions. Moreover, the inherent difficulty of constructing an emissions profile for the lifecycle of plastic helps explain why this massive and growing source of greenhouse gas emissions has remained overlooked.

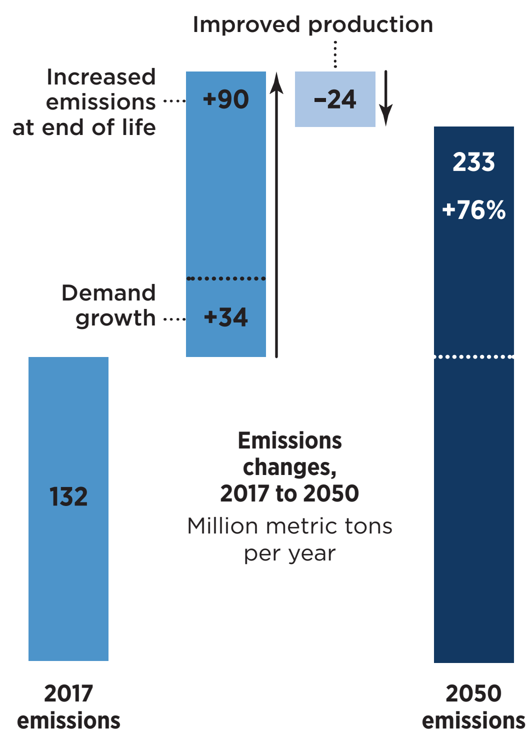
As made clear in the Extraction & Transport and Production & Manufacture chapters of this report, developing estimates of the greenhouse gas emissions intensity of plastic production is extremely challenging. The myriad sources of emissions, and the diversity in emissions intensity of such sources, significantly limits what bottom-up approaches using publicly available information can include. The bottom-up approach of identifying major sources is important both to demonstrate the sheer variety of emissions sources and to highlight the challenges in addressing this industry holistically. Because of these limitations, existing emissions estimates of the plastic production process are likely to undercount or omit sources of emissions, and these should be understood as minimum estimates.

Using existing cradle-to-resin emissions estimates and industry's growth rate projections, this report calculated several potential scenarios for cumulative emissions from plastic production. At current rates of emissions intensity, cumulative emissions over the period 2015–2050 from cradle-to-resin plastic production are likely to be at least 52 gigatons CO_2e. Even full incorporation of renewable energy in the production process would only reduce emission intensity by about half, and there are major emissions to such decarbonization.

FIGURE 18

Growth in Net CO_2 Emissions from Plastic in the EU

Material Economics found that emissions from plastic could grow significantly by 2050, largely due to increased emissions at the end of the plastic lifecycle and demand growth.



Source: Material Economics, The Circular Economy (2018).

Management of plastic waste is also a significant source of emissions, especially from waste-to-energy incineration and open burning. If industry plans for growth in both plastic production and the role of incineration in plastic waste management materialize, cumulative net emissions from

Opposite: © Tim Aubry/Greenpeace

incineration from 2015 to 2050 are likely to contribute at least an additional four gigatons of CO_2e. Notably, these are net emissions, assuming that energy from waste incinerators replaces other energy sources, including fossil energy. This figure only accounts for incineration of plastic packaging, about which the most is understood. If management of other kinds of plastic leads to a greater reliance on incineration, emissions from these sources will grow. This projection does not include the large but unmonitored emissions from open burning.

In 2019, the production and incineration of plastic will add an estimated 859 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal plants.

Projecting beyond 2050 is difficult, particularly in light of the need to reach net zero emissions by that year, but even conservative estimates are alarming. As noted earlier in this report, even assuming no growth in plastic production from 2050 to 2100 and full integration of renewable energy into industrial processes for plastic production, cumulative emissions reach 59.5 gigatons of CO_2e. Similarly, assuming no growth in the scale or net emissions intensity of incineration for the second half of the century, emissions from waste-to-energy processes would add an additional 15.4 gigatons of CO_2e.

These estimates are deliberately low. If growth in plastic production and incineration is allowed to continue apace through 2050, there is no reason to believe it will simply halt thereafter. Rather, these explicitly conservative estimates should be understood as demonstrations of the scale and severity of the potential future climate impact of the plastic lifecycle.

Finally, for plastic that makes its way into oceans, rivers, soils, and other destinations in the environment, emissions and other climate impacts continue to mount via off-gassing and interference with marine food webs. Although quantifiable emissions at this stage in the lifecycle appear small at present, the degree to which these emissions contribute to atmospheric greenhouse gas concentrations, and the rate at which they will grow as plastic continues to accumulate and degrade in the environment, is still unknown. Plastic degrading in the ocean presents yet another little studied but potentially catastrophic source of climate impacts if contamination by microplastic reduces the ability of plankton to absorb CO_2 and transport it to the ocean depths. As with all other stages in the plastic lifecycle, the continued growth in plastic production only exacerbates these risks.

In 2019, the production and incineration of plastics will add an estimated 859 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal plants. With the petrochemical and plastic industries planning a massive expansion in production, plastic will emit over 56 billion metric tons of carbon-dioxide-equivalent greenhouse gases between 2015 and 2050, 10–13 percent of the entire remaining carbon budget.

The foregoing summation of emissions from the plastic lifecycle points to a single conclusion: plastic itself is the problem. Decarbonization can only partially reduce emissions from the plastic production process. Ironically, as the energy grid shifts toward greater reliance on renewable energy, the net greenhouse gas impact of plastic incineration grows. Finally, plastic in the environment further contributes to accumulating greenhouse gases simply because of its fundamental chemical and physical nature. Because plastic itself is the problem, the most effective way to reduce the greenhouse gas emissions from the plastic lifecycle is to produce less plastic.

Lifecycle Plastic Emissions Relative to Mitigation Scenarios and Carbon Budget Targets

IEA, Carbon Tracker, and the IPCC are among several organizations that have developed methodologies for measuring greenhouse gas emissions and proposed pathways for emissions reductions. Despite differences in approach, each models the likelihood of reaching climate stabilization targets of 2°C and 1.5°C under certain scenarios and provides a point of reference for analyzing the emissions from the plastic lifecycle.[343]

Current emissions projections for the plastic lifecycle are inconsistent with meeting the 1.5°C temperature target. If the production, disposal, and incineration of plastic continue on their present growth trajectory, they will undermine global efforts to reduce emissions and keep warming below 1.5°C. By 2030, these emissions could reach 1.34 gigatons per year—equivalent to more than 296 five-hundred-megawatt coal plants.

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Even if growth slows after 2030, plastic production and incineration could emit 2.8 gigatons of CO_2 per year by 2050, releasing as much emissions as 615 five-hundred-megawatt coal plants. Critically, these annual emissions will accumulate in the atmosphere over time. Projected growth in plastic production and incineration will add an estimated 56 million tons of CO_2e through 2050, meaning that plastic alone could consume more than ten percent of the earth's remaining carbon budget.

If lifecycle emissions are considered through the end of the century, the expansion of plastic production and incineration will consume over 125 gigatons of CO_2e—and possibly much more—of the carbon budget. If this scenario becomes a reality, then the plastic lifecycle alone could potentially account for a quarter or more of the global carbon budget for all energy production, industrial activity, transportation, and land use.

Through the Paris Agreement, the nations of the world have committed to keeping global temperature rise "well below 2°C" and further committed to take action with the aim of holding it to 1.5°C. The most recent assessment by the IPCC demonstrates that even 1.5°C of warming poses unacceptable risks, and going beyond that limit is no longer a scientifically or morally defensible goal.

However, current national commitments fall well short of these goals.[344] Therefore, there is no room for increased emissions from plastic production and disposal, as industry plans. On the contrary, governments must seek additional, rapid emissions cuts. As this report demonstrates, the lifecycle of single-use plastic creates both the urgent need and a near-term opportunity for significant emissions reductions and suggests that there are far greater emissions reductions available by targeting plastic and the petrochemical sector generally.[345] Emissions cuts from reducing the production and consumption of plastic are especially attractive because they will help to address other important environmental and social issues, and they will not negatively impact efforts to achieve the Sustainable Development Goals (SDGs).

RECOMMENDATIONS

Heightened awareness and growing public concern about the plastic pollution crisis have inspired numerous plastic pollution mitigation strategies. This report examined several of the most widely promoted strategies according to five criteria: potential to achieve meaningful greenhouse gas emissions reductions; effectiveness as a lifecycle approach to plastic production and pollution; potential benefits or negative impacts on achieving other important social and environmental goals, such as cleaner water, improved air quality, and healthier ecosystems; feasibility and readiness of the solution; and scalability and affordability, which considers whether the strategy can be implemented at a scale sufficient to bring plastic-related emissions in line with climate stabilization targets by 2030 and 2050. The analysis is summarized visually in Table 9, which is adapted from a similar analysis developed by 5Gyres.

High-Priority Strategies

Stop the production and use of single-use, disposable plastic products. Whether evaluated in the context of extraction-related emissions, emissions from plastic manufacturing and incineration, or reducing the impacts of environmental plastic, the most direct and most effective way to address the plastic crisis is to dramatically reduce the production of unnecessary plastic, beginning with national or global bans on nearly all single-use, disposable plastic. Stopping the plastic pollution problem at its source—stopping the production of non-essential plastic—is the surest way to curtail emissions throughout the plastic lifecycle.

A related, complementary, and necessary strategy is to **stop new oil, gas, and petrochemical infrastructure.** The greenhouse gas emissions embedded in existing, proven reserves for oil, gas, and coal already exceed the atmosphere's remaining carbon budget under a 1.5°C scenario. Accordingly, the IPCC's SR 1.5 report emphasizes that a rapid and nearly complete transition away from fossil fuels is vital to keeping aggregate warming below 1.5°C. As documented by CIEL and others, the surplus of cheap natural gas liquids driven by the ongoing fracking boom is fueling a massive expansion of infrastructure for plastic production and manufacture in the United States and beyond. Just as significantly, the construction of these new facilities will create ongoing demand for new

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fossil fuel feedstocks, with implications for human health, the environment, and the climate at every stage of the plastic lifecycle.

Zero-waste systems, including bans on incineration and open burning, reduce plastic-related emissions directly by dramatically reducing the burning of plastic. This includes similar technologies such as gasification, pyrolysis, and plastic-to-fuel. Zero-waste systems also reduce emissions indirectly through improved source separation and collection, as well as upstream approaches like bottled water bans. Moreover, experience in communities around the world demonstrates that zero-waste approaches have significant co-benefits for environmental quality, human health, and livelihoods.

Each of the foregoing strategies complements and benefits from the implementation of **extended producer responsibility for the circular economy**. Modest or even significant increases in recycling will neither solve the plastic crisis nor significantly reduce plastic-related greenhouse gas emissions. When combined with zero-waste communities and bans on new infrastructure, however, extended producer responsibility can ensure that producers of plastic products and fast-moving consumer goods avoid unnecessary plastic production, design products for long and repeated use, and invest in the systemic changes required to make a circular economy succeed.

Finally, reducing the climate impacts of the plastic lifecycle will require that nations **adopt and rigorously enforce ambitious targets for reducing greenhouse gas emissions** from both fossil energy and industrial sources, including the entire plastic lifecycle. Setting these targets will not only address and reduce the greenhouse gas impact of plastic, but also transform the larger fossil economy in which plastic is embedded and help protect communities, human rights, and human lives from the urgent threat of climate change.

Complementary Interventions

Even as the world moves forward on these high-priority strategies to address the plastic and climate crises, this report identifies a number of complementary measures that can reduce plastic-related emissions, reduce the environmental and health impacts of plastic, or both. This includes measures to **reduce or limit construction of new oil, gas, and petrochemical infrastructure** until more comprehensive limits can be put in place.

Identifying and fixing leaking pipes and tanks in the plastic supply chain will not reduce plastic production or the emissions from waste and environmental plastic, but it could dramatically reduce upstream methane emissions that compound plastic's lifecycle greenhouse gas emissions.

Nations must adopt and rigorously enforce ambitious targets to reduce greenhouse gas emissions. Doing so will transform the larger fossil economy in which plastic is embedded and help protect communities, human rights, and human lives from climate change.

Similarly, for existing fossil fuel and plastic infrastructure, **mandating that gas from wells, pipelines, and facilities be captured rather than flared or vented** can reduce an ancillary but important source of emissions, with benefits both for the climate and nearby communities.

Beach cleanups and river controls are labor and resource intensive, but can have important benefits for ecosystems and local communities. These strategies will not meaningfully reduce greenhouse gas emissions, however, and their other benefits may be only temporary unless underlying sources and causes of plastic pollution are addressed.

In appropriate and likely limited circumstances, such as when ghost fishing nets are converted into carpets, **recycling ocean plastic** may make a modest but meaningful contribution to local ecosystems while simultaneously contributing to livelihoods.

Low-Ambition Strategies

Using renewable energy to fuel the plastic supply chain will not solve plastic's climate impacts. As Material Economics noted, a significant portion of greenhouse gas emissions from plastic production comes from the chemical processes involved in plastic manufacturing, emissions that will not be affected by the use of renewable energy. Moreover, producing plastic with renewable energy will do nothing to reduce the downstream emissions from the incineration and disposal of plastic or reduce its impacts on ocean ecosystems and carbon sinks. This assessment applies with still greater force to proposals to **maximize energy efficiency throughout the**

plastic supply chain. While improving energy efficiency in necessary processes is certainly vital, producing an unnecessary and high-emitting product more efficiently does little to safeguard the climate or the planet.

Modern landfilling practices may be a significant environmental improvement over unmanaged waste or unregulated land dumps and thus could be very worthwhile from a community perspective. However, the climate benefits from modern landfilling are marginal at best, and landfilling is, by definition, a disposal solution that will have few benefits for the many upstream impacts of plastic production and use.

Incinerating plastic under the guise of waste-to-energy has the potential to significantly increase greenhouse gas emissions from plastic production while simultaneously increasing toxic exposures for communities both near and far from incinerators.

While the concept of **cleaning plastic from the open ocean** is appealing, such strategies will do nothing to reduce the lifecycle greenhouse gas emissions of plastic; will not address the significant impacts of plastic on land, freshwaters, and coastlines; and will not address the plastic production and waste that give rise to ocean plastic. Such cleanup operations have little potential to capture the vast quantities of microplastic that contaminate the oceans' surface and depths, and biologists have raised concerns about potentially harmful impacts of these efforts on ocean wildlife.

False Solutions

Finally, this report exposes a small number of proffered "solutions" that are unlikely to benefit the climate, communities, or ecosystems. Analysis suggests that, viewed across their respective lifecycles and in the broader context of the climate and plastic crises, these false solutions do not represent useful investments given limited time, resources, and political will.

Biodegradable plastic poses an array of challenges and limitations. Many types of plastic identified as biodegradable can be broken down only with special equipment or under specific conditions that do not exist in most community composting facilities. Even the plastic that does break down may do so to only limited degrees. From a climate perspective, the fact that a plastic is biodegradable says little about the emissions arising from its production and use.

Relatedly, using **bio-feedstocks in petrochemical and plastic manufacturing** may reduce emissions associated with fossil fuel production, while simultaneously generating significant new emissions from land disturbance, chemically and mechanically intensive agriculture, and the harvest, transport, and processing of the feedstocks. Processing bio-feedstocks into plastic will itself produce significant greenhouse emissions. Further, the plastic produced may be chemically identical—or even combined with—fossil-based plastic, thus eliminating the environmental and social benefits of reduced plastic production. **Biodegradable plastic produced from bio-feedstocks** may alleviate some of the latter problems, but would raise the same greenhouse gas concerns as other bio-feedstocks.

Developing and deploying **plastic-eating organisms** will not reduce or address the significant greenhouse gas emissions that occur throughout the plastic lifecycle. Unless released directly into the environment, which would generate significant uncertainties and risks, plastic-eating organisms would be of limited benefit as an end-of-life, and potentially costly, waste management solution for plastic.

Using chemically recycled feedstocks from post-consumer plastic in petrochemical and plastic manufacturing does not hold the promise of true, closed-loop recycling. First, it does not address the high energy demands and emissions associated with plastic production. Second, it relies on post-consumer recovery of plastic that is unlikely to be efficient. Third, it is unsuitable for many common forms of plastic, such as PVC, which must be manually separated out. Fourth, the value of the recovered feedstock is so low compared to virgin feedstock that chemical recycling is not financially viable without heavy government subsidies.

Incinerating plastic under the guise of **waste-to-energy** has the potential to significantly increase greenhouse gas emissions from plastic production while simultaneously increasing toxic exposures for communities both near and far from incinerators. In so doing, waste-to-energy operations transfer the threat of plastic from the oceans to the air, while compounding its climate impacts. This is the very definition of a false solution.

TABLE 9

Recommendations

Strategies	**Greenhouse Gas Emissions** Reduces greenhouse gases or limits emissions growth	**Impact** Lifecycle approach	**Non-Climate Benefits** Will it have +/– impacts on SDGs	**Feasibility/ Deployability** Feasibility/ Is it ready for implementation	**Scalability & Affordability** Can it be implemented cost-effectively at scale
High-Impact Interventions to Reduce Greenhouse Gas Emissions from the Plastic Lifecycle					
Stop the production and use of single-use, disposable plastic products	High	High	High	High	High
Stop new and expanded petrochemical and plastic production infrastructure	High	High	High	High	High
Zero-waste communities	High	High	High	High	High
Extended producer responsibility for circular economy	Moderate	High	High	High	Moderate
Set and enforce meaningful emissions limits and monitoring requirements for point sources	High	Moderate	High	High	Moderate
Medium-Impact Interventions that May Benefit Climate or Sustainable Development Goals but Not Both					
Reduce construction of new petrochemical and plastic manufacturing infrastructure	Moderate	Moderate	High	High	Moderate
Reduce new pipeline and well pad construction	Moderate	Moderate	Moderate	High	Moderate
Identify and fix leaking pipes and tanks	Moderate	Moderate	Moderate	Moderate	Moderate
Beach cleanups	Low	Low	High	High	Moderate
River controls (catchment areas below artificial barriers)	Low	Moderate	High	High	Low
Low-Impact Interventions that Do Little to Safeguard the Climate or the Planet					
Mandate offsetting reforestation projects	High	Moderate	Low	Moderate	High
Use renewable energy sources throughout plastic supply chain	High	Low	Moderate	Moderate	Moderate
Ocean plastic recycling	Low	Low	High	Moderate	Low
Maximize energy efficiency throughout plastic supply chain	Low	Low	Moderate	High	Low
Modern landfill	Low	Low	Moderate	High	Low
Mandate capturing gas vs. loss (flaring/venting)	Low	Moderate	Moderate	Moderate	Low
False Solutions					
Biodegradable plastic	Low	Low	Moderate	Moderate	Low
Use bio-feedstocks in petrochemical and plastic manufacturing	Moderate	Low	Low	Moderate	Low
Plastic-eating organisms	Low	Low	Moderate	Moderate	Low
Ocean cleanup	Low	Low	Moderate	Low	Low
Use chemically recycled feedstocks in petrochemical and plastic manufacturing	Low	Low	Low	Moderate	Low
Further integrate petroleum refining, gas processing, petrochemical, and plastic manufacturing	Low	Low	Low	Moderate	Low
Waste-to-energy	Low	Low	Low	Moderate	Low

■ High ■ Moderate ■ Low

CHAPTER NINE

Conclusions

The profound and rising impact of the plastic crisis on ocean ecosystems and marine species has prompted global concern and growing calls for regulation at the local, national, and international levels. Mounting evidence demonstrates that, from wellhead to store shelves to water and food systems, the plastic lifecycle poses risks not only for the environment, but also for human health. Against this backdrop, the present report documents the array of mechanisms through which plastic also compounds the risks of climate change.

In the Paris Climate Agreement, the nations of the world committed to keep climate change to well below 2°C and to pursue efforts to stay within 1.5°C of warming. To date, the earth has warmed just over 1°C due to human activity, yet the devastating impacts of that change are already evident in countries and communities around the world. The overwhelming scientific consensus now demonstrates that warming of even 1.5°C will bring still greater risks and that warming beyond that level would cause irreparable, irreversible harm to ecosystems and still greater losses of human livelihoods, human rights, and human lives. To have any hope of avoiding these outcomes, the world must cut its emissions of greenhouse gases by 45 percent by 2030 and reach zero net emissions by mid-century.

Whether measured by its present scale or projected growth, the existing plastic economy is fundamentally inconsistent with that goal. On its present trajectory, emissions from plastic production and use would exceed the entire remaining carbon budget for all industrial greenhouse gas emissions even under a 2°C scenario. Even modest growth in plastic will make achieving a 1.5°C target virtually impossible. Meeting these targets will require immediate and dramatic reductions in plastic production and use as an essential component of the broader transition from the fossil economy. Accordingly, a fundamental finding of this report is that these climate impacts must play a larger and more explicit role in decisions about plastic policies, plastic production, and plastic-related investments. The ongoing, rapid growth of plastic production can and should appropriately be measured against the earth's rapidly dwindling carbon budget. Every new or proposed facility in the plastic supply chain should be evaluated for its impact on that budget by the corporate decisionmakers that propose it, by the potential investors who must evaluate it, and by the governments that must approve it.

Whether measured by its present scale or projected growth, the existing plastic economy is fundamentally inconsistent with the Paris Agreement.

This report also demonstrates that the true scale of climate risks from plastic, while clearly significant, remains largely unquantified. A recurring and troubling theme of the report is the degree to which entire categories of emissions sources are either inconsistently documented or wholly undocumented in the context of plastic. Plastic is the second-largest and fastest growing source of industrial greenhouse gas emissions, so addressing and closing these gaps should be a high priority.

This report also exposes the profound risks inherent in perpetuating a plastic economy while these information gaps remain unfilled. Nowhere are the risks of this systemic ignorance more evident and more profound than with plastic's impacts on

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the oceanic carbon sink. Though existing evidence is preliminary, and significant knowledge gaps remain, there is mounting evidence that microplastic is being found in the plankton that not only form the base of oceanic food chains but also provide the single most important mechanism for absorbing atmospheric carbon and transporting it to deep-ocean carbon sinks. In oceans around the world—in the North Atlantic, the North Pacific, the Indian Ocean, and the China Sea—zooplankton are being contaminated with microplastic. If, as laboratory experiments suggest, this contamination is having significant effects on the feeding, vitality, and survival rates of these organisms, the implications for the oceanic carbon sink—and for the global climate—are both profound and profoundly troubling. At present, the plastic contamination of oceanic plankton raises more questions than answers. These questions deserve urgent attention.

This report identifies many such questions. It highlights the degree to which the world remains surprisingly ignorant about the lifecycle and the impacts of one of the most ubiquitous products in the global economy and one of the most pervasive contaminants on the planet.

Despite these uncertainties, however, this report demonstrates clearly that the climate impacts of the existing plastic economy are real, significant, and fundamentally incompatible with maintaining a survivable climate.

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230. Calculated based on the approximate weight ratio for carbon to carbon dioxide of 12 to 44.

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237. Global plastic production is estimated to grow at the rate of 3.5- 3.8 percent annually 2015–2030 (ICIS) and 3.5 percent annually 2030–2050 (International Energy Agency World Energy Outlook 2015). A growth rate of 3.65 percent was applied in this analysis as the Ellen MacArthur Foundation report, 'The New Plastics Economy' projected that plastic production will be 1124 million metric tons by 2050. *See* World Economic Forum, *supra* note 12; Ellen MacArthur Foundation, *supra* note 225.

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Plastic & Climate

THE HIDDEN COSTS OF A PLASTIC PLANET

Amidst growing concern about the impacts of plastic on the oceans, ecosystems, and human health, there's another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change. This report examines each of these stages of the plastic lifecycle to identify the major sources of greenhouse gas emissions, sources of uncounted emissions, and uncertainties that likely lead to underestimation of plastic's climate impacts. The report compares greenhouse gas emissions estimates against global carbon budgets and emissions commitments, and it considers how current trends and projections will impact our ability to reach agreed emissions targets. It also compiles data, such as downstream emissions and future growth rates, that have not previously been accounted for in widely used climate models. This accounting paints a grim picture: plastic proliferation threatens our planet and the climate at a global scale.

Available online at **www.ciel.org/plasticandclimate**

CIEL Center for International Environmental Law · EIP Environmental Integrity Project · FracTracker Alliance insights empowering action · gaia Global Alliance for Incinerator Alternatives · 5 Gyres Science to Solutions · #break free from plastic

EXHIBIT 2

United States Government Accountability Office

GAO

Testimony
Before the Committee on the Budget, House of Representatives

For Release on Delivery
Expected at 10:00 a.m. ET
Tuesday, June 11, 2019

CLIMATE CHANGE

Opportunities to Reduce Federal Fiscal Exposure

Statement of J. Alfredo Gómez, Director, Natural Resources and Environment

GAO Highlights

Highlights of GAO-19-625T, a testimony before the Committee on the Budget, House of Representatives

Why GAO Did This Study

Since 2005, federal funding for disaster assistance is at least $450 billion, including approximately $19.1 billion in supplemental appropriations signed into law on June 6, 2019. In 2018 alone, there were 14 separate billion-dollar weather and climate disaster events across the United States, with a total cost of at least $91 billion, according to the National Oceanic and Atmospheric Administration. The U.S. Global Change Research Program projects that disaster costs will likely increase as certain extreme weather events become more frequent and intense due to climate change.

The costs of recent weather disasters have illustrated the need for planning for climate change risks and investing in resilience. Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events, according to the National Academies of Science, Engineering, and Medicine. Investing in resilience can reduce the need for far more costly steps in the decades to come.

Since February 2013, GAO has included *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* on its list of federal program areas at high risk of vulnerabilities to fraud, waste, abuse, and mismanagement or most in need of transformation. GAO updates this list every 2 years. In March 2019, GAO reported that the federal government had not made measurable progress since 2017 to reduce fiscal exposure to climate change.

View GAO-19-625T. For more information, contact J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

June 11, 2019

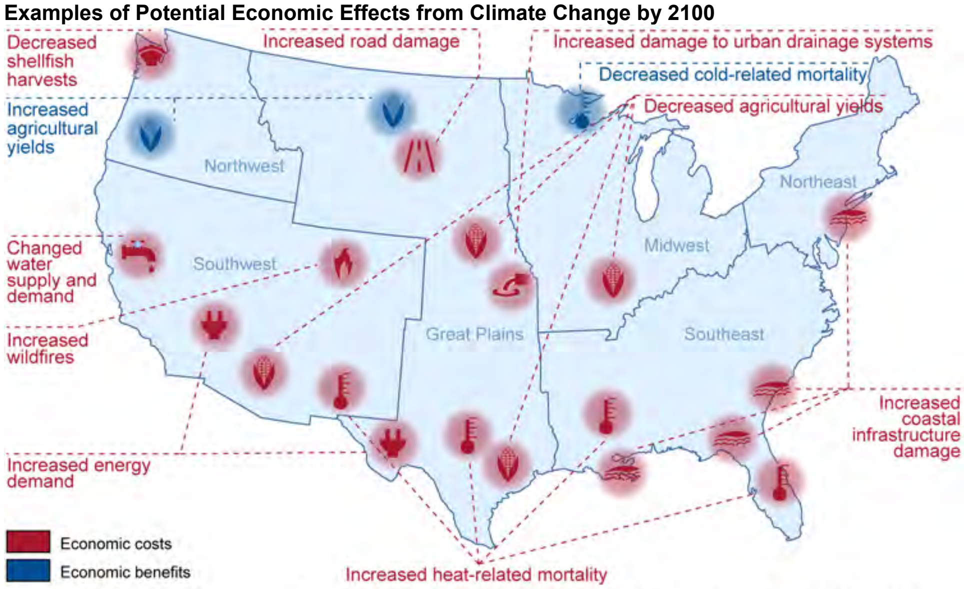
CLIMATE CHANGE

Opportunities to Reduce Federal Fiscal Exposure

What GAO Found

The estimated economic effects of climate change, while imprecise, can convey useful insight about potential damages in the United States. In September 2017, GAO reported that the potential economic effects of climate change could be significant and unevenly distributed across sectors and regions (see figure). This is consistent with the recent findings of the U.S. Global Change Research Program's Fourth National Climate Assessment, which concluded, among other things, that the continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal infrastructure.

Examples of Potential Economic Effects from Climate Change by 2100



Sources: GAO analysis of Environmental Protection Agency, *Climate Change Impacts in the United States: Benefits of Global Action* (Washington, D.C.: 2015), and Solomon Hsiang et al., "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017); Map Resources (map). | GAO-19-625T

Information about the potential economic effects of climate change could inform decision makers about significant potential damages in different U.S. sectors or regions. According to prior GAO work, this information could help decision makers identify significant climate risks as an initial step toward managing them.

The federal government faces fiscal exposure from climate change risks in several areas, including:

- **Disaster aid:** due to the rising number of natural disasters and increasing reliance on federal assistance. GAO has previously reported that the federal government does not adequately plan for disaster resilience. GAO has also reported that, due to an artifically low indicator for determining a jurisdiction's ability to respond to disasters that was set in 1986, the Federal Emergency

This testimony—based on reports GAO issued from October 2009 to March 2019—discusses (1) what is known about the potential economic effects of climate change in the United States and the extent to which this information could help federal decision makers manage climate risks across the federal government, (2) the potential impacts of climate change on the federal budget, (3) the extent to which the federal government has invested in resilience, and (4) how the federal government could reduce fiscal exposure to the effects of climate change.

GAO has made 62 recommendations related to the *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* high-risk area. As of December 2018, 25 of those recommendations remained open.

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Management Agency risks recommending federal assistance for juridisctions that could recover on their own.

- **Federal insurance for property and crops:** due, in part, to the vulnerability of insured property and crops to climate change impacts. Federal flood and crop insurance programs were not designed to generate sufficient funds to fully cover all losses and expenses. The flood insurance program, for example, was about $21 billion in debt to the Treasury as of April 2019. Further, the Congressional Budget Office estimated in May 2019 that federal crop insurance would cost the federal government an average of about $8 billion annually from 2019 through 2029.
- **Operation and management of federal property and lands:** due to the hundreds of thousands of federal facilities and millions of acres of land that could be affected by a changing climate and more frequent extreme events. For example, in 2018, Hurricane Michael devastated Tyndall Air Force Base in Florida, with a preliminary repair estimate of $3 billion.

The federal budget, however, does not generally account for disaster assistance provided by Congress or the long-term impacts of climate change on existing federal infrastructure and programs. GAO has reported that more complete information about fiscal exposure could help policymakers better understand the trade-offs when making spending decisions.

Further, federal investments in resilience to reduce fiscal exposures have been limited. As GAO has reported, enhancing resilience can reduce fiscal exposure by reducing or eliminating long-term risk to people and property from natural hazards. For example, a 2018 interim report by the National Institute of Building Sciences estimated approximate benefits to society in excess of costs for several types of resilience projects. While precise benefits are uncertain, the report estimated that for every dollar invested in designing new buildings to particular design standards, society could accrue benefits amounting to about $11 on average.

The federal government has invested in individual agency efforts that could help build resilience within existing programs or projects. For example, the National Climate Assessment reported that the U.S. military integrates climate risks into its analysis, plans, and programs. In additon, as GAO reported in March 2019, the Disaster Recovery Reform Act of 2018 could improve resilience by allowing the President to set aside a portion of certain grants for pre-disaster mitigation. However, the federal government has not undertaken strategic government-wide planning to manage climate risks.

GAO's March 2019 High-Risk report identified a number of recommendations GAO has made related to fiscal exposure to climate change. The federal government could reduce its fiscal exposure by implementing these recommendations. Among GAO's key government-wide recommendations are:

- Entities within the Executive Office of the President (EOP) should work with partners to establish federal strategic climate change priorities that reflect the full range of climate-related federal activities;
- Entities within EOP should use information on potential economic effects from climate change to help identify significant climate risks and craft appropriate federal responses;
- Entities within EOP should designate a federal entity to develop and update a set of authoritative climate observations and projections for use in federal decision making, and create a national climate information system with defined roles for federal agencies and certain nonfederal entities; and
- The Department of Commerce should convene federal agencies to provide the best-available forward-looking climate information to organizations that develop design standards and building codes to enhance infrastructure resilience.

Chairman Yarmuth, Ranking Member Womack, and Members of the Committee:

Thank you for the opportunity to discuss our work on how to limit the federal government's fiscal exposure by better managing climate change risks, an area that has been on our High-Risk List since February 2013.[1] Addressing climate change risks requires advanced planning and investment to reduce the need for far more costly steps in the decades to come, which, as we have previously reported, the federal government is not well organized to do. The costs associated with recent disasters have illustrated the need for such planning and investment. In 2018 alone, there were 14 separate billion-dollar weather and climate disaster events across the United States, with a total cost of at least $91 billion, according to the National Oceanic and Atmospheric Administration (NOAA).[2] Further, on June 6, 2019, a supplemental appropriation of approximately $19.1 billion was signed into law for recent disasters.

The U.S. Global Change Research Program (USGCRP), which coordinates and integrates the activities of 13 federal agencies that research changes in the global environment and their implications for society, reported in its November 2018 Fourth National Climate Assessment that climate change is playing a role in the increasing frequency of some types of extreme weather that lead to the billion-dollar disasters.[3] These changes include the rise in vulnerability to drought, lengthening wildfire seasons, and the potential for extremely heavy rainfall becoming more common in some regions. USGCRP reported in the prior assessment that the costs of many of these disasters will likely

[1]Our High-Risk List identifies federal program areas that are at high risk of vulnerabilities to fraud, waste, abuse, and mismanagement or most in need of transformation. See GAO, *High-Risk Series: An Update*, GAO-13-283 (Washington, D.C.: Feb. 14, 2013).

[2]NOAA National Centers for Environmental Information, U.S. Billion-Dollar Weather and Climate Disasters (2019). See: https://www.ncdc.noaa.gov/billions/time-series, accessed June 3, 2019.

[3]D.R. Reidmiller, C.W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart (eds.), *2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, DC: U.S. Global Change Research Program, November 2018). Under the Global Change Research Act of 1990 (Pub. L. No. 101-606, § 103 (1990)), USGCRP is to periodically prepare a scientific assessment—known as the National Climate Assessment—which is an important resource for understanding and communicating climate change science and impacts in the United States. The Office of Science and Technology Policy within the Executive Office of the President oversees USGCRP.

increase as extreme weather events become more frequent and intense with climate change.[4]

In my testimony today, I will discuss (1) what is known about the potential economic effects of climate change in the United States and the extent to which this information could help federal decision makers manage climate risks across the federal government, (2) the potential impacts of climate change on the federal budget, (3) the extent to which the federal government has invested in resilience to climate change impacts,[5] and (4) how the federal government could reduce fiscal exposure to the effects of climate change. My testimony is based on reports we issued from October 2009 to March 2019. More detailed information on our objectives, scope, and methodology can be found in those reports.

The work upon which this statement is based was conducted in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[4]Jerry M. Melillo, Terese (T.C.) Richmond, and Gary W. Yohe, eds., *Climate Change Impacts in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program (Washington, D.C.: May 2014).

[5]The National Academies of Sciences, Engineering, and Medicine (National Academies) define resilience as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. See the National Academies, Committee on Increasing National Resilience to Hazards and Disasters; Committee on Science, Engineering, and Public Policy; Disaster Resilience: A National Imperative (Washington, D.C.: 2012). We reported in May 2016 that two related sets of actions can enhance resilience by reducing risk. These include climate change adaptation and pre-disaster hazard mitigation. Adaptation is defined as adjustments to natural or human systems in response to actual or expected climate change. Pre-disaster hazard mitigation refers to actions taken to reduce the loss of life and property by lessening the impacts of adverse events and applies to all hazards, including terrorism and natural hazards, such as health pandemics or weather-related disasters. In this testimony, we use the term “resilience” for consistency and to encompass both of these sets of actions as they relate to addressing climate risks. GAO, *Climate Change: Selected Governments Have Approached Adaptation through Laws and Long-Term Plans,* GAO-16-454 (Washington, D.C.: May 12, 2016).

Information on the Potential Economic Effects of Climate Change in the United States Could Help Federal Decision Makers Better Manage Climate Risks

We reported in September 2017 that, while estimates of the economic effects of climate change are imprecise due to modeling and information limitations, they can convey useful insight into broad themes about potential damages in the United States.[6] We reported that, according to the two national-scale studies available at the time that examined the economic effects of climate change across U.S. sectors, potential economic effects could be significant and these effects will likely increase over time for most of the sectors analyzed.[7] For example, for 2020 through 2039, one of the studies estimated from $4 billion to $6 billion in annual coastal property damages from sea level rise and more frequent and intense storms.[8] In addition, the national-scale studies we reviewed and several experts we interviewed for the September 2017 report suggested that potential economic effects could be unevenly distributed across sectors and regions. For example, one of the studies estimated that the Southeast, Midwest, and Great Plains regions will likely experience greater combined economic effects than other regions, largely because of coastal property damage in the Southeast and changes in crop yields in the Midwest and Great Plains (see figure 1).[9] This is

[6]GAO, *Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure,* GAO-17-720 (Washington, D.C.: Sept. 28, 2017).

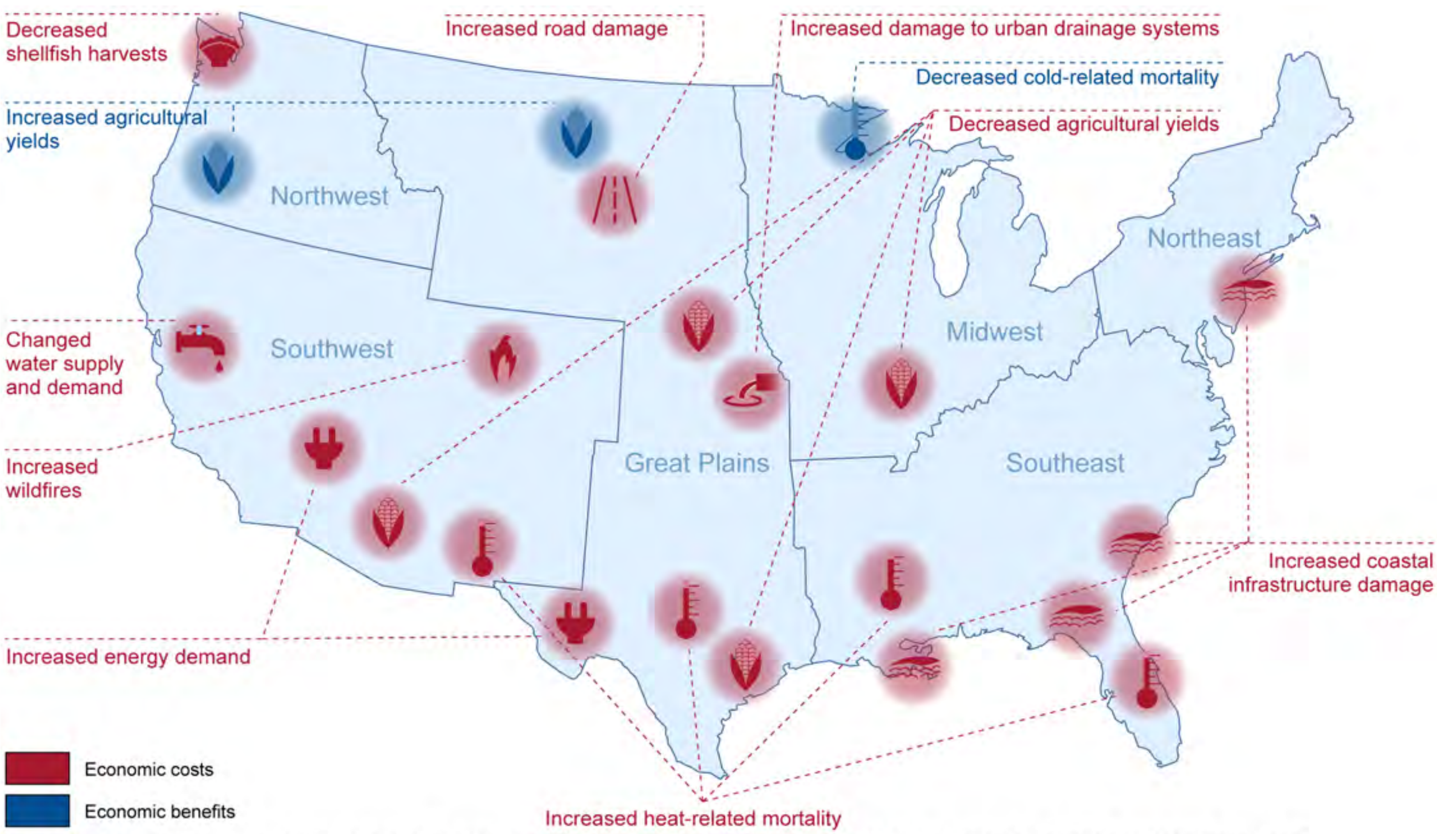
[7]These national-scale studies were the Environmental Protection Agency's *Climate Change Impacts and Risk Analysis*—a summary study of an ongoing EPA project—and the Rhodium Group's *American Climate Prospectus.* See Environmental Protection Agency, Office of Atmospheric Programs, *Climate Change in the United States: Benefits of Global Action*, EPA 430-R-15-001 (Washington, D.C.: 2015). The EPA project on which the summary study was based was coordinated by EPA's Office of Atmospheric Programs—Climate Change Division, with contributions from national laboratories and the academic and private sectors. The detailed methods and results of the project were published in a 2014 special issue of the peer-reviewed journal, *Climatic Change* entitled, "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." An update to this project was used in the 2018 Fourth National Climate Assessment. Also see Rhodium Group, LLC., *American Climate Prospectus: Economic Risks in the United States* (New York: October 2014). The *American Climate Prospectus* was funded by the Risky Business Project, a project funded by Bloomberg Philanthropies, the Paulsen Institute, and TomKat Charitable Trust; the Skoll Global Threats Fund; and the Rockefeller Family Fund. The Rhodium Group, LLC, a research consultancy and advisory company, coordinated the effort, which involved authors from universities and the private sector. This study was later published by the Columbia University Press in 2015: Trevor Houser et al., *Economic Risks of Climate Change: An American Prospectus* (New York: Columbia University Press, 2015). An update to this analysis was published in *Science* in June 2017: Solomon Hsiang et al "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017).

[8]Rhodium Group, *American Climate Prospectus.*

[9]Rhodium Group, *American Climate Prospectus.*

consistent with the findings of the Fourth National Climate Assessment.[10] For example, according to that assessment, the continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal property market and public infrastructure sector.

Figure 1: Examples of Potential Economic Effects from Climate Change by 2100



Sources: GAO analysis of Environmental Protection Agency, *Climate Change Impacts in the United States: Benefits of Global Action* (Washington, D.C.: 2015), and Solomon Hsiang et al., "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017); Map Resources (map). | GAO-19-625T

As we reported in September 2017, information on the potential economic effects of climate change could help federal decision makers better manage climate risks, according to leading practices for climate risk management, economic analysis we reviewed, and the views of several

[10]D.R. Reidmiller e.t. al, *Fourth National Climate Assessment, Volume II.*

experts we interviewed.[11] For example, such information could inform decision makers about significant potential damages in different U.S. sectors or regions. According to several experts and our prior work, this information could help federal decision makers identify significant climate priorities as an initial step toward managing climate risks.[12] Such a first step is consistent with leading practices for climate risk management and federal standards for internal control.[13] For example, leading practices from the National Academies call for climate change risk management efforts that focus on where immediate attention is needed.[14] As noted in our September 2017 report, according to a 2010 National Academies report, other literature we reviewed, and several experts we interviewed, to make informed choices, decision makers need more comprehensive information on economic effects to better understand the potential costs of climate change to society and begin to develop an understanding of the benefits and costs of different options for managing climate risks.[15]

[11]In that report, we also found that additional economic information could help federal, state, local, and private sector decision makers manage climate risks that drive federal fiscal exposure. GAO-17-720.

[12]GAO-17-720.

[13]National Research Council of the National Academies, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, *Adapting to the Impacts of Climate Change* and GAO, *Standards for Internal Control in the Federal Government*, GAO-14-704G (Washington, D.C.: September 2014).

[14]National Research Council of the National Academies, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, *Adapting to the Impacts of Climate Change* (Washington, D.C.: 2010).

[15]GAO-17-720.

The Federal Government Faces Fiscal Exposure from Climate Change Risks, but Does Not Have Certain Information Needed to Help Make Budget Decisions

The federal government faces fiscal exposure from climate change risks in a number of areas, and this exposure will likely increase over time, as we concluded in September 2017.[16] In the March 2019 update to our High-Risk List, we summarized our previous work that identified several of these areas across the federal government, including programs related to the following:[17]

- **Disaster aid.** The rising number of natural disasters and increasing reliance on federal assistance are a key source of federal fiscal exposure, and this exposure will likely continue to rise. Since 2005, federal funding for disaster assistance is at least $450 billion.[18] In September 2018, we reported that four hurricane and wildfire disasters in 2017 created an unprecedented demand for federal disaster resources and that hurricanes Harvey, Irma, and Maria ranked among the top five costliest hurricanes on record.[19] Subsequently, the fall of 2018 brought additional catastrophic

[16]GAO-17-720.

[17]We have identified other areas with potential links to climate and the federal budget in past reports, including global migration, state and local infrastructure, federal supply chains, and public health. See GAO, *Climate Change: Activities of Selected Agencies to Address Potential Impact on Global Migration,* GAO-19-166 (Washington, D.C.: Jan. 17, 2019); *Climate Information: A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information,* GAO-16-37 (Washington, D.C.: Nov. 23, 2015); *Federal Supply Chains: Opportunities to Improve the Management of Climate-Related Risks,* GAO-16-32 (Washington, D.C.: Oct. 13, 2015); and *Climate Change: HHS Could Take Further Steps to Enhance Understanding of Public Health Risks,* GAO-16-122 (Washington, D.C.: Oct. 5, 2015). We also have ongoing work in many areas related to federal fiscal exposure to climate change, examining issues such as how to identify and prioritize resilience projects to build resilience to climate change impacts, how to make water infrastructure more resilient to the impacts of climate change, and how to help communities voluntarily relocate to avoid climate change impacts.

[18]This total includes, for fiscal years 2005 through 2014, $278 billion that GAO found that the federal government had obligated for disaster assistance. See GAO, *Federal Disaster Assistance: Federal Departments and Agencies Obligated at Least $277.6 Billion during Fiscal Years 2005 through 2014,* GAO-16-797 (Washington, D.C.: Sept. 22, 2016). It also includes, for fiscal years 2015 through 2018, $124 billion in select supplemental appropriations to federal agencies for disaster assistance, approximately $7 billion in annual appropriations to the Disaster Relief Fund (a total of $28 billion for the 4-year period). For fiscal years 2015 through 2018, it does not include other annual appropriations to federal agencies for disaster assistance. Lastly, on June 6, 2019, the Additional Supplemental Appropriations for Disaster Relief Act of 2019 was signed into law, which provides approximately $19.1 billion for disaster assistance. H.R. 2157, 116th Cong. (2019) (enacted).

[19]GAO, *2017 Hurricanes and Wildfires: Initial Observations on the Federal Response and Key Recovery Challenges*, GAO-18-472 (Washington, D.C.: Sept. 4, 2018).

disasters such as Hurricanes Florence and Michael and devastating California wildfires, with further needs for federal disaster assistance. Disaster costs are projected to increase as certain extreme weather events become more frequent and intense due to climate change—as observed and projected by USGCRP.[20] In July 2015, we reported that the federal government does not adequately plan for disaster resilience and that most federal funding for hazard mitigation is available after a disaster.[21] In addition, our prior work found that the Federal Emergency Management Agency's (FEMA) indicator for determining whether to recommend that a jurisdiction receive disaster assistance—which was set in 1986—is artificially low because it does not accurately reflect the ability of state and local governments to respond to disasters.[22] Without an accurate assessment of a jurisdiction's capability to respond to a disaster without federal assistance, we found that FEMA runs the risk of recommending that the President award federal assistance to jurisdictions that have the capability to respond and recover on their own.

- **Federal insurance for property and crops.** The National Flood Insurance Program (NFIP) and the Federal Crop Insurance Corporation are sources of federal fiscal exposure due, in part, to the vulnerability of the insured property and crops to climate change.[23] These programs provide coverage where private markets for insurance do not exist, typically because the risk associated with the property or crops is too great to privately insure at a cost that buyers are willing to accept. From 2013 to 2017, losses paid under NFIP and

[20]Jerry M. Melillo, et. al., *Climate Change Impacts in the United States: The Third National Climate Assessment.*

[21]For example, from fiscal years 2011 to 2014, the Federal Emergency Management Agency obligated more than $3.2 billion for the Hazard Mitigation Grant Program for post-disaster hazard mitigation while obligating approximately $222 million for the Pre-Disaster Mitigation Grant Program. GAO, *Hurricane Sandy: An Investment Strategy Could Help the Federal Government Enhance National Resilience for Future Disasters*, GAO-15-515 (Washington, D.C.: July 30, 2015).

[22]GAO, *Federal Disaster Assistance: Improved Criteria Needed to Assess a Jurisdiction's Capability to Respond and Recover on Its Own,* GAO-12-838 (Washington, D.C.: Sept. 12, 2012).

[23]The NFIP is administered by FEMA within the U.S. Department of Homeland Security, and the Federal Crop Insurance Corporation is administered by the Risk Management Agency within the U.S. Department of Agriculture.

the federal crop insurance program totaled $51.3 billion.[24] Federal flood and crop insurance programs were not designed to generate sufficient funds to fully cover all losses and expenses, which means the programs need budget authority from Congress to operate. The NFIP, for example, was about $21 billion in debt to the Treasury as of April 2019.[25] Further, the Congressional Budget Office estimated in May 2019 that federal crop insurance would cost the federal government an average of about $8 billion annually from 2019 through 2029.[26]

- **Operation and management of federal property and lands.** The federal government owns and operates hundreds of thousands of facilities and manages millions of acres of land that could be affected by a changing climate and represent a significant federal fiscal exposure. For example, the Department of Defense (DOD) owns and operates domestic and overseas infrastructure with an estimated replacement value of about $1 trillion. In September 2018, Hurricane Florence damaged Camp Lejeune and other Marine Corps facilities in North Carolina, resulting in a preliminary Marine Corps repair estimate of $3.6 billion. One month later, Hurricane Michael devastated Tyndall Air Force Base in Florida, resulting in a preliminary Air Force repair estimate of $3 billion and upwards of 5 years to complete the work. In addition, we recently reported that the federal government manages about 650 million acres of land in the United States that could be vulnerable to climate change, including the possibility of more frequent and severe droughts and wildfires.[27] Appropriations for federal wildland fire management activities have increased

[24]FEMA and Risk Management Agency published data. This does not include the costs of running these programs or the premiums collected to partially offset the costs. Losses for the crop insurance program are losses associated with crops harvested in that year, also known as crop year.

[25]U. S. Department of The Treasury, Bureau of the Fiscal Service. *Monthly Treasury Statement. Table 6. Schedule C* (Washington, D.C.: April 2019).

[26]Congressional Budget Office, *CBO's May 2019 Baseline for Farm Programs* (Washington, D.C.: May 2, 2019).

[27]GAO, *Climate Change: Various Adaptation Efforts Are Under Way at Key Natural Resource Management Agencies,* GAO-13-253 (Washington, D.C.: May 31, 2013).

considerably since the 1990s, as we and the Congressional Research Service have reported.[28]

Although the federal government faces fiscal exposure from climate change across the nation, it does not have certain information needed by policymakers to help understand the budgetary impacts of such exposure.[29] We have previously reported that the federal budget generally does not account for disaster assistance provided by Congress—which can reach tens of billions of dollars for some disasters—or the long-term impacts of climate change on existing federal infrastructure and programs.[30] For Example, as we reported in April 2018, the Office of Management and Budget's (OMB) climate change funding reports we reviewed did not include funding information on federal programs with significant fiscal exposures to climate change identified by OMB and others—such as domestic disaster assistance, flood insurance, and crop insurance.[31] A more complete understanding of climate change fiscal exposures can help policymakers anticipate changes in future spending and enhance control and oversight over federal resources, as we reported in October 2013.[32] For budget decisions for federal programs with fiscal exposure to climate change, we found in the April 2018 report that information that could help provide a more complete understanding would include: (1) costs to repair, replace, and improve the weather-related resilience of federally-funded property and resources; (2) costs for

[28]*GAO, Budget Issues: Opportunities to Reduce Federal Fiscal Exposures Through Greater Resilience to Climate Change and Extreme Weather,* GAO-14-504T (Washington, D.C.: July 29, 2014) and Congressional Research Service, *Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress,* R44966 (Washington, D.C.: November 8, 2017).

[29]In our past work, we identified broad principles for an effective budget process, including that it should (1) provide information about the long-term effects of decisions; (2) provide information necessary to make important trade-offs between spending with long-term benefits and spending with short-term benefits, and (3) provide for accountability and be transparent, among other principles. Further, in October 2013, we reported that incorporating more complete information on fiscal exposures could help meet these principles for an effective budget process. See GAO, *Budget Process: Enforcing Fiscal Choices,* GAO-11-626T (Washington, D.C.: May 4, 2011) and GAO, *Fiscal Exposures: Improving Cost Recognition in the Federal Budget,* GAO-14-28 (Washington, D.C.: Oct. 29, 2013).

[30]GAO-14-505T.

[31]GAO, *Climate Change: Analysis of Reported Federal Funding,* GAO-18-223 (Washington, D.C.: Apr. 30, 2018).

[32]GAO-14-28.

federal flood and crop insurance programs; and (3) costs for disaster assistance programs, among other identified areas of fiscal exposure to climate change.[33] To help policymakers better understand the trade-offs when making spending decisions, we recommended in the April 2018 report that OMB provide information on fiscal exposures related to climate change in conjunction with future reports on climate change funding.[34]

Federal Investments in Resilience to Climate Change Impacts Have Been Limited

Although the federal government faces fiscal exposure to climate change, its investments in resilience to climate change impacts have been limited. One way to reduce federal fiscal exposure is to enhance resilience by reducing or eliminating long-term risk to people and property from natural hazards. For example, in September 2018 we reported that elevating homes and strengthened building codes in Texas and Florida prevented greater damages during the 2017 hurricane season.[35] In addition, one company participating in a 2014 forum we held on preparing for climate-related risks noted that for every dollar it invested in resilience efforts, the company could prevent $5 in potential losses.[36] Finally, a 2018 interim report by the National Institute of Building Sciences examined a sample of federal grants for hazard mitigation. The report estimated approximate benefits to society (i.e., homeowners, communities, etc.) in excess of costs for several types of resilience projects through the protection of lives and property, and prevention of other losses.[37] For example, while

[33]GAO-18-223.

[34]OMB disagreed with this recommendation and has not implemented it, but we continue to believe that the recommendation is valid. GAO-18-223.

[35]Specifically, FEMA officials said Hurricane Harvey demonstrated how prior hazard mitigation projects prevented greater damages (e.g., elevated homes and equipment sustained less damages). FEMA officials said Florida strengthened its building codes for resilience as a result of Hurricanes Andrew in 1992, and Matthew in 2016. GAO-18-472.

[36]GAO, *Highlights of a Forum: Preparing for Climate-Related Risks: Lessons from the Private Sector,* GAO-16-126SP (Washington, D.C.: Nov. 19, 2015).

[37]This report examined a narrow sample of hazard mitigation grants awarded by FEMA, the Economic Development Administration, and the Department of Housing and Urban Development from 1993 to 2016 to address various hazards. Extrapolation to a broader set of grants needs to be interpreted in the context of the selected sample. These hazards included fires at the wildland-urban interface (i.e., fires in areas where homes are built near or among lands prone to wildland fire), hurricane- and tornado-force winds, and riverine floods (i.e., floods that occur when river flows exceed the capacity of the river channel). See Multihazard Mitigation Council, a council of the National Institute of Building Sciences, *Natural Hazard Mitigation Saves: 2018 Interim Report (Washington, D.C.: December 2018)*.

precise benefits are uncertain, the report estimated that for every grant dollar the federal government spent on resilience projects, over time, society could accrue benefits amounting to the following:

- About $3 on average from projects addressing fire at the wildland urban interface, with most benefits (69 percent) coming from the protection of property (i.e., avoiding property losses).
- About $5 on average from projects to address hurricane and tornado force winds, with most benefits (89 percent) coming from the protection of lives. This includes avoiding deaths, nonfatal injuries, and causes of post-traumatic stress.
- About $7 on average from projects that buy out buildings prone to riverine flooding, with most benefits (65 percent) coming from the protection of property.

The interim report also estimated that society could accrue benefits amounting to about $11 on average for every dollar invested in designing new buildings to meet the 2018 International Building Code and the 2018 International Residential Code—the model building codes developed by the International Code Council—with most benefits (46 percent) coming from the protection of property.[38]

We reported in October 2009 that the federal government's activities to build resilience to climate change were carried out in an ad hoc manner and were not well coordinated across federal agencies.[39] Federal agencies have included some of these activities within existing programs and operations—a concept known as mainstreaming. For example, the Fourth National Climate Assessment reported that the U.S. military integrates climate risks into its analysis, plans and programs, with particular attention paid to climate effects on force readiness, military

[38]The International Code Council is a member-focused association with over 64,000 members dedicated to developing model codes and standards used in the design, build, and compliance process to construct safe, sustainable, affordable and resilient structures. The report used a baseline of buildings constructed to a prior generation of codes represented by 1990s-era design and National Flood Insurance Program requirements.

[39]GAO, *Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions,* GAO-10-113 (Washington, D.C.: Oct. 7, 2009).

bases, and training ranges.[40] However, according to the Fourth National Climate Assessment, while a significant portion of climate risk can be addressed by mainstreaming, the practice may reduce the visibility of climate resilience relative to dedicated, stand-alone approaches and may prove insufficient to address the full range of climate risks.[41]

In addition, as we reported in March 2019, the Disaster Recovery Reform Act of 2018 (DRRA) was enacted in October 2018, which could improve state and local resilience to disasters. DRRA, among other things, allows the President to set aside, with respect to each major disaster, a percentage of the estimated aggregate amount of certain grants to use for pre-disaster hazard mitigation and makes federal assistance available to state and local governments for building code administration and enforcement.[42] However, it is too early to tell what impact the implementation of the act will have on state and local resilience.

The federal government has made some limited investments in resilience and DRRA could enable additional improvements at the state and local level. However, we reported in September 2017 that the federal government had not undertaken strategic government-wide planning to manage significant climate risks before they become fiscal exposures.[43] We also reported in July 2015 that the federal government had no comprehensive strategic approach for identifying, prioritizing, and

[40]Lempert, R., J. Arnold, R. Pulwarty, K. Gordon, K. Greig, C. Hawkins Hoffman, D. Sands, and C. Werrell. 2018. Reducing Risks Through Adaptation Actions. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, D.C.: U.S. Global Change Research Program, 2018). We also reported in May 2014 that officials from the Office of the Secretary of Defense and the military departments stated that their goal is to address potential climate change impacts and vulnerabilities through existing infrastructure planning processes so that the effects of climate change are considered in the same way other impacts and vulnerabilities—such as force protection—are currently considered. GAO, *Climate Change Adaptation: DOD Can Improve Infrastructure Planning and Processes to Better Account for Potential Impacts,* GAO-14-446 (Washington, D.C.: May 30, 2014).

[41]Lempert, R., J. Arnold, R. Pulwarty, K. Gordon, K. Greig, C. Hawkins Hoffman, D. Sands, and C. Werrell, 2018: Reducing Risks Through Adaptation Actions. *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, D.C.: U.S. Global Change Research Program, 2018).

[42]FAA Reauthorization Act of 2018, Pub. L. No. 115-254, div. D, §§ 1206(a)(3), 1234(a)(2)(C), 1234(a)(5), 132 Stat. 3186, 3440, 3462 (2018). The FAA Reauthorization Act of 2018, which included the DRRA, became law on October 5th, 2018.

[43]GAO-17-720.

implementing investments for disaster resilience.[44] As an initial step in managing climate risks, most of the experts we interviewed for the September 2017 report told us that federal decision makers should prioritize risk management efforts on significant climate risks that create the greatest fiscal exposure.[45] However, as we reported in our March 2019 High-Risk List, the federal government had not made measurable progress since 2017 to reduce fiscal exposure in several key areas that we have identified.[46] The High-Risk List identified *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* as an area needing significant attention because the federal government has regressed in progress toward one of our criterion for removal from the list.[47]

[44]In our 2015 report, we recommended that the Mitigation Framework Leadership group—an interagency body chaired by FEMA—create a National Mitigation Investment Strategy to help federal, state, and local officials plan for and prioritize disaster resilience. In response, the Mitigation Framework Leadership Group developed a draft, high-level strategy. FEMA officials expect to publish the final version of the strategy by July 2019. However, the draft strategy does not explicitly address future climate change risks. GAO-15-515.

[45]GAO-17-720.

[46]GAO-19-157SP.

[47]We update our High-Risk List every 2 years. To determine which federal government programs and functions should be designated high-risk, we consider qualitative factors such as whether the risk could result in significantly impaired service, or significantly reduced economy, efficiency, or effectiveness; the exposure to loss in monetary or other quantitative terms; and corrective measures planned or under way. We have issued the following five criteria for an area to be removed from the list: leadership commitment, capacity, action plan, monitoring, and demonstrated progress. In the March 2019 report, the federal government regressed in progress toward meeting the monitoring criterion for the *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* high-risk area. Criteria for removing this area from the High-Risk List include demonstrating leadership commitment that is sustained and enhanced to address all aspects of the federal fiscal exposure to climate change cohesively.

The Federal Government Could Reduce Its Fiscal Exposure by Focusing and Coordinating Federal Efforts

As we reported in March 2019, the federal government could reduce its fiscal exposure to climate change by focusing and coordinating federal efforts.[48] However, the federal government is currently not well organized to address the fiscal exposure presented by climate change, partly because of the inherently complicated and crosscutting nature of the issue. We have made a total of 62 recommendations related to limiting the federal government's fiscal exposure to climate change over the years, 12 of which have been made since February 2017. As of December 2018, 25 of these recommendations remained open. In describing what needs to be done to reduce federal fiscal exposure to climate change, our March 2019 High-Risk report discusses many of the open recommendations.[49] Implementing these recommendations could help reduce federal fiscal exposure. Several of them, including those highlighted below, identify key government-wide efforts needed to help plan for and manage climate risks and direct federal efforts toward common goals, such as improving resilience:

- **Develop a national strategic plan:** In May 2011, we recommended that appropriate entities within the Executive Office of the President (EOP), including OMB, work with agencies and interagency coordinating bodies to establish federal strategic climate change priorities that reflect the full range of climate-related federal activities, including roles and responsibilities of key federal entities.[50]
- **Use economic information to identify and respond to significant climate risks:** In September 2017, we recommended that the appropriate entities within EOP use information on the potential economic effects of climate change to help identify significant climate risks facing the federal government and craft appropriate federal responses.[51] Such federal responses could include establishing a strategy to identify, prioritize, and guide federal investments to enhance resilience against future disasters.

[48]GAO-19-157SP.

[49]GAO-19-157SP.

[50]EOP neither agreed nor disagreed with our recommendation and as of March 2019, had not implemented it. GAO, *Climate Change: Improvements Needed to Clarify National Priorities and Better Align Them with Federal Funding Decisions,* GAO-11-317 (Washington, D.C.: May 20, 2011).

[51]EOP neither agreed nor disagreed with this recommendation and as of March 2019, had not implemented it. GAO-17-720.

- **Provide decision makers with the best available climate information:** In November 2015, we reported that federal efforts to provide information about climate change impacts did not fully meet the climate information needs of federal, state, local, and private sector decision makers, which hindered their efforts to plan for climate change risks.[52] We reported that these decision makers would benefit from a national climate information system that would develop and update authoritative climate observations and projections specifically for use in decision-making. As a result, we recommended that EOP (1) designate a federal entity to develop and periodically update a set of authoritative climate observations and projections for use in federal decision-making, which other decision makers could also access; and (2) designate a federal entity to create a national climate information system with defined roles for federal agencies and nonfederal entities with existing statutory authority.[53]
- **Consider climate information in design standards:** In November 2016, we reported that design standards, building codes, and voluntary certifications established by standards-developing organizations play a role in ensuring the resilience of infrastructure to the effects of natural disasters. However, we reported that these organizations faced challenges to using forward-looking climate information that could help enhance the resilience of infrastructure. As a result, we recommended in the November 2016 report that the Department of Commerce, acting through the National Institute of Standards and Technology—which is responsible for coordinating federal participation in standards organizations—convene federal agencies for an ongoing government-wide effort to provide the best available forward-looking climate information to standards-developing organizations for their consideration in the development of design standards, building codes, and voluntary certifications.[54]

In conclusion, the effects of climate change have already and will continue to pose risks that can create fiscal exposure across the federal government and this exposure will continue to increase. The federal

[52]GAO-16-37.

[53]EOP neither agreed nor disagreed with these recommendations and as of March 2019, had not implemented them.

[54]Commerce neither agreed nor disagreed with this recommendation and as of May 2018, had not implemented it. GAO, *Climate Change: Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications,* GAO-17-3 (Washington, D.C.: Nov. 30, 2016).

government does not generally account for such fiscal exposure to programs in the budget process nor has it undertaken strategic efforts to manage significant climate risks that could reduce the need for far more costly steps in the decades to come. To reduce its fiscal exposure, the federal government needs a cohesive strategic approach with strong leadership and the authority to manage risks across the entire range of related federal activities. The federal government could make further progress toward reducing fiscal exposure by implementing the recommendations we have made.

Chairman Yarmuth, Ranking Member Womack, and Members of the Committee, this completes my prepared statement. I would be pleased to respond to any questions that you may have at this time.

GAO Contact and Staff Acknowledgments

If you or your staff have any questions about this testimony, please contact me at (202) 512-3841or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this statement. GAO staff who made key contributions to this testimony are J. Alfredo Gómez (Director), Joseph Dean Thompson (Assistant Director), Anne Hobson (Analyst in Charge), Celia Mendive, Kiki Theodoropoulos, Reed Van Beveren, and Michelle R. Wong.

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James-Christian Blockwood, Managing Director, spel@gao.gov, (202) 512-4707
U.S. Government Accountability Office, 441 G Street NW, Room 7814, Washington, DC 20548

EXHIBIT 3

United States
Army War College

Implications of Climate Change for the U.S. Army

THE UNITED STATES ARMY WAR COLLEGE

STRENGTH and WISDOM

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Study Authors (in alphabetical order)

Colonel Max Brosig, U.S. Army National Guard

Colonel Parker Frawley, U.S. Army

Dr. Andrew Hill, U.S. Army War College

Prof. Molly Jahn, University of Wisconsin-Madison, NASA HARVEST Consortium

Colonel Michael Marsicek, U.S. Air Force

Dr. Aubrey Paris, Princeton University

Mr. Matthew Rose, U.S. Defense Intelligence Agency and Major, U.S. Army Reserve

Colonel Amar Shambaljamts, Mongolian Army

Ms. Nicole Thomas, U.S. Army

Executive Summary

Implications of Climate Change for the U.S. Army

Current conversations about climate change and its impacts are often rancorous and politically charged. As an organization that is, by law, non-partisan, the Department of Defense (DoD) is precariously unprepared for the national security implications of climate change-induced global security challenges. This study examines the implications of climate change for the United States Army. This includes national security challenges associated with or worsened by climate change, and organizational challenges arising from climate change-related issues in the domestic environment. Given that, the study's starting point is the implications of climate change for the U.S. Army, and the Army is therefore the focus of the analysis and recommendations. That said, much of the analysis involves DoD and other elements of the government, and most of the Army-specific recommendations have parallels that apply to other military services.

The study itself did not involve original research on the nature or magnitude of climate change. The analysis assumes, based on the preponderance of evidence available, that significant changes in climate have already occurred, likely to worsen in the years ahead. The study did not look to ascribe causation to climate change (man-made or natural), as causation is distinct from effects and not pertinent to the approximately 50-year horizon considered for the study. The study does, however, assume that human behavior can *mitigate* both the size and consequences of negative impacts that result from climate change.

Summary of Analysis

Initial findings of the study focus on changes to the physical environment and the human response to those changes.

Sea level rise, changes in water and food security, and more frequent extreme weather events are likely to result in the migration of large segments of the population. Rising seas will displace tens (if not hundreds) of millions of people, creating massive, enduring instability. This migration will be most pronounced in those regions where climate vulnerability is exacerbated by weak institutions and governance and underdeveloped civil society. Recent history has shown that mass human migrations can result in increased propensity for conflict and turmoil as new populations intermingle with and compete against established populations. More frequent extreme weather events will also increase demand for military humanitarian assistance.

Salt water intrusion into coastal areas and changing weather patterns will also compromise or eliminate fresh water supplies in many parts of the world. Additionally, warmer weather increases hydration requirements. This means that in expeditionary warfare, the Army will need to supply itself with more water. This significant logistical burden will be exacerbated on a future battlefield that requires constant movement due to the ubiquity of adversarial sensors and their deep strike capabilities.

A warming trend will also increase the range of insects that are vectors of infectious tropical diseases. This, coupled with large scale human migration from tropical nations, will increase the spread of infectious disease. The Army has tremendous logistical capabilities, unique in the world, in working in austere or unsafe environments. In the event of a significant infectious disease outbreak (domestic or international), the Army is likely to be called upon to assist in the response and containment.

Arctic ice will continue to melt in a warming climate. These Arctic changes present both challenges and opportunities. The decrease in Arctic sea ice and associated sea level rise will bring conflicting claims to newly-accessible natural resources. It will also introduce a new theater of direct military contact between an increasingly belligerent Russia and other Arctic nations, including the U.S. Yet the opening of the Arctic will also increase commercial opportunities. Whether due to increased commercial shipping traffic or expanded opportunities for hydrocarbon extraction, increased economic activity will drive a requirement for increased military expenditures specific to that region. In short, competition will increase.

The increased likelihood of more intense and longer duration drought in some areas, accompanied by greater atmospheric heating, will put an increased strain on the aging U.S. power grid and further spur large scale human migration elsewhere. Power generation in U.S. hydroelectric and nuclear facilities will be affected. This dual attack on both supply and demand could create more frequent, widespread and enduring power grid failures, handicapping the U.S. economy.

In addition to the changing environmental conditions that will contribute to a changing security environment, climate change will likely also result in social, political, and market pressures that may profoundly affect the Army's (and DoD's) activities. Studies indicate that global society, including in the U.S., increasingly views climate change as a grave threat to security. As the electorate becomes more concerned about climate change, it follows that elected officials will, as well. This may result in significant restrictions on military activities (in peacetime) that produce carbon emissions. In concert with these changes, consumer demands will drive market adaptation. Businesses will focus on more environmentally sound products and practices to meet demand.

The DoD does not currently possess an environmentally conscious mindset. Political and social pressure will eventually force the military to mitigate its environmental impact in both training and wartime. Implementation of these changes will be costly in effort, time and money. This is likely to occur just as the DoD is adjusting to changes in the security environment previously highlighted.

Summary of Recommendations

In light of these findings, the military must consider changes in doctrine, organization, equipping, and training to anticipate changing environmental requirements. Greater inter-governmental and inter-organizational cooperation, mandated through formal framework agreements, will allow the DoD to anticipate those areas where future conflict is more likely to occur and to implement a campaign-plan-like approach to proactively prepare for likely conflict and mitigate the impacts of mass migration. Focused research and early funding of anticipated future equipment and requirements will spread the cost of adaptation across multiple budget cycles, diminish the "sticker shock" and impacts to overall spending.

Finally, the DoD must begin now to promulgate a culture of environmental stewardship across the force. Lagging behind public and political demands for energy efficiency and minimal environmental footprint will significantly hamstring the Department's efforts to face national security challenges. The Department will struggle to maintain its positive public image and that will impact the military's ability to receive the required funding to face the growing number of security challenges.

The recommendations of this study follow.

1. THE ARMY OPERATING ENVIRONMENT

1.1 Problem: Hydration Challenges in a Contested Environment

Recommendation: *The Army must develop advanced technologies to capture ambient humidity and transition technology from the United States Army Research, Development, and Engineering Command (RDECOM) that supports the water sustainment tenants of decentralizing and embedded, harvest water, and recycle and reuse.*

Implementation Timing: 6-10 Years

Resource Requirement: Moderate

1.2 Problem: Lack of adequate preparation and coherence in doctrine, training, and capabilities development to support effective Arctic operations.

Recommendation: *The Army and the Department of Defense must begin planning and implementing changes to training, equipment, doctrine and capabilities in anticipation of an expanded role in the Arctic associated with global climate adaptation.*

Implementation Timing: Now to 10+ Years.

Resource Requirements: Moderate to High.

1. THE ARMY INSTITUTION

1.1 Problem: The Lack of a Culture of Environmental Stewardship

Recommendation: *Army leadership must create a culture of environmental consciousness, stay ahead of societal demands for environmental stewardship and serve as a leader for the nation or it risks endangering the broad support it now enjoys. Cultural change is a senior leader responsibility.*

Implementation Timing: Now

Resource Requirements: Low

1.2 Problem: Potential disruptions to readiness due to restrictions on fuel use.

Recommendation: *The Army must significantly increase investment in more realistic simulation that incorporates the advances in virtual and augmented reality. It should also continue to invest in the development of lower CO2 emissions platforms and systems.*

Implementation Timing: 6-10 years (Virtual Reality / Augmented Reality), 10+ years (alternate energy platforms).

Resource Requirements: Moderate to High.

2. THE JOINT FORCE AND DoD

2.1 Problem: Lack of coordination and consolidation in climate-change related intelligence.

Recommendation: *Advocate for a comprehensive organization, functional manager, technology, and process review study to identify the current state of intelligence community agencies with regard to climate change, with the goal of formalizing Interagency coordination on Climate Change-related intelligence.*

Implementation Timing: Now

Resourcing Requirements: Low

2.2 Problem: Lack of Organizational Accountability for and Coordination of Climate Change-Related Response and Mitigation Activities

Recommendation: *Re-commit to the Senior Energy and Sustainability Council (SESC). Add a resourcing element to the council by providing the USA and VCSA with funding across each POM cycle to support climate-related projects that improve readiness and resiliency of the force.*

Implementation Timing: Now, 1-10 Years

Resource Requirements: Low, though potentially moderate through reprogramming.

2.3 Problem: Lack of Climate Change-Oriented Campaign Planning and Preparation

Recommendation: *(A) Develop Bangladesh (worst case scenario) Relief Campaign Plan as notional plan for preparing for broader climate change-related requirements arising from large-scale, permanent population dislocations. (B) Work more closely with the CDC to ensure appropriate military support to infectious disease treatment and containment. (C) Ensure preparedness for global, regional or local disruptions in logistics that may affect the Army's operations or allies.*

Implementation Timing: Now

Resource Requirement: Low

3. NATIONAL CONTEXT

3.1 Problem: Power Grid Vulnerabilities

Recommendation: A. *An inter-agency approach, coupled with collaboration of the commercial sector, should catalogue the liabilities across the electrical grid and prioritize budget requests for infrastructure improvements.* B. *The DoD should pursue options to reverse infrastructure degradation around military installations, including funding internal power generation such as solar/battery farms and small-nuclear reactors.*

Implementation Timing: Now (A); 6-10, 10+ Years (B)

Resource Requirement: Low (A); High (B)

3.2 Problem: Climate Change and Threats to Nuclear Weapons Infrastructure

Recommendation: *The U.S. Department of Defense, in combination with the U.S. Department of Energy (DOE) should develop a long term 15 to 20 year tritium production plan that accounts for advances in nuclear technology and the possibility of rising climate induced water levels as well as increases to the overall average water temperature used to cool nuclear reactors. This plan should include projections of fiscal resources and military tritium requirements needed to maintain and modernize the U.S. nuclear stockpile. It should also include U.S. government requirements for use of helium-3, a decay product of tritium used primarily for neutron detection when searching for special nuclear material (SNM) and enforcing nuclear non-proliferation agreements.*

Implementation Timing: Now to 10+ Years

Resource Requirement: High

Finally, the study examined the threat climate change poses to the U.S. military's coastal infrastructure, i.e., coastal military facilities and key airports and shipping facilities. Additionally, the U.S. Army Corps of Engineers (USACE) manages the nation's system of inland waterways, and condition of much of that system will be affected by rising seas and changing weather. That said, the study found no basis for additional action. The DoD and USACE have adequate systems and processes in place to track and manage these risks.

Introduction

Current public discourse about climate change and its impacts are often rancorous and politically charged. As an organization that is, by law, non-partisan, the Department of Defense (DoD) is precariously unprepared for the national security implications of climate change induced global security challenges. This study seeks to determine likely national security challenges associated with or exacerbated by anticipated climate change in an effort to craft recommendations for the DoD. Many of the recommendations are specifically targeted at the Army, however the specific recommendation or its parallel can be applied across the military as a whole. The study of climate change as a threat to U.S. and global security is not new to the U.S. Army or DoD.[1,2,3] This study itself did not conduct specific research on the climate or climate change but assumed through the preponderance of evidence available that climate change is occurring. Additionally, the study did not look to ascribe causation to the climate change (man-made or natural) as causation is distinct from effects and not pertinent to the approximately 50 year horizon considered for the study.

In determining likely national security impacts and providing recommendations for the military, the authors relied upon the Intergovernmental Panel on Climate Change (IPCC) and the Representative Concentration Pathway (RCP) 4.5. RCP 4.5 is the middle ground prediction of temperature and rainfall variation provided by the IPCC for climate change studies. Use of this model is intended to provide a realistic anticipation of future impacts of climate change without forecasting either extremely dire and catastrophic impacts or minimizing them to such an extent that they are meaningless.

The findings generally are categorized as those relating to anticipated changes in the physical environment and those relating to anticipated changes in the social environment. That is, the authors, using available studies, determined if changes to societal norms would have an impact on the military's ability to execute anticipated missions. The corresponding recommendations consider a near, mid and long term horizon and a low, mid or high level of resources allocated against the challenges. The intent is to provide senior leaders with an easy to understand anticipation of risk associated with each recommendation.

For the purposes of this study the authors chose to use the IPCC definition of climate change. This definition is most compatible as it simply looks at changing climate variables over time without ascribing causation.

Climate Change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.[4]

1. Werrill, C. and F. Femia. "Chronology of Military and Intelligence Concerns about Climate Change." *The Center for Climate & Security.* 2017. https://climateandsecurity.org/2017/01/12/chronology-of-the-u-s-military-and-intelligence-communitys-concern-about-climate-change/.

2. "Report on Effects of a Changing Climate to the Department of Defense." *United States Department of Defense.* 2019. https://climateandsecurity.files.wordpress.com/2019/01/sec_335_ndaa-report_effects_of_a_changing_climate_to_dod.pdf.

3. Werrill, C. and F. Femia. "New Pentagon Report: "The effects of a changing climate are a national security issue." *The Center for Climate & Security.* 2019. https://climateandsecurity.org/2019/01/18/new-pentagon-report-the-effects-of-a-changing-climate-are-a-national-security-issue/.

4. "Global Warming of 1.5° C." *Intergovernmental Panel on Climate Change.* 2018. https://www.ipcc.ch/sr15/.

An aside on Climate Models and Risk: Uncertainty complicates choices about how to respond to or anticipate the consequences of climate change. Regardless of the cause, climatological data reflects an environment that is always changing. Where the choices lie hinges on whether or not we choose to act. There are four possible scenarios involving climate change and human action to mitigate or prepare for it. (See Figure 1, below.) Each approach carries a level of risk informed by the amount and type of action taken.

The matrix in Figure 1 summarizes payoffs from two different choices (mitigate and prepare or not), given two different contexts (climate change occurring or not). Obviously missing from this matrix is a sense of the probability of climate change itself, which would affect payoff calculations. However, for the sake of the present argument let us make the conservative assumption that climate change is a 50/50 proposition (data and theory indicate that climate change is already occurring).

Figure 1: Climate Change Risk / Response Matrix

Mitigation and Preparation	Climate Change Occurring: YES	Climate Change Occurring: NO
NO	Payoff: Catastrophe	Payoff: No change
YES	Payoff: Avoiding Catastrophe	Payoff: Economic Waste

First, we can assume no climate change is occurring and we can choose to do nothing. If our assumption about climate change is accurate, this is the most appealing option. Second, we can assume there is no change occurring, but that humans choose to act and mitigate human effects to the environment. This option is unappealing in that we will have wasted economic resources, pointlessly regulating and taxing ourselves. However, if climate change is occurring and we choose to do nothing, we invite catastrophe, though we cannot know just how bad this payoff would be. Finally, if we assume climate change is occurring and undertake mitigation and preparation, we may avoid catastrophe.[5]

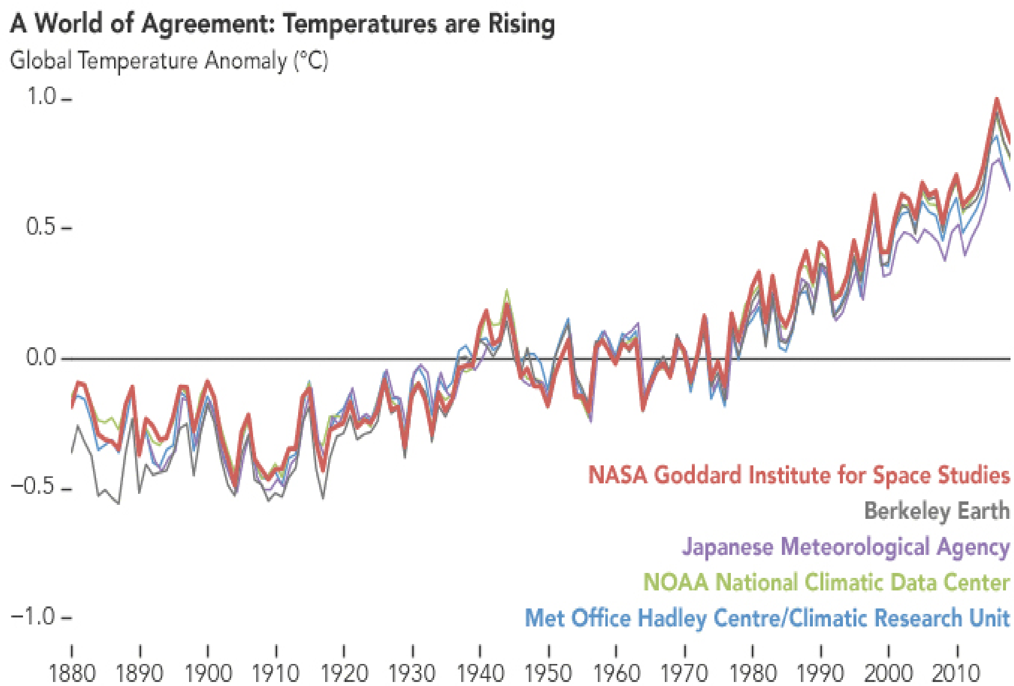
The only justification for doing nothing to mitigate and prepare for climate change is enough certainty that climate change is not occurring to justify the very considerable risk of doing nothing. The strength of scientific arguments in favor of significant warming projections suggests that such certainty is not defensible. (See Figure 2, next page.[6]) Prudent risk management therefore suggests that we should work to avoid the catastrophic outcome and prepare for and mitigate climate change.

Based on this argument, this report accepts as a core assumption the reality of climate change and climate-change related global warming, and therefore focuses on what the Army should do to prepare itself. Regardless of the science behind climatological projections of global warming, climate change is a controversial political issue. For the purposes of this study, we ignore that controversy. We must observe that the planet is warming with a broad range of impacts relevant to the U.S. Army, and we employ middle-of-the-curve projections to guide our analysis of recommendations.

5. Davis, Morton D., and Oskar Morgenstern. *Game Theory: A Nontechnical Introduction*. Mineola (New York): Dover Publications, 2013.

6. "Scientific Consensus: Earth's Climate is Warming." *NASA Global Climate Change, Vital Signs of the Planet*. 2018. https://climate.nasa.gov/scientific-consensus/ - *.

Figure 2: Temperatures Showing the Last Decade was the Warmest on Record



Part 1: The Challenge of Climate Change

Challenge 1: Climate Change and the Physical Environment

Climate change affects the physical environment of the planet. It therefore affects the conditions in which people live, and the environment in which military organizations operate. The effects of a warming climate with more extreme weather are astonishingly far-reaching. Scientific studies in very diverse fields describe effects that have accelerated over the past 50 years as glaciers, Arctic and Antarctic ice sheets retreat, major weather patterns shift, and demographic, economic and political forces put more people in harm's way, while creating additional multi-dimensional stress on conventional military forces. The trend toward larger, more coherent and integrated research investments, such as the NASA Harvest Consortium, allows science agencies to establish improved and tight interfaces with the DoD on topics relevant to the military that are outside of traditional lanes. This consortium leverages broad international cooperation and domestic collaborations using NASA earth observations to improve crop yield forecasting with the specific intent to establish tighter and more functional interfaces between NASA Applied Sciences Division and operational agencies, including DoD. Climate change also increases the risk of unrest and conflict globally. Human migration and refugee relocation due to chronic drought, flooding, episodes of extreme, unusual weather or other natural events create an environment ripe for conflict and large-scale humanitarian crises. In 2018, global international migration and internal displacement were estimated at a historic highs by the International Organization for Migration,[7] bringing increased risk of spread of infectious disease and other public health problems. The fight for dwindling resources along the seams of civilization are harbingers of future U.S. involvement. If the United States is obliged or

7. https://www.iom.int/wmr/chapter-2

chooses to respond in a humanitarian or military fashion to alleviate conflict or provide stability, then the importance of recognizing climate-related impacts allows for planners to be proactive rather than reactive in formulating a response.

Rising Seas and Changing Coastal Geography

Coastal flooding is a persistent but acute cause of human displacement. Historically, flood waters recede and people return to their homes. Warming changes this calculus, with rising seas introducing the possibility of permanent displacement of tens, even hundreds of millions of inhabitants of high-risk coastal areas.

The relationship between climate change and international security is not well understood because climate's largest effects on conflict and governance are indirect, mediated through a variety of effects on weather. These sustained shifts in weather in turn produce a wide variety of impacts from one pole to the other and from the sea to the highest mountains. Nevertheless, we can make logical predictions of potential conflict, disruption of trade and humanitarian crises given known risks and exacerbating factors. Consider the case of Bangladesh, a nation with a history of disastrous seasonal flooding. According to one observer, "[Located] in the Ganges Delta, made up of 230 major rivers and streams, 160 million people live in a place one-fifth the size of France and as flat as chapati…"[8] Almost half of the population of Bangladesh lives at sea level.[9] As seas rise and huge areas of Bangladesh become uninhabitable, where will tens of millions of displaced Bangladeshis go? How will this large scale displacement affect global security in a region with nearly 40% of the world's population and several antagonistic nuclear powers? For a recent security crisis benchmark, look at Syria.[10]

The Syrian civil war has been an international disaster with humanitarian and security impacts in the Middle East, Africa and Europe that will continue long into the future. Pre-war Syria had a population of about 22 million.[11] Almost five million Syrians have fled the country since the start of the civil war.[12] A host of factors contributed to the outbreak of civil war with causality still a matter of debate. There is, however, no question that the conflict erupted coincident with a major drought in the region which forced rural people into Syrian cities as large numbers of Iraqi refugees arrived.[13] The Syrian civil war has reignited civil war in Iraq, and brought the U.S. and Russian militaries into close contact under difficult circumstances. The Syrian population has declined by about ten percent since the start of the war, with millions of refugees fleeing the nation, increasing instability in Europe, and stoking violent extremism.[14]

By comparison, Bangladesh has *eight times* Syria's population, and a conflicted history as a former part of Pakistan. Bangladesh is a predominantly Muslim nation locked between India and Burma. The latter is already under international scrutiny for its poor treatment of the Rohingya minority, the largest percentage of which have

8. Harris, Gardiner. "Borrowed Time on Disappearing Land." *The New York Times.* 2014. https://www.nytimes.com/2014/03/29/world/asia/facing-rising-seas-bangladesh-confronts-the-consequences-of-climate-change.html.

9. Greenfieldboyce, Nell. "Study: 634 Million People at Risk from Rising Seas." *National Public Radio.* 2007. https://www.npr.org/templates/story/story.php?storyId=9162438.

10. Some claim that the Syrian civil war resulted from drought-induced migration, a secondary effect of climate change. We do not make that argument here, as recent research questions this relationship. See Selby, Jan, Omar S. Dahi, Christiane Fröhlich, and Mike Hulme. "Climate change and the Syrian civil war revisited." *Political Geography* 60: 232-244. 2017. https://www.sciencedirect.com/science/article/pii/S0962629816301822.

11. Barbash, Fred. "U.N.: Nearly half of Syria's population uprooted by civil war." *The Washington Post.* 2014. https://www.washingtonpost.com/news/morning-mix/wp/2014/08/29/u-n-nearly-half-of-syrias-population-uprooted-by-civil-war/?utm_term=.eaa5e39e17b7.

12. "The Syrian Refugee Crisis and its Repercussions for the E.U." *Migration Policy Centre.* 2016. http://syrianrefugees.eu/.

13. Hammer, Joshua. "Is a Lack of Water to Blame for the Conflict in Syria?" *Smithsonian Magazine.* 2013. https://www.smithsonianmag.com/innovation/is-a-lack-of-water-to-blame-for-the-conflict-in-syria-72513729/.

14. "The Syrian Refugee Crisis and its Repercussions for the E.U." *Migration Policy Centre.* 2016. http://syrianrefugees.eu/.

fled to Bangladesh. India is a nuclear-armed state perpetually on the verge of conflict with its nuclear-armed western neighbor, Pakistan. Indeed, Bangladesh's existence is the result of a war between those two nations. The permanent displacement of a large portion of the population of Bangladesh would be a regional catastrophe with the potential to increase global instability. This is a potential result of climate change complications in *just one country*.

Globally, over 600 million people live at sea level.[15] Sea level rise also poses a direct threat to Army/DoD installations and missions worldwide. The DoD must assess the vulnerabilities to installations and risks to mission at all locations, prioritizing those most at risk. Early recognition of the complex risks will allow planning and implementation to best mitigate the risk and spread costs out over multiple budgetary periods. The 2018 National Defense Authorization Act (NDAA) mandates that the Department of Defense submit a report to Congress with respect to the impact of climate change on DoD missions. Specifically, the NDAA requires that the report include "vulnerabilities to military installations and combatant commander requirements resulting from climate change over the next 20 years."[16] There are currently numerous studies already extant that detail the risks to military installations, some of them executed by government organizations, including the Army Corps of Engineers. Additionally, this report will examine mitigations to the risk associated with climate change impacts.

Opening the Arctic

The Arctic is undergoing some of the most significant and noticeable effects of climate change anywhere on the globe. According to the Intergovernmental Panel on Climate Change (IPCC), since satellite monitoring of the Arctic began in 1979, the Arctic ice extent has decreased from 3.5 – 4.1%.[17] Furthermore, the IPCC predicts with high confidence that the Arctic will warm more rapidly than other parts of the globe through at least the year 2100, well beyond the horizon of this study.[18] This warming will cause further diminishment of the Arctic ice, presenting many economic opportunities and security challenges for the United States and its allies.

As the sea ice in the Arctic continues to decrease, there are greater opportunities for all nations to take advantage of new shipping routes between ports in Asia and those in Europe or Eastern North America. According to researchers at the University of Reading in the UK, even if emissions diminish, as proposed by the Paris Accords, by 2050 opportunities for non-modified (that is, ships that are not double hulled or specifically designed for transit through ice prone environments) vessels to transit the Arctic Ocean will double. Furthermore, many of those journeys could take place directly across the pole in international waters, avoiding transit fees.[19] From a money and time saving perspective, these shorter routes will be more and more attractive to shipping companies as the ice recedes. Currently, a typical East Asia to Rotterdam route, transiting the Suez Canal, takes about 30 days. The most conservative estimates of sea ice change estimate non-specialized vessels will be able to complete that route across the Arctic in 23 days and that that route would be available for over half the year.[20]

Furthermore, according to a 2008 U.S. Geological survey, the Arctic likely holds approximately one quarter of the world's undiscovered hydrocarbon reserves.[21] Though the United States territorially possesses only a

15. Greenfieldboyce, Nell. "Study: 634 Million People at Risk from Rising Seas." *National Public Radio.* 2007. https://www.npr.org/templates/story/story.php?storyId=9162438.

16. "National Defense Authorization Act for Fiscal Year 2018." *115th Congress of the United States of America.* 2017. https://www.congress.gov/115/bills/hr2810/BILLS-115hr2810enr.pdf.

17. "Climate Change 2014 Synthesis Report." *International Panel on Climate Change*. 2015. http://ipcc.ch/report/ar5/syr/.

18. Ibid.

19. Amos, Jonathan. "Arctic Ocean shipping routes 'to open for months'." *BBC News*. 2016. http://www.bbc.com/news/science-environment-37286750.

20. Ibid.

21. Ibid.

small percentage of the Arctic area, estimates are that 20% of those undiscovered reserves are potentially in U.S. territory.[22] However, territorial claims in the Arctic are not well established and continue to be disputed amongst the Arctic nations.[23] As the extent of the resources available in the Arctic become more evident, there is a greater potential for conflict. The United States is likely to reach accommodation with allies in the region, but Russia's global pattern of aggression and attempts to reestablish great power status may set conditions for another flashpoint in the Arctic. The Arctic waters may make this evidently a Navy and Air Force issue, however the Army will be tasked with wide area security and reconnaissance roles as part of any joint efforts to secure Arctic interests.

Russia probably has the greatest immediate security concerns as it already earns transit fees from shipping companies using its Arctic waters. Russia has embarked on a rapid build-up in the Arctic, including expensive refurbishment of Soviet era Arctic bases. Russia's current Arctic plans include the opening of ten search and rescue stations, 16 deep water ports, 13 airfields and ten air defense sites.[24] (See Figure 3, below.[25]) These developments create not only security outposts for Russia, but also threats to the U.S. mainland. Russia's recent development of KH-101/102 air launched cruise missiles and SSC-8 ground launched cruise missiles potentially put much of the United States at risk from low altitude, radar evading, nuclear capable missiles.

Figure 3: Map of bases and estimated hydrocarbon reserves in the Arctic

22. "The U.S. Stakes Its Claim in the Arctic Frontier." *Stratfor*. 2015. https://worldview.stratfor.com/article/us-stakes-its-claim-arctic-frontier.

23. Millstein, Seth. "Who Owns the Arctic? And Who Doesn't?" *Timeline*. 2016. https://timeline.com/who-owns-the-arctic-2b9513b3b2a3.

24. Nudelman, Mike and Jeremy Bender. "This map shows Russia's dominant militarization of the Arctic." *Business Insider*. 2015. http://www.businessinsider.com/chart-of-russias-militarization-of-arctic-2015-8.

25. Ibid.

Russia is not the only nation considering security expansion in the Arctic. Since 2013, the United States Coast Guard has budgeted for the development and fielding of a new Polar Class heavy icebreaker to augment the one heavy and one medium icebreaker they now have in service. To date they have received almost $191 million in funding toward the acquisition, estimated to cost just less than $1 billion.[26] The FY2018 National Defense Authorization Act authorized the full procurement of the vessel.[27]

The relatively rapid pace of change in the Arctic will generate opportunities, forecast and unexpected, on which nations around the world will capitalize. However, with any advantage comes the need to secure it. The United States must be prepared not only to seize any opportunities, but also to protect those assets and project power into newly accessible areas. All of these factors suggest that military operations in the Arctic will become more common.

Increased Range of Insect-Borne Diseases

Infectious diseases remain a concern for expeditionary forces and indigenous populations alike. As the climate changes, the distribution and prevalence of endemic diseases will change. Diseases that were endemic before could become altered and mutate to new regions. Extensive research has shown local weather conditions and other related environmental factors strongly influence vector-borne diseases. [28][29] Diseases caused by a wide array of pathogens including bacteria, spirochetes, rickettsiae, protozoa, viruses, nematodes and fungi spread through arthropods (i.e. ticks and mosquitoes) are highly susceptible to localized weather conditions. [30, 31] The 2016 IPCC report and National Climate Assessment concluded there was an increased risk of some vector-borne diseases and that climate variability can alter the incidence of diseases carried by vectors (e.g., mosquitoes, fleas, ticks) through effects on vector geographic distribution, vector and pathogen biology, respectively.[32] Indeed, some major vector-borne diseases in the U.S. have doubled or even tripled since 2005.[33] Examples of vector-borne diseases likely susceptible to change include: Malaria, Dengue, Chikungunya, Leishmaniasis, Lyme disease and Zika.[34]

Consider the case of malaria, perhaps the most lethal infectious disease in the world. In 2015, the World Health Organization reported there were an estimated 304 million global cases and 639,000 deaths. [35] While considerable efforts aim at eradicating the disease through vaccine development, the international public health community continues to struggle with the extent of the

26. "Report to Congress on Coast Guard Icebreaker Program." *USNI News*. 2017. https://news.usni.org/2017/12/13/report-congress-coast-guard-icebreaker-program?utm_source=Sailthru&utm_medium=email&utm_campaign=EBB 12.14.17&utm_term=Editorial - Early Bird Brief.

27. "National Defense Authorization Act for Fiscal Year 2018." *115th Congress of the United States of America.* 2017. https://www.congress.gov/115/bills/hr2810/BILLS-115hr2810enr.pdf.

28. "Vector-Borne Diseases Fact Sheet." World Health Organization. October 2017. Accessed December 2017. http://www.who.int/mediacentre/factsheets/fs387/en/.

29. Githeko, Andrew K., Steve W. Lindsay, Ulisses E. Confalonieri, and Jonathon A. Patz. "Climate change and vector-borne diseases: a regional analysis." Bulletin of the World Health Organization 78, no. 9: 1136. 2000. http://www.who.int/bulletin/archives/78(9)1136.pdf.

30. Luber, George, and Kim Knowlton. "Human Health." *National Climate Assessment*. 2014. https://nca2014.globalchange.gov/report/sectors/human-health.

31. "Ticks and Tick-Borne Diseases." *Medscape.* Accessed December, 2017. https://reference.medscape.com/slideshow/tick-borne-illnesses-6006369.

32. Chrétien, Jean-Paul. "Adapting to Health Impacts of Climate Change in the Department of Defense." *Health Security* 14, no. 2: 86-92. 2016. https://www.ncbi.nlm.nih.gov/pubmed/27081888.

33. "Illnesses on the rise." *Centers for Disease Control and Prevention.* 2018. https://www.cdc.gov/vitalsigns/vector-borne/index.html.

34. Chrétien, Jean-Paul. "Adapting to Health Impacts of Climate Change in the Department of Defense." *Health Security* 14, no. 2: 86-92. 2016. https://www.ncbi.nlm.nih.gov/pubmed/27081888.

35. "Fact Sheet: World Malaria Report 2016." *World Health Organization*. http://www.who.int/malaria/media/world-malaria-report-2016/en/.

disease.[36] Today, the DoD and members of the U.S. Intelligence Community assess the risk of malaria to U.S. forces operating in East Africa [37] as high to intermediate depending on the country. A high-risk represents "an operationally significant attack rate (potentially 11-50% per month) could occur among personnel exposed to mosquito bites." [38]

The average projected climate changes in East Africa by 2050 show temperatures between 25-30° C. The projected average precipitation shows increased rainfall in select countries. Coupling the generally optimal conditions for malaria carrying mosquitos with the expected climate conditions in 2050, we can conclude that the environment will likely be much more favorable to malarial vectors.[39] The temperatures and increase of precipitation may lead to decreasing parasite development, more stable adult populations and increased bite rates.[40] It is also fair to conclude the more favorable conditions could lead to an increase of the prevalence of malaria.

Decreased Fresh Water Availability and Increased Demand

By 2040, the global demand for fresh water projects to exceed availability. As water availability decreases, the opportunity for social disruption will increase. Although the National Intelligence Council does not predict water shortage alone will lead to failed states,[41] the lack of water resources amplifies underlying existing issues such as lack of technology, poor governance, and inadequate economic resilience.[42] There are several factors contributing to the global water shortage including: population increase, climate change, and poor water management.[43] North Africa, Southern Africa, the Middle East, China, and the United States all have areas where the water deficiency is greater than 50%. By 2030, one-third of the world population is projected to inhabit these water-stressed regions.[44] In several places across the globe, water has prompted cooperative agreements designed to share the scarce resource.[45] However, there is a growing concern that as demand outstrips supply, water will become a bargaining weapon to accrue power, deprive access to vulnerable populations or even enable sabotage to disrupt supply and achieve desired effects.[46,47] Rising seas also place coastal fresh water supplies and agriculture at risk, as salt water moves inland, polluting rivers and aquifers, and literally salting the earth.[48]

36. "Malaria." *Bill & Melinda Gates Foundation*. https://www.gatesfoundation.org/What-We-Do/Global-Health/Malaria. Accessed December 2017.

37. The countries in the East Africa region for this study are; Sudan, South Sudan, Uganda, Democratic Republic of the Congo, Tanzania, Eritrea, Djibiouti, Ethiopia, Somalia, Kenya.

38. Defense Intelligence Agency, National Center for Medical Intelligence, Infectious Disease Risk Assessment Methodology.

39. Craig, M. H., R. W. Snow, and D. Le Sueur. "A climate-based distribution model of malaria transmission in sub-Saharan Africa." *Parasitol Today* 15, no. 3: 105-11. 1999. https://www.ncbi.nlm.nih.gov/pubmed/10322323?dopt=Abstract.

40. Patz, J. A., and S. H. Olson. "Malaria risk and temperature: Influences from global climate change and local land use practices." *Proceedings of the National Academy of Sciences* 103, no. 15: 5635-636. 2006. https://www.pnas.org/content/103/15/5635.

41. Engel, Rich. "National Intelligence Council Water Research." *National Intelligence Council.* 2012. https://www.wilsoncenter.org/sites/default/files/Engel Presentation.pdf

42. "Global Water Security." *National Intelligence Council*. 2012, https://www.dni.gov/files/documents/Special%20Report_ICA%20Global%20Water%20Security.pdf.

43. "Implications for US National Security of Anticipated Climate Change." *CENTRA Technology, Inc, and Scitor Corporation*. 2016. https://www.dni.gov/files/documents/Newsroom/Reports and Pubs/Implications_for_US_National_Security_of_Anticipated_Climate_Change.pdf.

44. Ibid.

45. Ibid.

46. Ibid.

47. Kenney, Carolyn. "Climate Change, Water Security, and U.S. National Security." *Center for American Progress.* 2017. https://www.americanprogress.org/issues/security/reports/2017/03/22/428918/climate-change-water-security-u-s-national-security/.

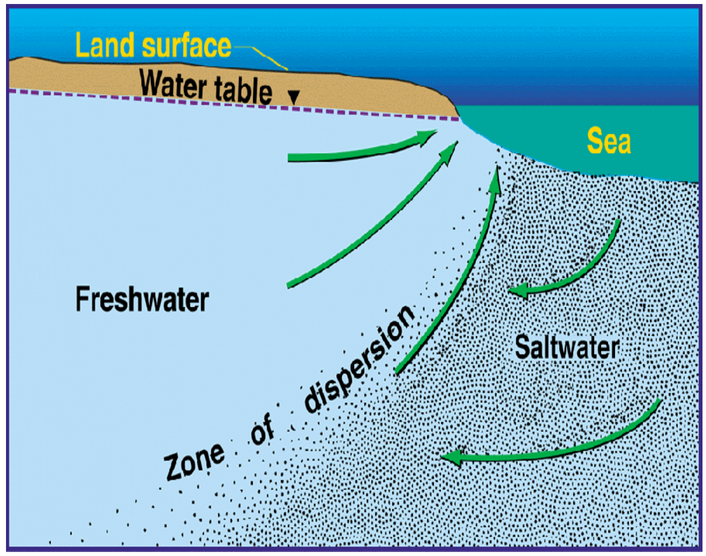
48. Paris, Aubrey. "Sea Level Rise: Sink or Swim." *United States Army War College – War Room.* 2017. https://warroom.armywarcollege.edu/articles/sea-level-rise-sink-swim/.

The predicted rise in average global temperatures equates to the need for more water to sustain all life. As ambient temperatures rise, so does the risk of raising body temperature. Proper water consumption rates reduce this risk if there is water readily available to consume. As the rigor of activities increases so does the need for increased hydration. Simultaneously as the demand for water increases in a warmer climate, the amount of water readily available for use is reduced due to evaporation.[49] The combination of expeditionary soldiers fighting in a hot climate with scarce water supplies exacerbates logistical requirements.

Saltwater intrusion is another factor increasing the risk for conflict in coastal areas with large populations. As the need for more water increases, fossil freshwater aquifers are tapped which are not replenished. Reduced water levels in some coastal aquifers can lead to increased salinity as a result of the intrusion of seawater into the aquifer. Typically, a water table in a coastal area pushes fresh water to the ocean, but in this case, the salt water makes its way into the aquifer rendering it unusable. (See Figure 4.)

49. "Climate Impacts on Water Resources." *The United States Environmental Protection Agency.* 2017. https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-water-resources.html.

Figure 4: Ground-water flow patterns and the zone of dispersion in an idealized, homogeneous coastal aquifer[50]



Decreased Food Security and Food System Stability

The United Nations (UN) Food Agricultural Organization (FAO) defines food security as a state when "all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active healthy life."[51] Food security is premised on four components: food availability, food accessibility, food utilization and food system stability.[52] (See Table 1, next page.) In its broadest terms, food security is the ability to have consistent access to food that is safe and meets dietary guidelines.[53]

50. Cooper, H.H. "Saltwater Intrusion." *United States Geologic Survey*. 1964. https://water.usgs.gov/ogw/gwrp/saltwater/salt.html.

51. "The State of Food and Agriculture: Climate Change Agriculture, and Food Security." *Food and Agriculture Organization of the United Nations.* 2016. http://www.fao.org/3/a-i6030e.pdf.

52. "Climate Change, Global Food Security, and the U.S. Food System." *USDA.* 2015. https://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf.

53. "Dietary Guidelines." *U.S. Office of Disease Prevention and Health Promotion*. 2019. https://health.gov/dietaryguidelines/.

Table 1: The Components of Food Security

Component	Definition
Availability	The existence of food in a particular place at a particular time. Addresses the "supply side" of food security, which is determined by food production, transportation, food stocks, storage, and trade.
Access	The ability of a person or group to obtain food. Economic access to food (including affordability) and allocation within society (including intranation and intrahousehold distribution) are integral to this component.
Utilization	The ability to use and obtain nourishment from food. This includes a food's nutritional value and how the body assimilates its nutrients. Sufficient energy and nutrient intake is also the result of biophysical and sociocultural factors related to food safety and food preparation, dietary diversity, cultural norms and religious practices, and the functional role of food in such practices.
Stability	The absence of significant fluctuation in availability, access, and utilization. When stable, food availability, access, and utilization do not fluctuate to the point of adversely affecting food security status, either on a seasonal or annual basis or as a result of unpredictable events. Weather, political unrest, or a change in economic circumstances may affect food security by introducing instabilities.

Source: "Climate Change, Global Good Security, and the U.S. Food System." USDA. 2015.

For seven out of eight Americans,[54] food insecurity is a problem relegated to places far afield from the continental United States. In fact, compared to 113 countries across the globe, the U.S. ranks second on the Global Food Security Index.[55] The U.S. spends 6.4 % of its income on food compared to countries such as Pakistan, Philippines, and Nigeria where a typical household spends more than 40 % of their earnings for sustenance.[56] Populations that dedicate more of their income to food are more vulnerable to fluctuations in food commodity prices. Recent effects of price shocks because of food availability have occurred in crisis areas such as Syria and Venezuela. Price fluctuations in food will affect countries differently. Countries that rely heavily on imports will be most affected.[57] The U.S., in contrast, has consistently led the world in global agricultural exports, long a source of economic power and global influence.

When food systems fail, whether a failure of agricultural production, a supply chain failure that interferes with food processing or transport, or economic or financial disruption affecting demand, outbreaks of civil conflict and social unrest become more likely.[58] Global food security hinges on the production of four crops: maize, wheat, rice, and soybeans.[59] These commodities, along with a long list of foodstuffs moving through both formal and informal channels, are the core outputs of the global food system – the poorly defined, highly dynamic, complex web of transfers and interactions. Climate-in-

54. "Overview: Food Security in the U.S." *USDA*. 2018. https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us/.

55. "Global Food Security Index for 2017" *The Economist Intelligence Unit.* 2017. https://foodsecurityindex.eiu.com/Resources.

56. Gray, Alex. "Which countries spend the most on food? This map will show you." *World Economic Forum.* 2016. https://www.weforum.org/agenda/2016/12/this-map-shows-how-much-each-country-spends-on-food/.

57. "Global Food Security: Market Forces and Selected Case Studies." *National Intelligence Council*. 2012. https://www.dni.gov/files/documents/nic/NICR 2012-23 Global Food Security FINAL.pdf.

58. Barbet-Gros, Julie and Jose Cuestra. "Food Riots: From Definition to Operationalization." *The World Bank.* 2015. http://www.worldbank.org/content/dam/Worldbank/document/Poverty%20documents/Introduction%20Guide%20for%20the%20Food%20Riot%20Radar.pdf.

59. Winkler, Elizabeth. "How the climate crisis could become a food crisis overnight." *The Washington Post*. 2017. https://www.washingtonpost.com/news/wonk/wp/2017/07/27/how-the-climate-crisis-could-become-a-food-crisis-overnight/?noredirect=on&utm_term=.e9f324e6c009.

fluenced impacts on food systems beyond impacts on crop production include interruption of planting or harvest due to adverse weather, rapid freeze-thaw cycles in spring and fall,[60] soil degradation, depletion of fossil water aquifers, intensified spread of agricultural pests and diseases,[61,62] and damage to shipping infrastructure as a consequence of flooding.[63] During a global food crisis in 2007-2008, social unrest was reported in 61 affected countries.[64] In war-time, the ability of the U.S. and allies to cooperate through extraordinary institutional innovations delivered under great duress, such as the Combined Food Board, improved provisioning of U.S. and allied war fighters, munitions workers and civilians.[65] Through the decades since the Second World War, these institutions have been dismantled in the U.S. as the policy of supply management, driven by the U.S. population's needs, shifted to policies that have emphasized agricultural exports as a critical component of the U.S. balance of trade.[66]

Where climate change damages agricultural production, security concerns will likely follow. The world population is expected to increase by 39% between 2005 and 2050, and 95% of that growth will occur in developing countries that are also food insecure.[67] Population increases, coupled with the food demand and effects of climate change disrupting crop production will likely result in price instability.[68] Furthermore, the wild card of weaponized genome editing and, more generally, horizontal environmental genetic alteration agents (HEGAA) applied to agriculture and food systems already under interacting stress from climate change, define a no-analogue future..[69]

Climate change will have diverse impacts on local, regional and global food system stability, far beyond its immediate effects on agricultural production affecting both availability of food and the resilience of underlying ecosystems.[70] Changes in the length and stability of growing seasons around the world, altered precipitation patterns resulting in droughts, high night temperatures, floods or shifted seasonal patterns will also impact crop production.[71] Some evidence indicates that rising CO_2 levels may increase crop yields to some extent via an effect known as CO_2 fertilization.[72] However, altered crop growth may affect nutrient composition, especially micronutrients such as zinc and iron, resulting in significant increases in mortality in vulnerable locations, which are those where DoD-supported humanitarian interven-

60. Sinha, Tushar and Keith A. Cherkauer. "Impacts of future climate change on soil frost in the midwestern United States." *Journal of Geophysical Research,* Vol. 115, D08105. https://doi.org/10.1029/2009JD012188.

61. Lenne, Jillian. "Climate change, crop plant diseases and future food production." *World Agriculture.* 2018. http://www.world-agriculture.net/article/climate-change-crop-plant-diseases-and-future-food-production.

62. Deutsh, Curtis A. *et al.* "Increase in crop losses to insect pests in a warming climate." *Science.* 2018. http://science.sciencemag.org/content/361/6405/916.editor-summary.

63. "Extreme Weather" in "National Climate Assessment." *U.S. Global Change Research Program.* 2014. https://nca2014.globalchange.gov/highlights/report-findings/extreme-weather.

64. Ibid.

65. Roll, Eric. *The Combined Food Board: A Study in Wartime International Planning*. Palo Alto: Stanford University Press, 1956.

66. Collingham, Lizzie. *The Taste of War.* New York: Penguin Press, 2011: 481-501.

67. Alexandratos, Nikos and Jelle Bruinsma. "World Agriculture Towards 2030/2050." *United Nations Food and Agriculture Organization*. 2012. http://www.fao.org/3/a-ap106e.pdf.

68. "Global Food Security." *National Intelligence Council: Intelligence Community Assessment*. 2015. https://www.dni.gov/files/documents/Newsroom/Reports and Pubs/Global_Food_Security_ICA.pdf.

69. Reeves, R.G. *et al.* "Agricultural research or a new bioweapon system?" *Science* 362 (6410): 35-37. 2018. http://science.sciencemag.org/content/362/6410/35.

70. "The State of Food and Agriculture: Climate Change, Agriculture, and Food Security." *Food and Agriculture Organization of the United Nations*. 2016. http://www.fao.org/3/a-i6030e.pdf.

71. "Climate Change and Food Security: A Framework Document." *Food and Agriculture Organization of the United Nations.* 2008. http://www.fao.org/3/k2595e/k2595e00.htm.

72. Kirscbaum, M.U.F. *Plant Phys* 155(1): 117-124. 2011. https://doi.org/10.1104/pp.110.166819.

tion is most likely.[73] Increased CO_2 levels in the oceans and changes in ocean temperature will alter the availability of fish and could potentially lead to the extinction of certain species.[74] Changes in temperature will also affect livestock by impacting their ability to thrive and provide adequate amounts of meat and milk.[75]

Increased Incidence of Extreme Weather

Numerous climate models suggest that a warming climate incurs more frequent extreme weather events and intensified weather patterns such as heat domes, polar vortices, super storms, monster ridges, and wider ranges of extremes, especially in spring and fall in temperate climates.[76] The U.S. Army is directly affected by these extremes, and has obligations connected to disaster recovery efforts related to a changing climate. Not only are Army personnel and installations at risk, the issue compounds when more than one major event occurs in a short interval or where natural disaster occurs where local social, political, and economic infrastructures are not resourced to handle the situation. Attention to a changing climate remains integral to the Army's preparation and response of devastating weather events like recent hurricanes Katrina, Rita, Harvey, Irma and Maria. Hurricane Michael in 2018 was the wettest hurricane on record, reflecting a more general trend of windier and wetter hurricanes.[77,78] Natural disasters like these will continue to draw in Army and other DoD resources.

In September 2016, U.S. the Intelligence Community (IC) conducted analysis of possible impacts of climate change on national security over the next 20 years.[79] Their report highlighted the projected occurrence of more extreme weather and how damaging it may be to natural systems such as oceans, lakes, rivers, ground water, reefs, and forests. Most of the critical infrastructures identified by the Department of Homeland Security are not built to withstand these altered conditions. The lower Mississippi River has sustained 100-, 200- and 500-year floods (meaning the chance is 1% or less that a flood of that magnitude would occur 500 simulations of the current year) in the last 8 years. Between 2016 and 2018, Ellicott City, Maryland sustained two 1,000-year floods.[80] Because most U.S. agricultural exports (80%) and imports (78%) are water-borne, floods that leave lasting damage to shipping infrastructure pose a major threat to U.S. lives and communities, the U.S. economy and global food security. The U.S. Intelligence Community's 2016 study further emphasized the social and economic implications realized by damaging these systems. The increased urbanization of areas prone to these weather events will only further stress governmental agencies tasked with recovery and support. Additionally, the study captured potential instability of countries, heightened social and political tensions, adverse effects on food prices and availability, increased risks to human health, negative impacts on investments and economic competitiveness.[81]

73. Myers, S.S. *et al.* "Increasing CO2 Threatens Human Nutrition." *Nature* 510(7503): 139-142. 2014. https://www.ncbi.nlm.nih.gov/pubmed/24805231.

74. "The State of Food and Agriculture: Climate Change, Agriculture, and Food Security." *Food and Agriculture Organization of the United Nations*. 2016. http://www.fao.org/3/a-i6030e.pdf.

75. Ibid.

76. "National Climate Assessment." *U.S. Global Change Research Program.* 2014. https://nca2014.globalchange.gov/report.

77. Belles, Jonathan. "Hurricane Florence Was the Nation's Second Wettest Storm Behind Harvey." *The Weather Channel.* 2018. https://weather.com/storms/hurricane/news/2018-09-19-hurricane-florence-harvey-north-carolina.

78. "Hurricanes and Climate Change." *Union of Concerned Scientists.* 2017. https://www.ucsusa.org/global-warming/science-and-impacts/impacts/hurricanes-and-climate-change.html.

79. "Implications for US National Security of Anticipated Climate Change." *US National Intelligence Council.* 2016. https://www.dni.gov/files/documents/Newsroom/Reports and Pubs/Implications_for_US_National_Security_of_Anticipated_Climate_Change.pdf

80. Di Liberto, Tom. "Torrential rains bring epic flash floods in Maryland in late May 2018." *Climate.gov.* 2018. https://www.climate.gov/news-features/event-tracker/torrential-rains-bring-epic-flash-floods-maryland-late-may-2018.

81. "Implications for US National Security of Anticipated Climate Change." *US National Intelligence Council.* 2016. https://www.dni.gov/files/documents/Newsroom/Reports and Pubs/Implications_for_US_National_Security_of_Anticipated_Climate_Change.pdf

Stress to the Power Grid

Changing levels of rainfall put the U.S.'s energy grid at risk. Over 7.3 billion people currently inhabit the planet, a little more than half of which live in cities.[82] In the United States alone, ten cities contain more than one million people, and more than 35 with a population of over 500,000.[83,84] The power grid that serves the United States is aging and continues to operate without a coordinated and significant infrastructure investment. Vulnerabilities exist to electricity-generating power plants, electric transmission infrastructure and distribution system components. Power transformers average over 40 years of age and 70 percent of transmission lines are 25 years or older. The U.S. national power grid is susceptible to coordinated cyber or physical attacks; electromagnetic pulse (EMP) attacks; space weather; and other natural events, to include the stressors of a changing climate.[85,86]

Effects of climate abnormalities over time introduce the possibility of taxing an already fragile system through increased energy requirements triggered by extended periods of heat, drought, cold, etc. If the power grid infrastructure were to collapse, the United States would experience significant

- Loss of perishable foods and medications
- Loss of water and wastewater distribution systems
- Loss of heating/air conditioning and electrical lighting systems
- Loss of computer, telephone, and communications systems (including airline flights, satellite networks and GPS services)
- Loss of public transportation systems
- Loss of fuel distribution systems and fuel pipelines
- Loss of all electrical systems that do not have back-up power[87]

The Presidential Policy Directive-Critical Infrastructure Security and Resilience lists 16 critical infrastructures susceptible to power grid failure that directly tie to U.S. national security and the homeland defense mission of the Department of Defense (DoD).[88] The Congressional Electro-Magnetic Pulse (EMP) Commission, in 2008, estimated it would cost $2 billion to harden just the grid's critical nodes.[89] The Task Force on National and Homeland Security calculates an additional $10 to $30 billion and many years necessary for a complete grid overhaul.[90] The EMP Commission further cited that some of the very improvements of network interconnectedness created through the updated Supervisory Control and Data Acquisition (SCADA) network, which control power distribution around the country, introduced additional weaknesses to cyber-attack.[91] The Center for Security

82. Giegengack, Robert. "The Carrington Coronal Mass Ejection of 1859." *Proceedings of the American Philosophical Society*, vol. 159, no. 4: 425-426. 2015.

83. "Ten U.S. Cities Now Have 1 Million People or More; California and Texas Each Have Three of These Places." *United States Census Bureau.* 2015. https://www.census.gov/newsroom/press-releases/2015/cb15-89.html.

84. "U.S. City Populations 2018." *World Population Review*. 2018. http://worldpopulationreview.com/us-cities/.

85. "Large Power Transformers and the U.S. Electric Grid," *U.S. Department of Energy*. 2012. https://www.energy.gov/sites/prod/files/Large Power Transformer Study - June 2012_0.pdf.

86. "Transmission & Distribution Infrastructure: A Harris Williams & Co. White Paper" *Harris Williams & Co*. 2014. https://www.harriswilliams.com/sites/default/files/industry_reports/ep_td_white_paper_06_10_14_final.pdf.

87. "Space Weather." *Department of Homeland Security*. No date. Accessed November 10, 2017. https://www.ready.gov/space-weather.

88. "Critical Infrastructure Security and Resilience." *The White House, Presidential Policy Directive*. 2013. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

89. Graham, William R. *et al.* "Critical National Infrastructures." *Report of Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack*. 2008. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf.

90. "A Call to Action for America." *Task Force on National and Homeland Security, Secure the Grid Coalition, and Other Partners*. 2017. https://emptaskforce.us/wp-content/uploads/2017/09/CAA-7-31-17.pdf.

91. Graham, William R. *et al.* "Critical National Infrastructures." *Report of Commission to Assess the Threat to the United States from*

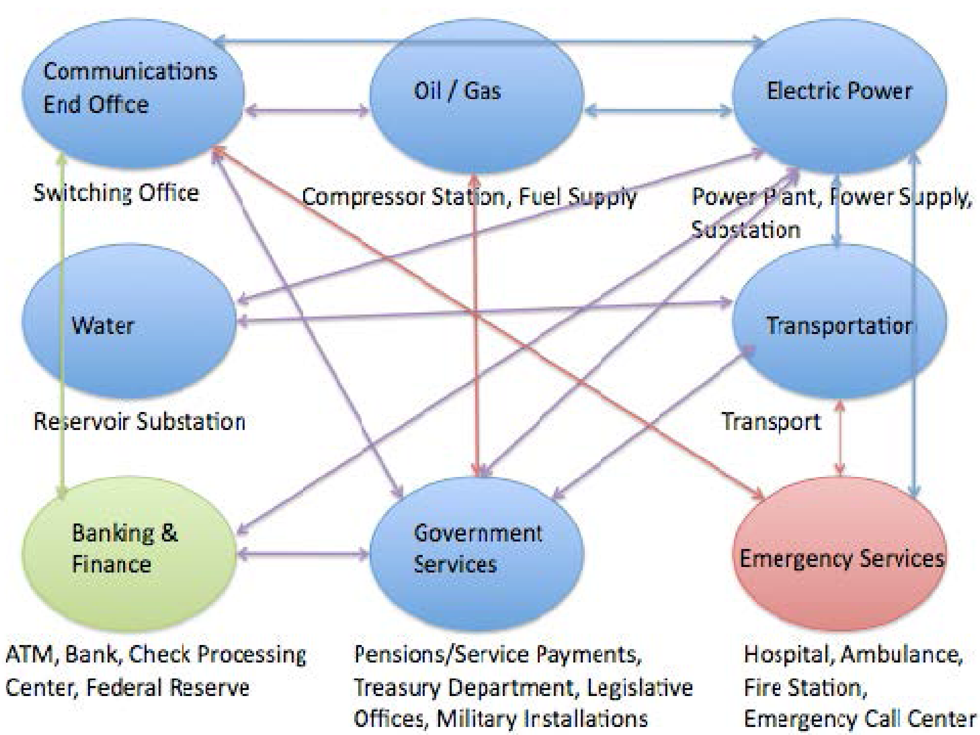
Policy reported that capability and capacity to repair or replace power grid unique infrastructure is reliant on production timelines exceeding a year. Most of these production facilities reside outside the United States, greatly adding to repair times and exacerbating vulnerability.[92]

Defense of the homeland requires reliable access to power generation capabilities to protect critical infrastructure areas, maintain sovereign security, and provide aid to the nation's population when needed. Department of Defense installations are 99 percent reliant on the U.S. power grid for electrical power generation due to the decommissioning of autonomous power generation capability for budgetary cost saving measures over the last two decades.[93]

While generators would allow continued operations for a time, a long-term outage of the power grid would rapidly erode the ability to perform numerous missions as resources were diverted toward humanitarian assistance/disaster response operations in the homeland.

Relief efforts aggravated by seasonal climatological effects would potentially accelerate the criticality of the developing situation. The cascading effects of power loss, as depicted below, would rapidly challenge the military's ability to continue operations. (See Figure 5.[94])

Figure 5: Essential Services Interconnectedness Affected by Power Grid Outage



Electromagnetic Pulse Attack. 2008. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf.

92. "Guilty knowledge: What the US Government Knows about the Vulnerability of the Electric Grid, But Refuses to Fix." *Center for Security Policy*. 2014. https://www.centerforsecuritypolicy.org/wp-content/uploads/2014/03/Guilty-Knowledge-6x9.pdf.

93. Koppel, Ted. *Lights Out: A Cyberattack, a Nation Unprepared, Surviving the Aftermath.* New York, NY: Crown Publishers, 2015: 216.

94. Jamieson, Isaac. "Addendum – EMP & Cyber Security" in *Smart Meters – Smarter Practices: Solving Emerging Problems.* EM-Radiation Research Trust. 2012. https://www.radiationresearch.org/articles/smart-meters-smarter-practices-document/.

While securing the U.S. power grid will take a whole of government approach, the Joint Force's responsibility to defend the homeland is the strongest reason for DoD to prioritize funding towards a solution. The Services must be clear in their assessment of installation vulnerability to an outage of the power grid and the consequences for homeland through missile defense, Defense Support to Civil Authorities, and military response to direct threats. Response delays in any of these areas will impair any effort to stabilize the situation or quickly respond to crisis anywhere in the United States.

Aside from power distribution concerns, our power generation capabilities are also at risk. Due to their water demands, safety requirements, and locations adjacent to waterways, nuclear power stations in the United States are at high risk of temporary or permanent closure due to climate threats, as demonstrated by the example facilities in Connecticut and Tennessee. The U.S. Nuclear Regulatory Commission (NRC) authorizes the current operation of 99 nuclear reactors, including both pressurized and boiling water reactors (PWR; BWR), which supplied 19.7% of the country's utility-scale energy in 2016.[95] In general, the country's reliance on nuclear energy has increased marginally over time, with a net 1.2% increase in nuclear-generated electricity from 2016 to 2017.

Ultimately, 59 (or 60%) of the country's nuclear reactors exist in regions that are likely to suffer from one or more climate threats. These regions include New England (major risk: sea level rise), Mid-Atlantic (major risks: sea level rise and/or severe storms), South Atlantic (major risks: sea level rise and/or severe storms), and East South Central (major risk: water shortage). Based on their locations, 100% of reactors in New England, 26% in the Mid-Atlantic region, 38% in the South Atlantic region, and 100% in the East South Central region are at risk of experiencing major climate threats.

95. "FAQ: What is U.S. electricity generation by energy source?" *U.S. Energy Information Administration*. 2018. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

The dangers facing some of these reactors have not gone unnoticed. For instance, Florida's Saint Lucie Nuclear Power Plant was shut down during Hurricane Matthew in 2016.[96] Operation of its sister facility, Turkey Point Nuclear Generating Station, was similarly ceased during Hurricane Irma in 2017.[97] Furthermore, expansion projects at Turkey Point, with proposals and construction spanning the last decade, have been criticized by several South Florida government officials who cite the challenge of rising sea levels.[98] New Jersey's Oyster Creek BWR will be decommissioned by the end of 2019 because of an unwillingness to construct costly cooling towers;[99] these structures will become increasingly important for reactors operating in regions where warming trends are apparent. Such complications, critiques, and closures are examples of impending climate change impacts on other nuclear energy facilities in the United States.

While it is true that nearly all types of energy infrastructure may suffer from climate changes unique to their locations, the only *clean energy* facilities likely to suffer as much or more than nuclear plants are their hydroelectric counterparts. In fact, hydropower's reliance on steady water access makes this sector particularly susceptible to climate-induced dryness. Experts expect drought to reduce hydropower generation due to declining reservoir levels, observed in 2007 when drought caused a 30% decrease in hydroelectric capacity in Tennessee.[100]

96. Prasad, Nithin. "FPL says Saint Lucie 2 Florida reactor shut ahead of Matthew." *Reuters*. 2016. https://www.reuters.com/article/us-storm-matthew-florida-nuclearpower/fpl-says-saint-lucie-2-florida-reactor-shut-ahead-of-matthew-idUSKCN1262I5.

97. Gardner, Timothy. "Florida nuclear plants to shut ahead of Hurricane Irma." *Reuters*. 2017. https://www.reuters.com/article/us-storm-irma-nuclearpower/florida-nuclear-plants-to-shut-ahead-of-hurricane-irma-idUSKCN1BI2IA.

98. Staletovich, Jenny. "Mayors make case against FPL nuclear expansion." *Miami Herald*. 2018. http://www.miamiherald.com/news/local/community/miami-dade/article18627960.html.

99. Oglesby, Amanda. "Christie: Oyster Creek shutdown schedule." *Asbury Park Press*. 2017. http://www.app.com/story/news/local/land-environment/2017/10/05/oyster-creek-early-closing/735491001/.

100. Tennessee River Drought Management Plan, http://web.knox-

This is consequential due to the nation's increasing demand for hydropower. In 2016, hydropower comprised 6.5% of utility-scale energy generated in the United States, making up the largest component (44%) of the country's renewable energy.[101]

From 2016 to 2017, a net 10.6% increase in U.S. hydropower generation was recorded. These numbers indicate that the two regions having the second- and third-fastest increase in hydropower usage (i.e., East South Central and West South Central) are also at high risk of future temperature increases and prolonged drought. Currently, 47 and 34 hydropower plants are operating in the East South Central and West South-Central regions, respectively, totaling at least 81 facilities that could suffer from reduced capacity in the near future.

Challenge 2: Climate Change and the Social, Economic, and Political Environment

Most of the preceding discussion of the physical environmental implications of climate change should be familiar. Less commonly discussed are the social, political, and economic effects of human concerns about climate change. Regardless of the actual physical effects of climate change, the belief in climate change as a threat to the earth and its inhabitants is an increasing force in international politics.[102] This suggests that to some extent the debate about whether the planet is warming, or if human activity is the cause, is irrelevant. If a powerful section of the human population believes that the planet is warming, believes that this warming is human-induced and that climate change is a threat, and if that section acts on those beliefs, climate change will have political, social, and economic consequences that the Army will be unable to ignore.

To understand the impacts of the indirect effects of mobilization around climate change (as opposed to the direct, physical effects), we propose the SMaRT framework: Social, Market, Regulatory, and Technological responses.

Social Responses

Climate change taps into profound fears of insecurity. Humans are highly motivated by symbols, and what more potent symbol is there of human thriving and the fragility of life than the planet itself? A recent Pew survey indicated that climate change trailed only ISIS globally as a security concern.[103]

The population of the United States is also concerned about climate change. Gallup News published a story in March, 2017 titled "Global Warming Concern at Three-Decade High in the U.S."[104] The polling data to support the story showed that, from a post-9/11 low of 51% in 2011, now 67% of the population worry about global warming a "great deal" or a "fair amount".[105] This concern is most prevalent among today's youth, indicating a propensity for the electorate to become more climate sensitive as that demographic ages.[106]

Powerful symbols engender social mobilization and change. To have a huge effect on human affairs, these symbols need not be deeply rooted in reality. Conquests of the companions of Mohamed remade the Middle East and North Africa. The Protestant reformation transformed European civilization. The American Revolu-

news.com/pdf/1013draft-drought-management-plan.pdf

101. "FAQ: What is U.S. electricity generation by energy source?" *U.S. Energy Information Administration*. 2018. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

102. "China, EU reaffirm Paris climate commitment, vow more cooperation." *Reuters*. 2018. https://www.reuters.com/article/us-china-eu-climatechange/china-eu-reaffirm-paris-climate-commitment-vow-more-cooperation-idUSKBN1K60TC.

103. Poushter, Jacob and Dorothy Manevich. "Globally, People Point to ISIS and Climate Change as Leading Security Threats." *Pew Research Center.* 2017. http://www.pewglobal.org/2017/08/01/globally-people-point-to-isis-and-climate-change-as-leading-security-threats/.

104. Saad, Lydia. Gallup, "Global Warming Concern at Three-Decade High in U.S." *Gallup News.* 2017. https://news.gallup.com/poll/206030/global-warming-concern-three-decade-high.aspx.

105. Ibid.

106. "Concern About Climate Change and Its Consequences." *Pew Research Center*. 2015. http://www.pewglobal.org/2015/11/05/1-concern-about-climate-change-and-its-consequences/climate-change-report-15/.

tion created a nation that would change the world. All of these phenomena derived much of their power from symbols. Grasping the power of the earth as a symbol requires little imagination compared to the nuances of Mohamed's revelations, Luther's theses, or the American case for independence.

Social mobilization around climate change will have winners and losers. Clear winners will be individuals and organizations perceived to be acting in the collective interest of both humanity and the natural environment. Clear losers will be individuals and entities whose actions are perceived to undermine environmental stability. Increased access to mass communication platforms means that no single entity will control the narrative regarding who these winners and losers are.

What is the current perception of the U.S. Army, the U.S. military, or the U.S. government as a steward of the environment? We have no good data on this question. Anecdotally, the U.S. government is perceived to be an irresponsible actor in the global environment. The U.S. withdrawal from the Paris accords elicited strong reactions in the developed world.[107] By contrast, although China is the largest carbon emitting nation,[108] it has been more thoughtful about how it projects its image globally with respect to carbon emissions, and Chinese clean energy initiatives have been widely publicized in the U.S.[109,110,111]

The energy and pollution practices of the U.S. military have been subject to less scrutiny both domestically and abroad and have not yet risen to the level of urgency of other issues such as sexual assault. However, as environmental and security concerns increasingly overlap, the international perception of the U.S. as an irresponsible actor could have serious implications for the U.S. military, which relies on allies to maintain its global posture. The U.S. military depends on access to the bases and ports of allies, it enjoys flyover privileges, and other preferential treatment. All of this exists because allies see the U.S. as aligned with their core interests. In the core powers of Europe, in the Commonwealth countries, in Japan, and elsewhere, social mobilization due to perceived climate change has the potential to create a fundamental misalignment between the U.S. and its key allies.[112] The U.S. may find itself more internationally isolated than at any times since its repudiation of the League of Nations.

Market Responses

The private sector will play the largest role as it explores ways to respond to society's evolving need to "protect, retreat [from], or accommodate" activities that cause climate change.[113] The market consequences of climate change are complex and ambiguous. Humanitarian and development organizations are also working intensely to build or rebuild markedly more resilient communities with enhanced distributed collective intelligence, decentralized grid structures and other strategies that may improve overall resilience. In general, however, market consequences of climate change are complex and am-

107. Shear, Michael D. and Alison Smale. "Leaders Lament U.S. Withdrawal but Say It Won't Stop Climate Efforts." *The New York Times.* 2017. https://www.nytimes.com/2017/06/02/climate/paris-climate-agreement-trump.html.

108. "Global Carbon Atlas." *Global Carbon Project.* 2018. http://www.globalcarbonatlas.org/en/CO2-emissions.

109. "China Steps Up Its Push into Clean Energy." *Bloomberg News.* 2018. https://www.bloomberg.com/news/articles/2018-09-26/china-sets-out-new-clean-energy-goals-penalties-in-revised-plan.

110. Dudley, Dominic. "China Is Set To Become The World's Renewable Energy Superpower, According To New Report." *Forbes.* 2019. https://www.forbes.com/sites/dominicdudley/2019/01/11/china-renewable-energy-superpower/ - 9eb1cfa745a2

111. Forsythe, Michael. "China Aims to Spend at Least $360 Billion on Renewable Energy by 2020." *The New York Times.* https://www.nytimes.com/2017/01/05/world/asia/china-renewable-energy-investment.html.

112. Milman, Oliver. "G20 leaders' statement on climate change highlights rift with US." *The Guardian.* 2017. https://www.theguardian.com/world/2017/jul/08/g20-climate-change-leaders-statement-paris-agreement.

113. "Technologies for adaptation to climate change." *United Nations Framework Convention on Climate Change (UNFCCC).* 2006: 13. https://unfccc.int/resource/docs/publications/tech_for_adaptation_06.pdf.

biguous. Highly entrenched economic interests may distort market signals. Global reductions in demand for hydrocarbons means that gasoline, diesel, and jet fuel should become less expensive. On the other hand, reduced demand tends to reduce incentives to explore potential oil fields or build new refining facilities. Much of the U.S.'s domestic oil extraction is unprofitable at oil prices below $30 a barrel. Technological advances tend to push this number lower, but exhaustion of oil fields tends to push the number higher. In all scenarios, global declines in oil consumption increase the sensitivity of oil markets to the choices of large consumers like the U.S. DoD.

Regulatory Responses

Regulations will play a factor in driving the behavior of both consumers and private sector companies. By establishing standards such as fuel economy, limiting carbon emissions, setting greenhouse gas targets, or providing tax incentives for individuals, the regulatory arm of the government can be a powerful tool over the next 30 years. The United States' participation in Organization for Economic and Cooperation Development (OECD) will continue to provide opportunities to identify shared values with partner nations and set global targets.

Regulatory action often flows from collective interest in change. In the case of climate change, many regulations may create compliance challenges for the U.S. military. We think it unlikely that the U.S. government would restrict military carbon emissions in combat operations, for example. We are less optimistic about the absence of such restrictions on force development. Indeed, we consider it likely that at some point in the next two decades the U.S. government will introduce carbon emissions restrictions that affect non-combat military operations. While the Air Force can quickly increase its reliance on flight simulation, the Army remains wedded to training and practicing in live scenarios. This makes the Army highly susceptible to disruptions in readiness development should the government introduce carbon emissions restrictions.

Technological Responses

To mitigate the effects of climate change, government organizations, non-governmental organizations, and the private sector will need to pursue technological enhancements. These enhancements must be "climate informed" so that improvements do not create unintended vulnerabilities.[114]

The clearest opportunities for climate-change related innovation are in clean energy production, transmission, and storage. Each of these areas creates risks and opportunities for the U.S. military. The automated, A.I.-enhanced force of the Army's future is one that runs on electricity, not JP-8. More efficient or resilient production of electricity through micro-nuclear power generation or improved solar arrays can fundamentally alter the mobility and the logistical challenges of a mechanized force. Light, quick-charging batteries (super-capacitors) have tremendous value in such a force; so does the wireless transmission of electrical current.[115]

Innovations such as weather control and weather mitigation techniques may serve to stave-off the worst impacts of climate change. For example, researchers are exploring ways to combat the effects of climate change through geoengineering. This controversial program involves either "capturing and storing some of the carbon dioxide that has already been emitted so that the atmosphere traps less heat or reflects more sunlight away from the earth so there is less heat to start with."[116] Other opportunities for technological change include weather

114. Hallegatte, Stephane *et al. Shock Waves: Managing the Impacts of Climate Change on Poverty*. 2016. Washington, DC: World Bank.

115. Bakken, Gretchen. *The Grid: The Fraying Wires Between Americans and Our Energy Future.* New York: Bloomsbury, 2016: 201-207.

116. Fountain, Henry. "Panel Urges Research on Geoengineering as a Tool Against Climate Change." *The New York Times.* 2015. https://www.nytimes.com/2015/02/11/science/panel-urges-more-research-on-geoengineering-as-a-tool-against-climate-change.html?mcubz=3.

control,[117]* pollution control, flood management, and agricultural changes.[118]

The last area of concern regarding weather threats centers around attribution. The United States defends itself daily from activities of rival nations that fall below the level of war but can still negatively target national security. Nations who feel they cannot compete with the United States directly use these methods to level the playing field. As an example, a 2015 DoD Cybersecurity Culture and Compliance Initiative states that the DoD had been the subject of over 30 million malicious attacks to its network in just the short period from September, 2014 to June, 2015.[119] Targeted attacks by hackers or computer viruses can leverage naturally occurring events like space weather to disguise their intrusion into U.S. networks as they create effects that mimic space weather threats. By using space weather events or manufacturing events that mimic space weather, adversaries can create a non-attributional attack on vital systems with little concern of detection until it is too late to react.

One such possible event made international news in the Spring of 2016. Swedish air traffic controllers reported widespread and persistent outages of their aviation radar network over the course of five days in November of 2015. Publicly attributed to a solar event, domestic and international flight operations halted while repair efforts searched for the cause of the outage. Anonymous sources pointed towards a more ominous culprit than space weather as further reporting claimed Swedish authorities traced the beginning of the outage to an advanced persistent threat group previously linked to the Russian military intelligence agency, Spetsnaz GRU. The Swedish Civil Aviation Administration later came back with another announcement that this was a naturally occurring event and no cause for alarm. However, rumors persist that the events engineered over the course of a week had little or nothing to do with a space weather event, but more to do with the Russians testing out their electronic warfare capability.[120] The fact that a series of geomagnetic storms did occur during this period does create some doubt as to the validity of the rumors, however, that does not preclude the capability exists. That only Sweden's radar network felt the effects of the storm lends credence to other explanations.

While all countries claim a purely scientific interest and capability for experimenting with the natural environment, a prudent strategic leader should look to the dual-use possibilities of such labors and seek mitigation strategies.

Challenge 3: The Army and DoD – Organizational Confusion and Lack of Accountability for Climate Change

No systemic understanding of the wide diversity of climate-change related intelligence.

The section above on the environmental effects of climate change demonstrates the wide variety of stakeholders who are monitoring climate change-related effects. These include public health organizations such and the W.H.O. and the Centers for Disease Control, energy producers and regulators such as the Federal Energy Regulatory Commission, weather observers such as NASA and the NOAA, humanitarian organizations like the World Food Program, national security entities like the U.S. military, and numerous private and public organizations like universities, NGOs, and so on. Climate change is at the center of a complex web of interactions. During this study, we were struck by how much many people knew about parts of the phenome-

117. * See Appendix: Weather Control.

118. "Technologies for adaptation to climate change." *United Nations Framework Convention on Climate Change (UNFCCC).* 2006: 13. https://unfccc.int/resource/docs/publications/tech_for_adaptation_06.pdf.

119. "Department of Defense Cybersecurity Culture and Compliance Initiative." *Office of the Secretary of Defense.* 2015. https://dod.defense.gov/Portals/1/Documents/pubs/OSD011517-15-RES-Final.pdf.

120. Russon, Mary-Ann. "Russia Blamed for Crashing Swedish Air Traffic Control to Test Electronic Warfare Capabilities." *International Business Times.* 2016. http://www.ibtimes.co.uk/russia-blamed-bringing-down-swedish-air-traffic-control-test-electronic-warfare-capabilities-1554895.

na, but we were also surprised by the lack of a holistic view of the problem, and a sense of how some areas would relate to each other. Climate change is a common cause linking a disparate set of challenges, but we currently have no systemic view to assess and manage risk. In contrast, in China, systems science and engineering is considered so important to the future of China that this is a course of study required for all cadres in the Chinese Communist Party's Central Party School in Beijing.[121] Thanks in part to some spectacular historical failures and collaboration with the University of Hull, the hard systems approaches have been amended to systematically take into account *wuli* (objective exploration of a problem, facts, futures), *shili* (mathematical and conceptual models used to organize a system), and *renli* (human relationships). The application of these approaches at large scale, coupled with intensive urban surveillance, state-influenced social media, and biometric fintech, have the potential to create very significant asymmetries in resilience between the U.S. and China to climate-induced effects and any other type of attack or disaster.

In the U.S., there are many actions that would be warranted by recent past experience to reduce vulnerabilities of the Army, the DoD and the nation such that the DoD is mobilized under a State of Emergency. No single approach is likely to be adequate to prepare the U.S. Army and the DoD as a whole for altered conditions that are either in place already or virtually certain to occur at some point in the future. In the past two decades, the DoD has been under increasing pressure from Congress to prepare strategies, plans and capabilities necessary to ensure preparedness for the wide array of potential impacts on weather resulting from climate change. The NDAA for 2018 mandated at least two studies to this effect, one focused on climate per se, and one focused on DoD vulnerabilities to disruption of the global food system. While there have been significant interagency investment and collaboration through the past two decades, there is an ongoing need for improved interagency collaboration between intelligence, defense, and civilian agencies on climate change data collection, analysis, and forecasting. Where not already routine, the intelligence community's analyses would be improved by the systematic inclusion, as a matter of course, of closely synched present day and near-term insights from climate projections, modeling, and weather data into established products and processes. DoD and natural science agencies would benefit from the additional qualitative and quantitative collection, provided by IC platforms, to improve their own processes and products.

The lack of organizational accountability in the DoD and the Army

They say that "what gets measured, gets done." In large, complex, bureaucracies, getting "new" things done often involves adding structure. Especially in long-established organizations, the addition of new structures can engender distress by way of competition for fixed resources and local or general cultural opposition, this can create circumstances where new structures become disconnected from the normal socialization, integration and resourcing processes. Such challenges can arise no matter how justified or important the "new" effort is. In many cases, new administrative structures, staffing and infrastructure are required. Under any circumstances, "best laid plans," can become hard to implement across the organization. Climate change presents the Army with a bureaucratically "new" and complex challenge that must be socialized, integrated, and resourced across the enterprise. Climate change is a national security imperative that cuts across the department and has no single organization wholly responsible for addressing it. But the Army and its sister Services are not alone in wondering how to address climate change. Congress' oversight authority enables it to query the Department of Defense (DOD) about its plans to address the impact of climate change. The 2018 National Defense Authorization Act (NDAA), di-

121. Hvistendahl, Mara. "A revered rocket scientist set in motion China's mass surveillance of its citizens." *Science* 359(6381): 1206-1209. 2018. https://www.sciencemag.org/news/2018/03/revered-rocket-scientist-set-motion-china-s-mass-surveillance-its-citizens.

rected the DOD to provide a report on the vulnerabilities to installations and combatant command requirements resulting from climate change over the next 20 years.[122] The report is required to list of the ten most vulnerable installations, mitigation and cost strategy, and frequency of humanitarian assistance/disaster relief (HADR) missions.[123] The Army will task within its organizations for the answer, but short of the occasional request from Congress, is there any organization within the Army that periodically assesses how it is doing across the enterprise? Who is deciding what trades to make, where to invest, what to invest in, or what the Army's priorities should be? The Army is making efforts toward addressing climate change, but who or what body is defining those priorities?

From an organizational structure, the Army does not have a good mechanism for holistically assessing and re-assessing the present and future impacts of climate change on the Army, nor is there a systematic mechanism in place to track present and past impacts on the force. Any new organizing construct within the Army to address the very diverse impacts of climate change across scales and geographies should reflect the Army leadership's objectives. It should provide visibility across the enterprise about what the Army is doing, and the level of readiness or preparedness being resourced. And it should also provide leadership with an understanding of how climate change has and will impact areas such as training, readiness, supply chain, and its future cost implications.

The Environmentally Oblivious Culture of the Army

The Army has thrived despite a culture of environmental oblivion that exists within the force. Conditions may no longer favor this tendency. Trends show that the United States is becoming more environmentally conscious and that the threat of climate change and our impact on the planet is seen as a threat to our national security by a majority of the population.[124]

The Army is not an environmentally friendly organization. Frankly, it is not designed to be. For good reasons, the Army focuses on the most effective means to dominate an enemy on the battlefield. However, in the course of this endeavor, the turbine engines that power helicopters and tanks burn thousands of pounds of JP-8 fuel per hour. Every time one of those turbine engines is shut off almost a pint of jet fuel is dumped overboard onto the ground. The munitions used in training rain lead and explosive residue into range complexes across the country. Armored vehicles churn up the soil in maneuver areas and contribute to erosion and sediment run off into streams. In myriad offices across the force, thousands of pages of PowerPoint presentations are printed off every day, simply to be thrown away after the briefing. In short, the Army is an environmental disaster. Incidentally, this makes the Army a likely target of social mobilization (see above).

Given the magnitude and variety of climate change-related challenges, what specific actions can be undertaken by leaders of the U.S. Army today? We now turn to this question.

122. "National Defense Authorization Act for Fiscal Year 2018." *115th Congress of the United States of America.* 2017:169. https://www.congress.gov/115/bills/hr2810/BILLS-115hr2810enr.pdf.

123. "National Defense Authorization Act for Fiscal Year 2018." *115th Congress of the United States of America.* 2017: 169-170. https://www.congress.gov/115/bills/hr2810/BILLS-115hr2810enr.pdf.

124. Saad, Lydia. Gallup, "Global Warming Concern at Three-Decade High in U.S." *Gallup News.* 2017. https://news.gallup.com/poll/206030/global-warming-concern-three-decade-high.aspx.

Part 2: Recommendations

This section describes recommendations for climate change-related actions by the U.S. Army. We summarize each recommendation in terms of timing of implementation (Now, 1-5 years, 6-10 years, or beyond 10 years), and we characterize the resourcing requirements associated with it. "Low" resourcing assumes no substantive additional resources are required to implement the recommendation. "Moderate" resourcing assumes that some reprogramming is needed, up to $100 million over a five-year period. "High" means that the recommendation requires substantive appropriations, in excess of $100 million over a five-year period. All resource projections are estimates.

RECOMMENDATION AREA 1: THE ARMY OPERATING ENVIRONMENT

Problem: Hydration Challenges in a Contested Environment

Recommendation: *The Army must develop advanced technologies to capture ambient humidity and transition technology from the United States Army Research, Development, and Engineering Command (RDECOM) that supports the water sustainment tenants of decentralizing and embedded, harvest water, and recycle and reuse.*

Implementation Timing: 6-10 Years

Resource Requirement: Moderate

Hydration in a Contested Arid Environment

The U.S. Army is precipitously close to mission failure concerning hydration of the force in a contested arid environment. The experience and best practices of the last 17 years of conflict in Afghanistan, Iraq, Syria, and Africa rely heavily on logistics force structures to support the warfighter with water mostly procured through contracted means of bottled water, local wells and Reverse Osmosis Water Purification Units (ROWPU). The Army must reinvest aggressively in technologies both in-house and commercial off the shelf in the next 5-10 years to keep pace with rising global temperatures, especially those arid areas in or poised for conflict. The Army must seek partnerships with industry, other nations, and other militaries currently working on the hydration issue.

The Army must re-examine its planning approach to the hydration issue. The table below comes from the Command and General Staff College Student Text, Theater Sustainment Battle book. The ability to supply this amount of water in the most demanding environment is costly in money, personnel, infrastructure, and force structure.[125] (See Table 2.) The calculations for water (8.34 pounds per gallon) in an arid environment equates to 66 pounds of water per soldier.

125. Johnson, Michael, CPT and LTC Brent Coryell. "Logistics Forecasting and Estimates in the Brigade Combat Team." 2016. *Army Sustainment*. http://www.alu.army.mil/alog/2016/NOVDEC16/PDF/176881.pdf.

Table 2: Daily water consumption factors in gallons per person[126]

Use	Temperate	Tropical	Arid	Arctic
Drinking water	1.5	3.0	3.0	2.0
Personal hygiene	1.7	1.7	1.7	1.7
Field feeding	2.8	2.8	2.8	2.8
Heat injury treatment	.1	.2	.2	.1
Vehicle maintenance			.2	
Standard planning factor	6.1	7.7	7.9	6.6

Current planning methodologies remain heavily vested in bottled water meaning a more considerable force is needed to transport it. As of the 2017 Modified Tables of Occupation and Equipment (MTOE), most units retain some level of water storage or transportation based on force structure. This structure makes sense and requires continuation. This structure only works through the supplying of potable water by support units or through locally procured methods. Force structure will not fix this problem. Very few Army units have water generation capabilities, and as of 2015, Brigade Combat Teams can no longer organically support their water needs. The additional units needed to support them creates an unsupportable logistical footprint and reduces the speed of the combat units.

Researchers at Ft. Lee, VA, with the Combined Arms Support Command (CASCOM), in the Petroleum and Water Department, believe water generation is one of the leading fields for material approaches in the Capability Needs Assessment Process. The objective is to develop technologies enabling a logistics transformation in the area of water sustainment by reducing the water distribution and storage load. Without technology advances, water remains 30%-40% of the force sustainment requirement. The reduction encompasses the water storage load on combat platforms, the Soldier, tactical systems, and current and future force water distribution requirements. The Army must develop advanced technologies to capture ambient humidity and transition technology from the United States Army Research, Development, and Engineering Command (RDECOM) that supports the water sustainment tenants of decentralizing and embedded, harvest water, and recycle and reuse. This technology enables water production capability to be embedded in platforms (possibility trailer mounted systems) creating distributed water production that reduces resupply and storage requirements and supports a self-sustainment concept of 3 to 7 days without resupply. The objective is achieving 7 gallons of water produced for every one gallon of fuel used.[127]

The U.S. army must take aggressive steps to manage the risk of emerging technologies. As with any emerging technology, there is a risk. There is a risk in the level of investment of both finances and resources. The amount of time given to the research versus the payoff. The hazard of hydration is identified and through investment, research and development, and partnerships, controls can be emplaced to mitigate, monitor, and ultimately reduce the risk.

The Department of the Army must seek partnerships with foreign regional militaries and organizations who have proven the ability to operate in an arid environment and leverage these techniques and apply them to U.S. military operations. Investments already by the Marine Corps in 2012 proved their worth. The Individual Water Purification System Block II allowed Marines to

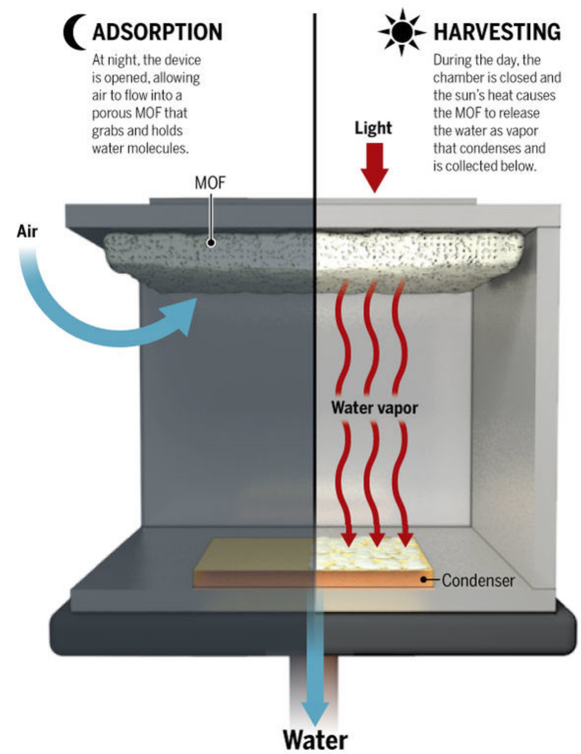
126. Ibid.

127. Burden, Jr., Charles E. Team Leader for Petroleum, Water and Material Handling Equipment, Combined Arms Support Command. Telephone interview by author, April 10, 2018.

self-purify water directly from the source. This system reduces weight and logistics supporting an ever-growing expeditionary force.[128] In the 2000s in Iraq, over 864,000 bottles of water were consumed each month at one Forward Operating Base (FOB) with that number doubling during hotter months.[129] Reducing the dependence on bottled water dramatically reduces the number of logistics formations freeing up that force structure for deliberate operations. Further reducing the cost of water was the Army's expenditures in the past for the Lightweight Water Purifier Units. This system developed in early 2002 by MECO Defense cut the price of a gallon of water from $5.00 to $.07.[130]

The Army must look at commercial, off-the-shelf (COTS) technologies to create a more self-sufficient warfighter. One of the most recent developments is in the area of atmospheric water gathering. Some researchers estimate there may be as much as 13 trillion liters of water in the air. Previous techniques have proven costly to operate regarding fuel. There is a newer device called a water harvester. Using metal-organic frameworks (MOF), scientists are creating a reaction to force water vapor in the air to condense producing 3 liters of water for every liter of material used.[131] (See Figure 6.)

Figure 6: Illustration of a micro water collector[132]



Ironically, Dr. Jay Dusenberry and his team at the U.S. Army Tank Automotive Research Development & Engineering Center (TARDEC), as early as 2003, worked on similar technology.[133] His opinion is an approach which focuses on multiple technologies such as small unit purifiers, desalinization, and reverse osmosis to supplement an atmospheric water gatherer. This is another capability that allows units to produce their own water. This paired with the water harvesting or mounted on a robot may provide complementary capabilities that would support sustainment for units over a wide range of operational scenarios and environmental conditions. He stresses the goal must be to produce as much water as possible at the point of need.

The U.S. Army continues to make great strides on ways to reduce its dependency on this time-proven supply

128. Browne, Mathuel. "Marines Invest in New System to Purify Water on the Go." *Armed with Science: The Official US Defense Department Science Blog*. 2017. http://science.dodlive.mil/2017/02/01/marines-invest-in-new-system-to-purify-water-on-the-go/.

129. Vitter, Scott and Corey James. "In a Position to Lead: How Military Technology and Innovation Can Ease the World's Water Challenges." *Earth Magazine.* 2017. https://www.earthmagazine.org/article/position-lead-how-military-technology-and-innovation-can-ease-worlds-water-challenges.

130. Klie, John and Stephen Rome. "US Army Reduces Water Costs with Mobile Purifier Units." *Water and Waste International.* 2005. http://www.waterworld.com/articles/wwi/print/volume-20/issue-10/features/us-army-reduces-water-costs-with-mobile-purifier-units.html.

131. Service, Robert F. "This new solar-powered device can pull water straight from the desert air." *Science.* 2017. http://www.sciencemag.org/news/2017/04/new-solar-powered-device-can-pull-water-straight-desert-air.

132. Ibid.

133. Dusenbury, Jay. "Water Treatment and Harvesting Systems." *US Army TARDEC/DARPA.* 2003. http://www.dtic.mil/dtic/tr/fulltext/u2/a461465.pdf.

process, but current funding priorities potentially will derail this effort in the areas of research and development. The technologies are appearing in the private sector which requires assimilation into the military formations. Force structure alone will not solve this problem. Soldiers operating in contested arid environments with reduced water sources need the ability to collect water from the atmosphere. Local procurement of water may not be safe or accessible due to conflict. The technology research being recommended could reduce conflict if placed in these water-challenged areas reducing or eliminating the need for U.S. military presence. The issue may well be served by the Cross Functional Teams (CFTs) model to address this dilemma aggressively.

Problem: Lack of adequate preparation and coherence in doctrine, training, and capabilities development to support effective Arctic operations.

Recommendation: *The Army and the Department of Defense must begin planning and implementing changes to training, equipment, doctrine and capabilities in anticipation of an expanded role in the Arctic associated with global climate adaptation.*

Implementation Timing: Now to 10+ Years.

Resource Requirements: Moderate to High.

Beginning immediately, the Army should implement Arctic training for a greater number of units to increase potential Arctic force capacity. In addition, the Army must focus on immediate doctrine development that will facilitate operations in remote and extreme environments. In the mid-term, over the five to ten-year span, the Army should focus on materiel solutions to operating in environmental extremes, coupled with execution of more environmentally friendly training practices. To enhance operational effectiveness, DoD must increase GPS satellite distribution to augment Arctic coverage and provide enhanced navigation capabilities through the establishment of eLORAN throughout U.S. and allied Arctic regions. Finally, long term focus must be placed on research, development and fielding of vehicles and equipment that have a decreased environmental impact and are able to transit the Arctic terrain effectively.

In terms of resource allocation requirements for the force, implementation for expansion of Arctic capabilities and capacity is a low to moderate priority in the near to mid-term. This priority increases to high from the mid to long term horizon. Correspondingly, the resources required for implementation of these recommendations also increase over time. Increased training and doctrine development are simply a reprioritization of existing resources, focused on burgeoning capabilities. In the mid-term, materiel solutions and augmentation of navigation capabilities for the Arctic are moderately resource intensive. Finally, the research, development and fielding of low environmental impact equipment with enhanced Arctic capabilities is very resource intensive and will require compromises and a realization of the increased importance of Arctic security.

The Arctic remains at the forefront of the earth's climate adaptation and variances in the global climate are most noticeable in the Arctic region. Increased accessibility to the region for economic activity will consequently increase the security requirements and competition in the region. Currently Russia is rapidly expanding their Arctic military capabilities and capacity.[134] The U.S. military must immediately begin expanding its capability to operate in the Artic to defend economic interests and to partner with allies across the region.

The Intergovernmental Panel on Climate Change's 2014 report illustrating the Representative Concentration Pathway (RCP) 4.5 model shows the Arctic Region anomalous temperature change through 2050 from +3 up to +6 degrees Celsius, more than any other area on the globe.[135] This rapid climate change will continue to

134. Nudelman, Mike and Bender, Jeremy. "This Map Shows Russia's Dominant Militarization of the Arctic." *Business Insider*. 2015. http://www.businessinsider.com/chart-of-russias-militarization-of-arctic-2015-8.

135. "Fifth Assessment Report - Synthesis Report." *Intergovernmental Panel on Climate Change*. 2015. http://ipcc.ch/report/ar5/

result in increased shipping transiting the Arctic,[136] population shifts to the region and increased competition to extract the vast hydrocarbon resources more readily available as the ice sheets contract.[137] These changes will drive an expansion of security efforts from nations across the region as they vie to claim and protect the economic resources of the region.

In this role, the Army must be trained and equipped to operate across vast distances in extremely remote and inhospitable terrain. Choosing not to prioritize resources to this effort puts the Army at substantial risk. Simply put, the competition for resources in the Arctic will increase security requirements and the potential for conflict. The Army will not be excluded from those requirements or any conflict that develops. The Army will simply be unprepared for the mission and the environment in which it will occur. This results in a significantly increased risk to mission as well as to personnel and equipment. Further risk is entailed with respect to service competition for resources. As Russian activity expands in the Arctic, both the Navy and the Air Force will compete for resources to meet the Russian threat. The Army must compete as well, not only to simply gain resources, but, moreover, to be ready to contribute as a member of the joint force.

There are three primary timelines associated with these recommendations: near term (immediate to 5 years), mid-term (5-10 years) and long term (beyond 10 years). Generally speaking, the investment associated with implementing the recommendation corresponds with the timeline, with more immediate recommendations being less cost intensive than longer term ones.

The first near term recommendation is to simply increase the number of soldiers and units exposed to training in the Arctic environment. The extreme climate and remoteness of the region requires specialized training that is currently available to only a small number of Army soldiers. This expansion in training must be accompanied by development of doctrine that addresses how brigades will fight in remote environments. In a wide area security mission in the Arctic's vast expanse, a brigade will be expected to defend a much wider area, forcing battalions to operate in a more autonomous mode, removed from bases of supply and centralized command nodes. Expanding area coverage requirements will drive the development of advanced persistent sensors, both air and ground based, that can operate in extreme climactic environments to enable the brigades and battalions to detect enemies and maneuver to counter potential attacks.

These near-term recommendations do not require a great deal of immediate investment. Primarily, the Army would need to reprioritize training funding to expand throughput and attendance at Arctic training areas. Additional investment would be required for sensor development, but the current capabilities both in the inventory and in commercial applications are not far removed from those the Army will require to meet near-term needs.

The mid-term recommendations will require close coordination between the Army and other elements of the DoD. The first series of recommendations concerns materials engineering solutions to problems associated with current equipment in cold weather environments. For example, the current rotary wing fleet has many restrictions on cold weather operations concerning battery usage and life as well as requirements for auxiliary power unit (APU) operations and fragility of elastomeric bearings in the tail rotor sections. These restrictions are easily mitigated when conducting operations from controlled environment hangars but will severely hamper maneuver operations from austere locations.

Next, in conjunction with the other services, the Army must expand search and rescue capabilities in the Arctic. An increase in population, economic activity and

syr/.

136. Amos, Jonathan. "Arctic Ocean Shipping Routes 'to Open for Months'." *BBC News*. 2016. http://www.bbc.com/news/science-environment-37286750.

137. Keil, Katherine. "The Role of Arctic Hydrocarbons for Future Energy Security." *Nautilus Institute for Security and Sustainability*. 2014. https://nautilus.org/napsnet/napsnet-special-reports/the-role-of-arctic-hydrocarbons-for-future-energy-security/.

unit training will increase requirements for search and rescue assets. Recently the Army has abdicated primary search and rescue responsibilities to the Air Force, as the proponent for combat search and rescue. However, the Army should expand capabilities and training to minimize response time for contingencies.

Additionally, in conjunction with the DoD and other services, the Army must invest in expanding Arctic navigation capabilities. Lack of GPS differential, ionospheric storms and low angle satellite intervisibility combine to reduce the effectiveness of GPS at high latitudes.[138] The DoD can mitigate this risk through augmentation of the GPS satellite fleet that will enable greater GPS differential to increase geolocation accuracy. Furthermore, establishment of eLORAN land-based navigation facilities to augment satellite aided navigation will ensure both accuracy and redundancy for operation in remote Arctic areas. Consideration should also be given to the limitations of satellite aided communications in the Arctic as any geosynchronous platform will experience the same limitations as the GPS satellites.

Finally, in the mid-term the Army must focus on reducing the environmental impact of training. The Arctic will remain a delicate environment that the public looks to as "unspoiled" wilderness. Operations that damage or degrade the environment will foster a negative view of the Army and must be mitigated through careful training execution that minimizes the risk of petroleum spills and localizes training impacts to the smallest area possible. There are further recommendations associated with this challenge for long term consideration.

Taken together, these mid-term recommendations will require moderate investment to bring to fruition. Material solutions to cold weather operating challenges are available for many of the Army's current platforms, however those materials will need extensive testing to incorporate into those platforms. Additionally, it is critical that those material solutions be viable across the spectrum of operational conditions as it is not realistic, for example, to install different batteries, APUs and bearings for different environments across the rotary wing fleet. Expanded search and rescue capabilities and capacity will require investment in both equipment and training. However, the equipment required is available either within other services or is currently in use in commercial applications. The most cost intensive of the mid-term recommendations is augmentation to navigation and communication capabilities. However, these costs can be somewhat mitigated through normal satellite attrition and replacement with upgraded capabilities. Additionally, low earth orbit (LEO) satellite options can be employed that simply augment coverage in the Arctic region. LEO satellites are less expensive to deploy and limited capabilities for a limited coverage area may decrease per unit costs.

The final recommendation considers long-term solutions to the challenge of increased operations in the Arctic. As previously discussed, the austere and remote nature of the Arctic, as well as the vast area under consideration will require units to operate in a much larger area than current doctrine dictates. This will significantly stress the Army's logistics capability to support those units in an environment with little transportation infrastructure. To mitigate this, the Army must invest in platforms that are far more fuel efficient or that operate off of alternative energy sources. A diminishing reliance on hydrocarbon-based fuels will not only decrease logistical requirements but will also decrease the environmental impact of operations in the Arctic. These developments can put the Army at the forefront of environmental stewardship and ensure that the public remains firmly rooted behind the Army's efforts.

In conjunction with development of new fuel sources, the Army must explore vehicles more well-suited to Arctic maneuver. Thawing of the permafrost will create large expanses of bogs and marshes across many areas of the Arctic. In addition, though the globe is warming, extreme weather conditions will persist in the Arctic.

138. "Polar Regions." *The Swedish Club: International Marine Insurance*. Accessed April 16, 2018. https://www.swedishclub.com/loss-prevention/trading-area/polar-regions/.

The Army needs to focus on the development of an infantry carrier vehicle with low surface pressure to maximize maneuverability in adverse terrain. An amphibious capable vehicle that has high weight distribution characteristics across the drive (either wheeled or tracked) contact patches will increase the speed of maneuver necessary for units to conduct wide area security across greater coverage areas.

These long-term recommendations will require significant investment to come to fruition. Research and development of new fuels and a new class of vehicles is a long lead time requirement that the Army must begin investing in now. However, the research into new fuels or energy sources can be shared across the services and is already underway in many cases. Commercial companies are also well invested in these capabilities already. Public demand is driving innovation in this field and will help mitigate costs for the Army in development and fielding.

RECOMMENDATION AREA 2: THE ARMY INSTITUTION

Problem: The Lack of a Culture of Environmental Stewardship

Recommendation: *Army leadership must create a culture of environmental consciousness, stay ahead of societal demands for environmental stewardship and serve as a leader for the nation or it risks endangering the broad support it now enjoys. Cultural change is a senior leader responsibility.*

Implementation Timing: Now

Resource Requirements: Low

The Army has attempted some small-scale efforts at environmental stewardship. At installations across the country there are areas that are off limits to training because some endangered species is resident there. In nearly every office there is a blue recyclables trash can and most installations have a recycle program that awards the unit that brings in the most waste to the recycling facility. This program, however, is a great example of one of the obstacles to environmental consciousness in the Army. In order for a unit to receive an annual award that may amount to $500 deposited into the unit's Morale, Welfare and Recreation (MWR) fund, every soldier in the unit must make the individual effort to identify those items eligible for recycling, separate their trash and then dispose of that trash in a special receptacle. The unit must then transport that refuse to the post recycling facility for credit. This is a classic example of concentrated costs with dispersed benefits, as demonstrated in Mancur Olson's *Logic of Collective Action*.[139,140] The reward is distributed to the organization, but not to the individual and therefore the individual does not see the direct benefits of his efforts to recycle. Whatever events may be sponsored from the MWR fund would likely occur anyway. The only benefit of the recycling award is that potentially the soldier may get an extra hamburger at the MWR picnic. This is not much of an incentive. Creating and promulgating a culture of environmental stewardship throughout an organization as vast and diverse as the Army will take years, and the tide of public opinion shows no signs of slowing.

The Army's norms and values must change.[141] The Army does not have a set of norms that promotes environmental stewardship or leadership where it is in the best interest of the force. To create these, the underlying assumptions that focus simply on the *ends* must change to consider the *ways*. Edgar Schein maintains that those assumptions are based on deeper dimensions such as

139. Olson, Mancur. *The Logic of Collective Action: Public Goods and Theory of Groups*, 2nd ed. Cambridge: Harvard University Press, 1971. Olson argued that in a large, or what he called *latent*, organization, rewards and punishment used to incentivize a greater good must be administered at the private level to incur direct costs or consequences associated with a given behavior.

140. Congleton, Roger D. "The Logic of Collective Action and beyond." *Public Choice Online* 164, no 3-4: 219. 2015. https://search-proquest-com.usawc.idm.oclc.org/docview/1727606018?pq-origsite=summon.

141. Gerras, Stephan J., Leonard Wong and Charles D. Allen. "Organizational Culture: Applying a Hybrid Model to the U.S. Army." *US Army War College.* 2008: 6.

reality, truth and human activity.[142] These are the same challenges echoed in climate change debates today.

The youth of the military is a powerful potential source of cultural change. If the younger population as a whole is more environmentally conscious in the United States, it stands to reason that the younger members of the military will be as well. However, the military as a highly hierarchical organization is resistant to the adoption of innovative input from lower ranking and younger individuals.

Army leaders can achieve the necessary cultural change through what Schein calls *embedding* and *reinforcing* mechanisms. "Embedding mechanisms emplace the assumptions into an organization," while "reinforcing mechanisms…support the embedded assumptions."[143] Schein's first embedding mechanism are those things that leaders pay attention to or measure on a regular basis. If Army leaders, for example, rewarded units with the lowest per soldier energy consumption in the barracks, that may create lower energy consumption. To use another embedding mechanism in this example, if the reward was a day room in the barracks outfitted with the latest Xbox or PlayStation, a UHD 70" OLED TV and the fastest Wi-Fi, the soldiers would see the benefit of reduced individual electricity consumption through a reward that they can individually appreciate. Finally, perhaps the most effective embedding mechanism is for Army leaders to put their money where their mouth is. How the Army chooses to allocate future resources will communicate to the soldiers where the real focus lies. Significant increases in the budget for simulations as well as R&D for alternative fuels and energy efficient platforms will help anchor the organizational changes into the long-term culture of the Army.

To support these embedding mechanisms, Schein suggests aligned reinforcing mechanisms, without which "cultural change is much more difficult, if not impossible".[144] The first of these is a change to organizational design or structure necessary to support the cultural change. An example of this might be to decrease future investments in logistical support capacity to match decreased support requirements achieved through increased fuel efficiency. These investments could then be redirected into developing additional combat capacity or capability.

Another important mechanism is the design of physical spaces and buildings. A focus on energy efficient design and renewable energy sources will reinforce a sense of conservation and efficiency. Couple this tactic with formal statements of mission and organizational philosophy that include references to environmental stewardship posted on the ubiquitous unit bulletin boards will support the foundational assumptions put in place by the embedding mechanisms.

The Army is at a crossroads. The current administration may have backed out of the Paris Accords, but the majority of the American people believe that climate change is a threat. Steps taken now can put the Army on a path to lead the nation in preparedness and environmental awareness. At the same time, the Army may come to recognize environmental awareness, not as an add-on, but as a core strategy to ensure the force is leveraging all insights possible for war-fighting and U.S. preparedness. Alternatively, the Army can continue its present trajectories, ignoring the myriad existing and potential threats that result from climate change and environmental concerns more broadly, including alienation of youth, allies and voters on whose largesse it depends, hurtling through the night in the belief that it is as unsinkable as the Titanic.

142. Ibid

143. Gerras, Wong, and Allen, 17.

144. Gerras, Wong, and Allen, 19.

Problem: Potential disruptions to readiness due to restrictions on fuel use.

Recommendation: *The Army must significantly increase investment in more realistic simulation that incorporates the advances in virtual and augmented reality. It should also continue to invest in the development of lower CO2 emissions platforms and systems.*

Implementation Timing: 6-10 years (VR/AR), 10+ years (alternate energy platforms).

Resource Requirements: Moderate to High.

The Army must significantly increase investment in more realistic simulation that incorporates the advances in virtual reality. The current resistance to greater simulation in training is primarily based on a lack of simulation realism.[145] However, the technology to perfectly replicate the sights, sounds, smells and feel of weapons, platforms and situations is developing rapidly. The Army is at risk of being left behind.

This change will impact nearly every facet of Army operations today. Nothing is likely to fully replace field training in the foreseeable future. However, the Army must invest now in developing future capabilities. The required investments cross the entire range of activities, from administration to training to combat.

Currently Army investment in virtual training is primarily based on the Virtual Battle Space (VBS) simulation platform that most of industry has already abandoned in favor of the Unity platform, "the engine of choice among virtual reality developers".[146] The Army is not investing enough in simulations to be agile and change with the industry, or to command industry trends. The 2018 National Defense Authorization Act authorizes nearly $700 billion in military spending for the year, yet industry expects the entire U.S. military to invest only $48.9 billion in simulations through 2025.[147] Greater simulation investment can create overall budget savings. Depending on the airframe, training in flight simulators costs only 5-20% the cost of operating the actual platform.[148] Beyond the environmental impact, increased investment in simulations can result in decreased training costs, longer life for the actual platforms, an increased opportunity for training repetitions and improvements in acquisition through better environments for prototyping and new platform integration.

Finally, the Army's primary platforms, its weapons systems and the vehicles, are not designed for energy and fuel efficiency or to minimize the impact to the environment. Alternative fuel research and new technologies that limit emissions and increase fuel efficiency are expensive. The slow pace of military acquisition ensures that development and integration of these technologies into future platforms will be laborious and incremental. However, if current requirement documents do not reflect an organizational drive to change the environmental footprint of future systems, the Army will remain decades behind the public demands.

145. "Going Virtual to Prepare for a New Era of Defense." *Government Business Council*. 2014. http://cdn.govexec.com/media/gbc/docs/gbc_rc_going_virtual_final.pdf.

146. Tucker, Patrick. "Better Simulation Could Save the Military Millions." *Defense One Online*. 2015. http://www.defenseone.com/technology/2015/01/better-simulation-could-save-military-millions/104172/.

147. "Military Simulation and Virtual Training Market: $15.8B Worth Global Opportunity by 2025." *Cision PR Newswire Online.* 2015. https://www.prnewswire.com/news-releases/military-simulation-and-virtual-training-market-158b-worth-global-opportunity-by-2025-499209471.html.

148. Going Virtual to Prepare for a New Era of Defense." *Government Business Council*. 2014. http://cdn.govexec.com/media/gbc/docs/gbc_rc_going_virtual_final.pdf.

RECOMMENDATION AREA 3: THE JOINT FORCE AND DoD

Problem: Lack of coordination and consolidation in climate-change related intelligence.

Recommendation: *Advocate for a comprehensive organization, functional manager, technology, and process review study to identify the current state of intelligence community agencies with regard to climate change, with the goal of formalizing Interagency coordination on Climate Change-related intelligence.*

Implementation Timing: Now

Resourcing Requirements: Low

To support and improve interagency collaboration in the Intelligence Community (IC), the Office of the Director of National Intelligence (ODNI) should initially assign an office and/or National Intelligence Manager (NIM) with the requisite authority and budget to coordinate and champion climate change endeavors within the IC and greater interagency. This office and/or NIM should manage a comprehensive organization, functional manager, technology, and process review study to identify the current state of IC agencies regarding climate change. Following the completion of the review, an IC-wide Climate Change strategy should be developed.[149]

The IC should dedicate collection, targeting, and analysis resources into monitoring global geo-engineering technologies and state-programs. This area of technology focus and growth is expected to continue globally; this topic, therefore, should be added to the National Intelligence Priorities Framework (NIPF). [150]

The IC should partner with allied nations on the collection and analysis of climate-related intelligence. This partnership should be included in existing partner engagement programs.

The National Intelligence Council should lead and ensure the reoccurring completion of a National Intelligence Estimate or akin intelligence assessment for use across the United States and partner governments, non-governmental organizations (NGOs), industry, and academic institutions. The Defense Intelligence Agency – in coordination with the Department of Defense – should lead and ensure the reoccurring completion of a Defense Intelligence Assessment on climate change drivers that are expected to affect the security environment globally. Both assessments should identify threats and opportunities for the National Security apparatus.

DoD Combatant Command theater and operational plans could be improved by including climate and related systems which affect the security environment into existing processes like, Joint Intelligence Preparation of the Environment (JIPOE), Infectious Disease Risk Assessments, and Country Cooperation Plans.[151] Inclusion of climate change data into existing and complementary intelligence planning processes would improve the Joint Planning Process and meet DoD's statutory requirements.

Initial resourcing for IC expansion to include climate change into existing products and processes is expected to be minimal. IC, DoD and natural science agencies are manned to react to burgeoning national security issues. Sensor improvement that can better collect on climate change and related driver issues can be included in requirement generation for future programs.

In terms of a NIM or like office to champion this issue in the IC, the ODNI may need to provide an initial allotment

149. "Functional Managers." *Office of the Director of National Intelligence: Intelligence Community Directive 113*. 2009. https://www.dni.gov/files/documents/ICD/ICD_113.pdf.

150. "National Intelligence Priorities Framework." *Office of the Director of National Intelligence: Intelligence Community Directive 204*. 2015. https://www.dni.gov/files/documents/ICD/ICD 204 National Intelligence Priorities Framework.pdf.

151. Defense Intelligence Agency, National Center for Medical Intelligence, "Infectious Disease Risk Assessment Methodology," in Annex.

of NIP funds for 2-3 years until programmatic can be determined.

The National Intelligence Council identified climate change and related drivers of instability were identified as a global trend with implications for the national security environment by 2035.[152] The IC and DoD are the responsible government-arms to observe, track, assess, and respond to national security threats that are increasingly emanating from climate change drivers.

While climate change and related drivers are expected to increasing affect and change the global landscape, there is still time. Initial investments in the next 5-10 years will ensure applicable government department and agencies are right fit for the future.

Secretary of Defense Mattis stated, "I agree that the effects of a changing climate – such as increased maritime access to the arctic, rising sea levels, desertification, among others– impact our security situation." To respond to these security implications he then indicated, "It is appropriate for the Combatant Commands to incorporate drivers of instability that impact the security environment in their areas into planning." The Chairman of the Joint Chiefs of Staff, General Joseph Dunford, explained military forces may have to be prepositioned globally to respond to natural disasters and other crises that are as a result of climate change. [153]

In June 2016, CIA Director John Brennan spoke at the Council on Foreign Relations, stating, "An Stratospheric Aerosol Injection (SAI) program could limit global temperature increases, reducing some risks associated with higher temperatures and providing the world economy additional time to transition from fossil fuels. The process is also relatively inexpensive—the National Research Council estimates that a fully deployed SAI program would cost about $10 billion yearly." [154]

The last two National Defense Authorization Acts and Intelligence Authorization Act noted climate change, food system security and stability, and other related issues that affect the IC and DoD's missions. These Congressional acts require the IC and DoD to study, analyze, and identify where these emerging areas affect their mission areas and the security environment.

Problem: Lack of Organizational Accountability for Climate-Change Related Activities

Recommendation: Re-commit to the Senior Energy and Sustainability Council (SESC). Add a resourcing element to the council by providing the USA and VCSA with funding across each POM cycle to support climate-related projects that improve readiness and resiliency of the force.

Implementation Timing: Now, 1-10 Years

Resource Requirements: Low, though potentially moderate through reprogramming.

There are a variety of options for rallying an organization around a mission. For enduring issues, the goal should be to institutionalize the thought. In other words, create a culture where military and civilians regularly consider how their mission could be impacted by climate change. The goal for enduring issues should also be to institutionalize the process, so that the mission does not get disconnected from the normal battle rhythm of a bureaucracy. When a disconnection happens, these missions lose visibility, prioritization, and oftentimes, resourcing.

Climate change will present a challenge to the Army and

152. "Global Trends, Paradox of Progress." *National Intelligence Council.* 2017: 6. https://www.dni.gov/files/documents/nic/GT-Full-Report.pdf.

153. "National Defense Authorization Act for Fiscal Year 2018 – Sec. 335." *115th Congress of the United States of America.* 2017. https://www.congress.gov/115/bills/hr2810/BILLS-115hr2810enr.pdf.

154. "Director Brennan Speaks at the Council on Foreign Relations." *Central Intelligence Agency – News and Information.* 2016. https://www.cia.gov/news-information/speeches-testimony/2016-speeches-testimony/director-brennan-speaks-at-the-council-on-foreign-relations.html.

the DoD for decades to come. With readiness as the number one priority, mitigating the disruption caused by extreme weather activity should be included amongst the Army's goals. The Army must be able to train, fight, and win across all domains and in all environments. To do this will take a collective effort to ensure a wide range of missions are able to support the needs of the force.

Considering the challenges presented by climate change, the Army should re-energize the Senior Energy and Sustainability Council (SESC) within the next six to twelve months. This cross-functional council can address complex, ambiguous problems routinely and ensure its recommendations are integrated across the organization. As the proponent for SESC, ASA IE&E already collaborates as-needed across the enterprise. SESC Council of Colonels level meetings are held periodically, but this is not a decision-making forum. A quarterly meeting at the General Officer Steering Committee (GOSC) and a semi-annual meeting with the Under Secretary of the Army and Vice Chief of Staff of the Army, will signal the importance of the issue, improve its visibility, and provide direction on prioritization of efforts. Policy drives resources, and a senior leader-driven council can shape how the Army operates in what will become one of the Army's future challenges. And for the Secretary of the Army and the Chief of Staff of the Army, the SESC will be their center of gravity for "All Things Climate Change." It will provide them with an organization that will: ensure their priorities are being addressed; oversee what the Army is doing to address climate change; and make strategic decisions about where to invest and take risk.

The Army should also add a resourcing element to the council by providing the USA and VCSA with funding across each POM cycle to support climate-related projects that improve readiness and resiliency of the force. The SESC could champion innovation by having funds available for organizations to compete to have climate-related projects. With an ability to resource projects, the SESC has the ability to make tangible changes on the ground that affect the force and local communities. Although it is difficult to predict when an extreme weather event will occur or how it will affect military operations, the Army must leverage the knowledge and resources it has to build resilience across the force. As retired General Martin Dempsey noted, "[w]e need to act based on the information we have, not remain immobile waiting for 'better options' to emerge."[155] Senior leader involvement will be key in creating a resilient force of the future.

Problem: Lack of Climate Change-Oriented Campaign Planning and Preparation

Recommendation: (A) Develop Bangladesh Relief Campaign Plan as notional plan for preparing for broader climate change-related requirements. (B) Work more closely with the CDC to ensure appropriate military support to infectious disease treatment and containment.

Implementation Timing: Now

Resource Requirement: Low

Bangladesh Crisis Campaign Plan

Climate change is likely to cause an increase in catastrophic climatic events. Some of these events, such as tropical cyclones, will have an acute impact on the affected residents of any given region. Others, such as relative sea level rise and increased desertification, will have a more long-lasting effect. Even acute incidents, given an increasing frequency and severity, may have impacts on the population that are more chronic in effect. The result of these events is likely to manifest itself in increased population migration to escape the destabilization brought on by climate change.

The DoD is unlikely to dedicate significant resources to better preparing the force for humanitarian and disaster response (HADR) missions. However, it should analyze areas where climate change events are likely to exacerbate other political, economic or social issues

155. Dempsey, Martin and Ori Brafman. *Radical Inclusion.* USA: Missionday. 2018: 120.

and where the scale of the potential human migration will tip the balance toward conflict and mass humanitarian strife. In other words, those areas where the United States will be compelled to respond. After an analysis to determine those areas at greatest risks, the Army should develop a campaign plan-like approach to mitigate future risk and to set conditions for a more successful response, if necessary.

The U.S. should immediately initiate a campaign plan to mitigate the effects of future crises and set conditions for more effective assistance. We recommend developing a campaign based on the notional scenario of a massive, permanent dislocation of the population of Bangladesh, rated as the planet's most at risk country from climate change, according to Verisk Maplecroft, a global risk analysis firm.[156] Additionally, Germanwatch, funded by the German Federal Ministry for Economic Cooperation and Development, rates Bangladesh as already the sixth most impacted country from climate events in the last 20 years.[157] Other factors also combine to create an even greater probability that the United States would intervene if a humanitarian disaster struck Bangladesh.

As discussed above, nearly 160 million people live in Bangladesh, nearly half of them at sea level.[158] Sea level rise and alluvial subsidence has resulted in a relative sea level rise for the delta of approximately 1.5 meters since 1960.[159] Both Al-Qaeda and affiliates of ISIS are currently active in Bangladesh.[160] In summary, 80 million people fleeing an uninhabitable portion of their country in what is already one of the most densely populated countries on earth will have nowhere to go. Bangladesh's neighbor, India, is a nuclear armed country persistently in conflict with Pakistan and with which the United States is trying to forge stronger ties to counter Chinese regional influence. These factors will drive U.S. involvement in any crisis.

This approach is not resource intensive but will significantly reduce mission risk. The military, in conjunction with interagency partners such as the State Department and USAID, should immediately establish liaison teams to work closely with the Bangladeshis to understand their plan to deal with internal migration and the resources they have available. After this analysis the U.S. can offer assistance to strengthen the resilience of government agencies and provide training for the Bangladeshi military. The Army Corps of Engineers, in conjunction with multi-national partners, can assist the Bangladeshis in determining what effective steps to take that can slow the effects of relative sea level rise. Through the State Department the U.S. should work with the Indian Government to establish a crisis response team with Bangladesh to help ensure mass migration does not result in conflict. Humanitarian relief supplies should be prepositioned at Diego Garcia to speed the response effort. In addition to interagency efforts, the U.S. should reach out to multi-national partners to determine what kind of coalition can be built to respond to the region, preventing the inefficient and piecemeal collaboration of an ad hoc coalition.

This is just a short list of the many steps the U.S. can take in an area where future intervention is highly likely. Through analysis, the U.S. can determine where, globally, campaign plans should be instituted so that the response efforts are less the execution of a hastily assembled contingency plan and more the sequenced execution of a resourced and ready plan.

156. "Environmental Risk and Climate Change." *Verisk Maplecroft*. 2011. https://www.maplecroft.com/about/news/ccvi.html.

157. Eckstein, David, Vera Kunzel, and Laura Schafer. "Global Climate Risk Index 2018." *Germanwatch: German Federal Ministry for Economic Cooperation and Development.* 2017. https://germanwatch.org/en/download/20432.pdf.

158. Greenfieldboyce, Nell. "Study: 634 Million People at Risk from Rising Seas." *National Public Radio.* 2007. https://www.npr.org/templates/story/story.php?storyId=9162438.

159. Schmidt, Charles W. "Delta Subsidence: An Imminent Threat to Coastal Populations." *Environmental Health Perspectives,* Vol. 123: 8. 2015. https://ehp.niehs.nih.gov/doi/10.1289/ehp.123-A204.

160. "The World Factbook: Bangladesh." *US Central Intelligence Agency*. 2018. https://www.cia.gov/library/publications/the-world-factbook/geos/bg.html.

Infectious Disease Treatment and Containment Support

The research in this report indicates a greater likelihood for outbreaks of vector borne infectious diseases worldwide, including in the United States. The Intergovernmental Panel on Climate Change (IPCC) research using Representative Concentration Pathways (RCP) 4.5 data (the midrange prediction of climate change used throughout this report) predicts areas in the Southeastern U.S. will see an increase in precipitation of .5-.8 mm/day and an increase in average annual temperatures of 1-3 degrees Celsius by 2050.[161] This change will likely allow the proliferation of disease vectors (such as mosquitoes and ticks) over a wider area than they currently inhabit and limit Winter kills of the vectors, resulting in a larger population to spread any diseases. This phenomenon is likely to increase the incidence of diseases such as Zika, West Nile Virus, Lyme disease and many others, some of which may be previously unseen in the U.S. As the largest source of potential capacity and capability to respond to widespread disease outbreaks in the United States, the military should be prepared to execute defense support to civil authority (DSCA) missions of this type.

The Centers for Disease Control (CDC) in Atlanta, Georgia undoubtedly has robust and detailed plans for widespread disease response. The Army, through the DoD, must liaise closely with the CDC and the IC to determine the validity of the plans and the expectations of the military in assisting in the response. Response to disease outbreaks generally follows two tracks, containment and treatment. From a military standpoint, containment of the disease resembles wide area security operations, and treatment is a robust logistics effort. The Army excels at these tasks.

To ensure proactive response, the active force, in support of Reserve Component units, should predetermine locations for key logistics nodes throughout the areas most at risk. These nodes will requires APODs, rail links and robust highway systems to speed the deployment of equipment and materials. Appropriate medical facilities should be identified capable of providing patient isolation and those areas lacking that capability must be identified. Army assets can fill those capability gaps in more remote areas.

Climate change is introducing an increased risk of infectious disease to the U.S. population. It is increasingly not a matter of "if" but of when there will be a large outbreak. The U.S. Army will be called upon to assist in much the same way it was called upon in other disasters. Detailed coordination with local, state and federal agencies in the most high risk regions will hasten response time and minimize risk to mission.

RECOMMENDATION AREA 4: NATIONAL CONTEXT

Problem: Power Grid Vulnerabilities

Recommendation: A. *An inter-agency approach, coupled with collaboration of the commercial sector, should catalogue the liabilities across the electrical grid and prioritize budget requests for infrastructure improvements.* B. *The DoD should pursue options to reverse infrastructure degradation around military installations, including funding internal power generation such as solar/battery farms and small-nuclear reactors.*

Implementation Timing: Now (A); 6-10, 10+ Years (B)

Resource Requirement: Low (A); High (B)

The susceptibilities of the power grid to climate effects should drive the DoD to pursue options to reverse infrastructure degradation around military installations and ensure that cutting edge strategies for decentralized power generation and storage are employed. Contracts with utilities, including rural electric cooperatives now thought to be especially vulnerable, should contain requirements that mandate tougher cyber security

161. "Climate Change 2014 Synthesis Report." *International Panel on Climate Change*. 2015. http://ipcc.ch/report/ar5/syr/.

protocols to limit damage done by the intensive cyber assaults the grid is currently sustaining, and ideally, to preclude further attack to the US electrical grid. This could reduce exposure to fluctuations in the survivability of military capability.[162] The ability to enable safety protocols like Faraday cages would prevent a massive grid failure in the event of a cascading grid collapse allowing for a logical and orderly redistribution of critical power where needed. The development of new options for replacing crucial extra high voltage large power transformers damaged by age and overload will remain essential due to year-long lead times for construction and production of this unique equipment existing outside the country. Additional infrastructure challenges lie in the lack of heavy lift capacity, bridges, and roadways needed to transport these transformers, given each weighing between 200 and 300 tons.[163] The development of a domestic production capability for these large transformers or innovative new, lighter technologies for replacing those systems remain a significant barrier to recovery from a widespread power outage. Distributed technologies that are hardened to cyber-attack, such as solar installations, may reduce several major classes of vulnerability simultaneously.

One option that has met with success stems from the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCTD). The purpose of the test was to improve cyber security around installations, bolster survivability during a blackout using a microgrid and smart grid technology demo and share that knowledge with the non-military services infrastructure supporting the test locations. Successful test results hold promise for investment on military installations across the DoD, as well as sharing with vital services supplying the military and the community. Adoption of this concept generates the possibly for integration of renewable, like micro-nuclear reactors, and other distributed energy generation concepts to increase endurance during a natural or man-made widespread outage of the power grid.[164] Addition of a SPIDERS infrastructure extends beyond military installations and local communities as cyber security improvements could also lead to protection of uplink and downlink stations thus improving resilience of space borne assets from infection.

The results of the SPIDERS JCTD highlight the importance of infrastructure investment and decisions at DoD facilities while reducing the unacceptably high risk of an extended outage of the power grid. The original SPIDERS initiative launched under the co-sponsorship of the DoD, Department of Energy (DOE), and Department of Homeland Security (DHS) and demonstrated the survivability of an installation protected by a cyber secure micro-grid, smart grid technologies and investment in infrastructure modifications. The SPIDERS technology delivered capabilities tied to power generation reliability, installation and cyber security, reduction of energy costs while being cost effective, and minimizing environmental impacts, all goals the DoD seeks to achieve.[165]

The Joint Staff can further signal their support to Congress by addressing this need through use of the Joint Risk Assessment Framework to develop a prioritized list of critical DoD infrastructure necessary to defend the homeland and execute Joint Strategic Capabilities Plan-directed contingency operations. Upon completion of this list and with SPIDERS funding approval, each affected Service can execute necessary activities to harden their networks, infrastructure, and power generation capabilities thus protecting military installations from cyber, physical, or coordinated attacks; electromagnetic

162. Mehta, Aaron. "Pentagon Weighs New Requirements to Secure Military's Vulnerable Power Grid. " *Defense News Online*. 2017. https://www.defensenews.com/pentagon/2017/11/29/pentagon-weighs-new-requirements-to-secure-militarys-vulnerable-power-grid/?utm_source=Sailthru&utm_medium=email&utm_campaign=EBB 11.30.17&utm_term=Editorial - Early Bird Brief.

163. Koppel, Ted. *Lights Out: A Cyberattack, a Nation Unprepared, Surviving the Aftermath*. New York, NY: Crown Publishers, 2015: 95-100.

164. "Technology Transition Final Public Report: Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS)." *Naval Facilities Engineering Command*. 2015. https://energy.gov/sites/prod/files/2016/03/f30/spiders_final_report.pdf.

165. Ibid.

pulse attacks; space weather; and other natural events.

The SPIDERS implementation across the Services promises to lessen the impacts of a U.S. power grid loss while hardening cyber protections to critical response capabilities. The NORTHCOM and PACOM Combatant Commands, Congress, and the Services' working together in support of this critical initiative enable a change in prioritization of infrastructure security, often overlooked, within the defense budget. The cost is such that, with the proper advocacy, a key vulnerability to the homeland defense mission becomes manageable and the Department of Defense priority of protecting the homeland is realized.

Problem: Climate Change and Threats to Nuclear Weapons Infrastructure

Recommendation: The U.S. Department of Defense, in combination with the U.S. Department of Energy (DOE) should develop a long term 15 to 20 year tritium production plan that accounts for advances in nuclear technology and the possibility of rising climate induced water levels as well as increases to the overall average water temperature used to cool nuclear reactors. This plan should include projections of fiscal resources and military tritium requirements needed to maintain and modernize the U.S. nuclear stockpile. It should also include U.S. government requirements for use of helium-3, a decay product of tritium used primarily for neutron detection when searching for special nuclear material (SNM) and enforcing nuclear non-proliferation agreements.

Implementation Timing: Now to 10+ Years

Resource Requirement: High

The U.S. Department of Defense (DoD) in combination with the U.S. Department of Energy (DOE) should develop a long term 15 to 20-year tritium production plan that accounts for advances in nuclear technology and the possibility of rising climate induced water levels as well as increases to the overall average water temperature used to cool nuclear reactors. This plan should include projections of fiscal resources and military tritium requirements needed to maintain and modernize the U.S. nuclear stockpile. It should also include U.S. government requirements for use of helium-3, a decay product of tritium used primarily for neutron detection when searching for special nuclear material (SNM) and enforcing nuclear non-proliferation agreements.[166]

Currently, the Department of Energy conducts tritium production using 2 to 4 commercial nuclear pressurized water reactors (PWRs) run by the Tennessee Valley Authority (TVA).[167] This commercial capability currently meets the U.S. stockpile tritium production capability; however, due to the overall age of the U.S. nuclear power industry, future PWRs may not be available to continue tritium production.[168] The loss of tritium production directly reduces the effectiveness of the U.S. nuclear stockpile by reducing or hindering the overall yield produced by the nuclear warheads. Without an effective U.S. nuclear stockpile, the U.S. cannot deter peer nuclear competitors and rogue nuclear states increasing the risk to all-out war against the United States.[169]

Directly tied to tritium production is the future of the nuclear power industry. It is filled with an aging fleet of reactors built in the late 1960s and 1970s. Most receive a commercial license by the Nuclear Regulatory Commission (NRC) to operate on average 30 years, but many have or are seeking extensions to increase the operations out to 40 and 50 years.[170] The age of the industry

166. Special Nuclear Material (SNM) refers to fissile nuclear material such as uranium 235 or plutonium 239 that is used as fuel in nuclear weapons.

167. *NNSA Expanding Tritium Production at TVA Reactors*. Vol. 245 Access Intelligence, LLC, 2010.

168. Horner, Daniel, "GAO Finds Problems in Tritium Production." *Arms Control Association.* 2010. https://www.armscontrol.org/act/2010_11/GAOTritium.

169. Schelling, Thomas C. *Arms and Influence.* New Haven: Yale University Press, 1966: 22-23.

170. Lester, Richard K. "A Roadmap for U.S. Nuclear Energy Innovation." *Issues in Science and Technology* 32, no. 2:45-54. 2016.

and the lack of new reactors coming on-line creates a significant risk to both the environment and the maintenance of the U.S. nuclear stockpile. "The highest priority of nuclear innovation policy should be to promote the availability of an advanced nuclear power system 15 to 20 years from now".[171]

Nuclear reactors produce far less atmospheric pollution than fossil fuels and radioactive waste can be minimized and managed accordingly. Reducing carbon monoxide emissions in the near future must include a replacement of the underlying nuclear power production capability in this country. Increasing the underlying U.S. baseline nuclear power generation capability from a mere 20% (and declining) to more than 80% (to cover the 60% coal production capability that currently exists) can significantly reduce greenhouse gases.[172] The government will need to lead this expansion which goes against the fossil fuel business paradigms that have existed for more than 100 years. Any nuclear industry expansion must include a long term review of tritium production requirements and analyze how the government will maintain its required tritium production capability.

The production of tritium directly effects the production of helium-3. Tritium has a half-life of 12.3 years. This means that if you have 10 liters of tritium, 12.3 years later you will only have 5 liters. Every time you hit a half-life milestone (every 12.3 years) the volume of tritium available drops in half. After about 7 half-lives, tritium has decayed away to trace amounts. This affects the amount of tritium needed in our existing nuclear stockpile and will not decrease over the next 50 to 75 years.

An added benefit to tritium decay is the production of helium-3. This direct byproduct currently supports the non-proliferation efforts of nuclear inspectors conducting treaty verification, Special Forces conducting critical lost or stolen SNM search missions, and the U.S. Army's Chemical, Nuclear, Radiological, and Nuclear (CBRN) Response forces conducting troop health and safety sweeps at suspect nuclear and industrial facilities or identifying the detection of SNM at suspect nuclear weapon production facilities. The Defense Threat Reduction Agency currently has research efforts looking at replacing helium-3 as a detection gas since its availability in the future may come into question. The risk to these programs remains high over the next 5 to 7 years until newer viable research methods reveal stable and reliable neutron detection methods for use by the Army's Special Forces and CBRN response forces in the field. The long-term outcome for neutron detection capability remains low due to these new technologies.

Any expansion of nuclear power should also take into account the stability of tritium production to maintain U.S. national security through a strong nuclear deterrence. The DoD, especially the Army, must consider the consequences if the U.S. nuclear stockpile can no longer maintain its effectiveness. Without an effective strategic nuclear deterrent, the risk of conventional conflict will increase.

The strategic nuclear force is the backbone of U.S. national defense. This is the last-ditch defensive capability designed to keep rational peer adversaries out of the U.S. homeland and out of direct conflict with U.S. military forces. Any erosion of this force or its value in present or future conflict mandates the need to identify alternative deterrence mechanisms at scale. The Army will need to compensate with adding more soldiers or robotic capabilities because countries may try to engage the U.S. more frequently in sub-kinetic or hybrid compelling and coercive actions to halt or dissuade U.S. foreign and national security policy motives around the world. The force may falter under the diversity of threats, with the potential for increased local escalation as a result of other peer competitors. A strong Army must compensate for such actions since it will be called on to hold ground, interact with populations (civilian and military), and advance and take positions to shut down enemy actions. The loss of an effective nuclear capability could overtask the U.S. Army and possibly bankrupt the coun-

https://issues.org/a-roadmap-for-u-s-nuclear-energy-innovation/.

171. Lester, 48.

172. Lester, 50.

try in an attempt to maintain U.S. post-Cold War hegemony.

The Army should support the DoD efforts to maintain and replace tritium production levels, especially in any future climate efforts that may change the availability of nuclear power generation in the commercial sector that ultimately effects the effectiveness of the nuclear stockpile.

The Army can achieve this through the Nuclear Weapon Council (a joint DoD and DOE senior decision committee focused on nuclear weapon matters) under the Nuclear Weapon Council Standing and Safety Committee (NWCSSC) (See Title 10 of U.S. Code section 179 for summary of the NWC).[173] Currently, the Army has a position on the NWCSSC to help review safety, military requirements, and future needs of the nuclear stockpile. The NWCSSC sends its recommendations to the NWC for approval. The Army should maintain an active role on the committee and start pushing for development of a long term 15 to 20 year plan for maintaining tritium production requirements. The Army should consider the consequences to the size and technological makeup of its forces if tritium production changes and reduces overall nuclear stockpile effectiveness. The United States government's ability to deter and dissuade must remain a number one priority in order for the U.S. to continue to push and achieve its national objectives of peace, prosperity, and open market competition for the benefit of the American people.[174] Without a credible strategic nuclear force, the Army and the DoD risks future long term conflicts requiring extensive resources in manpower and equipment.

173. "10 U.S. Code § 179 - Nuclear Weapons Council." *Legal Information Institute, Cornell Law School.* No date. https://www.law.cornell.edu/uscode/text/10/179.

174. Mattis, Jim. "Secretary's Preface," in *Nuclear Posture Review. US Department of Defense, Office of the Secretary of Defense*. 2018: I-III. https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF.

RECOMMENDATION DISCUSSION: ASSESSED AS REQUIRING NO ACTION

Problem: Port Access Challenges Due to Rising Seas

Recommendation: No action – Continue to Monitor.

Large-scale Army deployments overseas require access to ports in the continental United States. While rising seas are a near-term concern for some ports and shipyards, our research indicated that the major trans-shipping areas used by the U.S. Army are insensitive to the mid-range predictions for sea-level rise and would remain accessible to the Army in those scenarios.

Conclusion

The implications of significant, global, regional and local change produced by a general warming of the Earth's climate are far too extensive to be addressed by this study. Therefore, the guiding principle of this study was to explore diverse areas of importance for the Army that are or will be likely affected by climate change and to develop reasonable, useful recommendations in connection with those areas. A larger and perhaps even more urgent lesson from this study is the importance of developing regular administrative and institutional structures and processes that allow the Army and the DoD to detect, evaluate, respond and regularly review the implications of systemic risk relevant to the Army's missions and preparedness. Large scale threats like climate change and mass migrations are systemic risks, with emergent features not captured by the simple summation of threat-by-threat-by-threat assessments. The Army must find governance mechanisms that generate greater flexibility, without risk of compromise to the integrity of the force, to deal with the various significant stresses on the Army inherent to a warming climate. These stresses are occurring for military and civilian institutions alike against the backdrop of exponential changes in technology, human population, resource consumption, urbanization, sea level rise, etc.

It is useful to remind ourselves regularly of the capacity of human beings to persist in stupid beliefs in the face of significant, contradictory evidence.[175] Mitigation of new large-scale stresses requires a commitment to learning, systematically, about what is happening.

On 22 June, 1941, the Third Reich launched *Operation Barbarossa*, a massive invasion of the Soviet Union. The assault, named after the red-bearded ("barba rossa" in Italian) German crusader and emperor Frederick I, involved over 3.5 million Axis troops, killed millions, and almost destroyed the Soviet Union. Although the attack is sometimes called a "surprise," this is misleading. It is more accurate to say that *Barbarossa* surprised the one person who could not afford to be: Josef Stalin. How could a military operation involving about 150 *divisions* have found its political target so unprepared?

Life is full of the unexpected, or the overlooked obvious. The term "black swan event" describes surprises of an especially momentous and nasty type. Popularized by the mathematician Nicholas Nassim Taleb in his 2007 book of the same title, Taleb argued that black swan events have three characteristics: "rarity, extreme impact, and retrospective (though not prospective) predictability."[176] In recent years, the concept of black swan events has gained currency in political, military, and financial contexts.

The black swan has a venerable history as an illustration of the ancient epistemological problem of induction: simply stated, no number of observations of a given relationship are sufficient to prove that a different relationship cannot occur. No amount of white swan sightings can guarantee that a different color swan is not out there waiting to be seen. The discovery of black swans by European explorers in Australia has proven too tempting to ignore as a powerful metaphor for the problem of induction.

However, in emphasizing the importance of anticipation, Taleb's concept of the black swan ignores key facts about history and how it is understood by those who live it. Two characteristics of the strategic environment epitomize this problem.

175. This section adapted from Hill, Andrew: "Red Beard, Black Swan: Recognizing the Unexpected." *US Army War College, War Room.* 2017. https://warroom.armywarcollege.edu/articles/black_swan_red_beard/.

176. Taleb, Nicholas Nassim. *The Black Swan*: *The Impact of Highly Improbable Fragility.* New York: Random House, 2007: xxii.

First, the list of things that can happen but have not happened yet is long. It is, in fact, infinitely long. For each thing that exists (e.g., cats) we can come up with more variations that do not, to our knowledge, exist (flying cats, cats with gills, six-legged cats, and so on). It is fun to think about all the cataclysmic, history-altering events that might happen, but thinking about those things in a way that appropriately organizes them and informs strategy is extremely hard. That said, techniques used in Systems Thinking, when applied to this concern, often reveal relatively obvious blind spots that obscure even high impact, high likelihood events. The Chinese focus on building universities, programs and initiatives focused on Systems Thinking over the past 20 years, and the inclusion of this curriculum in the training cadets destined to lead China in the future should be notable, as it is may be the basis of large asymmetries with broad implications for the U.S. Army, the U.S. IC, the DoD, and allies.

Second, events that present as tremendous shocks have often taken months, years, or even longer periods to emerge. In the time between weak signals of change and the onset of a deeper crisis, there are often opportunities to prepare and adapt. These opportunities may be much more readily apparent if important "emergent properties" of major concern to the force, especially those resulting in threat that is orthogonal to force strength, are systematically characterized.

The real challenge with black swan events is not accurate anticipation, but timely recognition. While it can be useful to imagine what *might* happen, we should focus more on recognizing what *is* happening as quickly as possible and limiting the damage through timely learning.

The black plague took half a decade to advance from Sicily to the Baltic states. More recently, the 2008 financial crisis is already remembered as a "shock" event that surprised global finance.[177,178] However, the truth is more nuanced, and depressing. Notable observers of the system (including Dr. Taleb) recognized serious problems long before the fall of Lehman Brothers in September, 2008 (and the onset of a full-blown banking crisis).[179,180] Yet this was mostly recognition, not prediction. The clearest early signal of big trouble in the mortgage market came in the March-April, 2007 collapse of New Century Financial, an originator of risky mortgages, almost a year and a half before Lehman's end, and a year before Bear Stearns was rolled up.[181,182] What happened in the meantime? In *All the Devils Are Here*, Bethany McLean and Joe Nocera describe two embattled Bear Stearns asset managers who provide a microcosm of the wishful thinking that made the crisis much worse than it needed to be. In the face of mounting evidence that their investment strategy is failing, "the two men simply couldn't bring themselves to believe that the picture was as dire as the model suggested."[183]

When the facts do not match our strong theories for how the world works, we prefer to change the facts. How can we more quickly recognize the unexpected for what it really is?

177. Srivastava, Spriha. "On this day 8 years ago, Lehman Brothers collapsed: Have we learned anything?" *CNBC.* 2016. http://www.cnbc.com/2016/09/15/on-this-day-8-years-ago-lehman-brothers-collapsed-have-we-learned-anything.html

178. "Crash course: The origins of the financial crisis." *The Economist.* 2013. http://www.economist.com/news/schoolsbrief/21584534-effects-financial-crisis-are-still-being-felt-five-years-article.

179. Cox, Jeff. "Best and worst predictions of the past 25 years." *CNBC.* 2014. http://www.cnbc.com/2014/07/01/best-and-worst-predictions-of-the-past-25-years.html.

180. "The collapse of Lehman Brothers." *The Telegraph.* Accessed August 29, 2018. http://www.telegraph.co.uk/finance/financialcrisis/6173145/The-collapse-of-Lehman-Brothers.html.

181. "New Century files for Chapter 11 bankruptcy." *CNN Money.* 2007. http://money.cnn.com/2007/04/02/news/companies/new_century_bankruptcy/.

182. "Bearing all: The fall of Bear Stearns." *The Economist.* 2009. http://www.economist.com/node/13226308.

183. MacLean, Bethany and Joe Nocera. *All the Devils Are Here: The Hidden History of the Financial Crisis.* New York: Penguin, 2011.

In Frank Tashlin's classic children's book, *The Bear That Wasn't*, a bear awakes from hibernation and, exiting his cave, finds himself in a huge factory that has been built over his forest home. Encountering a foreman, the bear is told to get back to work, to which the bear replies, "I don't work here. I'm a bear." Incredulous, the foreman says, "You're not a bear. You are just a silly man who needs a shave and wears a fur coat."

Aside from its entertainment value, *the Bear that Wasn't* provides a humorous example of a profound philosophical problem: When the facts do not match our strong theories for how the world works, we prefer to change the facts. How can we more quickly recognize the unexpected for what it really is? The foreman (along with various executives that the bear meets) has a simple belief: *No bears are in factories.*

If we have a theory of factories that says (among other things), "No bears are in factories," the theory is based on our experiences observing who is in a factory (i.e., human workers). It is an *inductive* theory: every observation to date has been of human workers. We could not arrive at such a theory independent of our accumulated experience. In addition, the more workers we see, the more certain we become (in terms of probability) that all workers are human (and none are bears), but we will never, ever observe every possibility.

Although we should not make the unjustified leap from making a probabilistic statement based on induction to a universal statement based on deduction, we often do it anyway. Our beliefs then shape how we treat the evidence. For example, prior to seeing a non-white swan, we develop the following syllogism:

1. Major Premise: All swans are white.
2. Minor Premise: That bird is a swan.
3. Conclusion: That bird is white.

When we see a black swan, if we are unemotional, Spock-like empiricists, we will immediately recognize that "if swan, then white" is false. That is, we will know that our conclusion, "that bird is white," is false based on observation that the bird is black *and* a swan. Finding ourselves in a situation in which we believe that our premises are true but our conclusion is false, and therefore *not* entailed by the premises, we will conclude that our major premise must not be true, and therefore reject it.

Here is where human experience departs from the clean abstractions of logic. We are not Spock. We have emotional attachments to our beliefs. This is as true of attitudes towards a changing climate as it was of attitudes towards the financial crisis.

Three maxims can help us avoid dangerous failures of recognition, and speed learning when unexpected things happen.

1. Everything we believe about the world is provisional – "serving for the time being." Adding the words "so far" to assertions about reality reminds us of this.

2. Unjustified certainty is very costly. The greater your certainty that you are right when you are wrong, the longer it will take you to recognize and incorporate new data into your system of belief, and to change your mind. General Douglas MacArthur was a confident man, and this confidence usually served him well, such as when he undertook the risky landings at Incheon in the Korean War. Yet MacArthur's confidence betrayed him when China entered the war. He was certain that this would not happen, and MacArthur's certainty delayed his recognition of a key change, exposing forces under his command to terrible risk. Confidence in your beliefs is valuable only insofar as it results in different choices (e.g., I choose A or B). Beyond that point, confidence has increasing costs.

3. Pay special attention to data that is unlikely *in light of your current beliefs*; it has much more information per unit, all else equal. In this sense, information content is measured as the potential to change how you think about the world. Infor-

> mation that is probable in light of your beliefs will have minimal effects on your understanding. Improbable information, if incorporated, will change it.

It is doubtless correct that many awful things that have not happened before will yet happen. Foresight regarding such events would be nice. It would be nicer still if we could recognize more quickly what is happening right in front of us. That is the right starting point for thinking strategically about the warming climate.

Appendix: Weather Control

Weather control is a fascinating and worrying potential technology. If used in with intentionally nefarious intent, its effects could be catastrophic. It is not exactly climate change in the sense that we define it here, but it brings many of the problems of climate change, with the prospect of these problems arising at the time and place of an adversary's choosing.

Naturally occurring terrestrial and space weather events constitute only one set of challenges to national security. The concept of weaponizing the natural environment is nothing new. Congressional testimony dating back to the early 1950s recommends approval of research and development funding for weather modification experimentation. This in response to concerns Russia was beating us in learning how to control the weather and the potential threat that posed to the United States.[184] The United States has already demonstrated the potential to modify the weather in support of combat operations through its efforts in Vietnam. United States' cloudseeding techniques used aircraft to disperse lead iodide into the atmosphere above portions of Southeast Asia to create a super-saturated environment during the Vietnamese monsoon season. The increased precipitation produced significant degradation of Vietnamese logistic capabilities as vehicles, carts, and men remained bogged down on certain roadways and paths soaked by nearly continuous rainfall.[185]

Much like the United States, potential rivals already possess the capability to artificially manufacture effects that manipulate the terrestrial and space weather environment. An example is the superheating of the ionosphere through directed-energy generation. This capability has the potential to disrupt communications, limit capabilities of missile defense or other monitoring radars, and contaminate the ionosphere to such a degree as to prevent use of U.S. space or missile defense systems. Normally these ionospheric scintillation experiments, like those performed at the High Frequency Active Auroral Research Program (HAARP) in Alaska, are benign in nature and used for purely scientific research purposes. However, the U.S. Air Force, U.S. Navy, and the Defense Advanced Research Projects Agency (DARPA) originally developed, designed and operated HAARP as a joint project to perform experiments that manipulate and potentially control the ionosphere to enhance Department of Defense (DoD) command, control and communications capabilities. Experiments ranged from extremely low-frequency waves for submarine communications to over-the-horizon-radar enhancement and even super scintillation events to disrupt or disable space assets in low Earth orbit. The HAARP program transferred to the University of Alaska for educational research after the DoD successfully accomplished their original experimental goals and determined to cut costs by terminating the experiments and HAARP facility.[186]

However, the United States is not the sole possessor of a HAARP-like capability. Partner nations, such as Japan and Norway, operate their own antenna farms, as do Russia and China.[187] The use of ionospheric sounders operated by the Air Force make it possible to monitor

184. "Prohibiting *Hostile Use of Environmental Modification Techniques," in Multinational Corporations and United States Foreign Policy: Hearings Before the Subcommittee on Multinational Corporations of the Committee on Foreign Relations*, vol. 3, parts 15-17: 36-37. U.S. Senate Committee on Foreign Relations, Subcommittee on Multinational Corporations: 94th Cong., 2nd sess. 1976.

185. "Weather Modification." *U.S. Senate Subcommittee on Oceans and International Environment of the Committee on Foreign Relations*, 93rd Cong., 2nd sess., March 20, 1974:88-93. https://www.vietnam.ttu.edu/star/images/239/2390601002C.pdf.

186. National Research Council. *Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research: Report of a Workshop.* Washington, DC: The National Academies Press. 2014: 1,3.

187. National Research Council, 18-19.

when manipulations of the ionosphere occur, so it would be difficult to heat the ionosphere without anyone's knowledge. However, the current distribution of these ionospheric sounders leaves large gaps in coverage exposing them to possible exploitation by an adversary.

Still another artificially induced weather effect manifests through the use of a nuclear detonation to induce an artificial radiation belt. The consequences of such an event would produce significant and far-reaching impacts to U.S. national security. First, the electromagnetic pulse generated during the initial explosion mimics the disastrous costs produced by a Coronal Mass Ejection (CME) induced geomagnetic storm. The United States would witness widespread power grid outages, loss of communication and navigation capabilities, plus long-term modification to the space environment. Damage to space assets in various satellite orbits would vary depending on detonation altitude and a loss of asset capability expected. These concerns do not spring from speculation. On July 9, 1962, the United States exploded the STARFISH PRIME nuclear device in the low Earth orbit at around 400 kilometers. Only 24 satellites were in orbit during the time of this test and subsequent tests that followed, but eight satellites suffered immediate damage during the tests while still others demonstrated shortened life spans from the artificially induced radiation belts. This nuclear testing also impacted communications and changed the space operating environment for decades to follow.[188]

A similar detonation in today's congested space environment promises significantly worse outcomes. According to the Union of Concerned Scientists website, the space environment hosts over 1,738 known satellites as of August, 2017. No country has more to lose than the United States if a space-based nuclear detonation occurred. Leading all nations at 803 satellites, the United States has over 476 commercial, 150 governmental (with an additional 159 military), and 18 civil satellites on orbit at various altitudes above the Earth.[189] While other nations would feel the effects of such an event, they are less likely to feel the level of national security implications when compared to the United States. Concerns over North Korean intentions during recent tests of their growing nuclear capability raise this to a very real threat. There is evidence that North Korea reached back to the early experiments of the United States and the Soviet Union during the late 50s and early 60s to gain insights on their own nuclear program. An atmospheric or space-based test of a North Korean nuclear weapon, designed to demonstrate national power or will on the international stage, would generate substantial disadvantages to U.S. national security as losses of space capability occur across a wide range of possible platforms.[190]

Numerous additional examples exist that demonstrate the ability to manipulate the natural environment as an instrument of national power. Commonly referred to as Geoengineering, it is defined by the Intergovernmental Panel on Climate Change as "a broad set of methods and technologies that aim to deliberately alter the climate system to alleviate impacts of climate change."[191] However, many of the geoengineering experiments currently underway to combat climate change possess the dual-use potential for weaponization of the natural environment. A report on Chinese efforts in the arena of solar geoengineering call for a variety of terrestrial or space-based options to combat CO_2 concentrations. The various methods discussed could change the physical, chemical or biological characteristics of the Earth's climate system. While some of these options

188. Conrad, Edward E. *et al*. "Collateral Damage to Satellites from an EMP Attack." *Defense Threat Reduction Agency.* 2010: 11-15. https://apps.dtic.mil/dtic/tr/fulltext/u2/a531197.pdf.

189. "UCS Satellite Database." *Union of Concerned Scientists.* 2017. http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database.

190. Sanger, David E. and William J. Broad. "Prospect of Atmospheric Nuclear Test by North Korea Raises Specter of Danger." *The New York Times*. 2017. https://www.nytimes.com/2017/09/22/world/asia/north-korea-atmospheric-nuclear-test-risks.html.

191. "Climate Change 2014 Synthesis Report: Summary for Policy Makers." *Intergovernmental Panel on Climate Change.* 2014:89. https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf.

may reduce greenhouse gas concentrations, they may also potentially create negative effects to an environment where one did not exist previously.[192]

A report examining the United States' history in geoengineering reveals very similar possibilities. A National Center for Atmospheric Research, and Environmental Studies Program explored U.S. weather modification exertions back to 1947 and found a reactionary, checkered past. In developing science and technology options, along with the accompanying legislation, weather modification ran the gamut of beneficial and detrimental outcomes across society. The study recommends any plans using geoengineering in climate change mitigation would benefit from a guiding framework of rules and regulations. It further endorses the establishment of a centralizing U.S. federal weather modification governing body to provide proper stewardship of the environment during any experimental development or actual implementation.[193] Anything less could lead to a broad range of potential environmental, technical, political, and ethical issues.

These very concerns culminated in the United Nations General Assembly holding the Convention on the Prohibition of Military or any Hostile Use of Environmental Modification Techniques (ENMOD) of 1976. The ENMOD Convention was the tool used to capture the spirit of international disarmament law explicitly envisioned to keep the manipulation of the environment out of the armed conflict arsenal. An additional protocol added a further ban on the use of methods and means of warfare that purposefully and excessively damage the environment. The overall language bans the hostile use of the natural environment to wage war and went into force as of October, 1978. The United States, along with 77 other nations, have ratified the treaty and agreed to live by its restrictions.[194] A decision to weaponize weather in the future would carry with it an almost certain international condemnation for any nation willing to undertake the effort. If someone could prove who did it.

192. Cao, Long, Chao-Chao Gao and Li-Yun Zhao. "Geoengineering: Basic Science and Ongoing Research Efforts in China." *Advances in Climate Change Research*, vol 6: 188-196. 2015. https://www.sciencedirect.com/science/article/pii/S1674927815000829.

193. Hauser, Rachel. "Using Twentieth-Century U.S. Weather Modification Policy to Gain Insight into Global Climate Remediation Governance Issues." *Weather, Climate and Society*, vol. 5: 180-191. 2013. https://journals.ametsoc.org/doi/pdf/10.1175/WCAS-D-11-00011.1.

194. "1976 Convention on the Prohibition of Military or any Hostile Use of Environmental Modification Techniques." *International Committee of the Red Cross, Advisory Service on International Humanitarian Law*. 2003. https://www.icrc.org/en/document/1976-convention-prohibition-military-or-any-hostile-use-environmental-modification.

EXHIBIT 4

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL085378

Evaluating the Performance of Past Climate Model Projections

Zeke Hausfather[1], **Henri F. Drake**[2,3], **Tristan Abbott**[3], **and Gavin A. Schmidt**[4]

[1]Energy and Resources Group, University of California, Berkeley, CA, USA, [2]Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography, Woods Hole, MA, USA, [3]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [4]NASA Goddard Institute for Space Studies, Broadway, NY, USA

Key Points:
- Evaluation of uninitialized multidecadal climate model future projection performance provides a concrete test of model skill
- The quasi-linear relationship between model/observed forcings and temperature change is used to control for errors in projected forcing
- Model simulations published between 1970 and 2007 were skillful in projecting future global mean surface warming

Supporting Information:
- Supporting Information S1

Correspondence to:
Z. Hausfather,
hausfath@gmail.com

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Abstract Retrospectively comparing future model projections to observations provides a robust and independent test of model skill. Here we analyze the performance of climate models published between 1970 and 2007 in projecting future global mean surface temperature (GMST) changes. Models are compared to observations based on both the change in GMST over time and the change in GMST over the change in external forcing. The latter approach accounts for mismatches in model forcings, a potential source of error in model projections independent of the accuracy of model physics. We find that climate models published over the past five decades were skillful in predicting subsequent GMST changes, with most models examined showing warming consistent with observations, particularly when mismatches between model-projected and observationally estimated forcings were taken into account.

Plain Language Summary Climate models provide an important way to understand future changes in the Earth's climate. In this paper we undertake a thorough evaluation of the performance of various climate models published between the early 1970s and the late 2000s. Specifically, we look at how well models project global warming in the years after they were published by comparing them to observed temperature changes. Model projections rely on two things to accurately match observations: accurate modeling of climate physics and accurate assumptions around future emissions of CO_2 and other factors affecting the climate. The best physics-based model will still be inaccurate if it is driven by future changes in emissions that differ from reality. To account for this, we look at how the relationship between temperature and atmospheric CO_2 (and other climate drivers) differs between models and observations. We find that climate models published over the past five decades were generally quite accurate in predicting global warming in the years after publication, particularly when accounting for differences between modeled and actual changes in atmospheric CO_2 and other climate drivers. This research should help resolve public confusion around the performance of past climate modeling efforts and increases our confidence that models are accurately projecting global warming.

1. Introduction

Physics-based models provide an important tool to assess changes in the Earth's climate due to external forcing and internal variability (e.g., Arrhenius, 1896; IPCC, 2013). However, evaluating the performance of these models can be challenging. While models are commonly evaluated by comparing "hindcasts" of prior climate variables to historical observations, the development of hindcast simulations is not always independent from the tuning of parameters that govern unresolved physics (Gettelman et al., 2019; Mauritsen et al., 2019; Schmidt et al., 2017). There has been relatively little work evaluating the performance of climate model projections over their future projection period (referred to hereafter as model projections), as much of the research tends to focus on the latest generation of modeling results (Eyring et al., 2019).

Many different sets of climate projections have been produced over the past several decades. The first time series projections of future temperatures were computed using simple energy balance models in the early 1970s, most of which were solely constrained by a projected external forcing time series (originally, CO_2 concentrations) and an estimate of equilibrium climate sensitivity from single-column radiative-convective equilibrium models (e.g., Manabe & Wetherald, 1967) or general circulation models (e.g., Manabe & Wetherald, 1975). Simple energy balance models have since been gradually sidelined in favor of

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increasingly high resolution and comprehensive general circulation models, which were first published in the late 1980s (e.g., Hansen et al., 1988; IPCC, 2013; Stouffer et al., 1989).

Climate model projections are usefully thought about as predictions conditional upon a specific forcing scenario. We consider these to be projections of possible future outcomes when the intent was to use a realistic forcing scenario and where the realized forcings were qualitatively similar to the projection forcings. Evaluating model projections against observations subsequent to model development provides a test of model skill, and successful projections can concretely add confidence in the process of making projections for the future. However, evaluating future projection performance requires a sufficient period of time post-publication for the forced signal present in the model projections to be differentiable from the noise of natural variability (Hansen et al., 1988; Hawkins & Sutton, 2012).

Researchers have previously evaluated prior model projections from the Hansen et al. (1988) National Aeronautics and Space Administration Goddard Institute for Space Studies model (Hargreaves, 2010; Rahmstorf et al., 2007), the Stouffer et al. (1989) Geophysical Fluid Dynamics Laboratory model (Stouffer & Manabe, 2017), the IPCC First Assessment Report (FAR-IPCC, 1990; Frame & Stone, 2012), and the IPCC Third and Fourth Assessment reports (IPCC, 2001; IPCC, 2007; Rahmstorf et al., 2012). However, to-date there has been no systematic review of the performance of past climate models, despite the availability of warming projections starting in 1970.

This paper analyzes projections of global mean surface temperature (GMST) change, one of the most visible climate model outputs, from several generations of past models. GMST plays a large role in determining climate impacts, is tied directly to international-agreed-upon mitigation targets, and is one of the climate variables that has the most accurate and longest observational records. GMST is also the output most commonly available for many early climate models run in the 1970s and 1980s.

Two primary factors influence the long-term performance of model GMST projections: (1) the accuracy of the model physics, including the sensitivity of the climate to external forcings and the resolution or parameterization of various physical processes such as heat uptake by the deep ocean and (2) the accuracy of projected changes in external forcing due to greenhouse gases and aerosols, as well as natural forcing such as solar or volcanic forcing.

While climate models should be evaluated based on the accuracy of model physics formulations, climate modelers cannot be expected to accurately project future emissions and associated changes in external forcings, which depend on human behavior, technological change, and economic and population growth. Climate modelers often bypass the task of deterministically predicting future emissions by instead projecting a range of forcing trajectories representative of several plausible futures bracketed by marginally plausible extremes. For example, Hansen et al., 1988 consider a low-emissions extreme Scenario C with "more drastic curtailment of emissions than has generally been imagined," a high-emissions extreme Scenario A wherein emissions "must eventually be on the high side of reality," as well as a middle-ground Scenario B, which "is perhaps the most plausible of the three." More recently, the Representative Concentration Pathways (RCPs) used in CMIP5 and the IPCC AR5 report similarly includes a number of plausible scenarios bracketed by a low-emissions extreme Scenario RCP2.6 and a high-emissions extreme Scenario RCP8.5 (van Vuuren et al., 2011). Thus, an evaluation of model projection performance should focus on the relationship between the model forcings and temperature change, rather than simply assessing how well projected temperatures compare to observations, particularly in cases where projected forcings differ substantially from our best estimate of the subsequently observed forcings.

This approach—comparing the relationship between forcing and temperatures in both model projections and observations—can effectively assess the performance of the model physics while accounting for potential mismatches in projected forcing that climate modelers did not address at the time. In this paper we apply both a conventional assessment of the change in temperature over time and a novel assessment of the response of temperature to the change in forcing to assess the performance of future projections by past climate models compared to observations.

Climate modeling efforts have advanced substantially since the first modern single-column (Manabe & Strickler, 1964) and general circulation models (Manabe et al., 1965) of Earth's climate were published in the mid-1960s, resulting in continually improving model hindcast skill (Knutti et al., 2013; Reichler &

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Kim, 2008). While these improvements have rendered virtually all of the models described here operationally obsolete, they remain valuable tools as they are in a unique position to have their projections evaluated by virtue of their decades-long postpublication projection periods.

2. Methods

We conducted a literature search to identify papers published prior to the early-1990s that include climate model outputs containing both a time series of projected future GMST (with a minimum of two points in time) and future forcings (including both a publication date and future projected atmospheric CO_2 concentrations, at a minimum). Eleven papers with 14 distinct projections were identified that fit these criteria. Starting in the mid-1990s, climate modeling efforts were primarily undertaken in conjunction with the IPCC process (and later, the Coupled Model Intercomparison Projects, CMIPs), and model projections were taken from models featured in the IPCC FAR (1990), Second Assessment Report (SAR-IPCC, 1996), Third Assessment Report (TAR-IPCC, 2001), and Fourth Assessment Report (AR4-IPCC, 2007).

The specific models projections evaluated were Manabe, 1970 (hereafter Ma70), Mitchell, 1970 (Mi70), Benson, 1970 (B70), Rasool & Schneider, 1971 (RS71), Sawyer, 1972 (S72), Broecker, 1975 (B75), Nordhaus, 1977 (N77), Schneider & Thompson, 1981 (ST81), Hansen et al., 1981 (H81), Hansen et al., 1988 (H88), and Manabe & Stouffer, 1993 (MS93). The energy balance model projections featured in the main text of the FAR, SAR, and TAR were examined, while the CMIP3 multimodel mean (and spread) was examined for the AR4 (multimodel means were not used as the primary IPCC projections featured in the main text prior to the AR4). Details about how each individual model projection was digitized and analyzed as well as assessments of individual models included in the first three IPCC reports can be found in the supporting information.

The AR4 projection was excluded from the main analysis in the paper as both the observational uncertainties and model projection uncertainties are too large over the short 2007–2017 period to draw many useful conclusions, and its inclusion makes the figures difficult to read. However, analyses including the AR4 projection can be found in the supporting information.

We assessed model projections over the period between the date the model projection was published and the end of 2017 or when the model projection ended in cases where model runs did not extend through 2017. An end date of 2017 was chosen for the analysis because the ensemble of observational estimates of radiative forcings we used only extends through that date.

Five different observational temperature time series were used in this analysis—National Aeronautics and Space Administration GISTEMP (Lenssen et al., 2019), National Oceanic and Atmospheric Administration GlobalTemp (Vose et al., 2012), Hadley/UEA HadCRUT4 (Morice et al., 2012), Berkeley Earth (Rohde et al., 2013), and Cowtan and Way (Cowtan & Way, 2014). The observational temperature records used do not present a completely like-to-like comparison with models, as models provide surface air temperature (SAT) fields while observations are based on SAT fields over land and sea surface temperature (SST) fields over the ocean. This means that the trends in the models used here are likely biased high compared to observations, as model blended field trends are about 7% (±5%) lower than model global SAT fields over the 1970–2017 period (Cowtan et al., 2015; Richardson et al., 2016). However, the absence of SST fields from the models analyzed here prevents a comparison of blended SAT/SST against observations.

We compared observations to climate model projections over the model projection period using two approaches: change in temperature versus time and change in temperature versus change in radiative forcing ("implied TCR"). We use an implied TCR metric to provide a meaningful model-observation comparison even in the presence of forcing differences. Implied TCR is calculated by regressing temperature change against radiative forcing for both models and observations, and multiplying the resulting values by the forcing associated with doubled atmospheric CO_2 concentrations, F_{2x}, (following Otto et al., 2013):

$$TCR_{implied} = F_{2x}\Delta T/\Delta F_{anthro}$$

We express implied TCR with units of temperature using a fixed value of $F_{2x} = 3.7$ W/m^2 (Vial et al., 2013). ΔF_{anthro} includes only anthropogenic forcings and excludes volcanic and solar changes to avoid

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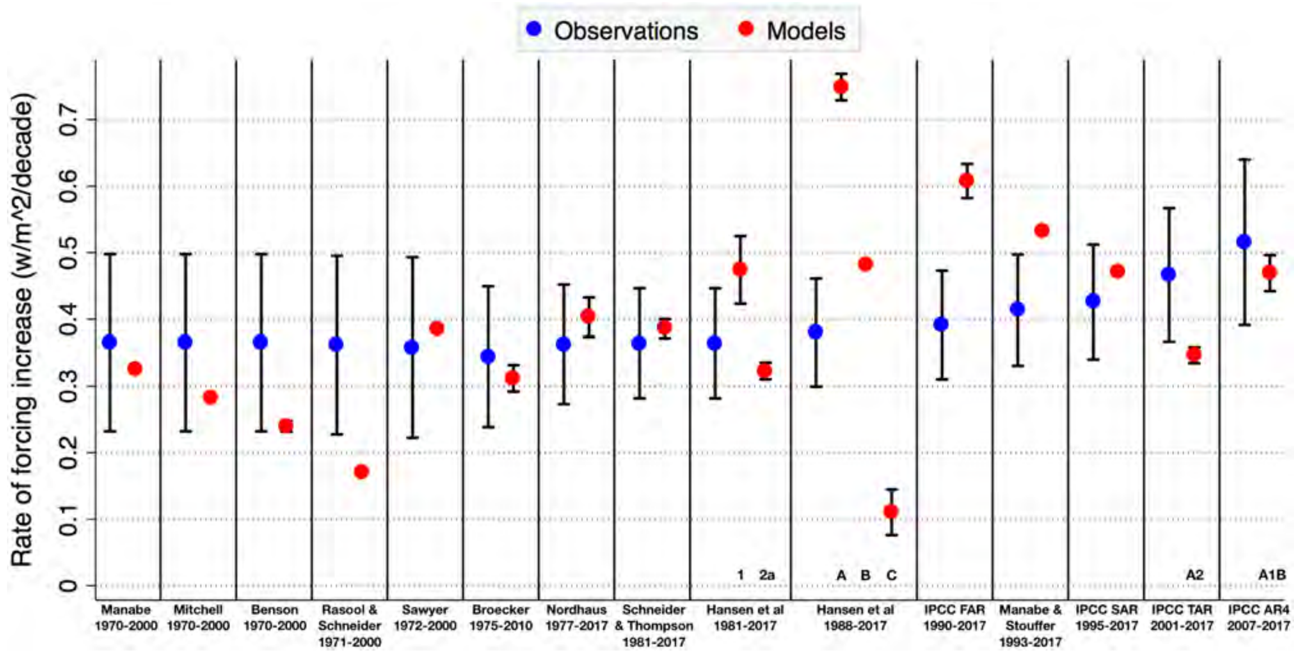

Figure 1. Rate of external forcing increase (in watts per meter squared per decade) in models and observations over model projection periods

introducing sharp interannual changes in forcing that would complicate the interpretation of TCR over shorter time periods. For the observational record, ΔF_{anthro} is based on a 1,000-member ensemble of observationally informed forcing estimates (Dessler & Forster, 2018). Model forcings are recomputed from published formulas and tables when possible and otherwise digitized from published figures (see supporting information section S2 for details). Instantaneous forcings rather than effective or efficacy-adjusted forcing are used, as those are all that is available for some early models (Hansen et al., 2005; Marvel et al., 2016; see supporting information section S1.0). Details on the approach used to calculate implied TCR can be found in supporting information section S1.2.

Comparing models and observations via implied TCR assumes a linear relationship between forcing and warming, an approach that has been widely used in prior analyses (Gregory et al., 2004; Otto et al., 2013). If forcing varies sufficiently slowly in time and deep ocean temperatures remain approximately constant, then a linear relationship is expected to hold with a constant of proportionality that depends on the strength of radiative feedbacks and ocean heat uptake (Held et al., 2010). In this regime, our implied TCR metric provides information about model physics and is unaffected by the time rate of change of forcing; moreover, previous studies have suggested that the temperature response to twentieth century anthropogenic forcing falls within this regime (Gregory & Forster, 2008; Gregory & Mitchell, 1997; Held et al., 2010).

However, sudden increases or decreases such as those associated with volcanic eruptions will not engender an equivalent immediate temperature response. For this reason, only anthropogenic forcings were used in estimating $TCR_{implied}$, as all models evaluated lacked additional volcanic events during their projection periods with the exception of Scenarios B and C of H88. Similarly, thermal inertia in the climate system can affect the relationship between temperature and external forcing if forcing increases sufficiently rapidly (Geoffroy et al., 2012). Scenarios where forcing is rapidly increasing will, all things being equal, tend to be further away from an equilibrium state than scenarios with more gradual increase after a given period of time (Rohrschneider et al., 2019) and thus have a lower implied TCR. With a few exceptions (e.g., RS71, H88 Scenarios A and C), however, most models evaluated had a rate of external forcing increase in the projection period within 1.3 times of the mean estimate of observational forcings and thus likely fall into the regime where implied TCR depends largely on radiative feedbacks and ocean heat uptake.

In this analysis we refer to model projections as consistent or inconsistent with observations based on a comparison of the differences between the two. Specifically, if the 95% confidence interval in the differences

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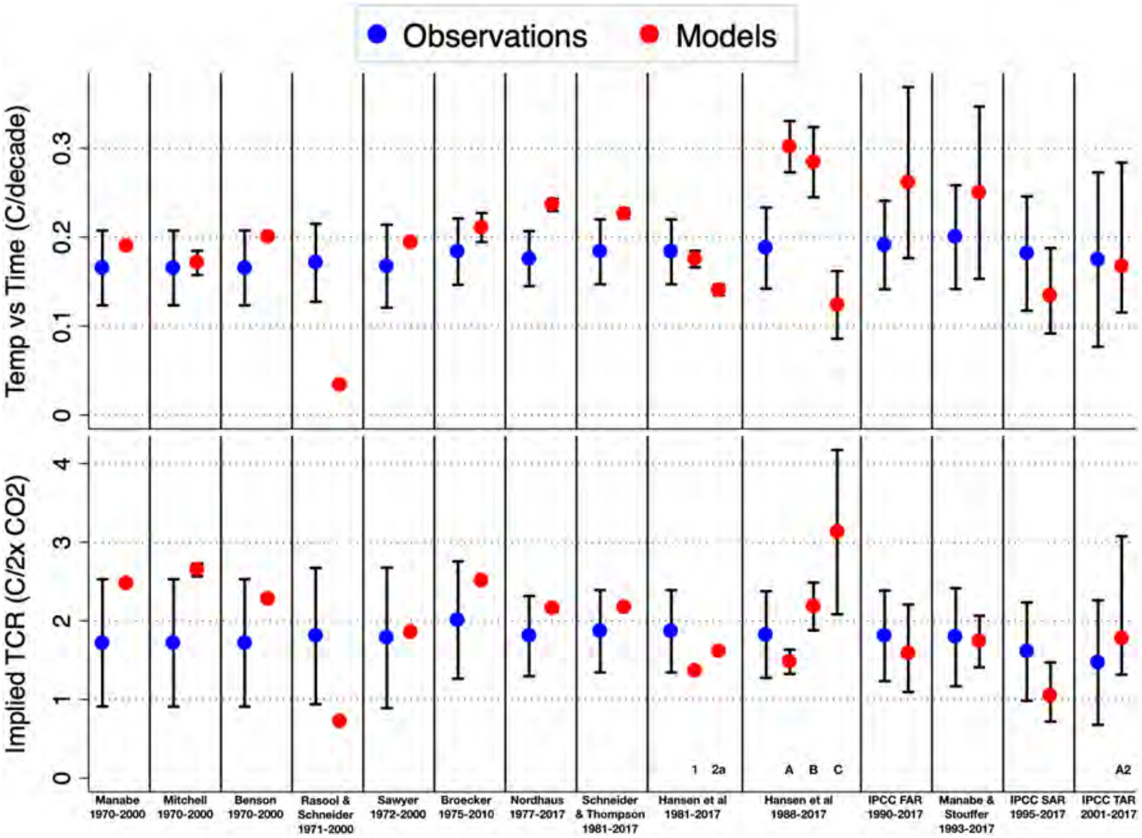

Figure 2. Comparison of trends in temperature versus time (top panel) and implied TCR (bottom panel) between observations and models over the model projection periods displayed at the bottom of the figure. Figure S1 shows a variant of this figure with the AR4 projections included

between the modeled and observed metrics includes 0, the two are deemed consistent; otherwise, they are inconsistent (Hausfather et al., 2017). Additionally, we follow the approach of Hargreaves (2010) in calculating a skill score for each model for both temperature versus time and implied TCR metrics. This skill score is based on the root-mean-square errors of the model projection trend versus observations compared to a zero-change null-hypothesis projection. See supporting information section S1.3 for details on calculating consistency and skill scores.

3. Results

A direct comparison of projected and observed temperature change during each historical model's projection period can provide an effective test of model skill, provided that model projection forcings are reasonably inline with the ensemble of observationally informed estimates of radiative forcings. In about 9 of the 17 model projections examined, the projected forcings were within the uncertainty envelope of observational forcing ensemble. However, the remaining eight models—RS71, H81 Scenario 1, H88 Scenarios A, B, and C, FAR, MS93, and TAR—had projected forcings significantly stronger or weaker than observed (Figure 1). For the latter, an analysis comparing the implied TCR between models and observations may provide a more accurate assessment of model performance.

Comparisons between climate models and observations over model projection periods are shown in Figure 2 for both temperature versus time and implied TCR metrics (differences between models and observations are shown in Figure S2). Overall the majority of model projections considered were consistent with observations under both metrics. Using the temperature versus time metric, 10 of the 17 model projections show results consistent with observations. Of the remaining seven model projections, four project more warming than observed—N77, ST81, and H88 Scenarios A and B—while three project less warming than observed—RS71, H81 Scenario 2a, and H88 Scenario C.

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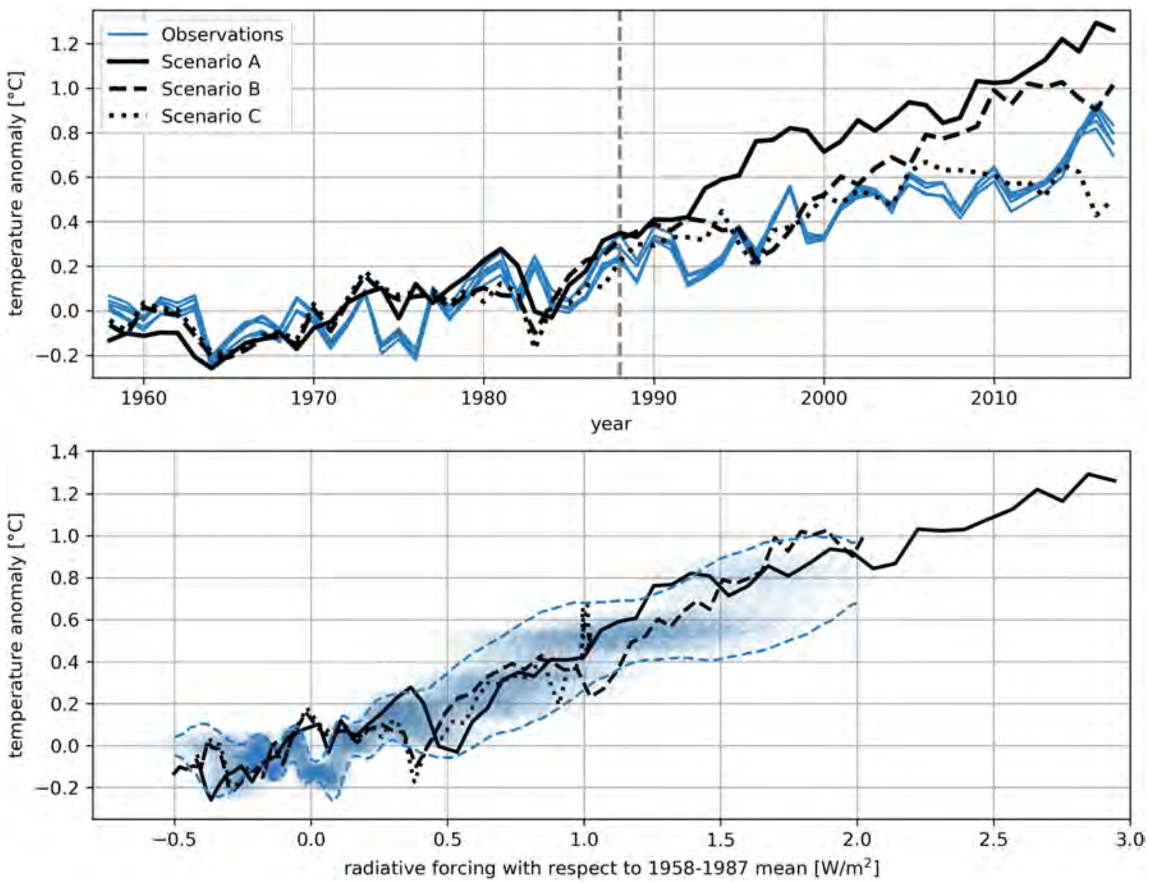

Figure 3. Hansen et al., 1988 projections compared with observations on a temperature versus time basis (top) and temperature versus external forcing (bottom). The dashed gray line in the top panel represent the start of the projection period. The transparent blue lines in the lower panel represent 500 random samples of the 5,000 combinations of the five temperature observation products and the 1,000 ensemble members of estimated forcings (the full ensemble is subsampled for visual clarity). The dashed blue lines show the 95% confidence intervals for the 5,000-member ensemble (see supporting information Text S1.4 for details). Anomalies for both temperature and forcing are shown relative to a 1958–1987 preprojection baseline.

When mismatches between projected and observed forcings are taken into account, a better performance is seen. Using the implied TCR metric, 14 of the 17 model projections were consistent with observations; of the three that were not, Mi70 and H88 Scenario C showed higher implied TCR than observations, while RS71 showed lower implied TCR (Schneider, 1975; see supporting information Text S2 for a discussion of the anomalously low-equilibrium climate sensitivity (ECS) model used in RS71).

A number of model projections were inconsistent with observations on a temperature versus time basis but are consistent once mismatches between modeled and observed forcings are taken into account. For example, whileN77 and ST81 projected more warming than observed, their implied TCRs are consistent with observations despite forcings within—though on the high end of—the ensemble range of observational estimates. Similarly, while H81 Scenario 2a projects less warming than observed, its implied TCR is consistent with observations.

A number of 1970s-era models (Ma70, Mi70, B70, B75, and N77) show implied TCR on the high end of the observational ensemble-based range. This is likely due to their assumption that the atmosphere equilibrates instantly with external forcing, which omits the role of transient ocean heat uptake (Hansen et al., 1985). However, despite this high implied TCR, a number of the models (e.g., Ma70, Mi70, B70, and B75) still end up providing temperature projections in-line with observations as their forcings were on the lower end of observations due to the absence of any non-CO_2 forcing agents in their projections.

In principle, the same underlying model should show consistent results for modestly different forcing scenarios under the implied TCR metric. However, the inconsistency of the H88 Scenario C is illustrative of

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Table 1
Model Skill Scores Over the Projection Period, Where 1 Represents Perfect Agreement With Observations and Less Than 0 Represents Worse Performance Than a No-Change Null Hypothesis

Model	Timeframe	$\Delta T/\Delta t$ skill	$\Delta T/\Delta F$ skill
Ma70	1970–2000	0.84 [0.57 to 0.99]	0.51 [−0.11 to 0.94]
Mi70	1970–2000	0.91 [0.69 to 0.99]	0.41 [−0.26 to 0.90]
B70	1970–2000	0.78 [0.45 to 0.97]	0.63 [0.06 to 0.96]
RS71	1971–2000	0.19 [0.16 to 0.25]	0.42 [0.28 to 0.59]
S72	1972–2000	0.83 [0.49 to 0.99]	0.83 [0.43 to 0.98]
B75	1975–2010	0.85 [0.64 to 0.98]	0.72 [0.31 to 0.97]
N77	1977–2017	0.67 [0.44 to 0.84]	0.79 [0.48 to 0.98]
ST81	1981–2017	0.76 [0.53 to 0.94]	0.82 [0.52 to 0.98]
H81(1)	1981–2017	0.93 [0.81 to 0.99]	0.74 [0.59 to 0.93]
H81(2a)	1981–2017	0.77 [0.66 to 0.91]	0.87 [0.69 to 0.99]
H88(A)	1988–2017	0.38 [0.01 to 0.68]	0.81 [0.63 to 0.98]
H88(B)	1988–2017	0.48 [0.08 to 0.77]	0.79 [0.41 to 0.98]
H88(C)	1988–2017	0.66 [0.48 to 0.89]	0.28 [−0.46 to 0.84]
FAR	1990–2017	0.63 [0.29 to 0.87]	0.86 [0.68 to 0.99]
MS93	1993–2017	0.71 [0.20 to 0.97]	0.87 [0.61 to 0.99]
SAR	1995–2017	0.73 [0.58 to 0.95]	0.66 [0.49 to 0.91]
TAR	2001–2017	0.81 [0.15 to 0.98]	0.76 [−0.13 to 0.98]
AR4	2007–2017	0.56 [0.35 to 0.92]	0.60 [0.37 to 0.93]

Note. Both temperature versus time (ΔT/year) and implied TCR ($\Delta T/\Delta F$) median scores and uncertainties are shown.

the limitations of the implied TCR metric when the model forcings differ dramatically from observations, as Scenario C has roughly constant forcings after the year 2000.

The H88 model provides a helpful illustration of the utility of an approach that can account for mismatches between modeled and observed forcings. H88 was featured prominently in congressional testimony, and the recent thirtieth anniversary of the event in 2018 focused considerable attention on the accuracy of the projection (Borenstein & Foster, 2018; United States. Cong. Senate, 1988). H88's "most plausible" Scenario B overestimated warming experienced subsequent to publication by around 54% (Figure 3). However, much of this mismatch was due to overestimating future external forcing—particularly from CH_4 and halocarbons (Figure S3). When H88 Scenario B is evaluated based on the relationship between projected temperatures and projected forcings, the results are consistent with observations (Figures 2 and 3).

Skill score median estimates and uncertainties for both temperature versus time and implied TCR metrics are shown in Table 1 (see supporting information Text S1.3). A skill score of one represents perfect agreement between a model projection and observations, while a skill score of less than 0 represents worse performance than a no-change null-hypothesis projection.

The average of the median skill scores across all the model projections evaluated is 0.69 for the temperature versus time metric. Only three projections (RS71, H88 Scenario A, and H88 Scenario B) had skill scores below 0.5, while H81 Scenario 1 had the highest skill score of any model—0.93. Using the implied TCR metric, the average projection skill of the models was also 0.69. Models with implied TCR skill scores below 0.5 include Mi70, RS71, and H88 Scenario C, while MS93 had the highest skill score at 0.87. H88 Scenarios A and B and the IPCC FAR all performed substantially better under an implied TCR metric, reflecting the role of misspecified future forcings in their high-temperature projections. It is important to note that the skill score uncertainties for very short future projection periods—as in the case of the TAR and AR4—are quite large and should be treated with caution due to the combination of short-term temperature variability and uncertainties in the forcings.

A number of model projections had external forcings that poorly matched observational estimates due to the exclusion of non-CO_2 forcing agents. However, all models included projected future CO_2 concentrations, providing a common metric for comparison, and these are shown in Figure S4. Most of the historical climate model projections overestimated future CO_2 concentrations, some by as much as 40 ppm over current levels, with projected CO_2 concentrations increasing up to twice as fast as actually observed (Meinshausen, 2017). Of the 1970s climate model projections, only Mi70 projected atmospheric CO_2 growth in-line with observations. Many 1980s projections similarly overestimated CO_2, with only the Hansen 88 Scenarios A and B projections close to observed concentrations.

The first three IPCC assessments included projections based on simple energy balance models tuned to general circulation model results, as relatively few individual model runs were available at the time. From the AR4 onward IPCC projections were based on the multimodel mean and model spread. We examine individual models from the first three IPCC reports on both a temperature versus time and implied TCR basis in Figure S5.

4. Conclusions and Discussion

In general, past climate model projections evaluated in this analysis were skillful in predicting subsequent GMST warming in the years after publication. While some models showed too much warming and a few showed too little, most models examined showed warming consistent with observations, particularly when mismatches between projected and observationally informed estimates of forcing were taken into account. We find no evidence that the climate models evaluated in this paper have systematically overestimated or underestimated warming over their projection period. The projection skill of the 1970s models is particularly impressive given the limited observational evidence of warming at the time, as the world was thought to have been cooling for the past few decades (e.g., Broecker, 1975; Broecker, 2017).

A number of high-profile model projections—H88 Scenarios A and B and the IPCC FAR in particular—have been criticized for projecting higher warming rates than observed (e.g., Michaels & Maue, 2018). However, these differences are largely driven by mismatches between projected and observed forcings. H88 A and B forcings increased 97% and 27% faster, respectively, than the mean observational estimate, and FAR forcings increased 55% faster. On an implied TCR basis, all three projections have high model skill scores and are consistent with observations.

While climate models have grown substantially more complex than the early models examined here, the skill that early models have shown in successfully projecting future warming suggests that climate models are effectively capturing the processes driving the multidecadal evolution of GMST. While the relative simplicity of the models analyzed here renders their climate projections operationally obsolete, they may be useful tools for verifying or falsifying methods used to evaluate state-of-the-art climate models. As climate model projections continue to mature, more signals are likely to emerge from the noise of natural variability and allow for the retrospective evaluation of other aspects of climate model projections.

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EXHIBIT 5

FRBSF Economic Letter

2019-09 | March 25, 2019 | Research from the Federal Reserve Bank of San Francisco

Climate Change and the Federal Reserve

Glenn D. Rudebusch

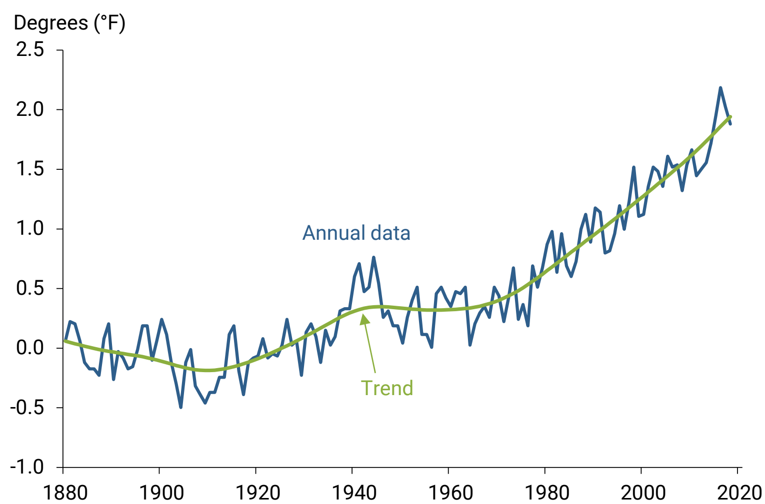
Climate change describes the current trend toward higher average global temperatures and accompanying environmental shifts such as rising sea levels and more severe storms, floods, droughts, and heat waves. In coming decades, climate change—and efforts to limit that change and adapt to it—will have increasingly important effects on the U.S. economy. These effects and their associated risks are relevant considerations for the Federal Reserve in fulfilling its mandate for macroeconomic and financial stability.

To help foster macroeconomic and financial stability, it is essential for Federal Reserve policymakers to understand how the economy operates and evolves over time. In this century, three key forces are transforming the economy: a demographic shift toward an older population, rapid advances in technology, and climate change. Climate change has direct effects on the economy resulting from various environmental shifts, including hotter temperatures, rising sea levels, and more frequent and extreme storms, floods, and droughts. It also has indirect effects resulting from attempts to adapt to these new conditions and from efforts to limit or mitigate climate change through a transition to a low-carbon economy. This *Economic Letter* describes how the consequences of climate change are relevant for the Fed's monetary and financial policy.

Climate change and the transition to a low-carbon economy

Surface temperatures were first regularly recorded around the world in the late 1800s. Since then, the global average temperature has risen almost 2°F (Figure 1) with further increases projected (IPCC 2018). Based on extensive scientific theory and evidence, a consensus view among scientists is that global warming is the result of carbon emissions from burning coal, oil, and other fossil fuels. Indeed, as early as 1896, the Swedish chemist Svante Arrhenius showed that carbon emissions from human activities could cause global warming through a greenhouse effect. The underlying science is straightforward: Certain gases in the atmosphere, such as carbon dioxide and methane, capture the sun's heat that is

Figure 1
Change in global average temperature relative to 1880–1900



Note: Global average surface temperature based on land and ocean data from the National Aeronautics and Space Administration (NASA): https://data.giss.nasa.gov/gistemp/

reflected off the Earth's surface, thus blocking that heat from escaping into space. These greenhouse gases act like a blanket around the earth holding in heat. As more fossil fuels are burned, the blanket gets thicker, and global average temperatures increase. Other empirical measurements have confirmed many related adverse environmental changes such as rising sea levels and ocean acidity, shrinking glaciers and ice sheets, disappearing species, and more extreme storms (USGCRP 2018).

Climate change also affects the U.S. economy. The latest *National Climate Assessment*, a 1,515-page scientific report produced by 13 federal agencies as required by law, summarized this impact:

> Without substantial and sustained global mitigation and regional adaptation efforts, climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century (USGCRP 2018, pp. 25–26).

Economists view these losses as the result of a fundamental market failure: carbon fuel prices do not properly account for climate change costs. Businesses and households that produce greenhouse gas emissions, say, by driving cars or generating electricity, do not pay for the losses and damage caused by that pollution. Therefore, they have no direct incentive to switch to a low-carbon technology that would curtail emissions. Without proper price signals and incentives in the private market, some kind of collective or government action is necessary. One solution would be to charge for the full cost of carbon pollution through an extra fee on emissions—a carbon tax—that would account for the costs of climate change on the economy and society. Many leading economists are calling for a carbon tax to correct market pricing (Climate Leadership Council 2019, Fried, Novan, and Peterman 2019).

A carbon tax that is set at the proper level can appropriately incentivize innovations in clean technology and the transition from a high- to a low-carbon economy. Such a carbon tax should equal the "social cost of carbon," which measures the total damage from an additional ton of carbon pollution (Auffhammer 2018). A crucial consideration in calculating this cost is that carbon pollution dissipates very slowly and will remain in the atmosphere for centuries, redirecting heat back toward the earth. Consequently, today's carbon pollution will create climate hazards for many generations to come. A second difficulty in calculating the social cost of carbon is tail risk, namely, the possibility of catastrophic future climate damage (Heal 2017). A final complication is that the causes and consequences of climate change are global in scope. The resulting intergenerational and international market failure is so problematic that some economists doubt that a carbon tax alone would suffice (Tvinnereim and Mehling 2018). Instead, a comprehensive set of government policies may be required, including clean-energy and carbon-capture research and development incentives, energy efficiency standards, and low-carbon public investment (Gillingham and Stock 2018).

Climate change and the Fed

Given the role of government in addressing climate change, how does the Federal Reserve fit in? In particular, how does climate change relate to the Fed's goals of financial and macroeconomic stability? With regard to financial stability, many central banks have acknowledged the importance of accounting for the increasing financial risks from climate change (Scott, van Huizen, and Jung 2017, NGFS 2018). These risks include potential loan losses at banks resulting from the business interruptions and bankruptcies caused by storms, droughts, wildfires, and other extreme events. There are also transition risks associated with the adjustment to a low-carbon economy, such as the unexpected losses in the value of assets or companies that depend on fossil fuels. In this regard, even long-term risks can have near-term consequences as investors reprice assets for a low-carbon future. Furthermore, financial firms with limited carbon emissions may still face substantial climate-based credit risk exposure, for example, through loans to affected businesses or mortgages on coastal real estate. If such exposures were broadly correlated across regions or industries, the resulting climate-based risk could threaten the stability of the financial system as a whole and be of macroprudential concern. In response, the financial supervisory authorities in a number of countries have encouraged financial institutions to disclose any climate-related financial risks and to conduct “climate stress tests” to assess their solvency across a range of future climate change alternatives (Campiglio et al. 2018).

Some central banks also recognize that climate change is becoming increasingly relevant for monetary policy (Lane 2017, Cœuré 2018). For example, climate-related financial risks could affect the economy through elevated credit spreads, greater precautionary saving, and, in the extreme, a financial crisis. There could also be direct effects in the form of larger and more frequent macroeconomic shocks associated with the infrastructure damage, agricultural losses, and commodity price spikes caused by the droughts, floods, and hurricanes amplified by climate change (Debelle 2019). Even weather disasters abroad can disrupt exports, imports, and supply chains close to home. As a much more persistent factor, Colacito et al. (2018) found that the current trend toward higher temperatures on its own has slowed growth in a variety of sectors. They estimated that increased warming has already started to reduce average U.S. output growth and that, as temperatures rise, growth may be curtailed by more than ½ percentage point later in this century.

On top of these direct effects, climate adaptation—with spending on equipment such as air conditioners and resilient infrastructure including seawalls and fortified transportation systems—is expected to increasingly divert resources from productive capital accumulation. Similarly, sizable investments would be necessary to reduce carbon pollution and mitigate climate change, and the transition to a low-carbon future may affect the economy through a variety of other channels (Batten 2018). In short, climate change is becoming relevant for a range of macroeconomic issues, including potential output growth, capital formation, productivity, and the long-run level of the real interest rate.

Nevertheless, some view the economic and financial concerns surrounding climate change as having either too short or too long a time horizon to affect monetary policy decisions. Indeed, at the short end, monetary policy typically does not react to temporary disturbances from weather events like hurricanes or blizzards. However, climate change could cause such shocks to grow in size and frequency and their disruptive effects could become more persistent and harder to ignore. At the long end, most of the consequences of climate change will occur well past the usual policy forecast horizon of a few years ahead. However, even longer-term factors can be relevant for monetary policy. For example, central banks routinely consider the policy implications of demographic trends, such as declining labor force participation, which have long-run effects much like climate change. In addition, prices of equities and long-term financial assets depend on expected future conditions, so even climate risks decades ahead can have near-term financial consequences. Climate change could also be a factor in achieving and maintaining low inflation. It took a decade or two—a relevant time scale for climate change—for the Fed to achieve its inflation objective after the Great Inflation of the 1970s and the Great Recession. Finally, the economic research that quantifies optimal monetary policy routinely uses a very long-run perspective that takes into account inflation and output quite far out in the future.

While the effects and risks of climate change are relevant factors for the Fed to consider, the Fed is not in a position to use monetary policy actively to foster a transition to a low-carbon economy. Supporting environmental sustainability and limiting climate change are not directly included in the Fed's statutory mandate of price stability and full employment. Furthermore, the Fed's short-term interest rate policy tool is not amenable to supporting low-carbon industries. Wind farms in Kansas and coal mines in West Virginia face the same underlying risk-free short-term interest rate. Instead, some have advocated that central banks use their balance sheet to support the transition to a low-carbon economy, for example, by buying low-carbon corporate bonds (Olovsson 2018). Such "green" quantitative easing is an option for some central banks but not for the Fed, which by law can only purchase government or government agency debt.

Conclusion

Many central banks already include climate change in their assessments of future economic and financial risks when setting monetary and financial supervisory policy. For the Fed, the volatility induced by climate change and the efforts to adapt to new conditions and to limit or mitigate climate change are also increasingly relevant considerations. Moreover, economists, including those at central banks, can contribute much more to the research on climate change hazards and the appropriate response of central banks.

Glenn D. Rudebusch is senior policy advisor and executive vice president in the Economic Research Department of the Federal Reserve Bank of San Francisco.

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EXHIBIT 6

Global increase in major tropical cyclone exceedance probability over the past four decades

James P. Kossin[a,1], Kenneth R. Knapp[b], Timothy L. Olander[c], and Christopher S. Velden[c]

[a]Center for Weather and Climate, National Centers for Environmental Information, National Oceanic and Atmospheric Administration, Madison, WI 53706; [b]Center for Weather and Climate, National Centers for Environmental Information, National Oceanic and Atmospheric Administration, Asheville, NC 28801; and [c]Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, WI 53706

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Theoretical understanding of the thermodynamic controls on tropical cyclone (TC) wind intensity, as well as numerical simulations, implies a positive trend in TC intensity in a warming world. The global instrumental record of TC intensity, however, is known to be heterogeneous in both space and time and is generally unsuitable for global trend analysis. To address this, a homogenized data record based on satellite data was previously created for the period 1982–2009. The 28-y homogenized record exhibited increasing global TC intensity trends, but they were not statistically significant at the 95% confidence level. Based on observed trends in the thermodynamic mean state of the tropical environment during this period, however, it was argued that the 28-y period was likely close to, but shorter than, the time required for a statistically significant positive global TC intensity trend to appear. Here the homogenized global TC intensity record is extended to the 39-y period 1979–2017, and statistically significant (at the 95% confidence level) increases are identified. Increases and trends are found in the exceedance probability and proportion of major (Saffir–Simpson categories 3 to 5) TC intensities, which is consistent with expectations based on theoretical understanding and trends identified in numerical simulations in warming scenarios. Major TCs pose, by far, the greatest threat to lives and property. Between the early and latter halves of the time period, the major TC exceedance probability increases by about 8% per decade, with a 95% CI of 2 to 15% per decade.

tropical cyclone | hurricane | intensity | trend | climate

During the lifetime of a tropical cyclone (TC), intensity (i.e., the magnitude of the surface winds) is modulated by a number of environmental factors. The maximum intensity that a TC can achieve is dictated by its ambient "potential intensity," which is based on the thermodynamic state of the ambient environment (1). Other factors such as ambient vertical wind shear can inhibit a TC from reaching its potential intensity (2–4), but an increase in mean potential intensity is expected to manifest as an increase in mean measured intensity if these other factors remain unchanged (5, 6). Potential intensity has been increasing, in general, as global mean surface temperatures have increased (1, 7), and there is an expectation that the distribution of TC intensity responds by shifting toward greater intensity (8). In this case, positive trends should manifest in mean TC intensity, but are expected to be proportionally greater at the higher intensity quantiles (7, 9). This expectation is borne out in numerical simulations and projections (10). Testing this expectation with observations, however, is problematic because the instrumental record of TC intensity, known as the "best-track" record, is heterogeneous in time and by region (11–14).

To address the heterogeneities in the best-track data, a new global record of intensity was previously constructed (7) by applying a well-known intensity estimation algorithm (the advanced Dvorak Technique, or ADT) (15, 16) to a globally homogenized record of geostationary satellite imagery (the Hurricane Satellite record, or HURSAT) (17, 18). The original version of the ADT-HURSAT record spanned the 28-y period 1982–2009. Global trend analyses using quantile regression on these data provided two key results: 1) There were positive trends found in most of the quantiles of the intensity distribution, but 2) these trends had not risen to the 95% significance level (figure 6 of ref. 7). During this same 28-y period, positive trends in potential intensity in active TC regions were identified (7), which is consistent with the observed increasing trends in TC intensity (8). To better understand the lack of statistical significance of the observed intensity trends, an idealized experiment was performed (7) based on the expected intensity changes that might occur in the environment of observed increases in potential intensity (8). The experiment suggested that the observed changes in the mean tropical environment should cause an increase in TC intensity at a rate similar to the observed rate, but there was only about a 50 to 60% probability that the increasing intensity trends would rise to a statistically significant level within a 28-y period. The purpose of this paper is to extend the ADT-HURSAT data record to span the 39-y period 1979–2017 and explore these data to determine whether statistically significant positive global trends have yet emerged in this extended period of data.

Results

Development of the ADT-HURSAT Data. The Dvorak Technique has served as a fundamental operational tool for estimating TC intensity in all TC-prone regions of the globe for more than 40 y (13, 19–21). The technique utilizes satellite imagery to identify and measure specific features in the cloud presentation of a TC,

Significance

Tropical cyclones (TCs), and particularly major TCs, pose substantial risk to many regions around the globe. Identifying changes in this risk and determining causal factors for the changes is a critical element for taking steps toward adaptation. Theory and numerical models consistently link increasing TC intensity to a warming world, but confidence in this link is compromised by difficulties in detecting significant intensity trends in observations. These difficulties are largely caused by known heterogeneities in the past instrumental records of TCs. Here we address and reduce these heterogeneities and identify significant global trends in TC intensity over the past four decades. The results should serve to increase confidence in projections of increased TC intensity under continued warming.

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The authors declare no competing interest.

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[1]To whom correspondence may be addressed. Email: james.kossin@noaa.gov.

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and relates these to the current intensity of the storm. The technique could be considered a statistical regression- and analog-based algorithm, but it is somewhat subjective because it requires the analyst or forecaster to follow a sequence of steps while making expert judgments at many of the steps. Because of the subjective nature of the technique, different forecasters may introduce biases into the intensity estimates based on their personal perception and interpretation of the Dvorak Technique decision flowcharts and rules. To remove this subjectivity, the fully automated ADT was introduced and presently serves as an important tool for TC forecasters around the world (15, 16).

The ADT is largely based on the "Enhanced Infrared" version of the Dvorak Technique (20), which utilizes infrared brightness temperatures to measure TC features such as cloud-top temperature above the eyewall, which is related to convective vigor, and eye temperature, which is related to the strength of the TC transverse circulation, both of which are related to intensity. The ADT is typically applied to geostationary satellite imagery, which has been measured with increasingly better and higher-resolution sensors since the 1970s (17, 18). In order to create a homogeneous global record of TC intensity, a homogeneous collection of global geostationary satellite imagery known as the HURSAT record was created (7, 17, 18). HURSAT imagery has been resampled to a consistent 8-km spatial resolution and 3-hourly temporal resolution and has been further homogenized through recalibration procedures. A final homogenization step was the removal of data from geostationary satellites that were stationed over and near the 60°E meridian (*SI Appendix*, Fig. S1). This last step addresses the discontinuity in satellite view angle that was introduced in 1998 when satellites were introduced over an area that was previously devoid of geostationary satellites (7). The ADT algorithm is applied to the global HURSAT data to form the ADT-HURSAT homogenized global record of TC intensity.

Over the period 1979–2017 considered here, there are about 225,000 ADT-HURSAT intensity estimates in about 4,000 individual TCs worldwide. The minimum estimated intensity is 25 kt, and the maximum is 170 kt (*SI Appendix*, Fig. S2). As discussed in ref. 7, the distributions of intensity and lifetime maximum intensity (LMI) estimates (*SI Appendix*, Fig. S2) are affected by cases where an eye forms under the dense cirrus cloud that overlies the TC central region but is not evident in the infrared imagery because cirrus is opaque at that wavelength. In these cases, the TC is likely to be intensifying as the eye forms, but the ADT will maintain a more constant intensity. This usually occurs near but below about 65 kt (the minimum threshold for Saffir−Simpson category 1), which projects onto the intensity distribution by increasing the frequencies near but below this threshold. In cases where the eye does eventually appear in the infrared imagery, the ADT will identify an "eye scene" and will begin intensifying the TC. As the intensity estimates increase, eye scenes become more frequent. If an eye never appears in the infrared and no eye scene is identified by the ADT during a TC lifetime, the LMI will more likely be underestimated at an intensity near but below 65 kt, which contributes to the jump in LMI frequency around 65 kt evident in *SI Appendix*, Fig. S2*B*.

When comparing all ADT-HURSAT and International Best Track Archive for Climate Stewardship (IBTrACS) intensity estimates (*Methods*) globally, the spread demonstrates a far-from-perfect fit (*SI Appendix*, Fig. S3), although, given the known issues with global best-track data (e.g., refs. 12–14), it is not always clear which of the two data records is the more accurate for any particular estimate. Regardless, the key point here is that the ADT-HURSAT record is homogenous in time and by region, whereas the best-track data are not. The ADT-HURSAT record, particularly in light of the fact that it necessarily uses coarse (8 km) resolution satellite data, is not designed to be a substitute for the best track, nor is it designed to be used on a point-by-point or storm-by-storm basis. The ADT-HURSAT should be considered a record that sacrifices some measure of absolute accuracy for homogeneity, and which allows more robust trend analysis.

Changes in TC Intensities over the Past Four Decades. Over the past 40 y (and longer), anthropogenic warming has increased sea surface temperature (SST) in TC-prone regions (22–24), and, in combination with changes in atmospheric conditions, this has increased TC potential intensity in these regions (7). Based on physical understanding and robust support from numerical simulations, an increase in environmental potential intensity is expected to manifest as a shift in the TC intensity distribution toward greater intensity and an increase in mean intensity. More importantly, the shift is further expected to manifest as a more substantial increase in the high tail of the distribution (6, 9, 25), which comprises the range of intensities that are responsible for the great majority of TC-related damage and mortality (26). Consequently, detection and attribution of past and projected TC intensity changes has often focused on metrics that emphasize changes in the stronger TCs (6, 10, 27, 28), and we will follow that emphasis here. As discussed above, the ADT-HURSAT intensities near but below the minimum 65-kt threshold for a minimal Saffir−Simpson category 1 hurricane are generally less reliable, particularly at times when a developing eye is obscured under the TC cirrus cloud canopy.* This can be mitigated by simply focusing only on estimates within Saffir−-Simpson categories 1 to 5, which is also appropriate for our emphasis on changes in the stronger TCs. Our metrics of interest in this work are based on the proportions of major hurricane intensities (Saffir−Simpson categories 3 to 5 that have winds equal to or greater than 100 kt) to all hurricane intensities (Saffir−Simpson categories 1 to 5).

We begin with a broad view of the change in the global distribution of ADT-HURSAT intensity estimates between the early and latter halves of the 39-y period 1979–2017. Fig. 1 shows the change in the exceedance probabilities (complementary cumulative distribution function) among all estimates greater than hurricane intensity (65 kt). There is a clear shift toward greater intensity that manifests as increased probabilities of exceeding major hurricane intensity (100 kt). The probability of major hurricane exceedance increases from 0.27 to 0.31, which represents about a 15% increase. The centroids of the early and latter subperiods are around 1988 and 2007, respectively, with a separation of about 19 y. This represents an increase in probability of major hurricane intensity of about 8% per decade. The probability difference between the early and latter halves of the period is statistically significant after accounting for serial correlation in the two samples (*Methods*). The CIs for the early and latter halves are [0.25 0.28] and [0.29 0.32], respectively. The range of exceedance probability increases within these 95% CIs is then about 2 to 15% per decade.

For comparison, the change in best-track intensities over the same period is roughly 17% per decade (Table 1 and *SI Appendix*, Fig. S4), or about twice the increase in major hurricane intensity exceedance found in the homogenized ADT-HURSAT data. This is consistent with the expectation that the best-track data contain nonphysical technology-based trends in the estimation of TC intensity, particularly at the greater intensities. In this case, it appears that the trends in the best track are about

*TCs are referred to by different names in different regions (e.g., hurricanes in the North Atlantic and typhoons in the western North Pacific), but, for simplicity, here we refer to any Saffir−Simpson category 1 or greater intensity as "hurricane" intensity, and Saffir−-Simpson category 3 or greater intensity as "major hurricane" intensity regardless of geographic region. For our data, which are provided in 5-kt bins, major hurricane intensity is 100 kt or greater.

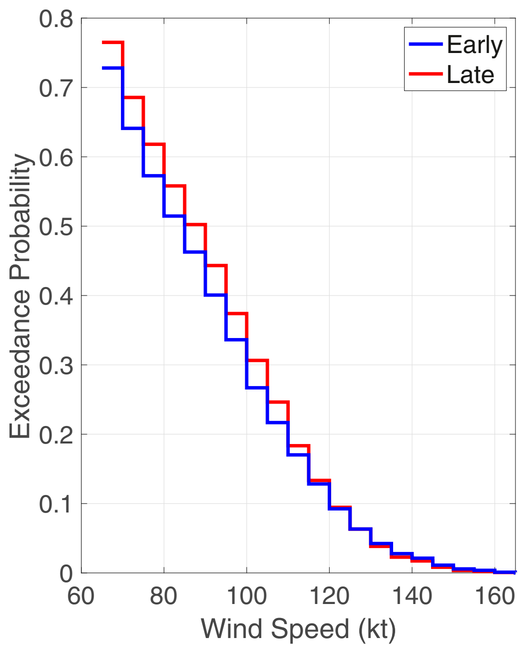

Fig. 1. Comparison of complementary cumulative distribution functions of the global ADT-HURSAT hurricane intensity estimates between the early and latter halves of the 39-y period 1979–2017.

equally split between actual physical trends and spurious technology-based trends.

Another way to explore changes in the intensity distribution is to consider time series of the proportion of major hurricane intensities. Fig. 2 shows a triad time series (3-y bins) of the global fractional proportion of major hurricane intensities to all hurricane intensities (*Methods*). The time series exhibits a statistically significant increasing trend that represents a 25% (about 6% per decade) increase in the likelihood that any estimate of at least hurricane intensity is at or above major hurricane intensity (Table 1).

Similar to the Dvorak technique, the ADT uses a "scene-typing" strategy to provide intensity estimates (16, 21). In particular, an essential aspect of these routines is the ability to recognize the presence of a TC eye in a satellite image. The appearance of an eye generally signals that a TC has reached hurricane intensity, and major hurricanes, as well as rapidly intensifying hurricanes, generally (almost always) exhibit an eye (29, 30). We can exploit these facts to indirectly identify intensity trends by looking for changes in the proportion of eye scenes (*SI Appendix*, Fig. S5). Here, again, there is an apparent trend toward increasing likelihood of finding an eye scene, which is consistent with the increasing likelihood of finding a major hurricane intensity. This is a particularly useful result because the identification of an eye scene is largely insensitive to any potential heterogeneities that may still remain in the resampled and recalibrated infrared brightness temperatures in the HURSAT data (15). Additionally, when the ADT identifies an eye scene, it produces an estimate of the eye diameter. Smaller eyes are generally related to greater intensity (31), and there is a shift toward smaller eyes in the ADT data (*SI Appendix*, Fig. S6). This is consistent with the increasing intensity trends, but also uncovers a potential bias in the ADT-HURSAT intensities. As eye sizes become smaller, and, particularly, as eye diameters smaller than about 20 km become more likely (*SI Appendix*, Fig. S6), they would be expected to be more difficult to resolve in the 8-km resolution HURSAT data. This could cause the ADT to underestimate the intensity trend, particularly at the smallest-eye/greatest-intensity end of the spectrum, which may also help to explain the absence of a probability shift at the most intense part of the intensity spectrum, as seen in Fig. 1. This is difficult to quantify, however, and is left here as an open question for possible future exploration.

The main focus of this work is the identification of global changes in TC intensity (Figs. 1 and 2). When the global data are parsed into regional subsets, there is an expectation for changes in signal-to-noise ratios and greater sensitivity to known regional modes of variability (e.g., the Interdecadal Pacific Oscillation [IPO], Atlantic Multidecadal Oscillation [AMO], or Indian Ocean Dipole [IOD]). Nonetheless, it is generally informative to identify changes and trends within individual ocean basins, and results of the regional analyses are shown in Table 1 and Fig. 3. The greatest changes are found in the North Atlantic, where the probability of major hurricane exceedance increases by 49% per decade, significant at greater than the 99% confidence level (Table 1). Consistent with this, an increasing trend is found in the triad time series of the proportion of major hurricane intensities (Fig. 3) that represents an increase of 42% per decade, significant with 98% confidence (Table 1). Large and significant increases are also found in the southern Indian Ocean. More modest increases are found in the eastern North Pacific and South Pacific, and there is essentially no change found in the western North Pacific. The northern Indian Ocean exhibits a decreasing trend, but it is highly insignificant and based on a small sample of data (Table 1). With the exception of the northern Indian Ocean, all of the basins are contributing to the increasing global trend shown in Fig. 2.

Discussion

The global TC intensity trends identified here are consistent with expectations based on physical process understanding (1) and trends detected in numerical simulations under warming

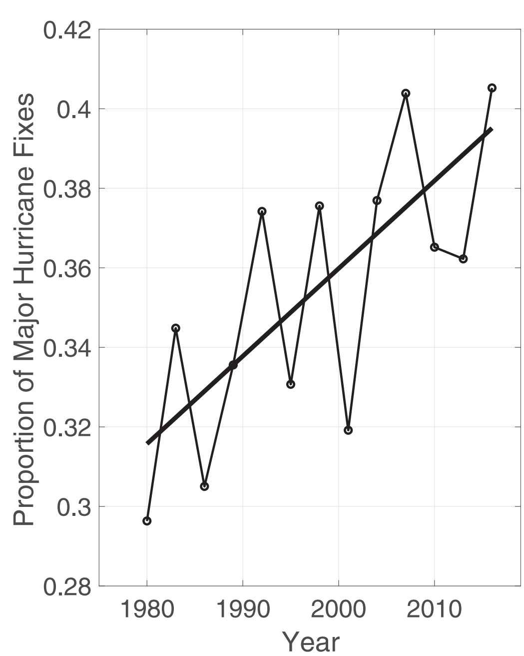

Fig. 2. Time series of fractional proportion of global major hurricane estimates to all hurricane estimates for the period 1979–2017. Each point, except the earliest, represents the data in a sequence of 3-y periods. The first data point is based on only 2 y (1979 and 1981) to avoid the years with no eastern hemisphere coverage. The linear Theil–Sen trend (black line) is significant at the 98% confidence level (Mann–Kendall P value = 0.02). The proportion increases by 25% in the 39-y period (about 6% per decade).

Table 1. Differences in major hurricane intensity exceedance probability (P_{maj}) between the early and later halves of the period of analysis

	ADT-HURSAT							
	Global	NA	EP	WP	NI	SI	SP	Best-track global
Early (1979–1997)	P_{maj} = 0.27	P_{maj} = 0.18	P_{maj} = 0.25	P_{maj} = 0.35	P_{maj} = 0.16	P_{maj} = 0.21	P_{maj} = 0.24	P_{maj} = 0.21
	CI=[0.25,0.28]	CI=[0.13,0.22]	CI=[0.22,0.28]	CI=[0.31,0.37]	CI=[0.08,0.25]	CI=[0.17,0.25]	CI=[0.19,0.28]	CI=[0.20,0.23]
	N_{tot} = 8,848	N_{tot} = 777	N_{tot} = 2,411	N_{tot} = 3,071	N_{tot} = 227	N_{tot} = 1,299	N_{tot} = 1,063	N_{tot} = 11,959
	N_{maj} = 2,362	N_{maj} = 136	N_{maj} = 606	N_{maj} = 1,060	N_{maj} = 37	N_{maj} = 271	N_{maj} = 252	N_{maj} = 2,570
Late (1998–2017)	P_{maj} = 0.31	P_{maj} = 0.34	P_{maj} = 0.27	P_{maj} = 0.34	P_{maj} = 0.16	P_{maj} = 0.28	P_{maj} = 0.29	P_{maj} = 0.28
	CI=[0.29,0.32]	CI=[0.30,0.38]	CI=[0.24,0.30]	CI=[0.32,0.37]	CI=[0.08,0.24]	CI=[0.24,0.32]	CI=[0.23,0.34]	CI=[0.27,0.30]
	N_{tot} = 9,275	N_{tot} = 1,572	N_{tot} = 2,089	N_{tot} = 3,236	N_{tot} = 237	N_{tot} = 1,331	N_{tot} = 807	N_{tot} = 14,463
	N_{maj} = 2,842	N_{maj} = 529	N_{maj} = 565	N_{maj} = 1,105	N_{maj} = 37	N_{maj} = 374	N_{maj} = 232	N_{maj} = 4,117
Change	8% decade^{-1}	49% decade^{-1}	4% decade^{-1}	−1% decade^{-1}	0% decade^{-1}	18% decade^{-1}	8% decade^{-1}	17% decade^{-1}
Sig. lev.	>95%	>99%	<90%	<90%	<90%	>90%	<90%	>99%
Triad time series	6% decade^{-1}	42% decade^{-1}	7% decade^{-1}	2% decade^{-1}	−15% decade^{-1}	31% decade^{-1}	8% decade^{-1}	
	P = 0.02	*P* = 0.02	*P* = 0.25	*P* = 0.58	*P* = 0.71	*P* = 0.004	*P* = 0.13	

CI is the pointwise 95% CI on P_{maj}. The significance level (Sig. lev.) of the difference is also shown. N_{tot} and N_{maj} are the total number of hurricane and major hurricane estimates, respectively, in each period. The bottom row shows the Theil–Sen trend amplitudes and Mann–Kendall significance levels (*P* values) for the triad time series shown in Figs. 2 and 3.

scenarios (10). As the tropics have warmed, SSTs and TC potential intensity have increased in regions where TCs track, and this provides an a priori expectation that TC intensity has increased, all other factors being equal. Detecting increases in the instrumental record has been hindered by heterogeneities in the best-track data, which we have addressed by creating a globally homogenized record of TC intensity based on homogenized satellite data. This record is limited to the geostationary satellite period, however, and is thus limited to the past four decades.

The amplitude and significance of the trends among the individual ocean basins vary considerably, and are very likely influenced by internal and externally forced regional variability, particularly at decadal and interdecadal timescales. For example, the large trends in the North Atlantic are linked to observed regional multidecadal variability, which very likely represents internal quasi-oscillatory factors (e.g., the Atlantic meridional overturning circulation) and/or both natural and anthropogenic nonoscillatory external factors (e.g., mineral aerosols, or African dust, volcanic activity, and anthropogenic aerosols and greenhouse gas) (5, 32–34). Within the period of our homogenized data, this multidecadal variability manifests as a pronounced trend (red curve in Fig. 3), which complicates detection because the climate drivers of the variability are not fully understood (35, 36). Similarly, multidecadal variability within this period in the Indian and Pacific Oceans manifests as a trend in the Indian Ocean (blue curve in Fig. 3) and a change point in the Pacific Ocean (green curve in Fig. 3). All of these regional climate drivers are likely projecting onto the observed changes and trends in TC intensity documented here. These effects are further complicated by the projection of these modes from one region onto another. For example, Pacific multidecadal variability projects onto TC activity in the Atlantic and eastern North Pacific (37), and Atlantic multidecadal variability projects onto TC activity in the western North Pacific (38).

The lack of significant trends in western North Pacific TC intensity, which has been previously documented (e.g., refs. 39 and 40), substantially reduces the global trend, as the western North Pacific contributes the largest number of estimates to the global sample (Table 1). The lack of intensity trends in the western North Pacific may be due to a pronounced poleward migration of TC tracks (6, 41, 42). This moves TCs into regions of lower potential intensity, which counteracts the effects of increasing mean-state potential intensity (43). This highlights an important relationship between TC track and intensity. The variability and trends in track characteristics introduce an additional source of variability in TC intensity and its trends beyond changes in the thermodynamic state of the ocean/atmosphere (43, 44). Track variability is driven largely by atmospheric variability, which introduces substantial shorter timescale noise that is mostly absent in SST and potential intensity variability.

Ultimately, there are many factors that contribute to the characteristics and observed changes in TC intensity, and this work makes no attempt to formally disentangle all of these factors. In particular, the significant trends identified in this empirical study do not constitute a traditional formal detection, and cannot precisely quantify the contribution from anthropogenic factors. From a storyline, balance-of-evidence, or Type-II error avoidance perspective (e.g., refs. 6 and 45), the consistency of the trends identified here with expectations based on physical understanding and greenhouse warming simulations increases confidence that TCs have become substantially stronger, and that there is a likely human fingerprint on this increase. Given the well-understood impacts and risk that increasingly powerful TCs carry with them, strict adherence to Type-I error avoidance could be considered overly conservative.

Methods

Best-Track and ADT-HURSAT Data. The global best-track intensity data used here are taken from the IBTrACS Version 4.0 data record (46). These data (wind intensity and geographic position) are provided every 6 h on the primary synoptic hours (0, 6, 12, and 18 UTC) during the lifetimes of each TC. The ADT-HURSAT data are provided every 3 h, but only the primary synoptic hour data are used here to match the native temporal resolution of the best-track data. The 6-hourly data from both the ADT-HURSAT and IBTrACS are traditionally referred to as "fixes." These fixes include the estimated location of the TC center at that time and, when available, the estimated wind intensity. The best-track and ADT-HURSAT intensity data are provided within 5-kt bins.

As shown in *SI Appendix*, Fig. S1, there is a lack of available geostationary satellite data in the eastern hemisphere in the years 1978 and 1980. The ADT-HURSAT analyses here exclude these 2 y but include 1979, for which global data are available. The time series analyses shown in Figs. 2 and 3 are based on 3-y triads, with the exception of the first data point, which comprises the years 1979 and 1981. The remaining triads comprise the years 1982–1984, 1985–1987, . . ., 2015–2017. The results are not highly sensitive to this choice. Analyzing annual mean time series or 3-y running mean time series does not change the results in a substantial way.

There are a number of intensity estimates in the IBTrACS data with no corresponding intensity estimate in the ADT-HURSAT, due to missing HURSAT data. These gaps can be due to satellite issues or requirements that occurred in real time, or lost or compromised data that occurred later. Similarly, there are intensity estimates in the ADT-HURSAT with no

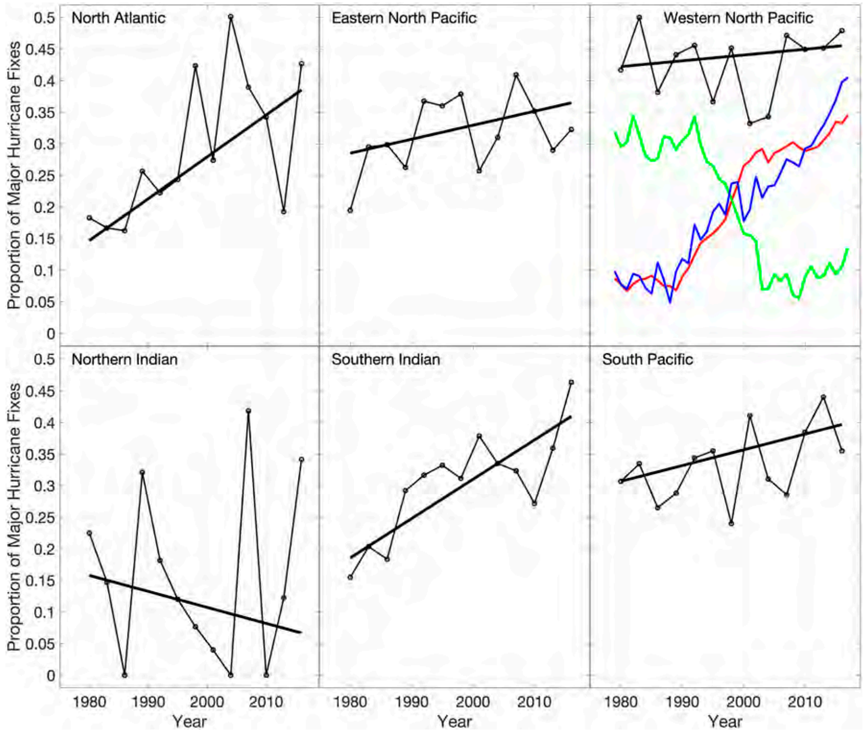

Fig. 3. As in Fig. 2, but for individual ocean basins. The red, green, and blue curves shown arbitrarily in the western North Pacific panel are time series of annually averaged indices representing Atlantic, Pacific, and Indian Ocean multidecadal variability, respectively, and represent 11-y centered means that have been normalized and shifted for plotting purposes.

corresponding intensity estimate (only position) in the IBTrACS, due to various inconsistencies in the collection and reporting of the operational best-track data. The analyses presented here use all of the data available in each of the two datasets, except for the direct comparison shown in *SI Appendix*, Fig. S3. Using only the matched data does not change the analyses in any substantial way.

The HURSAT data rely on best-track center position estimates. These estimates generally become available from the various regional forecast offices around the globe within a year after the end of their respective TC seasons, and, when all of the data are available, the HURSAT data for that year can be constructed. For the analyses here, 2017 is the extent of the available HURSAT data.

The time series of indices of Atlantic, Pacific, and Indian Ocean multidecadal variability shown in Fig. 3 represent the annual mean AMO, IPO, and IOD indices, respectively. These indices are available at the website listed in *Data Availability*.

Metrics of Interest. As noted above, the HURSAT data rely on best-track position estimates, and thus are subject to whatever heterogeneities may exist in the best-track measures of TC frequency and track duration. This also introduces potential heterogeneity into metrics such as accumulated cyclone energy (ACE) and power dissipation, which depend strongly on frequency and track duration. To mitigate the projection of these potential heterogeneities onto the analyses presented here, we focus on intensity metrics that have comparatively minimal dependence of absolute measures of frequency and duration (i.e., intensive, or bulk properties). Actual numbers of estimates are included in Table 1, but changes in these numbers should be interpreted with caution, as they are more likely to be affected by absolute frequency data issues than the probabilities and proportions that are the focus of this work.

Compositing Analysis. As noted above, the ADT-HURSAT data used here span the years 1979–2017. The two periods considered here comprise all of the estimates in the first half (1979–1997) and last half (1998–2017) of these years. The results are robust to using the first and last 15 y or to shifting the year of separation of the two periods. The centroids of the early and later periods are 1988 and 2007, respectively. The composite difference values are then separated by about 19 y.

Statistical Significance. In comparison to the methods of refs. 7 and 9, which concentrated only on the LMI of each TC, the analyses presented here are based on all intensity estimates. This choice is based on the argument that a TC poses a threat at any time during its lifetime, and particularly during (possibly prolonged) periods of major hurricane intensity. These periods will also have a substantial effect on integrated hazard metrics such as ACE and power dissipation index, which LMI does not project onto as clearly. However, while LMI data are essentially independent between the individual TCs, there can be substantial serial correlation along individual TC tracks, and this needs to be taken into account when forming CIs for differences in the probability of exceedance (there is no correlation between one track and another). To address this, every track from every TC was tested for serial correlation at progressively greater lags (*SI Appendix*, Fig. S7). The mean decorrelation timescale (i.e., the time at which the mean lag correlation crosses zero) for the ADT-HURSAT tracks during periods of hurricane intensity is between 12 h and 18 h. For the significance testing on the separation of the cumulative distribution functions shown in Fig. 1, the degrees of freedom in the early and later samples are reduced by a factor of 3, which assumes a decorrelation time of 18 h. The pointwise 95% confidence bounds in Table 1 are given by $F_X(x) \pm z_{0.025}\sqrt{F_X(x)[1-F_X(x)]/N_{eff}}$, where $F_X(x) = P(X \geq x)$ is the complementary cumulative distribution function, x = 100 kt, $z_{0.025}$ is the critical z value (~1.96), and N_{eff} is the reduced (effective) degrees of freedom (one-third of the total number in the sample).

The points in each of the individual triad time series (Figs. 2 and 3) do not show significant temporal autocorrelation (based on a Durbin–Watson test), and none required adjustment of the degrees of freedom to determine significance levels. The significance of the trends is based on the P value of a nonparametric Mann–Kendall test in each time series (Table 1). The slopes of the trend lines are given by Theil–Sen trend lines, which provide a robust nonparametric alternative to ordinary least-squares regression that are insensitive to outliers. The global trend amplitude and significance are essentially unchanged under ordinary least-squares regression and are also robust to the removal of the endpoints of the time series.

Data Availability. The ADT-HURSAT data are available in Datasets S1–S9 and are described in *SI Appendix*. IBTrACS data are available at https://www.ncdc.noaa.gov/ibtracs/. The climate indices shown in Fig. 3 are from the

National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratories (ESRL) Physical Sciences Division website: https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/.

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EXHIBIT 7

EPA United States Environmental Protection Agency

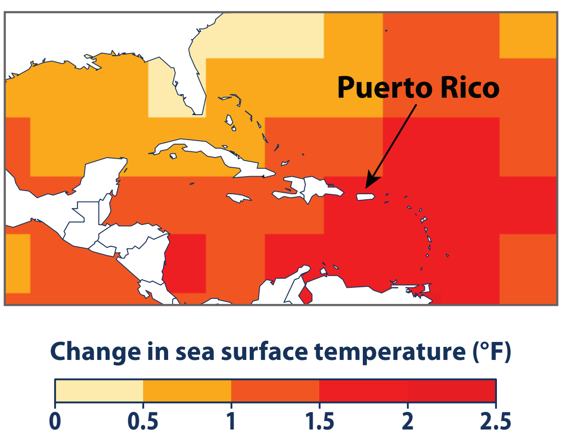
August 2016
EPA 430-F-16-063

What Climate Change Means for Puerto Rico

Puerto Rico's climate is changing. The Commonwealth has warmed by more than one degree (F) since the mid-20th century, and the surrounding waters have warmed by nearly two degrees since 1901. The sea is rising about an inch every 15 years, and heavy rainstorms are becoming more severe. In the coming decades, rising temperatures are likely to increase storm damages, significantly harm coral reefs, and increase the frequency of unpleasantly hot days.

Our climate is changing because the earth is warming. People have increased the amount of carbon dioxide in the air by 40 percent since the late 1700s. Other heat-trapping greenhouse gases are also increasing. These gases have warmed the surface and lower atmosphere of our planet about one degree during the last 50 years. Evaporation increases as the atmosphere warms, which increases humidity, average rainfall, and the frequency of heavy rainstorms in many places—but contributes to drought in others.

Greenhouse gases are also changing the world's oceans and ice cover. Carbon dioxide reacts with water to form carbonic acid, so the oceans are becoming more acidic. Worldwide, the surface of the ocean has warmed about one degree during the last 80 years. Warming is causing mountain glaciers to retreat, and even the great ice sheets on Greenland and Antarctica are shrinking. Thus the sea is rising at an increasing rate.



Rising sea surface temperatures since 1901. The waters around Puerto Rico have warmed by nearly two degrees. Source: EPA, Climate Change Indicators in the United States.

Rising Seas and Retreating Shores

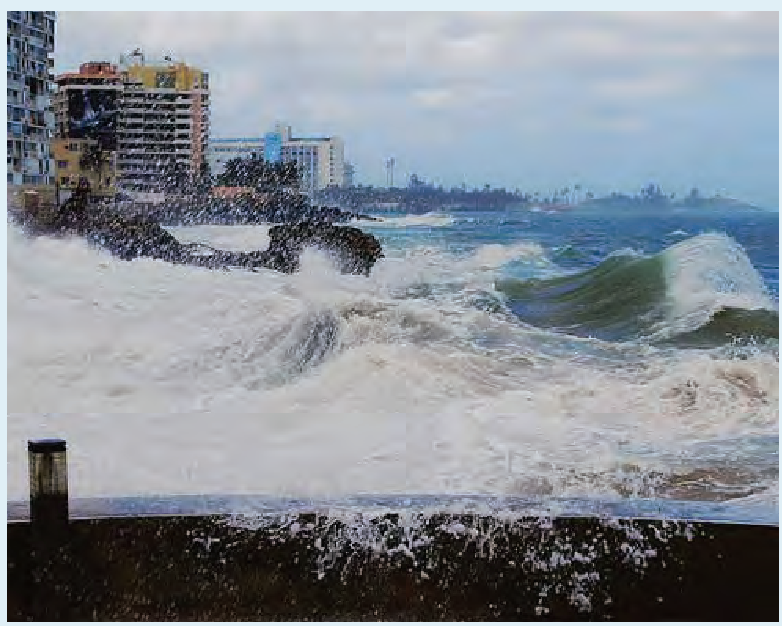
Sea level has risen by about four inches relative to Puerto Rico's shoreline since 1960. As the oceans and atmosphere continue to warm, sea level around Puerto Rico is likely to rise one to three feet in the next century. Rising sea level submerges marshes, mangroves, and dry land; erodes beaches; and exacerbates coastal flooding.

Storms, Homes, and Infrastructure

Tropical storms and hurricanes have become more intense during the past 20 years. Although warming oceans provide these storms with more potential energy, scientists are not sure whether the recent intensification reflects a long-term trend. Nevertheless, hurricane wind speeds and rainfall rates are likely to increase as the climate continues to warm.

Cities, roads, and ports in Puerto Rico are vulnerable to the impacts of both winds and water during storms. Greater wind speeds and the resulting damages can make insurance for wind damage more expensive or difficult to obtain. Coastal homes and infrastructure are likely to flood more often as sea level rises because storm surges will become higher as well. As a result, rising sea level is likely to increase flood insurance premiums for people living along the coast.

The changing climate is also likely to increase inland flooding. Since 1958, rainfall during heavy storms has increased by 33 percent in Puerto Rico, and the trend toward increasingly heavy rainstorms is likely to continue. More intense rainstorms can increase flooding as inland rivers overtop their banks more frequently, and more water accumulates in low-lying areas that drain slowly.



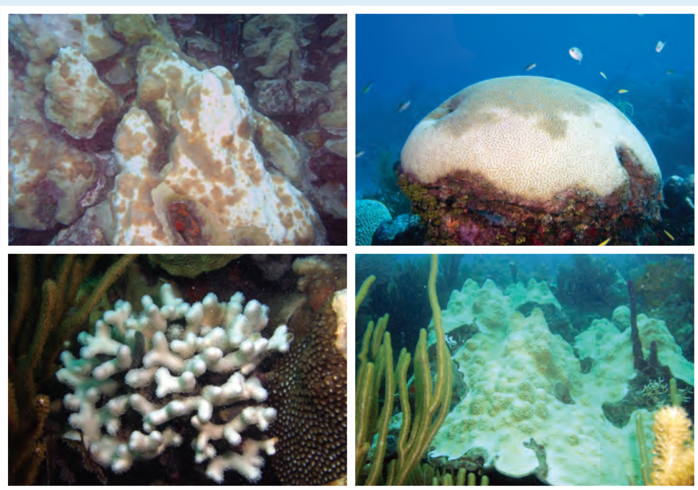
Storm surge in San Juan. Credit: Jorge Rodriguez/Creative Commons.

Water Resources

Although heavy rainstorms may become more common, total rainfall is likely to decrease in the Caribbean region, especially during spring and summer. Warmer temperatures also reduce the amount of water available because they increase the rate at which water evaporates (or transpires) into the air from soils, plants, and surface waters. With less rain and drier soils, Puerto Rico may face an increased risk of drought, which in turn can affect public water supplies, agriculture, and the economy. For example, during the 2015 drought—one of the worst in Puerto Rico's history—hundreds of thousands of people faced water restrictions, and some people's water was turned off for one or two days at a time.

Coral Reefs and Ocean Acidification

In the next several decades, warming waters are likely to harm most coral reefs, and widespread loss of coral is likely due to warming and increasing acidity of coastal waters. Rising water temperatures can harm the algae that live inside corals and provide food for them. This loss of algae weakens corals and can eventually kill them. This process is commonly known as "coral bleaching" because the loss of algae also causes corals to turn white.



Bleached corals off the coast of Puerto Rico. © Hector Ruiz; used by permission.

Increasing acidity can also damage corals. Ocean acidity has increased by about 25 percent in the past three centuries, and it is likely to increase another 40 to 50 percent by 2100. As the ocean becomes more acidic, corals are less able to remove minerals from the water to build their skeletons. Shellfish and other organisms also depend on these minerals, and acidity interferes with their ability to build protective skeletons and shells.

Warming and acidification could harm Puerto Rico's marine ecosystems and economic activities that depend on them. Coral reefs provide critical habitat for a diverse range of species, while shellfish and small shell-producing plankton are an important source of food for larger animals. Healthy reefs and fish populations support fisheries and tourism.

Ecosystems

Warmer temperatures and changes in rainfall could expand, shrink, or shift the ranges of various plants and animals in Puerto Rico's forests, depending on the conditions that each species requires. For example, as summer rainfall decreases, tree species that prefer drier conditions could move into areas once dominated by wet forest species. Other species might shift to higher altitudes. Many tropical plants and animals live in places where the temperature range is fairly steady year-round, so they cannot necessarily tolerate significant changes in temperature. Coqui frogs, bromeliads, mosses, and lichens are potentially vulnerable.

Freshwater ecosystems also face risks due to climate change. Rivers, streams, and lakes hold less dissolved oxygen as they get warmer, which can make conditions less hospitable for fish and other animals.

Agriculture

Higher temperatures are likely to interfere with agricultural productivity in Puerto Rico. Hot temperatures threaten cows' health and cause them to eat less, grow more slowly, and produce less milk. Reduced water availability during the dry season could stress crops, while warmer temperatures could also reduce yields of certain crops. Studies in other tropical countries indicate that climate change may reduce plantain, banana, and coffee yields.

Human Health

Hot days can be unhealthy—even dangerous. Certain people are especially vulnerable, including children, the elderly, the sick, and the poor. Rising temperatures will increase the frequency of hot days and warm nights. High air temperatures can cause heat stroke and dehydration and affect people's cardiovascular and nervous systems. Warm nights are especially dangerous because they prevent the human body from cooling off after a hot day. Since 1950, the frequency of warm nights in Puerto Rico has increased by about 50 percent. Currently in San Juan, the overnight low is above 77 degrees about 10 percent of the time.

Puerto Rico's climate is suitable for mosquito species that carry diseases such as malaria, yellow fever, and dengue fever. While the transmission of disease depends on a variety of conditions, higher air temperatures will likely accelerate the mosquito life cycle and the rate at which viruses replicate in mosquitoes.

Certain types of water-related illnesses already occur in Puerto Rico, supported by its warm marine environment. These include vibriosis, a bacterial infection that can come from direct contact with water or eating infected shellfish, and ciguatera poisoning, which comes from eating fish that contain a toxic substance produced by a type of algae. Higher ocean temperatures can increase the growth of these bacteria and algae, which may increase the risk of these associated illnesses.

The sources of information about climate and the impacts of climate change in this publication are: the national climate assessments by the U.S. Global Change Research Program, synthesis and assessment products by the U.S. Climate Change Science Program, assessment reports by the Intergovernmental Panel on Climate Change, and EPA's *Climate Change Indicators in the United States*. Mention of a particular season, location, species, or any other aspect of an impact does not imply anything about the likelihood or importance of aspects that are not mentioned. For more information about climate change science, impacts, responses, and what you can do, visit EPA's Climate Change website at www.epa.gov/climatechange.

EXHIBIT 8

Evolving Hurricane Risk in Puerto Rico

Kerry Emanuel
Lorenz Center
Massachusetts Institute of Technology

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Summary

We apply basic physical theory and an established technique for estimating hurricane risk from global climate simulations to analyze hurricane risk in Puerto Rico and how it is changing is response to anthropogenic climate change. Consistent with previous analyses and a recently published review of hurricanes and climate change, we present evidence that global warming has tangibly increased the risk of high intensity hurricanes and of heavy hurricane-related rains in Puerto Rico. While it is not possible to ascribe any particular weather event to a unique cause, it is possible assess the probability of weather events and to analyze how such probabilities are evolving over time as a consequence of climate change, whether natural or anthropogenic. The weight of evidence suggests that the likelihood of hurricane winds in Puerto Rico of a magnitude equal to or greater than those experienced during Hurricane Maria of 2017 increased by a factor of about 8 between the middle of the twentieth century and the 20 years centered on 2017 while the probability of regionally averaged rainfall of 600 mm or greater increased by about a factor of 10.

1. Background

Tropical cyclones are giant heat engines that extract heat energy from the ocean at high temperature and export it at the very low temperatures of the upper tropical atmosphere (Emanuel, 1986). The rate of heat input depends largely on the difference between the ocean temperature and that of the first 10 miles or so of the atmosphere, while the efficiency of the engine depends on both the surface temperature and the temperature at the coldest point in the vertical temperature profile. Knowledge of the ocean temperature and the temperature profile of the atmosphere above it can be used to calculate a thermodynamic bound on hurricane wind speeds known as the potential intensity. Comparison between calculated values of potential intensity and wind speeds achieved in computer simulations of hurricane show very good agreement (Rousseau-Rizzi and Emanuel, 2019). Most real hurricanes are prevented from reaching their thermodynamic potential by interaction with atmospheric winds and by storm-induced upwelling of cold water from deeper in the ocean (see the review by Emanuel, 2018). Nevertheless, analysis of the peak wind speeds achieved by hurricane worldwide show that the ratio of these peak winds to the local potential intensity falls along a well-defined universal distribution function (Emanuel, 2000). This strongly suggests that real hurricane wind intensity varies in proportion to the potential intensity.

Addition of greenhouse gases to the atmosphere increases the downwelling flux of infrared radiation at the surface. Absent any compensating factors, the surface must export the excess heat by transferring it directly to the atmosphere. Over tropical oceans, this largely occurs through an increase in evaporation of seawater. The increased evaporative potential goes hand-in-hand with an increase in hurricane potential intensity, so that the addition of greenhouse gases should increase the thermodynamic potential for hurricanes (Emanuel, 1987). Figure 1 shows, using analyzed climate data, that the predicted increase in hurricane potential intensity is in fact occurring.

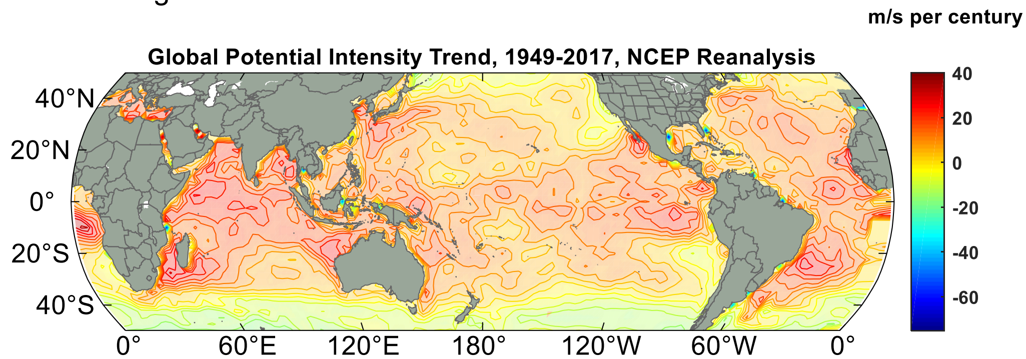

***Figure 1**: Trends in potential intensity (in meters-per-second-per-century) from 1949 to 2017 using NOAA NCEP reanalysis data. These are the trends in the annual maximum values at each grid point.*

The tropical mean rate of increase is about 7 meters-per-second-per-century, consistent with an increase in tropical ocean temperature of about 2°C per century (Emanuel, 1987).

Figure 2 shows the same trend but using another climate reanalysis data set that only extends back to 1979, when satellite data became plentiful. In this case, trends are shown only where they are statistically significant in the sense that there is no more than a 5% probability that the trend could be a result of chance.

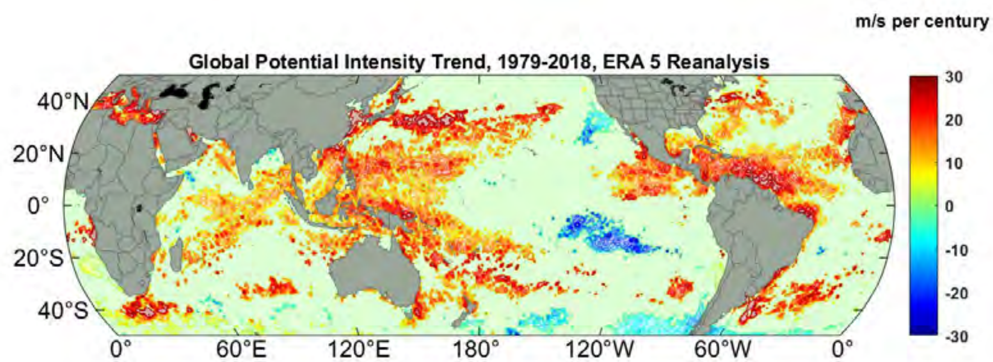

***Figure 2**: Same as Figure 1 but using the ERA 5 reanalysis data from 1979-2018 and showing trends only where they are statistically significant at the 5% level.*

This shows a tropical mean trend over this period of about 5 meters-per-second-per century. Again, these trends are consistent with theoretical predictions dating back to 1987. Theoretically, rising potential intensity should result in an increase in the frequency of the most intense category of tropical cyclones, but high intensity storms are rare and to see this signal against the background of natural and random variability would be difficult. For example, Bender et al. (2010) project an 80% increase in the number of Category 4 and 5 hurricanes in the Atlantic by the end of this century, but show that it would take about 60 years for even such a strong signal to emerge from the background noise. Signal detection should never be confused with risk assessment.

This same study projects, as do many others, that the overall frequency of tropical cyclones should decrease as the climate warms. The overall number is dominated by the far more numerous weaker storms, yet most of the damage and loss of life are owing to strong storms, whose frequency is projected to increase. Weaker storms are expected to become less numerous primarily because of increased thermodynamic inhibition to the formation of tropical cyclones as temperatures increase.

Not all studies indicate a decrease in overall frequency, however. Using a downscaling method to be described presently, Emanuel (2013) projected an increase in overall storm frequency as the climate warms. Recently, Bhatia et al. (2018) also show, using a uniquely high resolution global model, a small increase in global tropical cyclone frequency.

One of the most lethal aspects of tropical cyclones is the storm surge; essentially the same physical phenomenon as a tsunami but caused by wind rather than by shaking sea floor. As sea levels continue to rise, storm surges will propagate further inland, compounding the problem of higher storm intensity.

As we have seen in the recent tragic examples of Hurricanes Harvey and Florence in the U.S. and Tropical Cyclone Idai in Mozambique, flooding cause by torrential rains is often the leading cause of damage, injury, and loss of life in tropical cyclones. As temperature increases, the capacity of the atmosphere to retain water vapor increases exponentially, doubling for each 10ºC increase in temperature. Basic theory backed up by modeling studies, shows unequivocally that hurricanes will produce more rain – much more rain – as temperatures continue to increase. This may prove to be one of the most lethal consequences of climate change.

Very recently, Knutson et al. (2019) published a comprehensive review of the status of research on the effects of climate change on hurricanes. That study reveals a strong consensus among scientific researchers that global warming will increase the incidence of high category hurricanes which, together with sea level rise, will tangibly increase risks associated with storm surges. There is also a near 100% consensus that tropical cyclone rainfall will increase significantly as the climate warms.

While there is an increasingly strong consensus on the effect of climate change on global tropical cyclone activity, less work has been done on regional changes in storm activity. A major current limitation of global climate models is their inability to resolve tropical cyclone inner cores, where the highest winds and heaviest rains occur. This handicap will gradually diminish as the power of supercomputers increases, but this will take many decades. Until then, the scientific community will continue to use a technique known as "downscaling" to estimate regional impacts of climate change. Basically, downscaling involves embedding a high resolution regional computational model within a lower resolution global climate model. This acts like a magnifying glass, allowing one to resolve smaller scale features such as tropical cyclones.
In the following section, we describe one such widely-used downscaling technique and, in Section 3, apply it to estimate climate change effects on tropical cyclones in Puerto Rico.

2. Downscaling Method

Details of the method used here are described in two key references: Emanuel et al. (2006) and Emanuel et al. (2008). Comparison with historical hurricane data and the application of extant methods are described in these two references and in Emanuel (2006). Some applications of the method are given in a set of published papers (e.g. Emanuel, 2010; Emanuel and Jagger, 2010; Emanuel et al., 2010; Emanuel, 2011; Federov et al., 2010; Gnanadesikan et al., 2010; Lin et al., 2010; Mendelsohn et al., 2012).

Basically, the technique begins by randomly seeding the time-evolving climate state of a climate data set or climate model, with weak tropical cyclone-like vortices. As in the case of real tropical cyclones, these vortices move with the large-scale airflow in which they are embedded, plus a flow-relative drift that results from the earth's rotation and sphericity. A highly-resolved, coupled atmosphere ocean hurricane intensity model is then run along the track of each of the vortices. This model was originally developed to help forecast the intensity of hurricanes in near real-time and is still used for that purpose.

In practice, the intensity model predicts that well over 99% of the randomly seeded storms die after a short time. These events are discarded and the survivors are regarded as constituting the tropical cyclone climatology associated with the climate state represented by the climate data set or climate model. Even though only a tiny fraction of the initial seeds survive, the technique is fast enough that it is easy to generate tens or hundreds of thousands of synthetic tropical cyclones.

In a series of papers, some of which are cited above, the synthetic tropical cyclones produced by this technique are rigorously compared against historical hurricanes.

Figure 3 shows an example of 1000 randomly selected tracks produced by this method applied to the ERA40 reanalysis, color coded by Saffir-Simpson intensity. The method captures the known global distribution of tropical cyclones fairly well.

Figure 4 compares annual exceedence frequencies of storm lifetime maximum wind speeds achieved in 7064 synthetic North Atlantic with 355 historical storms recorded over the period 1980-2010. The ordinate shows the number of events whose wind speeds exceed the value given on the abscissa. This comparison shows that the downscaling method captures the full spectrum of observed hurricane intensities.

Further comparisons with historical events shows that this downscaling techniques captures the essential features of the spatial and seasonal distribution of tropical cyclones as well as the observed response of hurricanes to natural climate variations such as El Niño. This gives us some confidence in applying the technique to assessing tropical cyclone risk in the current climate as well as in future climates as simulated by global climate models.

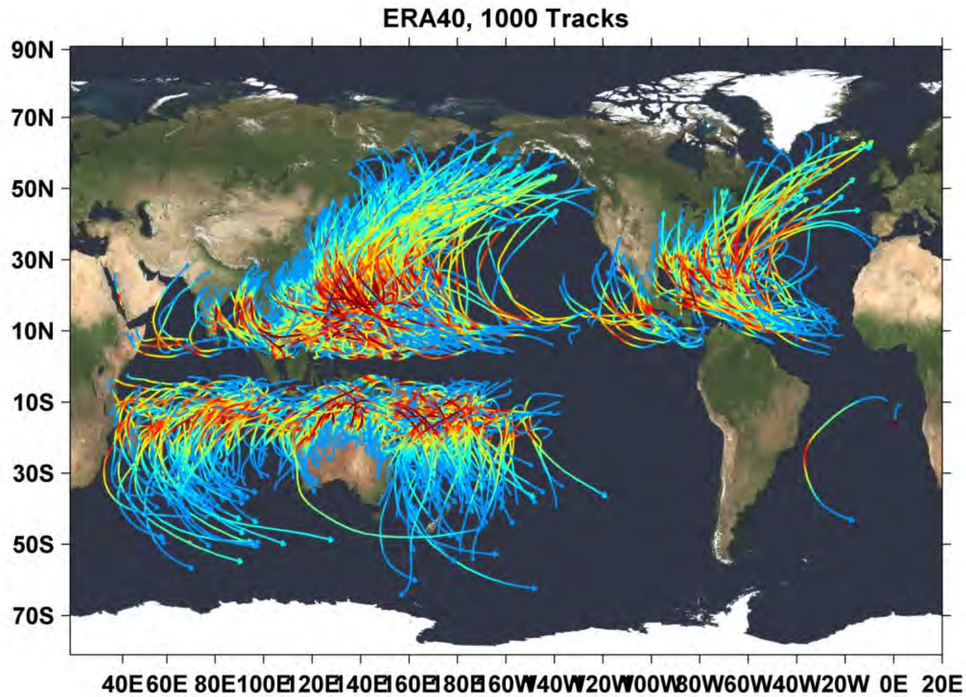

Figure 3: *1000 randomly selected tracks generated using statistics from the ERA40 reanalysis. Colors show Saffir-Simpson intensity.*

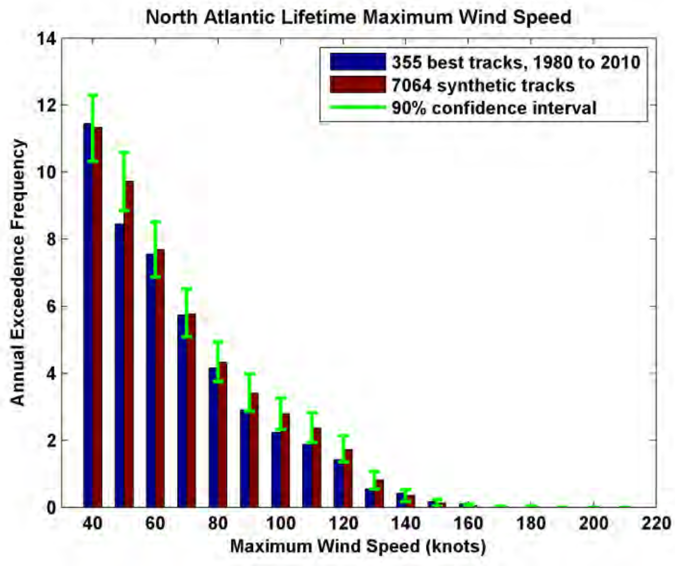

Figure 4: *Annual exceedence frequencies of lifetime maximum wind speeds of 355 historical events (blue) and 7064 synthetic events (red), during the period 1980-2010. The green error bars show the limits within which 90% of the historical frequencies would lie were they drawn from the same distribution as the synthetic frequencies.*

3. Evolving Tropical Cyclone Risk in Puerto Rico

To assess tropical cyclone risk in Puerto Rico, we created 2000 synthetic hurricanes for each of three climate states and six climate models, for a total of 36,000 events. The climate models used were six of those of the CMIP5 generation of climate models, used for the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC, 2014). Only storms passing over one (or more) of a set of line segments surrounding Puerto Rico (see Figure 5) were included in these data sets. Note that storms passing just outside these line segments could also bring heavy rains and high winds to the island, but the strongest events will be included using this filter. We downscaled events for the period 1950-1969, 2007-2026, and 2081-2100. The second two of these periods use climate simulations that assume no attempts to curb greenhouse gas emissions.

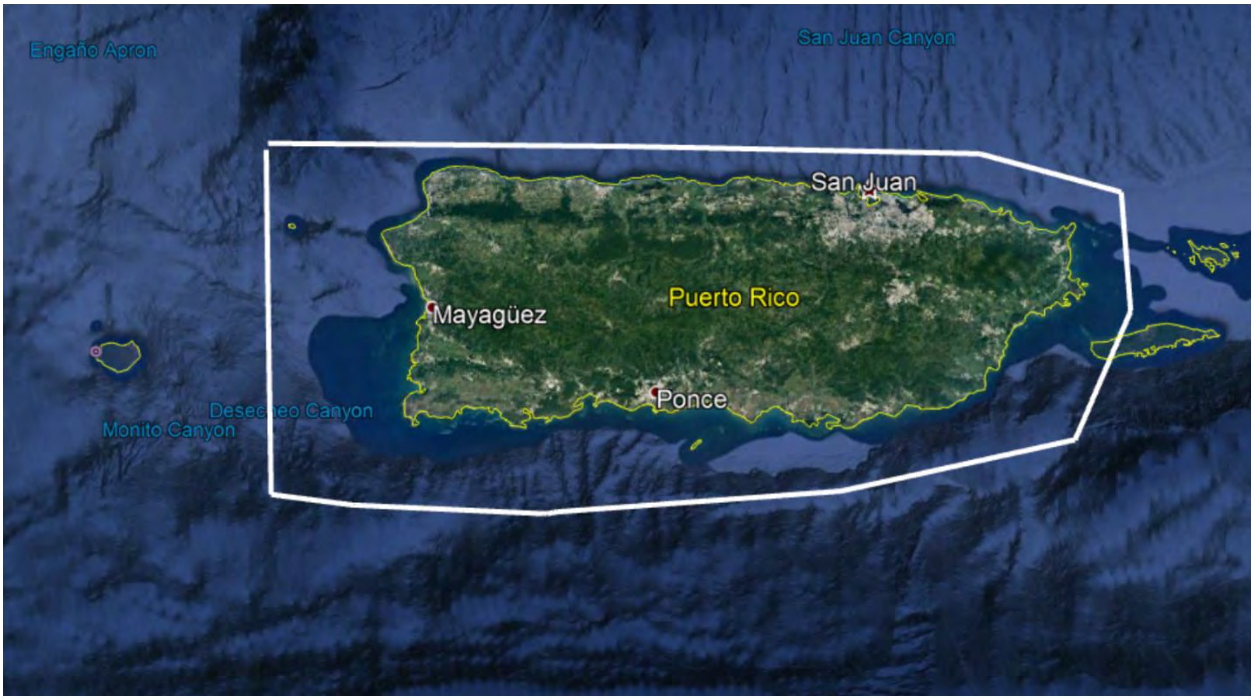

Figure 5: *Filter used to create synthetic hurricanes affecting Puerto Rico. Only storms passing over any of the white line segments were included in this study.*

Tracks of the 50 most intense hurricanes to affect Puerto Rico, out of a set of 2,000 tracks downscaled from one of the climate models for the period 1950-1969, are shown in Figure 6. These most intense storms typically originate well to the east of the island, off the west coast of Africa. After striking Puerto Rico, roughly one third of these intense storms go on to make landfall in the continental U.S. Figure 7 is identical to Figure 6 except that it overlays 10 of the most intense historical tracks to affect Puerto Rico during 1950-1969.

The synthetic hurricane model includes a detailed wind field that describes how winds vary around the center of the storm and how they respond to variations in the roughness of the underlying surface. However, the small mountains of Puerto Rico do not span enough horizontal distance to appreciably affect the model winds. This is evident in Figure 8, which contours the maximum wind speed experienced at each point during the course of an intense hurricane downscaled from one of the six CMIP5 climate models.

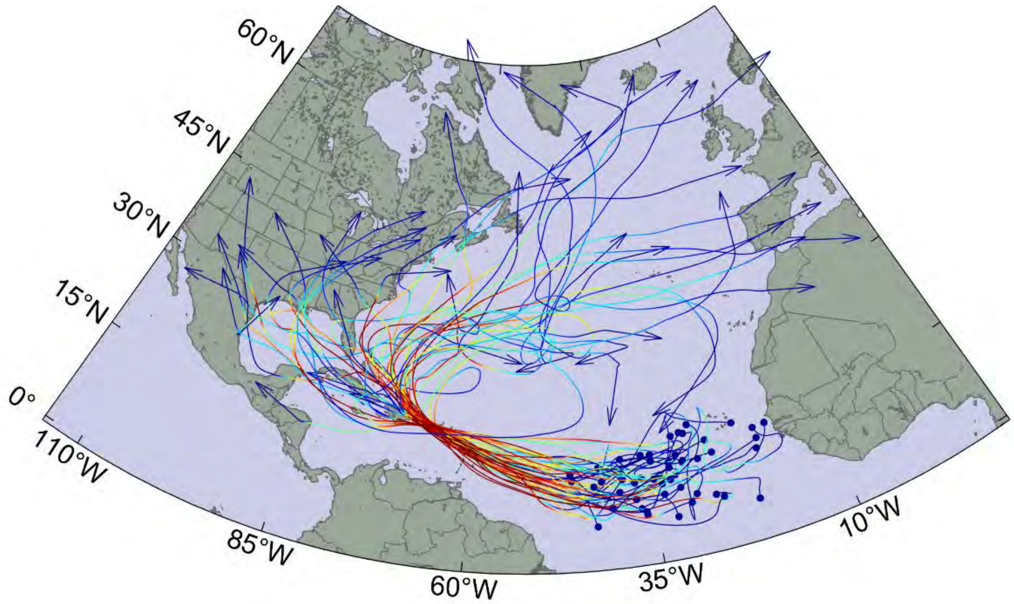

Figure 6: *Tracks of the 50 most intense hurricanes, out of a total set of 2,000 events affecting Puerto Rico, downscaled from one of the six CMIP5 models used in this study, for the period 1950-1969. Colors are an indication of wind intensity.*

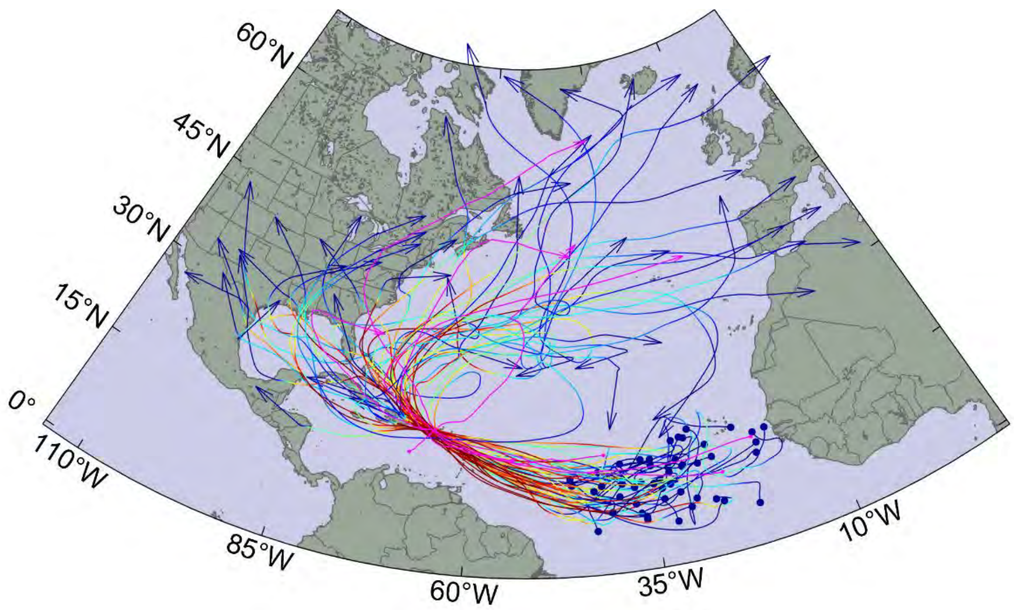

Figure 7: *As in Figure 6 but also showing, in magenta, the 10 most intense historical hurricanes to affect Puerto Rico during 1950-1969.*

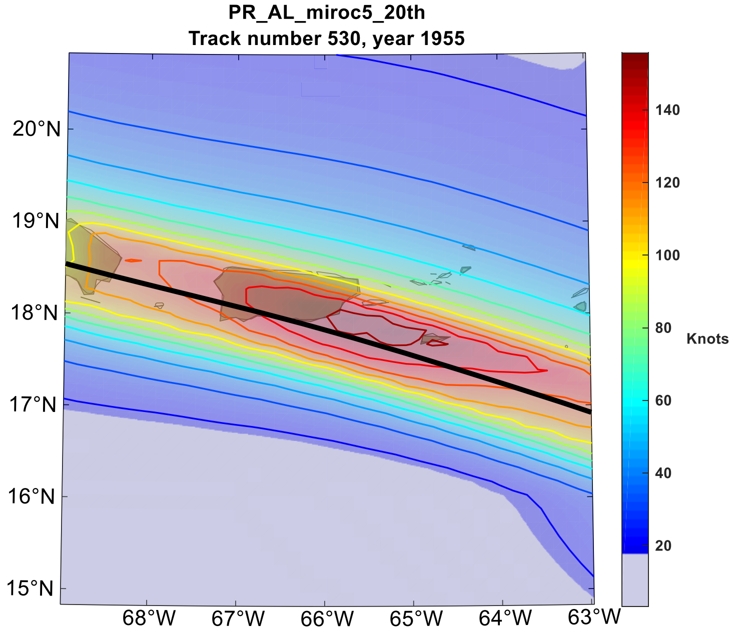

Figure 8: A "wind swath" of the most intense hurricane out of a set of 2,000 that affect Puerto Rico during the period 1950-1969, downscaled from one of the six CMIP5 climate models. The contours show the highest surface wind speed experienced at each point in the course of the event. The black line shows the track of the center of the storm. Note that the wind model does not have enough spatial resolution to resolve variations in surface wind speed caused by the small mountains of Puerto Rico.

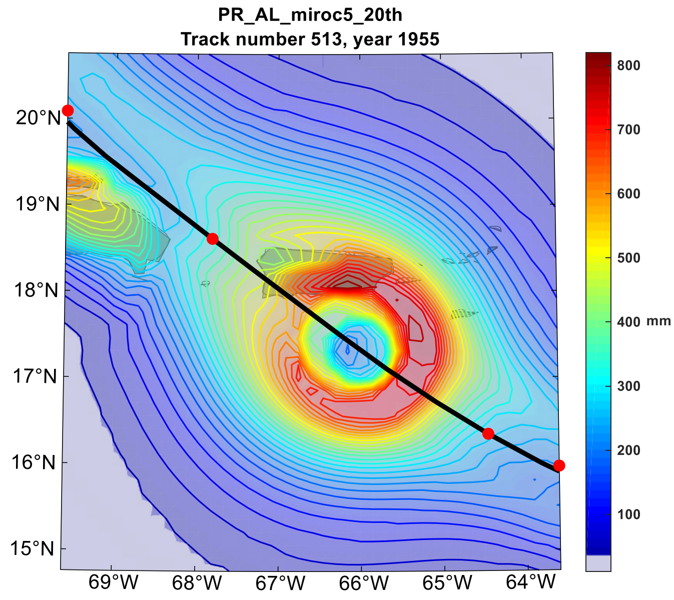

Figure 9: Storm total rainfall, in millimeters, from a downscaled storm whose center passed from southeast to northwest along the black line. The red dots show storm center positions every 12 hours. This storm was downscaled from the same model used in Figures 6-8, also during the period 1950-1969.

Figure 9 shows an example of storm total rainfall produced by a different storm downscaled from the same climate model during the period 1950-1969. The storm passed over the southwest side of the island and moved slowly, allowing heavy rains to fall for a long time. The storm was undergoing an eyewall replacement cycle, accounting for the annual pattern of rain. Rain totals close to 800 mm (about 30 inches) occurred on the southeast-facing slopes of the Cordillera Central. This can be compared to regional totals of 600 mm in Hurricane Maria of 2017. (There were larger values at a few individual rain gauges, but these cannot be compared to the regional average rainfall produced by this model.)

As mentioned previously, we produced synthetic hurricane events for the mid 20th century (1950-1969), for the period 2007-2026, and finally for the end of the century, 2081-2100. These last two periods downscaled climate simulations that assumed that greenhouse gases would continue to accumulate in the atmosphere with no attempt at abatement. The 2007-2026 period is intended to represent the time frame in which Hurricane Maria occurred in 2017, the middle of that period.

The results of these experiments are summarized in Figures 10 and 11. The first shows the annual "exceedance frequency"; that is, the expected annual frequency of wind speeds along any of the line segments in Figure 5 that exceed the value on the bottom axis. Note that the frequencies are on a log scale. The dots represent the mean among the six models downscaled, and the shading represents one standard deviation up and down. The blue dots and shading pertain to 1950-1969, the green to 2007-2026, and the red to 2081-2100. The vertical black line represents the peak surface winds in Hurricane Maria of 2017 at the time it made landfall in Puerto Rico.

This suggests that hurricane winds of Maria's magnitude in Puerto Rico could have been expected to occur roughly once in 240 years in the middle of the 20th century, but the probability had increased to roughly once in 30 years by 2017, a roughly 8-fold increase in likelihood.

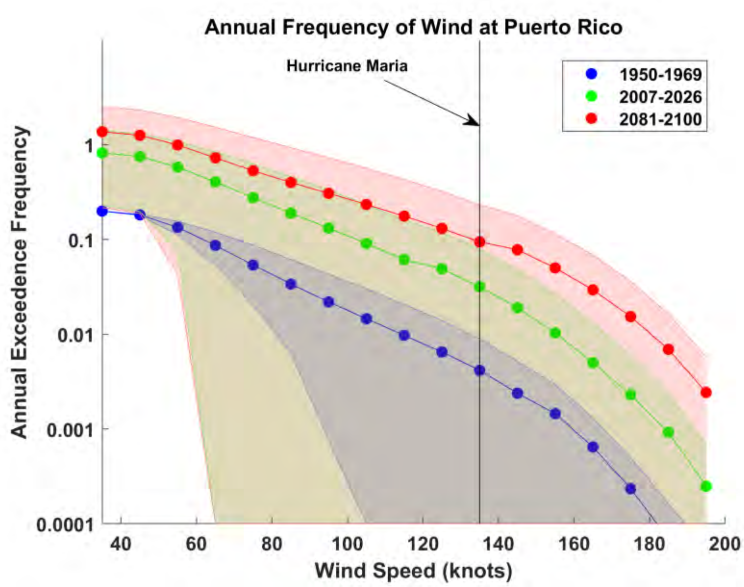

Figure 10: *Frequency with which hurricane surface winds of magnitudes exceeding the value on the bottom axis occur as storms cross the line segments indicated in Figure 5. The dots indicate the multi-model mean, and the shading shows one standard deviation among the six models, up and down. Blue is for 1950-1969, green for 2007-2026, and red for 2081-2100. The vertical black line shows Hurricane Maria's landfall intensity in Puerto Rico.*

The likelihood further increases to once in about 10 years by the end of the century. It may seem odd that the risk increases somewhat more between the middle of the 20th century and the beginning of the 21st than it does between the beginning and end of the 21st century. This is owing to the fact that as temperatures continue to rise, hurricane intensity and probability do not increase indefinitely but rather saturate at a particular value (Emanuel and Sobel, 2013). Thus, even though the temperature can increase without limit, hurricane activity is limited and powerful anthropogenic warming brings us close to that limit by mid-century.

The equivalent chart for storm-total rainfall in the Comerio region of Puerto Rico is shown in Figure 11, with Maria's storm total rainfall indicated again by the vertical black line. The probability of rains of that magnitude are estimated to have been about once in a thousand years around 1960, increasing to once in a hundred years by 2017 and projected to increase to once in 20 years by the end of the century. Note that unlike winds, hurricane rainfall can continue to increase indefinitely as temperatures rise.

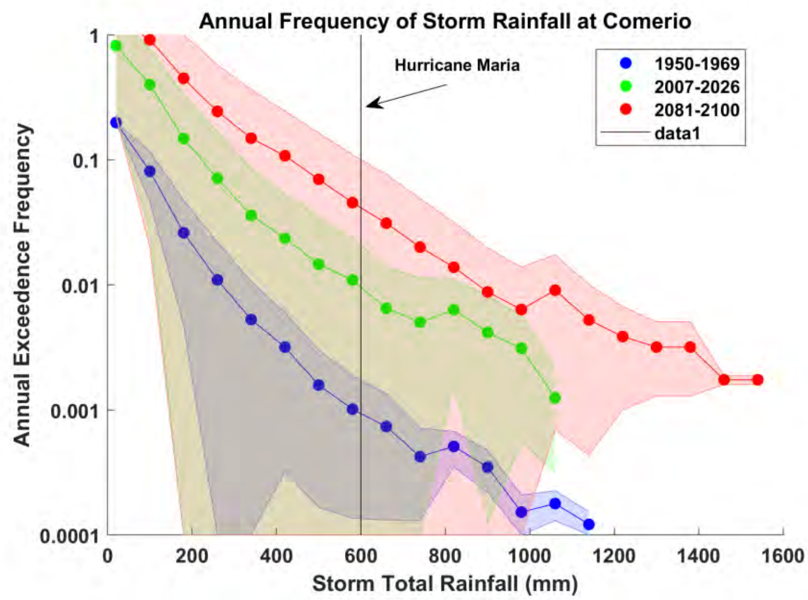

Figure 11: *Annual exceedance frequency of tropical cyclone storm total rainfall with conventions as in Figure 10. The vertical line shows the estimated regional rainfall total of Hurricane Maria in the mountainous Comerio region.*

Both Figures 10 and 11 show considerable spread among the six climate models used in this downscaling analysis. This is in accord with the general experience that today's climate models, though they show reasonable agreement on global metrics like global mean temperature, differ more widely on change in regional climate. Nevertheless, both figures exhibit a weight of evidence that climate warming has already greatly increased the risk of high-intensity hurricane events in Puerto Rico.

4. Conclusions

When bell-shaped probability distributions shift, there can be large changes in the tails of the distributions. For many type of risks, many of the more serious consequences are concentrated in one or the other tail, for the simple reason that societies are usually very well adapted to frequent (non-tail) events. One problematic aspect of tail risk is that in short and flawed historical records of natural phenomena like hurricanes, detecting trends in rare events is difficult if not impossible. But as these are the most important trends, it is imperative to press forward with the best possible assessments of evolving risk by bringing to bear scientific understanding of the climate system, including models, which are codifications of that understanding. We can no more afford to wait until signals emerge in observations of climate than we can wait until an asteroid impact occurs before acting on reliable predictions of asteroid motions made using the laws of physics.

Here we have estimated how hurricane risk in Puerto Rico is evolving and how it will continue to evolve barring concerted action to reduce greenhouse gas emissions. We have used a combination of basic theory and state-of-the-art downscaling models applied to six global climate models run through the end of this century assuming a business-as-usual emissions trajectory. Although there is some uncertainty in these risk assessments owing to differences among the global climate models, the magnitude of the predicted changes leaves little doubt that hurricane risk in Puerto Rico is increasing and had already made an event of the magnitude of Hurricane Maria far more likely in 2017 than it was just 57 years earlier. This risk continues to increase, and although wind intensity should eventually plateau at a somewhat higher level than is now possible, hurricanes rains will continue to increase as long as temperatures do so.

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EXHIBIT 9

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL082077

Special Section:
The Three Major Hurricanes of 2017: Harvey, Irma and Maria

Key Points:
- Hurricane Maria was the most extreme rainfall event when compared to 129 tropical cyclones
- Return periods for Hurricane Maria's precipitation decreased by at least half across Puerto Rico, indicating increased likelihood in recent years
- The probability of Maria's heaviest precipitation has likely increased as a result of long-term climate trends

Supporting Information:
- Supporting Information S1
- Figure S1

Correspondence to:
D. Keellings,
djkeellings@ua.edu

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Extreme Rainfall Associated With Hurricane Maria Over Puerto Rico and Its Connections to Climate Variability and Change

David Keellings[1] and José J. Hernández Ayala[2]

[1]Department of Geography, University of Alabama, Tuscaloosa, AL, USA, [2]Department of Geography, Environment, and Planning, Sonoma State University, Rohnert Park, CA, USA

Abstract Hurricane Maria was associated with record-breaking rainfall over Puerto Rico and caused unprecedented flooding and landslides. Here we analyze the extreme rainfall produced by Hurricane Maria using 35 stations with daily precipitation data from 1956–2016. A covariate-based extreme value analysis point process approach that accounts for natural climate variability and long-term climate change influences on extreme rainfall is applied. Hurricane Maria produced the single largest maximum rainfall event since 1956 and had the highest total averaged precipitation of 129 storms that have impacted the island since 1956. Return periods for an event of Hurricane Maria's precipitation magnitude decreased in 48.6% of stations across Puerto Rico and at least halved when averaged across the island. Within the most affected areas it is likely that the probability of precipitation of Maria's magnitude has increased by a factor greater than 1 (best estimate 4.85) as a result of long-term climate trends.

Plain Language Summary Hurricane Maria was associated with record-breaking rainfall over Puerto Rico, which caused unprecedented flooding and landslides across the island and led to widespread devastation. Here we analyze the extreme rainfall produced by Hurricane Maria using 35 historical weather stations with daily precipitation data from 1956–2016. We use a statistical analysis technique to determine how unusual Maria's rainfall was and if Maria's rainfall can be attributed to climate variability and/or climate change. We find that Hurricane Maria produced the single largest maximum rainfall event since 1956 and had the highest precipitation of 129 storms that have impacted the island since 1956. Our study concludes that extreme precipitation, like that of Hurricane Maria, has become much more likely in recent years and long-term trends in atmospheric and sea surface temperature are both linked to increased precipitation in Puerto Rico. These results place Maria prominently in the context of extreme storms that have impacted Puerto Rico and indicate that such events are becoming increasingly likely.

1. Introduction

On 20 September 2017, Hurricane Maria made landfall on the southeast coast of Puerto Rico as a strong Category 4 hurricane. Tropical cyclones (TCs) are not uncommon to the island, the long-term average for TC landfalls in the northern Caribbean where Puerto Rico is located is one per year (Pielke et al., 2003), the National Hurricane Center Report (2018) on Maria highlights it as the strongest hurricane to make landfall on the island since 1928 (Pasch et al., 2018). Maria broke rainfall records that resulted in unprecedented flooding and mudslides and combined with sustained winds of 249 km/hr at landfall that contributed to a near complete loss of the electrical grid and municipal water supplies for 3.4 million residents (Pasch et al., 2018). All infrastructure was affected with 80% destruction of communication systems, including utility poles and cellular towers, and ultimately the storm resulted in a cost of 90 billion dollars in damage between Puerto Rico and the U.S. Virgin Islands, which exceeds the previously most costly storm to affect Puerto Rico directly, Hurricane Georges in 1998, by 85 billion dollars (Pasch et al., 2018). The official death toll of Hurricane Maria is 64 deaths, though a mortality study by Kishore et al. (2018) found the number of excess deaths associated with Maria is more than 70 times the official estimate bringing the total count closer to 5,000. Disaster-related deaths are difficult to determine. While direct causes of death, such as flying debris or drowning, are relatively easy to assign, indirect deaths resulting from delayed medical treatment or worsening of preexisting conditions are much more difficult to capture (Kishore et al., 2018). Further hindering this effort in Puerto Rico is the requirement that every hurricane-related death be confirmed by the Institute of Forensic Sciences, which requires bodies to be brought to San Juan and delays the issuance of a death

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certificate (Kishore et al., 2018). A recent report concluded that the total excess mortality associated with Hurricane Maria in Puerto Rico was 2,975, which is 46 times the official government estimate (Santos-Burgoa et al., 2018). Additionally, estimates of between 114,000 and 212,000 residents are expected to migrate away from the island in the first year, and up to 14% of the total population by the end of the second year following the event (Meléndez & Hinojosa, 2017).

Several recent studies have focused on the relationship between climate change and the intensity of hurricanes. Mann and Emanuel (2006) found that the underlying factors in the increasing trends of Atlantic hurricane intensity appear to be the influence of primarily anthropogenic forced large-scale warming, while Elsner (2006) found causal evidence that increasing near-surface air temperatures lead to an increase in sea surface temperature (SST) as evidence to support a hypothesis of human-induced climate change influencing the intensity of TCs in the Atlantic. No trend in hurricane frequency has been detected. Other studies have looked at the influences that teleconnections, such as the El Nino–Southern Oscillation (ENSO), and anthropogenic influences, such as carbon dioxide (CO_2), have on hurricane rainfall variability. A recent study by Risser and Wehner (2017) used a covariate-based extreme value analysis (EVA) approach where they found that human-induced climate change likely increased Hurricane Harvey's total rainfall by at least 19% and increased the chance of the observed precipitation by a factor of at least 3.5. Emanuel (2017) examined the annual probability of Hurricane Harvey's observed rainfall finding that it had become 6 times more likely since the end of the twentieth century and that a similar magnitude event will be roughly 18 times more likely by 2081–2100. Another study found that Hurricane Harvey was 3 times more likely due to anthropogenic climate change (Van Oldenborgh et al., 2017). Patricola and Wehner (2018) examined the anthropogenic influence on major TCs finding that relative to preindustrial conditions, climate change has intensified extreme rainfall in Hurricanes Katrina, Irma, and Maria.

Here we focus on two main questions regarding the rainfall associated with Hurricane Maria. How does the extreme rainfall associated with Hurricane Maria compare to the precipitation climatology of TCs in Puerto Rico and how much of the rain attributed to the storm can be explained by natural climate variability and anthropogenic climate change? To address these questions, data from 47 sites are used to estimate Hurricane Maria's rainfall over the 3-day period the storm was within a 500-km radius of the island. Historical data from 35 stations are used in an EVA point process model to examine the relationship between modes of natural variability (North Atlantic Oscillation [NAO], Atlantic Multidecadal Oscillation [AMO], and ENSO), long-term trends associated with anthropogenic climate change (atmospheric CO_2, global temperature, SST, and Cloud cover), and the extreme rainfall associated with Hurricane Maria. Changes in return periods associated with Maria's peak precipitation are estimated for each of 35 historical stations.

2. Data

Six-hourly TC positions were extracted from the International Best Track Archive for Climate Stewardship for the years 1970–2017 (Knapp et al., 2010). A Geographic Information System was utilized to calculate a 500-km buffer around the island, allowing us to define the portion of Maria's track that was within the radius. Maria spent 3 days within the radius from 19 to 21 September 2017. This method has been used by researchers examining TC rainfall in Puerto Rico and the extreme floods associated with those events (Hernández Ayala et al., 2017; Hernández Ayala & Matyas, 2016, 2018). Those studies identified 86 TCs within the 500-km radius around Puerto Rico from 1970–2010. In this study we expanded their data set to include an extra 43 TCs that were within the 500-km radius during 1956–1970 and 2011–2017 for a total of 129 storms.

Daily rainfall totals were obtained from the National Centers for Environmental Information (NCEI) for 19 stations and from the U.S. Geological Survey for 28 rain gauges with daily data for Hurricane Maria, for a total of 47 sites. Daily rainfall totals were obtained from the NCEI for 35 historical stations with a minimum of 70% of observations during the hurricane season that spans from 1 June to 30 November for a period that begins 1 June 1956 and ends 30 November 2016. A recent study examining extreme rainfall associated with Hurricane Harvey in Texas used a similar data coverage percentage to examine the storm's relationship with climate variability and change (Risser & Wehner, 2017).

The teleconnection indices were obtained from the Climate Prediction Center. The Niño 3.4 SST standardized anomalies are part of the ERSSTv5 monthly index from the National Oceanic and Atmospheric

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Administration's National Center for Environmental Prediction (http://www.cpc.ncep.noaa.gov/data/indices/). We used the NAO index constructed by projecting the daily (00Z) 500-mb height anomalies over the Northern Hemisphere onto the leading mode of variability in the NAO (Hurrell, 1995). The AMO index used is based on North Atlantic SST anomalies calculated from detrended long run averages of mean SST observations (Enfield et al., 2001). Global mean CO_2 measurements are a combination of data obtained from the International Institute for Applied Systems Analysis or IIASA (see https://tntcat.iiasa.ac.at/RcpDb) available for 1950–2005 and the record from the Mauna Lua Observatory available for 1958–2017.

Global mean surface temperature data were obtained from the National Aeronautics and Space Administration Goddard Institute for Space Science surface temperature analysis (Hansen et al., 2010). Monthly mean SST data (extended reconstructed SST V5) for a section of the Atlantic Ocean where TCs that impact Puerto Rico develop (12 N, 30 N and 45 W, 80 W) were obtained from the National Oceanic and Atmospheric Administration's Earth Systems Research Lab for 1956–2017. Monthly mean cloud cover data for the same section of the Atlantic Ocean were obtained from the International Comprehensive Ocean-Atmosphere Data Set for 1956–2017. It is well known that there is a relationship between warm Atlantic SSTs and the intensity and frequency of major TCs (Emanuel, 2005, Webster et al., 2005), and for that reason SSTs in a section of the Atlantic, where a significant increasing trend in SSTs has been found (Deser et al., 2010), were examined in this study. Since cloud cover is highly influenced by changes in SST, it was also included as one of the independent variables in this study.

3. Methods

3.1. Spatial Interpolation

The mean total average and the maximum rainfall were extracted from the 3-day precipitation totals for Hurricane Maria for the dates (19–21 September) that the storm was within a 500-km radius of Puerto Rico. The mean total average and maximum rainfall for Hurricane Maria were then compared to the other 129 TCs that have impacted Puerto Rico since 1956. Geostatistical interpolation was combined with historical observations in order to maximize the available record for analysis as only 7 of the 35 historical stations remained operational during the passage of Maria. An inverse distance weighted and ordinary kriging (OK) surface of maximum rainfall for Hurricane Maria were constructed from the 47 stations with data for the 3-day period in order to examine the spatial distribution of extreme precipitation associated with the event. The inverse distance weighted and OK surfaces were highly correlated (0.930), and the OK interpolated surface was then used to extract the maximum rainfall for each of the 35 historical station locations. The OK method has been used previously in Puerto Rico to examine the spatial distribution of TC rainfall and its relation to extreme floods (Hernández Ayala et al., 2017; Hernández Ayala & Matyas, 2018).

We have divided the stations on the island into two regions. The entire island forms the large region containing all 35 stations. The small region contains 19 stations. Stations were grouped in this way to differentiate between Hurricane Maria's precipitation impact on the entire island as a whole versus the diagonal swath of Maria from southeast to northwest where the highest precipitation values (>300 mm) were recorded (Figures 1a and 1b). Puerto Rico historically exhibits high spatial variability in hydrology given its varied topography and diverse precipitation formation mechanisms (Hernández Ayala et al., 2017). This variability is illustrated in Maria's rainfall with some stations at low elevation in the east and west periphery of the island experiencing much lower precipitation than those closer to Maria's track or those at higher elevation.

3.2. EVA

An EVA was conducted for each of the 35 historical stations individually based on daily precipitation time series for the hurricane seasons of 1956–2016. The 2017 observations were intentionally excluded to provide an out-of-sample analysis of Hurricane Maria. We use a point process approach to EVA and extend it to incorporate atmospheric variables (Coles, 2001). Such an approach has previously been used to examine the influence of covariates on extreme meteorological values (Furrer et al., 2010; Keellings & Waylen, 2014; Photiadou et al., 2014) and more recently, in block maxima form, to attribute risk of individual events (Risser & Wehner, 2017). The point process approach is advantageous in that far more of the information about the upper tail of the distribution is available than would be possible using a smaller sample of block maxima (Coles, 2001). A relative threshold equivalent to the 99th percentile of observations at each station

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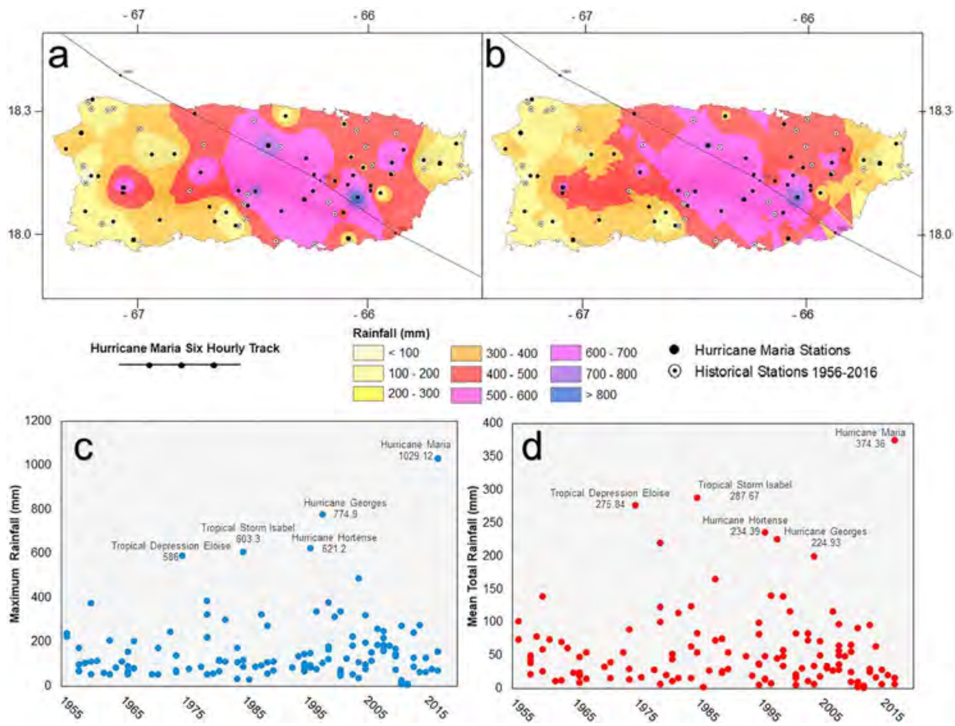

Figure 1. Maximum daily rainfall interpolated surfaces for Hurricane Maria using inverse distance weighted (a) and ordinary kriging (b). Island maximum (c) and island mean total rainfall (d) from 129 historical tropical cyclones with the top five storms labeled.

is used to define an extreme data series of precipitation events crossing this threshold. These extreme events are said to be part of a Poisson process as they are occurring randomly and at a variable rate (Coles, 2001). Statistical theory states that maximizing the likelihood of this Poisson process leads to estimates of the parameters μ (location or central tendency), σ (scale or variance), and ξ (shape or skew) of the limiting generalized extreme value (GEV) distribution of the corresponding block maximum (Coles, 2001). The cumulative distribution function of the GEV is given by

$$P(x) = \exp\left[-\left\{1+\xi\frac{x-\mu}{\sigma}\right\}^{\frac{-1}{\xi}}\right]$$

Multiple covariates are introduced into the estimation of GEV parameters such that those parameters are allowed to vary over time and thus characterize changes in the distribution of extreme precipitation events over time. Multiple covariates are used: annually averaged Niño3.4 index, annually averaged AMO index, seasonally averaged NAO index, seasonally averaged global CO_2, global mean surface temperature, seasonally averaged SST, and cloud cover. These covariates were chosen as they are known to influence TC activity in the Atlantic, and they provide a clear distinction between modes of natural variability and long-term change associated with human influences (Hernández Ayala & Matyas, 2016; Patricola et al., 2014; Risser & Wehner, 2017).

The covariates are introduced as non-stationary signals in Generalized Linear Models of both the location and log-transformed scale parameters of the GEV such that

$$\mu(x) - \beta_{0_{(i)}} + \beta_{1(i)}x$$
$$\ln\{\sigma(x)\} = \beta_{0_{(i)}} + \beta_{1(i)}x$$
$$\xi(x) = \beta_{0(i)}$$

where $\beta_{0(i)}$ are the stationary model parameter estimates and $\beta_{1(i)}x$ are linear transformations of the time-varying covariates (Coles, 2001). The shape parameter, ξ, was modeled as an intercept only term as this

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parameter is numerically difficult to estimate with any accuracy (Katz et al., 2002). All possible linear combinations of covariates are examined and Akaike information criterion (AIC) in combination with the likelihood ratio test is used to select the best model, as this is most appropriate for comparing nested models fitted with fixed maximum likelihood estimation (Coles, 2001). The best estimates of all statistical parameters in the AIC/likelihood ratio test selected model are obtained through maximum likelihood estimation (MLE), and bootstrapping is used to quantify uncertainty in these estimates (see the supporting information for more details). From these estimates return values (corresponding to the quantiles of the distribution of extreme precipitation), return probabilities (the probability of a particular magnitude of precipitation), and return periods (the inverse return probability) are calculated.

4. Results

As a tropical island, Puerto Rico receives a lot of precipitation, especially in the north and central regions of the island, where rainfall can range from 3,000–4,300 mm annually (Colón-Torres, 2009). Out of 129 storms that impacted Puerto Rico since 1956, including those to hit directly or within a 500-km radius of the island, the extreme rainfall associated with Hurricane Maria had the largest maximum daily precipitation of 1,029 mm, equivalent to over one fourth of the average total annual rainfall at the wettest location on the island at the Yunque National Rainforest. Overall, Hurricane Maria exhibited the highest values in maximum daily precipitation (based on all days when storm was within 500 km of island) and total mean precipitation (mean precipitation total from that accumulated at each station while storm within 500 km of island) when compared to the other 128 TCs that have impacted Puerto Rico since 1956 (Figures 1c and 1d). Hurricane Maria exhibited a 30% increase from the previous TC-related highest total mean rainfall event (Tropical Storm Isabel in 1985; José J. Hernández Ayala & Matyas, 2018). When compared to Hurricane Georges, the last major storm to make landfall on the island in 1998, and previously the costliest weather event, Maria exhibited a 66% increase in island mean total rainfall and a 33% increase in island maximum total precipitation.

Previous work of Hernández Ayala and Matyas (2016) found that extreme rainfall (>50 mm) occurred across Puerto Rico when a storm center passed within a distance of 233 km or less, total precipitable water (TPW) exceeded 44.5 mm, midlevel relative humidity was greater than 44.5%, and horizontal translational speed measured at 6.4 m/s or less. Hurricane Maria exceeded those thresholds with a TPW of 51.5 mm, a midlevel relative humidity of 53%, and an average horizontal translational speed of 3.65 m/s between 19 and 21 September, considering measurements before and after landfall on the island. In perspective of past events, Tropical Storm Eloise (1975) and Hurricanes David (1979), Hortense (1996), and Georges (1998) triggered flash floods and mudslides that caused combined losses of more than 3 billion dollars and more than 50 fatalities over the island (Bennett & Mojica, 1998; Hebert, 1976, 1980; J.J. Hernández Ayala et al., 2017; Pasch et al., 2001; Pasch & Avila, 1999) yet all of these impacts combined do not match the life and economic losses associated with Hurricane Maria.

Hurricane Maria's highest precipitation peaks were clustered in the eastern region of the island, especially in the southeast where a station recorded 1,029 mm of rain on 20 September 2017 (Figure 1). Hurricane Maria's precipitation decreased from east to west, with the exception of an area in the interior west where some sites recorded values between 300 and 500 mm. The spatial pattern of maximum rainfall associated with Hurricane Maria (higher east and lower west) is generally similar to that exhibited when TCs approach within 220 km of Puerto Rico's coast and are embedded in moisture environments of 50 mm of TPW (José J. Hernández Ayala & Matyas, 2018).

Return period estimates for Maria's observed maximum daily precipitation are shown in Figure 2a. Results from the EVA show 10% to almost 100% reductions in Maria's estimated return period through the record across much of the island (Figure 2b) and a significant (as per Mann-Kendall test; Kendall, 1955) decreasing trend in return period estimates of Maria's maximum daily precipitation at 17 of the 35 stations, which suggests that a rainfall event of the magnitude of Hurricane Maria has become more likely at these locations (Figure 2c). The changes in return periods were estimated from GEV parameters of stationary or null models fitted to moving windows of 30 years through the record 1956–2016, at stations where inclusion of covariates offered no model improvement, and by allowing GEV parameters to vary through time with covariates, at stations where inclusion of covariates improved model fit. The majority of stations show a decreasing

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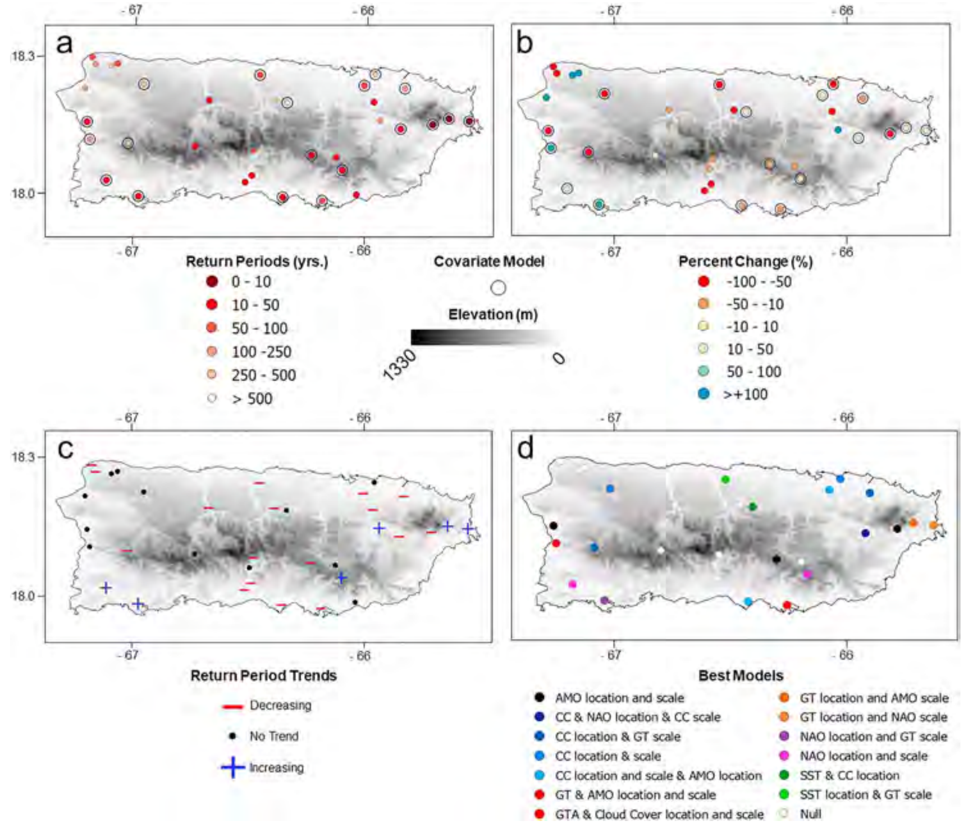

Figure 2. (a) Estimates of Maria's maximum daily precipitation return period at 35 historical stations (using the ordinary kriging interpolation estimates). (b) Percent change in estimate of Maria's maximum daily precipitation return period between beginning and end of record (1956–2016). A circular outline is shown to highlight stations where a covariate model was selected over the null model. (c) Stations with positive, no trend, or negative trends in estimated return periods. (d) Extreme value analysis point process selected best models at each of the 35 stations with covariate and related generalized extreme value parameter indicated. AMO = Atlantic Multidecadal Oscillation; NAO = North Atlantic Oscillation; SST = sea surface temperature; CC = cloud cover; GT = global mean surface temperature; GTA = global surface temperature anomalies.

trend in return period (Figure 2c). Six stations exhibit increasing trends in return periods that may be explained by the highly variable nature of TC rainfall in the central and western regions of the island and influence of varied precipitation mechanisms (Colón-Torres, 2009; José J. Hernández Ayala & Matyas, 2018).

When return period estimates of Maria's maximum daily precipitation are averaged within the large and small regions, we find that estimated return periods and their 90% confidence intervals are decreasing through the record in both regions (Figures 3a and 3b). The return period estimate has decreased from approximately 300 to 115 years corresponding to a roughly threefold increase in return probability in the large region. In the small region, the return period estimate has decreased from approximately 290 to 152 years corresponding to a roughly twofold increase in return probability.

The AIC and likelihood ratio test selected best models include covariates at 19 stations (54.3%) indicating statistically significant relationships between extreme rainfall and the climate variability and change variables, predominantly AMO, NAO, global temperature, and cloud cover (Figure 2d). Eleven of these stations are located within the small region. These results suggest that fluctuations in SSTs in the Atlantic (as indicated by the AMO and NAO indices) in combination with the long-term upward trend in global temperatures and cloud cover are related to extreme rainfall events in Puerto Rico. It is also of note that ENSO offered no model improvement and was thus not included as a covariate in any model.

The covariate-based EVA models permit exploration of the effects of those covariates on extreme precipitation so that we may isolate the effects of modes of natural and long-term anthropogenic sources of variation.

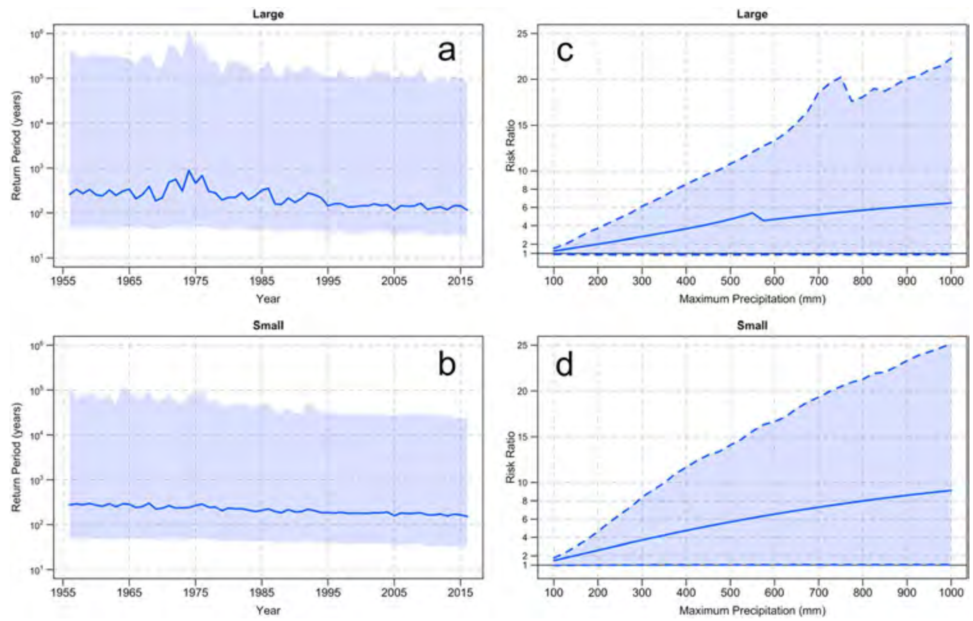

Figure 3. Return period for observed Hurricane Maria maximum daily precipitation with 90% confidence interval using the kriged station average for the large (a) and small (b) regions. Risk ratio comparing the probability of a range of peak storm precipitation for 2017 values of all covariates versus 1956 values of long-term trend covariates holding all other covariates constant at observed 2017 values (solid line) for the large (c) and small (d) regions. Likely (66%) confidence bound shown as dashed line.

This is possible through comparison of conditional probabilities of event magnitude in actual versus counterfactual realities. First, the covariate model can be used to estimate the probability of exceeding, Z, above some threshold, z, of precipitation conditional upon observed 2017 values of the covariates, for example, AMO and global temperature:

$$p_1(z) \equiv P(Z > z | 2017 \text{ values of AMO and global temperature})$$

Second, the probability of Z exceeding threshold z is calculated again, but in the counterfactual reality of 2017 observed AMO and 1956 observed global temperature:

$$p_0(z) \equiv P(Z > z | 2017 \text{ value of AMO}, 1956 \text{ value of global temperature})$$

The likelihood of these two events can then be compared using the risk ratio as is commonly used in probabilistic event attribution (National Academies of Sciences, Engineering, and Medicine, 2016; Pall et al., 2014; Risser & Wehner, 2017):

$$RR(z) = \frac{p_1(z)}{p_0(z)}$$

Here risk refers to the relative risk of the event under observed conditions versus the counterfactual reality. Figures 3c and 3d show the best estimates of this risk ratio for a range of storm event peak precipitation (100–1,000 mm) for the large and small regions. Only stations where the best model included long-term trend covariates (atmospheric CO_2, global mean surface temperature, SST, and cloud cover) were included in calculation of risk ratios. The small region comprised 9 (of 17 stations, 53%) stations with long-term covariates identified in the best model and the large region comprised 14 (of 35 stations, 40%) stations. The best estimates of risk ratios in both regions are above one for the entire range of maximum daily precipitation. However, the likely lower bound is below one in the large region and thus not statistically significant. For Maria's mean maximum daily precipitation (large region: 350 mm, small region: 412 mm) the best estimates of the risk ratio are 3.22 (lower bound 0.79) for the large region and 4.85 (lower bound 1.02) for the small

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region. These lower bound estimates are notably static across the range of maximum precipitation and thus insensitive to observational uncertainty. The step change at around 550 mm in Figure 3c is caused by a single station, in the large region, exhibiting a negative shape parameter value in the fitted GEV model. A negative shape parameter indicates a thin upper tail of precipitation and a bounded distribution that reaches an upper limit. In reality statistical precipitation distributions are bounded, but it is not uncommon to fit unbounded distributions as is the case for all other stations on the island (Cooley et al., 2007; Risser & Wehner, 2017). Concordant patterns of estimated return periods and risk ratios were found under identical analysis using only data from the seven stations that remained operational during the passage of Maria (see the supporting information).

As with other attribution studies using similar statistical methods applied to observational data, as was done here, it is essential to be aware that these results should only be interpreted in the Granger causality sense (Granger, 1969). As such, these results cannot prove any causal relationships, but they can make risk ratio attribution statements to climate trends. For Hurricane Maria's precipitation over Puerto Rico our models suggest that there is a likely increase in the chance of observing Maria's peak precipitation, which is attributable to long-term climate trends, at over half of the stations in the small region as the likely lower bound risk ratio is above one. In the large region, less than half of the stations exhibit an increase in the risk ratio and the likely lower bound is below one.

5. Conclusions

In the sense of the historical record, Hurricane Maria was an unprecedented storm event for Puerto Rico. The island has not been impacted by a storm producing as much peak or total precipitation at any time during the past 60 years. In a statistical sense, Maria's precipitation is an extreme outlier in the historical record at most locations across the island and as such may have been the result of physical processes that were not present during 1956–2016. As EVA provides an estimated limiting GEV distribution based on observations, it is, therefore, limited by those observations in providing a statistical representation of underlying physical processes. In this study, the out-of-sample estimation of Maria's peak precipitation return periods may be overestimated given the length of the historical record. However, the lower bound of the risk ratios in Figures 3c and 3d are stable over the range of all maximum precipitation values, including historically observed levels and those far exceeding that of Maria, suggesting that the changes in extreme statistics are robust. Almost half of the stations exhibit large reductions in return period estimates through the record with Maria's peak precipitation estimated to be much more likely in recent years. When stations are aggregated into large and small regions both agglomerations show a halving of Maria's estimated return period during the record.

Puerto Rico exhibits large variability in its hydroclimate at inter and intra-annual timescales as a result of the random passage of tropical systems and other heavy precipitation producing events such as easterly waves, cold fronts, and convective storms. Since 1956, 129 tropical storms have passed within 500 km of the island and together Puerto Rico and Hawaii account for 32% of the observed flows above the 99th percentile of all unit discharges in the United States despite representing less than 5% of all observations (O'Connor & Costa, 2004). Such extreme variability present within the historical record across Puerto Rico has likely made EVA estimation of return periods and risk ratios difficult and may account for both the lack of stations with significant physical covariate-based models and lack of those with likely lower bounds of relative risk above one.

Data limitations and the inherent stochastic nature of rainfall in Puerto Rico have restricted our ability to reach definitive conclusions on the relationships between Maria's precipitation and climate variability and change. Only 19 of 34 stations saw improvement over null models through introduction of physical covariates, but ENSO was not statistically significant as a covariate suggesting that modes of Atlantic variability and long-term trends related to human-induced climate change have more influence here. Nine (of 17) stations in the small region of the island, which was most affected by Maria's precipitation, have likely lower bounds of relative risk above one indicating a significant long-term climate trend influence on the storm's precipitation there. Further studies based on dynamical modeling are needed to confirm this finding.

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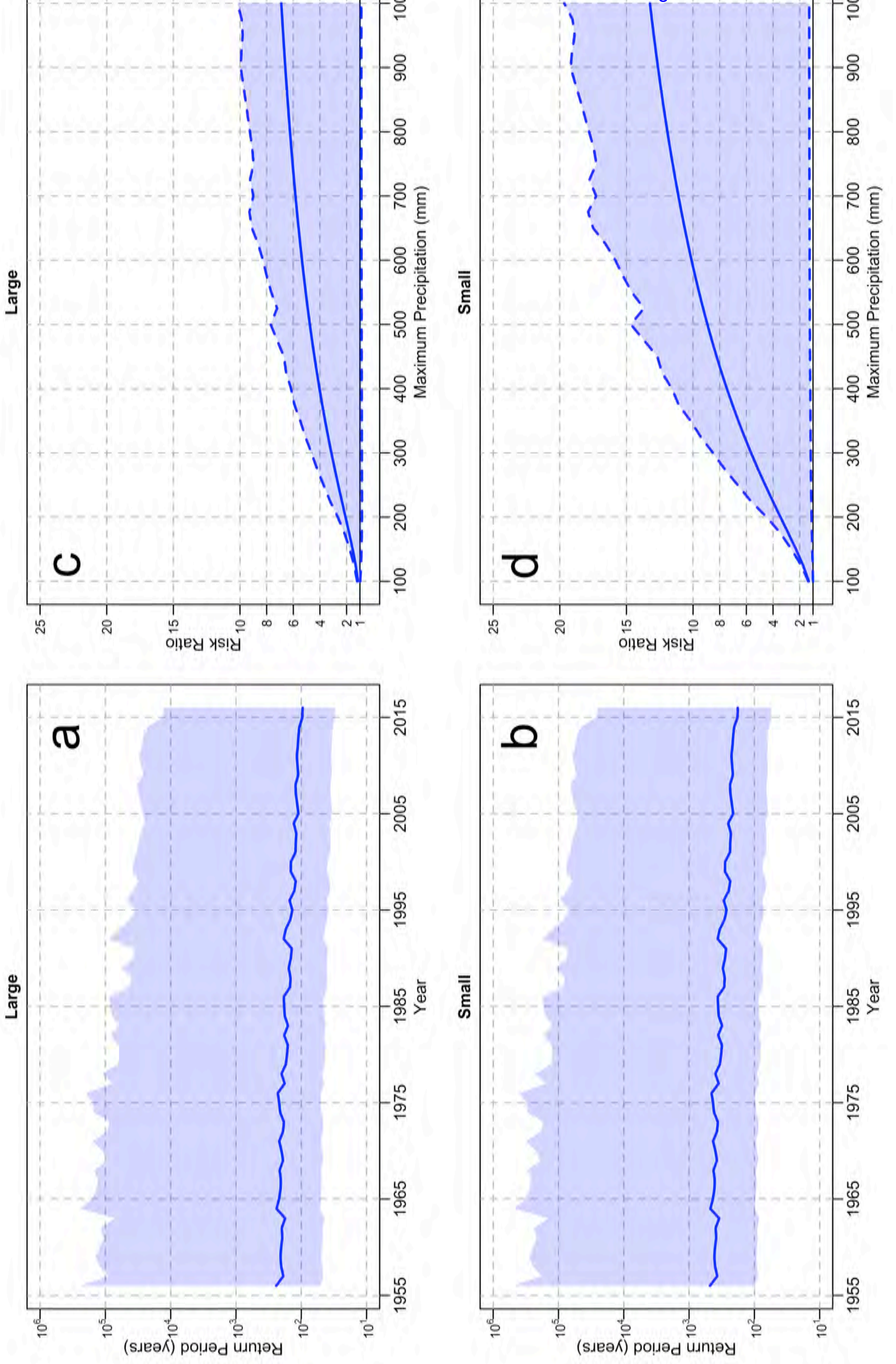
Erratum

In the originally published version of this article, the reference Colon, T., & Jose, A. (2009). Climatologia de Puerto Rico. La Editorial Universidad de Puerto Rico. San Juan, should have been listed as Colón-Torres, J. A. (2009). Climatología de Puerto Rico. La Editorial Universidad de Puerto Rico. San Juan, PR. This reference and its citations in text have since been corrected, and the present version may be considered the authoritative version of record.


Large
a
Return Period (years)
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Risk Ratio
Maximum Precipitation (mm)
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d

AGU PUBLICATIONS

Geophysical Research Letters

Supporting Information for

Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change

David Keellings[1] and José J. Hernández Ayala[2]

[1]Department of Geography, University of Alabama, Tuscaloosa, Alabama, USA
[2]Department of Geography, Environment and Planning, Sonoma State University, Rohnert Park, California, USA

EVA Analysis

Maximum likelihood estimation is used for Generalized Extreme Value (GEV) distribution parameter estimates as part of a point process extreme value theory modeling approach via the extRemes and ismev packages for R. Akaike Information Criterion (AIC) and the likelihood ratio test are used to select the best model from either the null/stationary model or one of a combination of physical atmospheric covariates. The covariates are introduced as non-stationary signals in Generalized Linear Models (GLMs) of both the location and log-transformed scale parameters of the GEV such that:

$$\mu(x) = \beta_{0(i)} + \beta_{1(i)}x\ldots$$
$$\ln\{\sigma(x)\} = \beta_{0(i)} + \beta_{1(i)}x\ldots$$
$$\xi(x) = \beta_{0(i)}$$

where $\boldsymbol{\beta_{0(i)}}$ are the stationary model parameter estimates and $\boldsymbol{\beta_{1(i)}x}$ are linear transformations of the time-varying atmospheric covariates AMO, ENSO, NAO, CO2, global mean surface temperature (GT), monthly mean sea surface temperature (SST), monthly mean cloud cover (CC). Additional covariates are added through linear combinations of coefficient terms. The shape parameter, ξ, was modeled as an intercept only term as this parameter is numerically difficult to estimate with any accuracy (Katz et al., 2002). In addition to parameter estimates, the r-year return value for year t, vt(r), is estimated from the 1-1/r quantile of the distribution of extreme precipitation values. Here, the r-year return value is equivalent to the magnitude or peak precipitation, in an event above the 99th percentile threshold of all daily precipitation, expected to be exceeded on average once every r years such that:

$$\boldsymbol{P\left(Z_t > v_t(r)\right) = \frac{1}{r}}$$

Based on the non-stationary form of the GEV CDF, noted in the main text, vt(r) can be defined as (Coles, 2001):

$$\boldsymbol{v_t(r) = \begin{cases} \mu_t - \dfrac{\sigma_t}{\xi_t}\left[1 - \left\{-\log\left(1 - \dfrac{1}{r}\right)\right\}^{-\xi_t}\right], \xi_t \neq 0 \\ \mu_t - \sigma_t \log\left\{-\log\left(1 - \dfrac{1}{r}\right)\right\}, \qquad \xi_t = 0 \end{cases}}$$

The return period for a particular magnitude event x in year t, $p_t(x)$, indicates that there is a one in $p_t(x)$ chance that such an event will occur in year t and is, therefore, the inverse probability of such an event calculated as:

$$\boldsymbol{P(Z_t > x) = \frac{1}{p_t(x)}}$$

The return period is estimated by (Coles, 2001):

$$\boldsymbol{p_t(x)} = \begin{cases} \left(\boldsymbol{1} - \boldsymbol{exp}\left\{-(\boldsymbol{1} - \frac{\boldsymbol{\xi_t(\mu_t - x)}}{\boldsymbol{\sigma_t}})^{-\boldsymbol{1}/\boldsymbol{\xi_t}}\right\}\right)^{-\boldsymbol{1}}, \boldsymbol{\xi_t} \neq \boldsymbol{0} \\ \left(\boldsymbol{1} - \boldsymbol{exp}\left\{-\boldsymbol{exp}\left\{\frac{(\boldsymbol{\mu_t - x})}{\boldsymbol{\sigma_t}}\right\}\right\}\right)^{-\boldsymbol{1}}, \quad \boldsymbol{\xi_t} = \boldsymbol{0} \end{cases}$$

Best estimates of the return values and return periods are determined by substituting the best estimates of the coefficients into the above equations following the relationships in the GLMs.

Bootstrapping is used to quantify uncertainty in the estimation of all values. Best estimates of all values are determined using the entire record of daily precipitation and all subsequent events above the 99th percentile threshold. Bootstrapping estimates of confidence bounds are obtained through re-sampling from the entire record to estimate the sampling distribution of the coefficients (and subsequent GLM estimated GEV parameters), return values, and return periods. A minimum of 1000 bootstrap samples are constructed for estimation of each value by drawing random samples of T years from {1,2,3,…, T}. The bootstrap sampling distribution of values can then be used to calculate the confidence interval for all values.

Table 1. Combinations of covariates introduced on each GEV parameter in the GLMs. The constant parameter model is referred to as the null model. All possible combinations of covariates and parameters were assessed at each of the 35 stations and these combinations were selected using AIC and likelihood ratio tests, as specified in the methods section. For map of stations and selected models see Figure 2d.

Location	Scale	Shape
Constant	Constant	Constant
AMO only	AMO only	Constant
CC only	CC only	Constant
CC only	GT only	Constant
GT only	AMO only	Constant
GT only	NAO only	Constant
NAO only	GT only	Constant
NAO only	NAO only	Constant
SST only	GT only	Constant
GT + AMO	GT + AMO	Constant
GT + CC	GT + CC	Constant
CC + AMO	CC only	Constant
SST + CC	Constant	Constant
CC + NAO	CC only	Constant

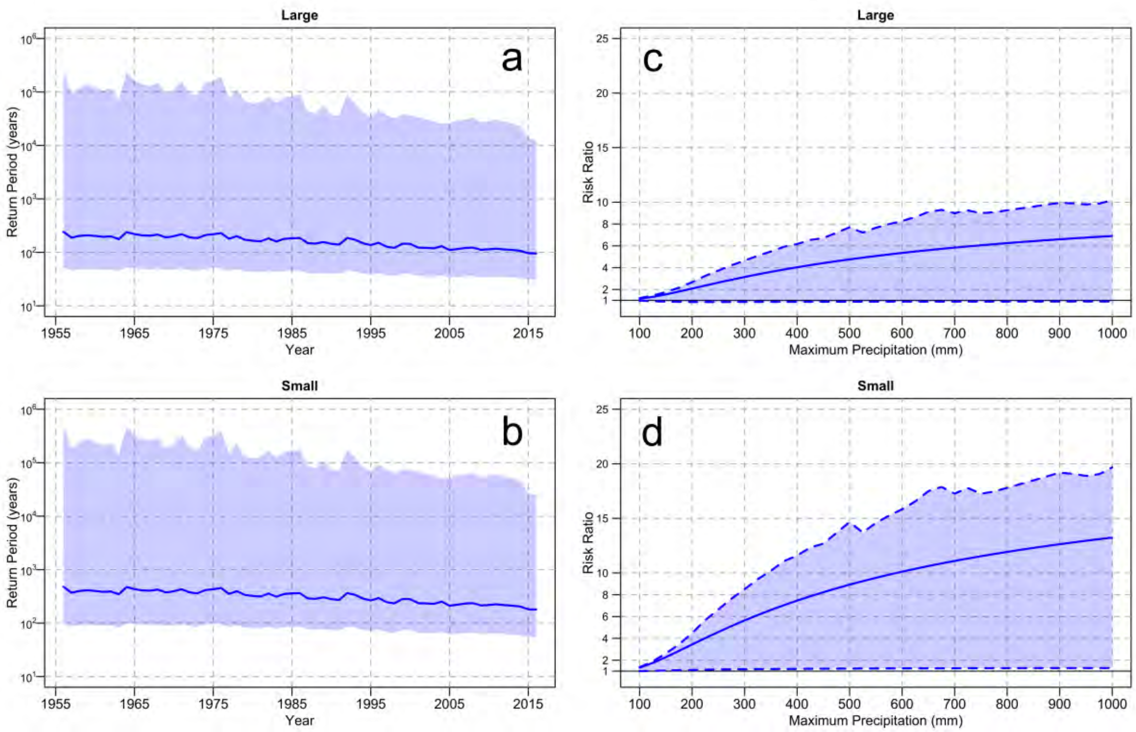

Figure 1. Return period for observed Hurricane Maria maximum daily precipitation with 90% confidence interval using the seven historical stations remaining operational during the passage of Maria for the large (a) and small (b) regions. Risk ratio comparing the probability of a range of peak storm precipitation for 2017 values of all covariates versus 1956 values of long-term trend covariates holding all other covariates constant at observed 2017 values (solid line) for the large (c) and small (d) regions. Likely (66%) confidence bound shown as dashed line.

EXHIBIT 10

BRIEFING PAPER

GLOBAL CLIMATE RISK INDEX 2020

Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2018 and 1999 to 2018

David Eckstein, Vera Künzel, Laura Schäfer, Maik Winges

GERMANWATCH

Brief Summary

The Global Climate Risk Index 2020 analyses to what extent countries and regions have been affected by impacts of weather-related loss events (storms, floods, heatwaves etc.). The most recent data available—for 2018 and from 1999 to 2018 —were taken into account.

The countries and territories affected most in 2018 were Japan, the Philippines as well as Germany. For the period from 1999 to 2018 Puerto Rico, Myanmar and Haiti rank highest.

This year's 15th edition of the Climate Risk Index clearly shows: Signs of escalating climate change can no longer be ignored – on any continent or in any region. Impacts from extreme weather events hit the poorest countries hardest as these are particularly vulnerable to the damaging effects of a hazard and have a lower coping capacity and may need more time to rebuild and recover. The Climate Risk Index may serve as a red flag for already existing vulnerabilities that may further increase as extreme events will become more frequent or more severe due to climate change. The heatwaves in Europe, North America and Japan also confirm: High-income countries are feeling climate impacts more clearly than ever before. Effective climate change mitigation is therefore in the self-interest of all countries worldwide.

At this year's Climate Summit in Madrid, the second review of the Warsaw International Mechanism for Loss and Damage will investigate whether the body fulfills its mandate to avert, minimise and address loss and damage and whether it is equipped to do so in the future. In that process, COP25 needs to debate the lack of climate finance to address loss and damage. Furthermore, the implementation of measures for adapting to climate change must be strengthened.

Imprint

Authors: David Eckstein, Vera Künzel, Laura Schäfer, Maik Winges

Contributors: Rixa Schwarz, Wanja Amling, Emma Opfer, Juan Carlos Zevallos Diaz

Editing: Joanne Chapman-Rose, Janina Longwitz

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Publisher:
Germanwatch e.V.

Office Bonn
Dr. Werner-Schuster-Haus
Kaiserstr. 201
D-53113 Bonn
Phone +49 (0)228 / 60 492-0, Fax -19

Office Berlin

Stresemannstr. 72
D-10963 Berlin
Phone +49 (0)30 / 28 88 356-0, Fax -1

Internet: www.germanwatch.org
Email: info@germanwatch.org

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Comments welcome. For correspondence with the authors contact: kri@germanwatch.org

Content

How to Interpret the Global Climate Risk Index

The Germanwatch Global Climate Risk Index is an analysis based on one of the most reliable data sets available on the impacts of extreme weather events and associated socio-economic data. The Germanwatch Climate Risk Index 2020 is the 15th edition of this annual analysis. Its aim is to contextualise ongoing climate policy debates – especially the international climate negotiations – looking at real-world impacts over the last year and the last 20 years.

However, the index must not be mistaken for a comprehensive climate vulnerability[1] scoring. It represents one important piece in the overall puzzle of climate-related impacts and the associated vulnerabilities. The index focuses on extreme weather events but does not take into account important slow-onset processes such as rising sea-levels, glacier melting or more acidic and warmer seas. It is based on past data and should not be used as a basis for a linear projection of future climate impacts. More specifically, not too far-reaching conclusions should be drawn for the purpose of political discussions regarding which country or region is the most vulnerable to climate change. Also, it is important to note that the occurrence of a single extreme event cannot be easily attributed to anthropogenic climate change. Nevertheless, climate change is an increasingly important factor for changing the likelihood of the occurrence and the intensity of these events. There is a growing body of research that is looking into the attribution of the risk[2] of extreme events to the influences of climate change.[3]

The Climate Risk Index (CRI) indicates a level of exposure and vulnerability to extreme events, which countries should understand as warnings in order to be prepared for more frequent and/or more severe events in the future. Not being mentioned in the CRI does not mean there are no impacts occurring in these countries. Due to the limitations of the available data[4], particularly long-term comparative data, including socio-economic data, some very small countries, such as certain small island states, are not included in this analysis. Moreover, the data only reflects the direct impacts (direct losses and fatalities) of extreme weather events, whereas, indirect impacts (e.g. as a result of droughts and food scarcity) are not captured. The results of this index must be viewed against the background of data availability and quality as well as the underlying methodology for their collection. Data quality and coverage may vary from country to country as well as within countries. This has led to an underrepresentation of, for example, African countries when it comes to heatwaves. Finally, the index does not include the total number of affected people (in addition to the fatalities), since the comparability of such data is very limited.

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[1] According to IPCC (2014b) we define vulnerability as "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt".

[2] According to IPCC (2012) we define disaster risk as "the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

[3] See, for instance: American Meteorological Society 2018, Herring et al. (2018), Trenberth et al. (2018), Zhang et al. (2016); Hansen et al. (2016); Haustein et al. (2016) & Committee on Extreme Weather Events and Climate Change Attribution et al. (2016); Stott et al. (2015)

[4] See also the Methodological Remarks in Chapter 5.

Key Messages

- Japan, the Philippines and Germany are at the top of the list of the most affected countries in 2018.
- Between 1999 and 2018, Puerto Rico, Myanmar and Haiti were the countries most affected by extreme weather events.
- Altogether, about 495 000 people died as a direct result of more than 12 000 extreme weather events globally and losses between 1999 and 2018 amounted to around US$ 3.54 trillion (in purchasing power parities).
- Heatwaves were one major cause of damage in 2018. Of the ten most affected countries in 2018, Germany, Japan and India were suffering from extended periods of heat. Recent science has found a clear link between climate change and the frequency and severity of extreme heat. In Europe, for example, extreme heat spells are now up to 100 times more likely to occur than a century ago. Furthermore, due to a lack of data, the impacts of heatwaves, for example on the African continent, may be underrepresented.
- In many cases (e.g. Puerto Rico), single exceptional disasters have such a strong impact that the countries and territories concerned also have a high ranking in the long-term index. Over the last few years, another category of countries has been gaining relevance: Countries like Haiti, the Philippines and Pakistan that are recurrently affected by catastrophes continuously rank among the most affected countries both in the long-term index and in the index for the respective year.
- Of the ten most affected countries and territories in the period 1999 to 2018, seven were developing countries in the low income or lower-middle income country group, two were classified as upper-middle income countries (Thailand and Dominica) and one was an advanced economy generating high income (Puerto Rico).
- This year's climate summit in Madrid needs to address the lack of additional climate finance to help the poorest people and countries to address Loss and Damage. They are hit hardest by climate change impacts because they are more vulnerable to the damaging effects of a hazard but have lower coping capacity. The climate summit needs to result in: a) a decision on how the need for support for vulnerable countries concerning future loss and damage is to be determined on an ongoing basis and b) the necessary steps to generate and make available financial resources to meet these needs. c) strengthening the implementation of measures for adapting to climate change.

1 Key Results of the Global Climate Risk Index 2020

People all over the world are facing the reality of climate change – in many parts of the world this is manifesting in an increased volatility of extreme weather events. Between 1999 and 2018, about 495 000 people died worldwide and losses of US$ 3.54 trillion (in PPP) were incurred as a direct result of more than 12 000 extreme weather events. Slow-onset processes will add an additional burden in the future. The UNEP Adaptation Gap Report 2016 warns of increasing impacts and resulting increases in global adaptation costs by 2030 or 2050 that will likely be much higher than currently expected: "[...] two-to-three times higher than current global estimates by 2030, and potentially four-to-five times higher by 2050".[5] Costs resulting from residual risks or unavoidable loss and damage are not covered in these numbers. Current estimates of climate finance needs for residual loss and damage range between US$ 290 billion to US$ 580 billion in 2030 (Markandya/González-Eguino 2018).[6] Similarly, the Intergovernmental Panel on Climate Change (IPCC) estimates in its recent Special Report on "Global Warming of 1.5°C" that the "mean net present value of the costs of damages from warming in 2100 for 1.5°C and 2°C (including costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large scale discontinuities) are US$ 54 trillion and US$ 69 trillion, respectively, relative to 1961–1990".[7] This gives the indication that the gap between the necessary financing to deal with climate induced risks and impacts is even bigger than earlier projected. On the other hand, the report highlights the importance of enhanced mitigation action towards limiting a global temperature increase to well below 2°C or even to 1.5°C, which could avoid substantive costs and hardships.[8]

The **Global Climate Risk Index (CRI)** developed by Germanwatch analyses quantified impacts of extreme weather events[9] – both in terms of fatalities as well as economic losses that occurred – based on data from the Munich Re NatCatSERVICE, which is considered worldwide as one of the most reliable and complete databases on this matter. The CRI examines both absolute and relative impacts to create an average ranking of countries in four indicating categories, with a stronger emphasis on the relative indicators (see chapter "Methodological Remarks" for further details on the calculation). The countries ranking highest (figuring in the "Bottom 10"[10]) are the ones most impacted and should consider the CRI as a warning sign that they are at risk of either frequent events or rare, but extraordinary catastrophes.

The CRI does not provide an all-encompassing analysis of the risks of anthropogenic climate change, but should be seen as just one analysis explaining countries' exposure and vulnerability to climate-related risks based on the most reliable quantified data available – alongside other analyses.[11] It is based on the current and past climate variability and – to the extent that climate change has already left its footprint on climate variability over the last 20 years – also on climate change.

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[5] UNEP 2016, p. xii

[6] Their figures depend on the climate scenario, the discount rate, the assumed parameters of the climate model and the socioeconomic model. The analysis is based on the case where equilibrium temperatures increase by 2.5–3.4 °C, implying some mitigation, but less than is required under the Paris accord. They note that uncertainties regarding these sources are very large and meaningful projections of residual damages in the medium to long-term are not possible

[7] IPCC 2018a, p 153

[8] Ibid. 2018a

[9] Meteorological events such as tropical storms, winter storms, severe weather, hail, tornados, local storms; hydrological events such as storm surges, river floods, flash floods, mass movement (landslide); climatological events such as freezing, wildfires, droughts.

[10] The term "Bottom 10" refers to the 10 most affected countries in the respective time period.

[11] See e.g. analyses of Columbia University; Maplecroft's Climate Change Vulnerability Index

Countries Most Affected in 2018

Japan, the Philippines and **Germany** were the most affected countries in 2018 followed by **Madagascar, India** and **Sri Lanka**. Table 1 shows the ten most affected countries (Bottom 10) in 2018, with their average weighted ranking (CRI score) and the specific results relating to the four indicators analysed.

Table 1: The 10 most affected countries in 2018

Ranking 2018 (2017)	**Country**	**CRI score**	Death toll	Deaths per 100 000 inhabitants	Absolute losses (in million US$ PPP)	Losses per unit GDP in %	Human Development Index 2018 Ranking[12]
1 (36)	Japan	5.50	1 282	1.01	35 839.34	0.64	19
2 (20)	Philippines	11.17	455	0.43	4 547.27	0.48	113
3 (40)	Germany	13.83	1 246	1.50	5 038.62	0.12	5
4 (7)	Madagascar	15.83	72	0.27	568.10	1.32	161
5 (14)	India	18.17	2 081	0.16	37 807.82	0.36	130
6 (2)	Sri Lanka	19.00	38	0.18	3 626.72	1.24	76
7 (45)	Kenya	19.67	113	0.24	708.39	0.40	142
8 (87)	Rwanda	21.17	88	0.73	93.21	0.34	158
9 (42)	Canada	21.83	103	0.28	2 282.17	0.12	12
10 (96)	Fiji	22.50	8	0.90	118.61	1.14	92

PPP = Purchasing Power Parities. GDP = Gross Domestic Product.

Japan (1) was hit by three exceptionally strong extreme weather events in 2018. From 6th to 8th of July, heavy rainfalls with more than 200 mm/day were measured, which is about twice as much rainfall as is usually experienced on the wettest day in Japan. The torrential rainfalls resulted in flash floods and mudslides, killing more than 200 people and leading to over 5 000 houses being damaged and the evacuation of 2.3 million people.[13] Overall, the rainfalls caused damage of over US$ 7 billion. From mid-July to the end of August 2018, two-tiered high-pressure systems caused a severe heatwave that led to 138 fatalities and more than 70 000 people requiring hospitalization due to heat strokes and heat exhaustion.[14] In the city of Kumagaya, temperatures of 41.1°C were reported – a national heat record in Japan.[15] In September 2018, Typhoon Jebi made landfall on Japan, becoming the most intense tropical cyclone in the country for over 25 years.[16] Jebi broke several historical records for sustained winds in Japan, causing economic damage of over US$ 12 billion.[17]

Typhoon Mangkhut ploughed through the northern part of the **Philippines** (2) in September 2018 as a category 5 typhoon – the most powerful typhoon recorded worldwide in 2018[18]. It reached top

[12] UNEP 2018
[13] World Weather Attribution 2018
[14] The Japan Times 2018
[15] The Strait Times 2018
[16] The Guardian 2018d
[17] The New York Times 2019b
[18] CNN 2018a

speeds of up to 270 kilometres per hour[19] when it made landfall, affecting more than 250 000 people across the country. About 59 people were killed, most by landslides set off by the heavy rainfalls.[20]

Germany (3) experienced the hottest year since records began due to a severe heatwave.[21] The period between April and July 2018 was the hottest ever recorded in Germany, with temperatures 2.9°C above average.[22] Overall, the heatwave led to the death of 1 234 people. After heavy rainfalls in January, only 61% of the usual amount of rain fell during summer, resulting in 70% of the soil being affected by drought in October 2018.[23] Around 8 000 farmers were prompted to call for federal emergency relief worth around EUR 1 billion (US$ 1.18 billion) in order to compensate for their losses[24], after a massive decline in harvest caused a total of EUR 3 billion (US$ 3.54 billion) in damage.[25]

In January 2018, **Madagascar** (4) was hit by Cyclone Ava, which made landfall on the eastern part of the island, where towns were flooded and buildings collapsed.[26] Ava reached top speeds of 190 kilometres per hour and killed 51 people.[27] It was followed by Cyclone Eliakim in March 2018 impacting more than 15 000 people, which included 17 deaths and nearly 6 300 being temporarily displaced.[28] Cyclone Ava and Eliakim together were responsible for 70 000 people being forced to seek refuge.[29]

The yearly monsoon season, lasting from June to September, severely affected **India** (5) in 2018. The state of Kerala was especially impacted – 324 people died because of drowning or being buried in the landslides set off by the flooding,[30] the worst in one hundred years. Over 220 000 people had to leave their homes, 20 000 houses and 80 dams were destroyed.[31] The damage amounted to EUR 2.4 billion (US$ 2.8 billion).[32] Furthermore, India's east coast was hit by the cyclones Titli and Gaja in October and November 2018. With wind speeds of up to 150 kilometres per hour, cyclone Titli killed at least eight people and left around 450 000 without electricity.[33]

Sri Lanka (6) started the year 2018 with severe monsoon rains from 20th to 26th May affecting 20 districts, especially the south and west coast.[34]The provinces of Galle and Kalutara were the most affected. In Galle, 166mm of rain fell in 24 hours – usually the district has an average precipitation of 290mm in the full month of May.[35]. At least 24 people died, more than 170 000 people were affected[36] and nearly 6 000 people were displaced.[37]

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[19] CNN 2018b
[20] BBC 2018c
[21] Deutscher Wetterdienst (DWD) 2019
[22] Scinexx 2018
[23] Frankfurter Allgemeine Zeitung 2018a
[24] Deutsche Welle 2019b
[25] Bayerische Landesbank 2019
[26] Al Jazeera 2018
[27] Le Monde 2018
[28] OCHA 2018
[29] Deutsche Welle 2019a
[30] Zeit 2018
[31] The Guardian 2018b
[32] Frankfurter Allgemeine Zeitung 2018b
[33] BBC 2018c
[34] Ministry of Irrigation and Water Resources and Disaster Management 2018
[35] FloodList 2018d
[36] Disaster Management Centre of Sri Lanka 2018
[37] FloodList 2018e

Seasonal rains affected **Kenya** (7) and **Rwanda** (8) and other countries in East Africa.[38] Between March and July 2018, Kenya[39] experienced almost twice the normal rainfall of the wet season.[40] Kenya's most important rivers in the central highlands overflowed affecting 40 out of 47 counties[41] and causing the death of 183 people, injury of 97 and the displacement of 321 630 people[42], as well as the loss of livelihoods and livestock.[43] The heavy rains of March 2018 caused flooding along the Sebeya River in **Rwanda** (8). Approximately 25 000 people from 5 000 households were affected, and their homes were either destroyed or damaged by mud and overflow.[44] The floods aggravated cholera cases and resulted in an epidemic of the mosquito-borne chikungunya virus.[45]

Canada (9) started the year with extremely cold temperatures of -45.2°C and -48.2°C in the east, the lowest in 100 years.[46] In May 2018, over 4 000 people were displaced because of flooding, which affected the southern region of British Colombia. Record highs in temperatures in April melted heavy snowpacks, which caused rivers to overflow.[47] The same region suffered the worst wildfire season on record resulting in the evacuation of 16 000 people.[48] 2 117 wildfires burned 1 354 284 hectares,[49] and caused smoke-filled skies in west Canada, making the air quality among the worst in the world.[50] In July 2018, a severe heatwave reached Canada, killing 93 people in Quebec due to heat-related complications.[51]

Fiji (10) suffered the effects of three cyclones between February and April 2018. Cyclone Gita, with peak sustained winds of 126 kilometres per hour[52], reached the South of Fiji causing US$ 1.23 million of damage and the evacuation of 288 people.[53] Two weeks later, the Cyclone Josie and the severe flooding it caused, took the lives of eight people and almost 2 300 people were displaced[54]. Keni was last cyclone of the season was, making landfall in April. It affected Kadavu as a category 3 tropical cyclone[55] and 8 935 people had to leave their homes. Overall, cyclones Keni and Josie affected around 150 000 people.[56]

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[38] World Weather Attribution 2018a
[39] Rainfall totals in Nairobi at the five stations exceeded the normal amounts by two to three times in March and one to two times in April (Kilavi et al. 2018)
[40] Kilavi et.al. 2018
[41] The Guardian 2018c
[42] Kenya Red Cross 2018
[43] UNICEF 2018
[44] IFRC 2018.
[45] The Guardian 2018c
[46] The Weather Network 2018
[47] FloodList 2018c
[48] Daily Hive 2018
[49] British Columbia Official Website 2018
[50] BBC 2018a
[51] Summer 2018 was the hottest on record in the Atlantic coast and in the south, the third-warmest summer on record (Government of Canada 2018)
[52] Fiji Meteorological Services 2018
[53] Fijian Broadcasting Corporation. 2018
[54] FloodList 2018a
[55] FloodList 2018b
[56] Government of Fiji 2018

Countries Most Affected in the Period 1999–2018

Puerto Rico, Myanmar and **Haiti** have been identified as the most affected countries[57] in this twenty-year period. They are followed by the **Philippines, Pakistan** and **Vietnam**. Table 2 shows the ten most affected countries in the last two decades with their average weighted ranking (CRI score) and the specific results relating to the four indicators analysed.

Table 2: The Long-Term Climate Risk Index (CRI): The 10 countries most affected from 1999 to 2018 (annual averages)

CRI 1999-2018 (1998-2017)	**Country**	**CRI score**	Death toll	Deaths per 100 000 inhabitants	Total losses in million US$ PPP	Losses per unit GDP in %	Number of events (total 1999–2018)
1 (1)	Puerto Rico	6.67	149.90	4.09	4 567.06	3.76	25
2 (3)	Myanmar	10.33	7 052.40	14.29	1 630.06	0.83	55
3 (4)	Haiti	13.83	274.15	2.81	388.93	2.38	78
4 (5)	Philippines	17.67	869.80	0.96	3 118.68	0.57	317
5 (8)	Pakistan	28.83	499.45	0.30	3 792.52	0.53	152
6 (9)	Vietnam	29.83	285.80	0.33	2 018.77	0.47	226
7 (7)	Bangladesh	30.00	577.45	0.39	1 686.33	0.41	191
8 (13)	Thailand	31.00	140.00	0.21	7 764.06	0.87	147
9 (11)	Nepal	31.50	228.00	0.87	225.86	0.40	180
10 (10)	Dominica	32.33	3.35	4.72	133.02	20.80	8

Compared to the CRI 2019, which considered the period from 1998 to 2017[58], there have been a few changes in the CRI ranking: while Puerto Rico remains at the top of the list, Myanmar and Haiti each move up one place to become one of the three most affected countries over the past two decades. These rankings are attributed to the aftermath of the exceptionally devastating events such as Hurricane Maria in Puerto Rico in 2017 and hurricanes Jeanne (2004) and Sandy (2016) in Haiti. Likewise, Myanmar was struck hard by Cyclone Nargis in 2008, which was responsible for an estimated loss of 140 000 lives as well as the property of approximately 2.4 million people.[59] Honduras, which consistently featured among the three most affected countries in previous CRI rankings, falls out of the Bottom 10 due to the observation period of this year's CRI edition starting in 1999 (Hurricane Mitch, which was in 1998, was the major extreme weather event which had significantly affected Honduras' CRI score).[60]

[57] Note: Puerto Rico is not an independent national state but an unincorporated territory of the United States. Nevertheless, based on its geographical location and socio-economic indicators Puerto Rico has different conditions and exposure to extreme weather events than the rest of the USA. The Global Climate Risk Index aims to provide a comprehensive and detailed overview of which countries and regions are particularly affected by extreme weather events. Therefore, Puerto Rico was considered separately in our analysis.

[58] See Eckstein et al. 2018

[59] See OCHA 2012

[60] Nicaragua falls out of the Bottom 10 for the same reason.

Particularly in relative terms, poorer developing countries are hit much harder. These results emphasise the particular vulnerability of poor countries to climatic risks, despite the fact that the absolute monetary losses are much higher in richer countries. Loss of life, personal hardship and existential threats are also much more widespread in low-income countries.

Exceptional Catastrophes or Continuous Threats?

The Global Climate Risk Index 2020 for the period 1999–2018 is based on average values over a twenty-year period. However, the list of countries featured in the long-term Bottom 10 can be divided into two groups: those that have a high ranking due to exceptional catastrophes and those that are continuously affected by extreme events.

Countries falling into the former category include Myanmar, where Cyclone Nargis in 2008 caused more than 95% of the damage and fatalities in the past two decades, and Puerto Rico, where more than 98% of the damage in both categories was caused by Hurricane Maria in 2017. With new superlatives like Cyclone Idai in March 2019 being the deadliest and costliest cyclone on record in the Indian Ocean, and one of the worst tropical cyclones to ever affect Africa and the Southern Hemisphere, it seems to be just a matter of time until the next exceptional catastrophe occurs.[61] The severe 2017 hurricane season made 2017 the costliest year ever in terms of global weather disasters.[62]

Over the last few years, another category of countries has been gaining relevance: Countries like Haiti, the Philippines and Pakistan that are recurrently affected by catastrophes continuously rank among the most affected countries both in the long-term index and in the index for the respective year. Furthermore, some countries were still in the process of recovering from the previous year's impacts. One example is the Philippines, which is regularly exposed to tropical cyclones such as Bopha 2012, Hayan 2013 and Mangkhut 2018, due to its geographical location.

The appearance of some European countries among the Bottom 30 countries[63] can to a large extent be attributed to the extraordinary number of fatalities due to the 2003 heatwave, in which more than 70 000 people died across Europe. Although some of these countries are often hit by extreme events, the relative economic losses and the fatalities are usually relatively minor compared to the countries' populations and economic power.

2 The Role of Climate Change in Extreme Weather Events

In its "Fifth Assessment Report" published in 2014, the Intergovernmental Panel on Climate Change (IPCC) has already predicted that risks associated with extreme events will continue to increase as the global mean temperature rises.[64] Linking particular extreme weather events to human-induced and natural climate drivers remains a scientific challenge that attribution science tries to tackle. The field has recently taken huge leaps forward – even though gaps in knowledge and especially in data remain. In general, many studies conclude that "the observed frequency, intensity, and duration of some extreme weather events have been changing as the climate system has warmed".[65] Nevertheless, it is not trivial to investigate the impact of climate change on a single weather event as different

[61] New York Times 2019a, World Bank 2019
[62] MunichRe 2018, see also CRI2019 for an in-depth chapter on tropical cyclones
[63] The full rankings can be found in the Annexes.
[64] IPCC 2014a, p.12
[65] Committee on Extreme Weather Events and Climate Change Attribution et al. 2016, p. 2

regional circumstances need to be taken into account and data might be very limited.[66] Over the past few years, substantial research has been conducted on the attribution of extreme events to climate change, i.e. to what extend anthropogenic climate change has contributed to the events' likelihood and strength.[67] In the field known as Probabilistic Event Attribution (PEA), based on climate model experiments, studies compare the probability of an extreme weather situation, in today's world with human-caused greenhouse gas emissions, to a world without human induced climate change.[68] Due to methodological improvement, "fast track attribution" is now more feasible and can be undertaken within months of the event (as opposed to decades).[69] Additionally, more knowledge is generated on how underlying factors contributing to extreme weather are influenced by global warming. For example, higher temperatures intensify the water cycle, leading to more droughts as well as floods due to drier soil and increased humidity.[70] Of course, these approaches can only lead to statements about the change in probability of a certain event happening.

Considering this, the report "Explaining Extreme Events of 2017 From a Climate Perspective" offered new findings from 17 peer-reviewed analyses. The American Meteorological Society has published the report on an annual basis since 2012 in its bulletin, analysing selected extreme weather events. Out of the 146 research findings, 70% "identified a substantial link between an extreme event and climate change".[71] Again, "scientists have identified extreme weather events that they said could not have happened without warming of the climate through human-induced climate change."[72] Among others, one study concluded that the intense marine heatwaves in the Tasman Sea off Australia in 2017 and 2018 were "virtually impossible" without climate change.[73] Another study took a closer look at the persistent spring to summer heatwave in Northeast China in 2017 and concluded that the likelihood of such temperatures increased by about one third due to anthropogenic climate change.[74] For its part, the "Fourth Climate Assessment Report" (2018) considers, with a high level of confidence, a future increase in the frequency and intensity of extreme high temperature and precipitation events as the global temperature increases as being "virtually certain".[75]The data on the countries in the CRI 2020 show how destructive extreme precipitation can be – namely through the floods and landslides, which have hit many regions in South and South East Asia and Africa – regions which now feature in the Bottom 10. Extreme precipitation is expected to increase as global warming intensifies the global hydrological cycle. Thereby, single precipitation events are expected to increase in intensity at a higher rate than global mean changes in total precipitation as outlined by Donat et al. (2016). Furthermore, those increases are expected in wet as well as dry regions.[76] A study by Lehmann et al. (2015) strengthens the scientific link between record-breaking rainfall events since 1980 and rising temperatures. According to the scientists, the likelihood of a new extreme rainfall event being caused by climate change reached 26% in 2010.[77] A recent study by Blöschel et al. (2017) concludes that the timing of floods is shifting due to climate change. The research focuses on Europe and shows that floods occur earlier in the year, posing timing risks to people and animals. Flooding rivers affect more people worldwide than any other natural disaster and result in multi-billion dollars of damage annually.[78] Nevertheless, the study is not fully able to single out human-

[66] Hansen et al. 2016
[67] Stott et al. 2015
[68] Carbon Brief 2014
[69] Haustein et al. 2016
[70] WMO 2017
[71] American Meteorological Society 2018, without page number
[72] Ibid.
[73] Perkins-Kirkpatrick et al 2018, p54
[74] Wang et al. 2018
[75] Wuebbles el al. 2017
[76] Donat et al. 2016
[77] Lehmann et al. 2015
[78] Blöschl et al. 2017

induced global warming as a cause – a problem researchers on extreme weather attribution are still facing.

Researchers explained that the sea surface temperature plays a key role in increasing storms, wind speeds and precipitation.[79] Another study on this subject showed that the rainfall during storms like Hurricane Harvey in 2017 is equivalent to the amount of evaporation over the ocean and thus the corresponding cooling effect of tropical cyclones on sea temperature. It is still difficult to distinguish between natural variability and human-induced extremes, but the rising sea level, which is largely caused by climate change, is responsible for the increased intensity of floods, storms and droughts. For example, a study shows that torrential rains like those in 2016 in Louisiana, USA, are now 40% more likely than in pre-industrial times. The rainfall was increased because the storm was able to absorb abnormal amounts of tropical moisture on its way to the US coast, releasing three times the precipitation of Hurricane Katrina in 2005.[80] Another example is a regional model used to analyse the occurrence of heatwaves in India, finding causalities regarding the 2016 heatwave and climate change. The model indicated that sea surface temperatures influence the likelihood of record-breaking heat.[81] Other studies have found similar results. A publication regarding the 2015 Southern African droughts also found causalities with regards to sea surface temperatures causing reduced rainfall, and increased local air temperatures.[82] Moreover, the above-mentioned study from 2018 concludes that Hurricane Harvey could not have produced such an enormous amount of rain without human-caused climate change.[83]

Furthermore, there is increasing evidence on the link between extreme El Niño events and global warming. Cai et al. (2018) found that the robust increase in the variability of sea surface temperatures is "largely influenced by greenhouse-warming-induced intensification of upper-ocean stratification in the equatorial Pacific, which enhances ocean-atmosphere coupling."[84] As a consequence, the frequency of strong El Niño events increases as well as extreme La Niña events. This finding is considered a milestone in climate research[85] and strengthens past research in the field.[86] In addition, the IPCC's Special Report "Global Warming of 1.5°C" was published in October 2018. It aims to determine the difference in consequences of 1.5°C climate change compared to 2°C. In order to do so, it investigates the effects of past global warming of the same extent. It identifies trends of increasing intensity and frequency of weather extremes during the past 0.5°C global increase. Furthermore, it shows that, at least in some regions, the likelihood of droughts and heavy precipitation is higher based on a 2°C increase, compared to one of 1.5°C.[87]

Extreme weather events are not the only risks aggravated by the influence of climate change. In their latest reports, the IPCC (2019)[88] focuses on the effect of climate change on, for example, the desertification and degradation of land. It suggests that climate change will accelerate several desertification processes and that, in the future, the risks of desertification will increase. This has various implications, such as the loss of biodiversity and an increase in the likelihood of wildfires. Williams et al. (2019) conclude that this is because of the increasing vapour pressure deficit due to the warming climate.[89]

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[79] Trenberth et al. 2015; Zhang et al. 2016
[80] Climate Central 2016a
[81] Climate Central 2016b
[82] Funk et al. 2016
[83] Trenberth et al. 2018
[84] Cai et al. 2018, p. 201.
[85] Ham Y-G 2018
[86] Cai et al. 2014, Cai et al. 2012, Yeh et al. 2009
[87] IPCC 2018a
[88] IPCC 2019
[89] Williams et al 2019

Climate Change is a Real Game Changer for Heatwaves

Interview with Friederike Otto, leading scientist in the field of event attribution and Acting Director of the Environmental Change Institute at the University of Oxford

How well can extreme weather events generally be attributed to climate change?

This is highly dependent on the type of extreme weather event and the region in which it occurs. Large-scale events are generally easier to attribute, since the climate models available to us are more suitable for that. The least uncertainty arises from large-scale precipitation events. In addition, the confidence of the results depends on the data availability. In the case of droughts, robust conclusions are possible if good observational data is available. While there is data on the lack of precipitation, unfortunately, quite often there is a lack of relevant data beyond that, e.g. on soil moisture. This is especially true for countries of the global South. Regarding tropical storms, the resolution of most state-of-the-art models is not high enough. We can however robustly attribute precipitation associated with hurricanes in the Atlantic Ocean. In contrast, it is much more difficult in other regions.

How strong (and how well measurable) is the influence on heatwaves?

Climate change is a real game changer. The probability of heatwaves has already changed by orders of magnitude in Europe and will do so in almost every region of the world. Nevertheless, extreme weather events always have multiple causes, urbanization and land use, for example, play a role here.

How strong (and how well measurable) is the influence on heavy rain?

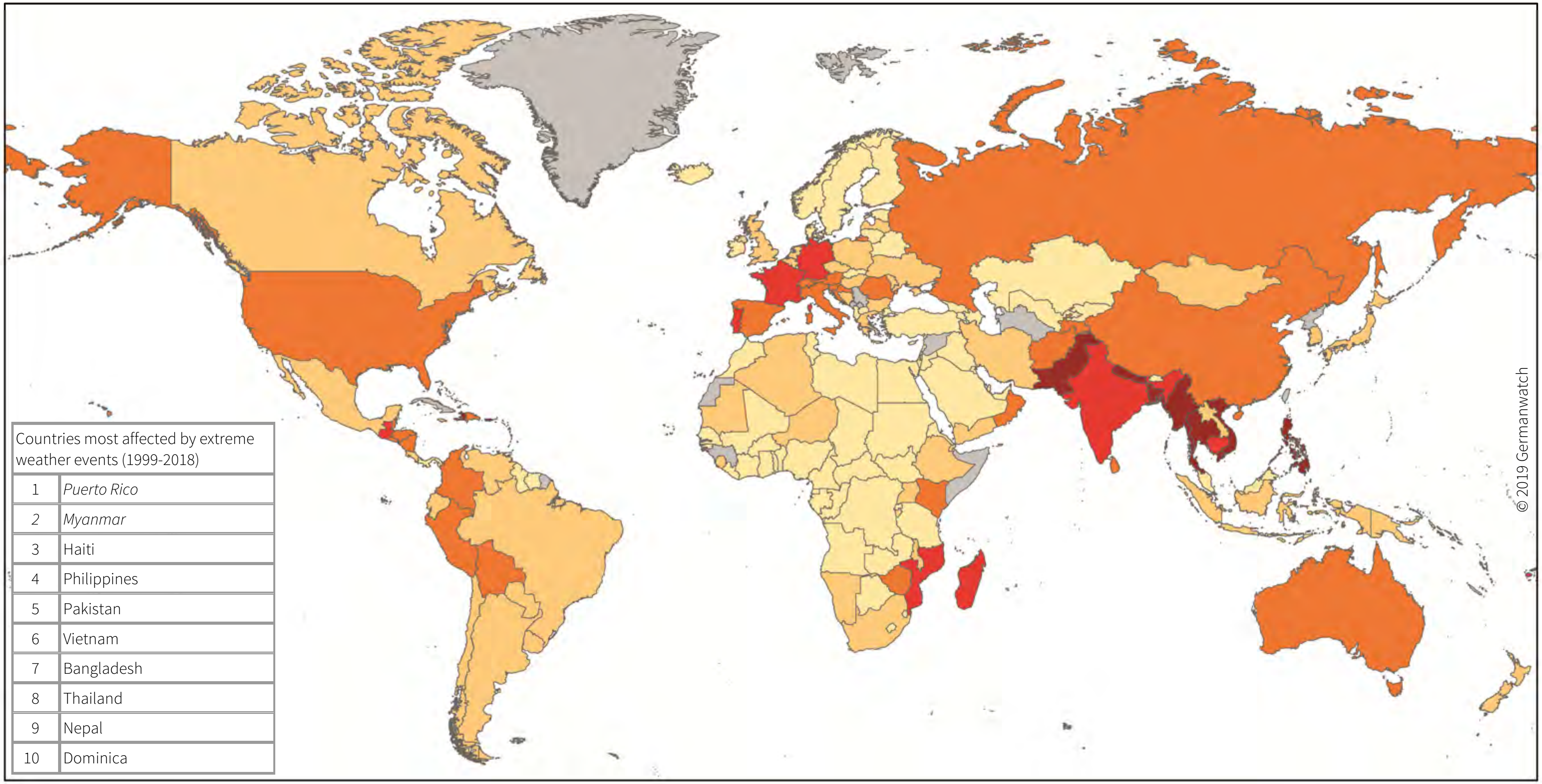
Climate change essentially affects weather in two ways: Firstly, through the thermodynamic effect, in other words the warming of the atmosphere. Warmer air can absorb more water vapour. Hence, we expect more extreme precipitation on a global average. The second effect is trickier. As we change the composition of the atmosphere, so does the atmospheric circulation and thus where weather systems are created and how they move. This effect varies by region and season, which is why we need attribution research. One example: While we can generally say that tropical cyclones will bring more intense and higher amounts of precipitation, we do not know whether and how their frequency will change.

What are the greatest challenges for attribution science?

There are two bottlenecks. Firstly, there is a lack of observational data, which is essential to carry out valid research of meteorological events. In many regions of the world, meteorological stations are missing. Without observational data, climate models cannot be evaluated. Secondly, the field of research is very small. There are too few people working on attribution and it is very difficult to acquire sufficient funding.

What advantages does it have that extreme weather events can be better attributed to climate change?

We currently know relatively little about what the concrete effects of climate change mean in time frames and on local scales where humans live and make decisions. Attribution science is important to understand what climate change actually means. Many adaptation measures are based on trends in observational data. Yet, these trends have multiple causes. Limited resources for adaptation to climate change can only be used efficiently, if we know what the consequences of climate change are.



Italics: Countries where more than 90% of the losses or deaths occurred in one year or event

Climate Risk Index: Ranking 1999 - 2018 **1 - 10** **11 - 20** **21 - 50** **51 - 100** **>100** **No data**

3 Heatwaves Sweep the World

A string of deadly heatwaves took its toll on millions around the world in 2018. Temperatures far above the long-term average were witnessed foremost in the Northern Hemisphere, wreaking havoc on human health, agriculture, ecosystems and infrastructure.[90] As highlighted in Chapter 1, extreme heat caused a significant number of deaths in Japan and Germany as temperatures soared past 40°C.[91] In California, Sweden, Russia and Greece heatwaves triggered the most destructive wildfires experienced in recent years with a high number of fatalities and significant damage[92]. In the UK and across Northern Europe extreme heat aggravated prolonged dry spells, leading to dire droughts. In India, temperatures of up to 50°C were measured, the extreme water stress was omnipresent. Due to the drought in the southern Indian state of Tamil Nadu and empty water reservoirs, Chennai, a city with over a million inhabitants, could only be supplied with water by trucks and trains. The water supplies for the population had to be accompanied by the police.

A heatwave, also referred to as an extreme heat event, is commonly described as a period of abnormally hot weather[93], spanning **at least five consecutive days with a temperature of 5°C above average**.[94] It typically forms when a high-pressure system shifts into a region and stalls. The system can force warm air downward, creating a 'cap' that traps air in one place as it prevents the hot air near the surface from rising. The effects of heatwaves may be less obvious at first glance compared to other natural disasters such as storms or flooding, however, heatwaves cost just as many lives. According to our index, a total of 2 928 people reportedly died in 2018 from heat-related impacts, compared to 3 622 fatalities caused by floods, and 2 463 fatalities due to severe storms. Furthermore, with regard to overall losses, heat resulted in a total of US$ 60.42 billion (in PPP) in damage globally in 2018.

Heatwave Effects and Interactions with other Extreme Weather Events

Science suggests that periods of extreme heat will not only become **more commonplace** due to increasing global temperatures but will also interact with and **exacerbate already existing risks** such as droughts and extreme rainfall or floods.[95]

Warmer temperatures increase the evaporative demand, which, alongside concurrent shifts in precipitation, amplify drought conditions. The converse also holds true. Conditions of drought can boost or curb heatwave temperatures.[96] Like heatwaves, record droughts have made headlines in recent years, highlighting their devastating implications. Heatwave-fuelled droughts are being felt not only in industrialised countries like Germany, where record highs in 2018 caused widespread crop failure to the detriment of thousands of farmers[97], but, first and foremost, in developing countries, where those affected are poorly equipped to cope with severe climate conditions.

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[90] The New York Times 2018
[91] New Scientists 2018
[92] San Francisco Chronicle 2018
[93] IPCC 2012a
[94] Deutsche Welle 2018b
[95] This chapter focuses on how heatwaves can exacerbate droughts.
[96] Nature Climate Change 2018
[97] Deutsche Welle 2019b

In Sweden, a heatwave followed an exceptionally dry and warm period in the summer of 2018, which resulted in the worst outbreak of forest fires on record, engulfing roundabout 50 forests[98], equivalent to approximately 25 000 hectares, which destroyed almost 3 million cubic meters of wood[99].

How Climate Change Affects Heatwaves

The latest attribution research states that CO_2 emissions from human activities have doubled the likelihood of severe heat events in northern Europe (World Weather Attribution 2018). Studies further show that large-scale heat events, such as the Northern Hemisphere heatwave in 2018, could occur every year if global temperatures were to climb to 2°C above the pre-industrial levels, or it could occur in two out of every three years in a 1.5°C scenario (Vogel et al. 2018, see further information on attribution science in chapter 2). Another study warns that if current greenhouse emission pathways remain unaltered, three out of four people on the planet could, by the year 2100, be exposed to more than 20 days per year of the heat and humidity linked to fatal heatwaves (Nature Climate Change 2017).

Climate science indicates that heatwaves often have a common trigger: profound recent changes to jet streams — strong winds at altitudes of around 10 kilometres above the earth's surface which affects weather systems around the globe. Powered by differences in temperature between cooler polar regions and warmer air masses, circulating jet streams can be stalled due to changed conditions, leading to unusual weather patterns. While reinforcing cold snaps in one place, a jet stream can fan blasts of heat in another (Mann et al. 2018).

The IPCC's Fifth Assessment Report confirms that the warming of the planet is already having an effect on jet streams and, hence, on global weather patterns: "It is likely that circulation features have moved poleward since the 1970s, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams and a contraction of the northern polar vortex. Evidence is more robust for the NH [Northern Hemisphere] (IPCC 2013)."

Evidence is also mounting that the warming Arctic, which is warming twice as fast as the rest of the planet, constitutes a major factor for why the polar jet stream keeps getting stalled (Popular Mechanics 2019). Recent heatwaves sweeping the Northern Hemisphere are largely attributed to the accelerated warming of the Arctic causing an altering of the polar jet stream, illustrating the increasing risk of heatwaves due to global warming (New Scientist 2018).

Over and above the interconnections with other extreme events, heatwaves also have a number of sectoral impacts.

Heatwaves and Health

Heatwaves affect human health worldwide, leading to increased morbidity and mortality[100]. The combination of heat and high humidity is particularly exhausting for the human body as it slows down the evaporation of sweat, the body's cooling system.[101] The effect of high heat on health mostly manifests itself in cardiological and respiratory diseases.[102] The population groups especially affected are the elderly as well as those working outdoors or in non-cooled buildings.[103] A special

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[98] The Local 2018
[99] Forestry.com 2018
[100] Anderson and Bell, 2011; Haines et al., 2006; Loughnan et al., 2010; Martiello and Giacchi, 2010; Zeng et al., 2016
[101] Hajat et al 2010; Kjellstrom et al 2016; Kravchenko et al 2013
[102] e.g. Bunker et al 2015
[103] e.g. Bai et al., 2014, Yin and Wang, 2017

burden also lies on the poor and vulnerable, due to unevenly distributed access to proper health care. Inhabitants of cities are particularly in danger of suffering from the "urban heat island" effect, which enhances the intensity of heatwaves in cities. A lack of consideration in urban planning of rising temperatures, resulting in dense infrastructure, can lead to a temperature increase of up to 12°C in cities compared to rural environments, particularly at night.[104]

In the summer of 2003, anthropogenic climate change increased the risk of heat-related mortality in Central Paris by 70%, and by 20% in London, which experienced lower extreme heat. Out of the estimated 315 and 735 summer deaths attributed to the heatwave event in Greater London and Central Paris, respectively, 64 (±3) deaths were attributable to anthropogenic climate change in London, and 506 (±51) in Paris.[105]

Agriculture and Food Security

Combined heatwaves and drought can lead to severe harvest failures with major implications for agricultural producers and the food security of communities all over the world. Adverse-effects are not only felt directly where climate extremes occur, but also indirectly in that regions suffer from the repercussions of reduced exports and higher food prices.[106] As highlighted in this year's CRI's Bottom 10, a European heatwave and drought in the summer of 2018 led to widespread harvest failures and a massive decline in agricultural productivity in many countries across the continent. Struggling to cope with the consequences, various national governments sought help from the European Commission.[107] In Germany alone, some 8 000 farmers were prompted to call for federal emergency relief worth around EUR 1 billion (US$ 1.18 billion) in order to be compensated for their losses,[108] after a massive decline in harvest resulted in total damages of EUR 3 billion (US$ 3.54 billion).[109] However, the countries most susceptible to heatwaves and prolonged drought – mainly in the global South – are often in a much more precarious situation as they cannot rely upon government support in the form of financial resources or technologies. Furthermore, many African countries are particularly drought-prone and are already subjected to desertification and other forms of land degradation, which negatively impacts agriculture and frequently spurs conflicts over subsistence crops, thus perpetuating food insecurity and the risk of hunger.[110]

Forestry

Heatwaves can have devastating effects on forests. Heat causes the soil to dry out as water increasingly evaporates and exacerbates the risk of forest fires.[111] If a heatwave only lasts for a very limited time span, the trees are generally able to cope well with the high temperatures (>40 °C), if they have sufficient water sources.[112] But frequently, heatwaves occur in combination with droughts. A devastating combination for forests as it has contributed to tree mortality worldwide.[113] The negative effects on trees are manifold. Trees cool their leaves evaporatively by transpiration, and the stem tissues convectively through heat transfer.[114] Therefore, a lack of water hinders the cooling of the leaves and stem tissues, potentially leading to damage. Other negative effects include a reduction in tree growth and negative impacts on physiological processes such as reduced photosynthesis.[115]

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104 United States Environmental Protection Agency
105 Mitchell et al. 2016
106 Global Food Security Programme 2015
107 Deutsche Welle 2018a
108 Deutsche Welle 2019b
109 Bayern LB 2019
110 UNFCCC 2007
111 Focus 2019
112 Teskey et al 2015
113 Allen et al. 2010
114 Kolb & Robberecht 1996
115 Teskey et al 2015

The impact of extreme heat and droughts does not often materialise directly. Damage usually occurs years after the event. Trees that have already been weakened by the direct impacts become more vulnerable in subsequent years to extreme events; insects and diseases then become the primary causes of death.[116]

In the European heatwave of 2003, that was accompanied by a drought, another factor came to light: due to a 30% decline in gross primary production (biomass) across Europe, the forests in the region became a net source of CO2 (0.5 PgC per year) – rather than a carbon-sink, as in previous years.[117]

Heatwaves – a Global Threat

The occurrence of heatwaves is a global problem, both for countries in the global South and in the global North. The Intergovernmental Panel on Climate Change (IPCC) concludes that it is likely that [due to climate change] the frequency of heatwaves has increased in large parts of Europe, Asia and Australia.[118] According to the IPCC's special report on 1.5 degrees "**the number of highly unusual hot days is projected to increase the most in the tropics**".[119]

The current figures on the effects of heatwaves on different parts of the world must, however, be viewed against the background of data availability and quality as well as the underlying methodology for their collection. For instance, the accurate attribution of a human loss to a particular extreme weather event faces certain methodological boundaries that data collectors have to work with (e.g. to determine whether the death of an elderly person during a heatwave is indeed the result of the extreme temperature or only due to the high age). Similarly, data quality and coverage may vary from country to country as well as within countries. Currently, many more studies have been conducted for developed countries, compared to developing countries.[120] There are efforts to change this[121], but the limited availability of data in developing countries is a barrier.[122] A recent study by Campbell et al. (2018)[123] found that **heatwave and health impact research is not evenly distributed across the globe**. They highlight that regions most at risk from heatwaves and health impact are under-represented in the research (Campbell et al. 2018). These circumstances may cause countries with large data gaps to appear less affected by heatwaves than they might be in reality. We also have to note that climate change disproportionately affects the poor. Many **low-income urban residents live in precariously located informal settlements**, characterised by poor-quality housing that is susceptible to extreme heat and they have less access to affordable healthcare. These factors make them both more exposed to heatwaves, and less able to deal with them when they occur.[124]

Looking at the results of the CRI 2020, four countries (Japan, Germany, India and Canada) of the Bottom 10 were especially affected by heatwaves. Below, a closer look is taken at the impacts of heatwaves as well as the related challenges in Europe and India.

European Heatwaves

In the summer of 2018, Europe suffered from heatwaves accompanied by a dry spell, which led to crop failure and numerous forest fires.[125] July 2018 was the warmest July ever recorded in Northern

[116] Allen et al. 2010, Gessler 2019
[117] Ciais et al. 2005
[118] IPCC 2014c
[119] IPCC 2018
[120] Otto et al. 2015
[121] Climate Central 2019
[122] Huggel et al. 2015
[123] Campbell et al. 2018
[124] C40 2019
[125] Imbery et al. 2018b

Europe. With temperatures of up to 26°C, the Baltic Sea was warmer than ever before.[126] In Germany 1 234 people died from the heat in 2018 and health risks were increased.[127] Power plants had to reduce production or be shut down entirely in Sweden, France, Finland[128] and Germany[129] as low water levels of nearby rivers reduced the availability of cooling water for the power plants. Due to low water levels, barges could only operate at limited capacity, leading to fuel shortages and disruption to production processes.[130]

Although Europe – especially France – has made progress in preventing heat fatalities by implementing better early warning systems,[131] disruptions have still been significant. Partly because **adaptation measures could not keep up with the rapid changes**. As an example: While it is clear that houses must be equipped with better insulation to deal with extreme heat[132] in Germany, less than 1% of residential buildings are being adapted annually.[133] Furthermore, there was a **lack of risk management**. German farmers were not adequately prepared.[134] In total, insurance experts estimate that only 0.2% of German farmland was covered by insurance against heat and drought.[135] As a result, leading politicians are currently considering subsidies for insurance products.[136] Being particularly dependent on the jet stream, **extreme heat during European summers is likely to occur more often and intensively in the future**. In 2019, in Germany the heat record was broken yet again several times, raising it by 2.3°C to 42.6°C in just one summer.[137]

Indian Heatwaves

As highlighted in Chapter 1, India suffered from one of the longest ever recorded heatwaves in 2018, with hundreds of deaths[138], when temperatures climbed to up to 48°C. Prolonged drought and resultant widespread crop failures, compounded by a water shortage, brought about violent riots and increased migration [139].

India is among those countries that were particularly affected by extreme heat in both 2018 and 2019. Since 2004, India has experienced 11 of its 15 warmest recorded years.[140] Since 1992, an estimated 25 000 Indians have died as a result of heatwaves.[141] Contributing factors include increasing temperatures, the "El Niño Modoki", an irregular El Niño in which the Central Pacific Ocean is warmer than the East Pacific, and the loss of tree cover, reducing shade as well as the moisture in the soil.[142] India is particularly vulnerable to extreme heat due to low per capita income, social inequality and a heavy reliance on agriculture.[143] The worst hit regions have also been among India's poorest. Additionally, a high number of people are working in areas such as agriculture and construction. A study by the International Labour Organization concludes that by 2030, India would lose 5.8% of its

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[126] Imbery et al. 2018b
[127] Bundesärztekammer et al. 2019
[128] Patel 2018
[129] Vogel et al. 2019
[130] Deutschlandfunk 2018; NT-V 2018
[131] Watts et al. 2019
[132] Salagnac 2007
[133] Handelsblatt 2019; Climate Transparency 2019
[134] Deutsche Welle 2019b
[135] GDV – Gesamtverband der Deutschen Versicherungswirtschaft 201
[136] Tagesspiegel 2019
[137] FAZ 2019
[138] Reuters 2018
[139] Future Earth 2019
[140] Earth observatory 2019
[141] The Guardian 2018a
[142] The Times of India 2019
[143] IPCC. 2014c

working hours due to heat stress, which is equivalent to 34 million full-time jobs out of a total of 80 million worldwide.[144]

In response to the growing number of deaths from heatwaves, the Indian government began implementing countermeasures. Heat plans include a combination of public awareness campaigns, training for medical staff, reducing school days, building heat shelters for the homeless equipped with drinking water, free water distribution and simple policy changes.[145]

Adapting to and Coping with Heatwaves

To limit the negative impacts of more frequent and more severe heatwaves in the future, more ambitious mitigation efforts are of utmost importance. Nevertheless, as outlined, today many regions of the world are already facing the dire consequences of these events. This calls for substantial efforts in two areas. Firstly, **adaptation measures must be implemented to prevent or limit the damage** heatwaves can cause. This has to be done with caution in order to prevent maladaptation – an intended adaptation measure that (unintendedly) increases vulnerability towards climate change and, hence, the risk of negative impacts, or that diminishes welfare.[146] Secondly, **coping strategies to deal with unavoidable consequences** and to ensure swift reactions during and after heatwaves must be introduced and strengthened .

Adaptation and coping measures vary greatly by sector, since heatwaves manifest differently. Regarding negative impacts on **health**, vulnerable people should be identified, approached and educated, since they sometimes may not acknowledge their own risk factors.[147] **Heat preparedness plans and early warning systems can reduce fatalities significantly**.[148] By introducing clear communication structures, responsibilities and instructions for heat events, adverse health effects can be minimised.[149] It is crucial to take into account different living conditions. Inhabitants of informal settlements are more susceptible to heat stress, creating yet another challenge for an already vulnerable population.[150] Furthermore, Infrastructure measures in urban areas should focus on reducing the urban heat island effect by increasing tree coverage and creating green belts that allow winds to circulate. Furthermore, green roofs and lighter coloured pavements and buildings can reflect some of the sun's radiation.[151] However**, the widespread installation of air conditioning systems has to be considered maladaptation**. Not only do high electricity consumption and most cooling agents contribute to climate change, but the high demand for electricity puts further stress on electricity grids[152] and the units' thermal discharge heats up cities even more.[153]

There are many promising **adaptation measures for agriculture and ensuring food security**, such as the usage of more adapted crops, crop diversification and rotation, modifications to crop calendars, agroforestry and the usage of cover crops that provide shade for cash crops, reduce soil erosion and manage nutrient levels.[154] Introducing irrigation farming to areas that used to rely purely on rainwater has to be well thought-out. It bears the risk of further increasing stress on water supplies and, hence, has to be considered a maladaptation in many cases. **As agriculture is also a**

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[144] ILO 2019
[145] The Guardian 2018a
[146] UNEP 2019
[147] Carter 2018
[148] Center for Climate and Energy Solutions 2019; Watts et al. 2019
[149] WHO Europe 2008
[150] NDRC 2013
[151] Chandra 2019
[152] Strohmayer 2019
[153] Louis 2018
[154] European Environment Agency 2019

major contributor to climate change, it is all the more important that farming practices which are low in greenhouse gas emissions be employed.

There are two strategies deal with forest heat stress. **Buffering measures aim at preventing and curbing disturbances**, for example preventing the spread of invasive species that benefit from heat stress, setting up firefighting reservoirs and building access roads for heavy machinery. This approach cannot prevent heat stress but can help with the associated consequences such as the aforementioned spread of vermin and fire. In many cases, it is only effective for a limited time span. Moreover, it often involves intense management and is therefore costly. In the long-run, **increased resilience can only be achieved by facilitating an ecosystem shift** by, for example, introducing genetic diversity and a large spectrum of forest types. Reducing non-climatic stressors, such as planting monocultures, aids both strategies.[155] Besides being carbon-sinks, **forests are themselves adaptation measures.** They regulate regional water supplies and temperature fluctuations and can therefore, among other things, alleviate the impacts of storms, flash floods and storm surges[156] and reduce heat stress in urban environments.[157]

In principle, **adaptation measures must be tailored to regional contexts**. Not only does climate change manifest itself differently in every region of the world, but cultural rules and practices or strategies to deal with extreme weather and seasonal variability also vary greatly. Traditional farmers, for example, have developed several coping mechanisms like crop diversification, or informal risk sharing arrangements and banking systems.[158] While in many cases these are or will not be sufficient going forwards, the existing mechanisms should be applied, strengthened or integrated wherever possible.[159]

Poor and vulnerable people are often more susceptible to climate change impacts. Moreover, adaptation measures themselves often entail distributional effects. This is why **adaptation measures should especially support the poor and vulnerable** and must avoid maintaining and enhancing social injustices and power imbalances.[160]

4 Addressing Climate Risks and Impacts: a Stocktake of 2019 Developments

The Climate Risk Index (CRI) 2020 clearly shows: Signs of escalating climate change can no longer be ignored – on any continent or in any region. In addressing the related climate risks and impacts, the year 2019 has been characterised less by political milestones but rather by initiatives for action and its further scientific underpinning. Above all, research on climate risks and concrete climate change impacts has made significant progress. **Two Special Reports of the Intergovernmental Panel on Climate Change** (IPCC), one on the Ocean and Cryosphere in a Changing Climate[161] and the second on impacts of climate change on land [162] clearly show that both **extreme weather**

[155] Pramova 2012
[156] Pramova 2012
[157] McDonald 2018
[158] Hutfils 2019
[159] Germanwatch 2019
[160] UNEP 2019
[161] IPCC 2019a
[162] IPCC 2019b

events and slow onset processes have tended to be underestimated in the past and have already caused devastating consequences worldwide today. Significant increases in the near future are predicted. The reports show, with a high level of confidence, that climate change, including increases in the frequency and intensity of extremes but also the shrinking cryosphere in the Arctic and high-mountain areas, has led to predominantly negative impacts on food security, water resources, water quality, livelihoods, health and well-being as well as on the culture of human societies, particularly for indigenous peoples. The reports note that some impacts of climate-related changes challenge current governance efforts to develop and implement adaptation responses from local to global scales, and in some cases, push them to their limits. People with the highest exposure and vulnerability are often those with the lowest capacity to respond. Drawing an even more severe picture, a recent study by Climate Central concludes that **rising sea levels are threatening to erase coastal mega-cities** such as Bangkok, Shanghai and Mumbai. Around 150 million people are now living on land that will be below the high-tide line by the mid-century, based on moderate emission cuts.[163]

On a political level, addressing the need to ramp up climate action was the goal of the **United Nations Climate Action Summit** (UNSG) in New York. On 23rd September, UN Secretary-General António Guterres brought together national governments, their subnational and local counterparts, civil society and private businesses to, amongst others, advance global efforts to address and manage the impacts and risks of climate change, particularly in those communities and nations, which are most vulnerable. One concrete outcome of the UNSG summit was a "Call for Action on Adaptation and Resilience". It aims for progress in dealing with climate impacts through better adaptation and strengthened resilience.

Fostering implementation is also the goal of the **Global Commission on Adaptation** (GCA), which seeks to accelerate adaptation action and support. In early September 2019, it presented its flagship report, which concluded that investment of US$ 1.8 trillion in just five areas of adaptation during the upcoming decade **could prevent US$ 7 trillion in losses and damages by 2050**. Spending US$ 800 million per year on early warning systems alone would avoid losses of US$ 3 billion to US$ 16 billion per year. However, **in 2017 only US$ 13.3 billion in public and private adaptation finance was provided and mobilised**.[164] Furthermore, that does not include any financing for loss and damage.[165]

Whether the UN summit or the GCA were and will contribute to increased resilience for vulnerable people, can only be determined in the upcoming years. However, the considerable lack of resilience financing points to the **need for more encompassing, systematic and longer-term support** in general. While presenting selected success stories as well as funding lighthouse projects adds a lot of value, it will not suffice if the international community does not provide the means to put those lessons learned to use across the world.

Resilience Agenda at Chilean COP25 in Madrid

Climate change-related losses and damages threaten livelihoods, food security, human security and sustainable economic development. However, climate change impacts hit the poorest countries hardest because they lack the economic and financial capacity to deal with the loss and damage. Those most affected are those least responsible for the cause of the climate crisis. So far, there is a lack of political and legal rules to determine how those responsible for climate change should pay for the consequences of their emissions. In the context of the UN climate negotiations, additional

[163] Kulp et al. 2019
[164] OECD 2019
[165] Global Commission on Adaptation 2019

financial resources to help the poorest people and countries cope with loss and damage are lacking. During the forthcoming climate summit in Madrid one of the big issues therefore must be: How can developing countries be supported in dealing with increasing loss and damage? How can polluters, in particular, contribute to the costs?

The CRI 2020 clearly shows the devastating impacts of climate change induced extreme weather events. COP25 will put Loss and Damage prominently on the agenda as **the body dealing with averting, minimizing and addressing Loss & Damage** (the Warsaw International Mechanism for Loss and Damage – WIM) **will be reviewed** in Madrid for the second time. The review must identify successes but also gaps in the implementation in order to decide which crucial steps should be taken to make the WIM fit for purpose. The review should help to officially address the "elephant in the room", namely the **lack of climate finance to address loss and damage**. One of the WIM's tasks – *"Enhancing action and support, including finance, technology and capacity-building"* – has not been implemented sufficiently yet, even the space for debates itself is lacking while at the same time, needs and affectedness are rising. The review therefore needs to assess:

a) how the mechanism can effectively assist vulnerable countries in dealing with loss and damage;
b) whether the WIM is able to meet the needs of vulnerable countries in dealing with future loss and damage based on best available science, taking into account the latest IPCC reports; and
c) how financial resources can be generated and made available to meet these needs.

Regarding adaptation, COP25 uses a similar implementation approach as the UN Climate Action Summit. Accordingly, adaptation is one of the initiatives the COP Presidency launched under the topic "Time to Act". However, some important negotiation issues remain on the agenda, such as the National Adaptation Plans (NAPs). This is a particularly interesting item, since the first NAP cycle will end in 2020. Developing countries should have completed a NAP process by then and have a respective plan in place. At present, however, there are only 13 countries worldwide, which have submitted a NAP and the process has turned out to be highly complex and challenging, especially for the least developed countries. **More support, in terms of finance and capacity building through strong partnerships, is required** in that regard in order to prepare those countries for the effects of climate change that do not possess the capacity to do so on their own and in order to share successful approaches.

5 Methodological Remarks

The presented analyses are based on the worldwide data collection and analysis provided by Munich Re's NatCatSERVICE. "The information collated by MunichRe, the world's leading re-insurance company, can be used to document and perform risk and trend analyses on the extent and intensity of individual natural hazard events in various parts of the world."[166] Broken down by countries and territories, Munich Re collects the number of total losses caused by weather events, the number of deaths, the insured damages and the total economic damages. The last two indicators are stated in million US$ (original values, inflation adjusted).

In the present analysis, only weather-related events – storms, floods as well as temperature extremes and mass movements (heat and cold waves etc.) – are incorporated. Geological incidents like earthquakes, volcanic eruptions or tsunamis, for which data are also available, are not relevant

[166] MunichRe NatCatSERVICE

in this context as they do not depend on the weather and therefore are not possibly related to climate change. To enhance the manageability of the large amount of data, the different categories within the weather-related events were combined. For single case studies on particularly devastating events, it is stated whether they concern floods, storms or another type of event.

It is important to note that this event-related examination does not allow for an assessment of continuous changes of important climate parameters. For instance, a long-term decline in precipitation that was shown in some African countries as a consequence of climate change cannot be displayed by the CRI. Nevertheless, such parameters often substantially influence important development factors like agricultural outputs and the availability of drinking water.

Preparing an index requires the analysis of a vast amount of data. Thus, data availability and quality play an important role as well as the underlying methodology for their collection. For instance, the accurate attribution of a human loss to a particular extreme weather event faces certain methodological boundaries that data collectors have to work with (e.g. to determine whether the death of an elderly person during a heatwave is indeed the result of the extreme temperature or due to the high age alone). Similarly, data quality and coverage may vary from country to country as well as within countries. A recent study by Campbell et al. (2018) found that heatwave and health impact research is not evenly distributed across the globe. They highlight that “regions most at risk from heatwaves and health impact are under-represented in the research.”[167] The data analysed for the CRI rely on scientific best practice and methodologies used are constantly evolving with the view of ensuring the highest degree of accuracy, completeness and granularity.

Although certainly an interesting area for analysis, the present data do not allow for comprehensive conclusions about the distribution of damages below the national level. The respective data quality would only be sufficient for a limited number of countries. The island of Réunion, for example, would qualify for a separate treatment but data are insufficient.

Analysed Indicators

For the examination of the CRI, the following indicators were analysed:

1. number of deaths,
2. number of deaths per 100 000 inhabitants,
3. sum of losses in US$ in purchasing power parity (PPP) as well as
4. losses per unit of gross domestic product (GDP).

For the indicators 2–4, economic and population data primarily provided by the International Monetary Fund were taken into account. It must be added, however, that especially for small (e.g. Pacific Small Island Developing States) or extremely politically unstable countries (e.g. Somalia), the required data are not always available in sufficient quality for the entire time period observed. Those countries needed to be omitted from the analyses.

The CRI 2020 is based on the loss figures of 181 countries from the year 2018 and the period 1999 to 2018. This ranking represents the most affected countries. In each of the four categories ranking is used as a normalisation technique. Each country's index score has been derived from a country's average ranking in all four indicating categories, according to the following weighting: death toll, 1/6; deaths per 100 000 inhabitants, 1/3; absolute losses in PPP, 1/6; losses per GDP unit, 1/3.

[167] Campbell et al. 2018

For example, in the Climate Risk Index for 1999-2018, Bangladesh ranks 9th in fatalities among all countries analysed in this study, 37th in Fatalities per 100 000 inhabitants, 17th in losses and 40th in losses per unit GDP (see Annexes, Table 4). Hence, its CRI Score is calculated as follows:

CRI Score = 9 x 1/6 + 37 x 1/3 + 17 x 1/6 + 40 x 1/3 = 30.00

Only six countries have a lower CRI Score for 1999-2018, hence Bangladesh ranks 7th in this index category (see Table 2).

The Relative Consequences Also Depend on Economic and Population Growth

Identifying relative values in this index represents an important complement to the otherwise often dominating absolute values because it allows for analysing country specific data on damages in relation to real conditions and capacities in those countries. It is obvious, for example, that for richer countries like the USA or Japan damages of one billion US$ cause much less economic consequences than for the world's poorest countries, where damages in many cases constitute a substantial share of the annual GDP. This is being backed up by the relative analysis.

It should be noted that values, and hence the rankings of countries regarding the respective indicators do not only change due to the absolute impacts of extreme weather events, but also due to economic and population growth or decline. If, for example, population increases, which is the case in most of the countries, the same absolute number of deaths leads to a relatively lower assessment in the following year. The same applies to economic growth. However, this does not affect the significance of the relative approach. Society's ability of coping with damages through precaution, mitigation and disaster preparedness, insurances or the improved availability of means for emergency aid, generally grows along with increasing economic strength. Nevertheless, an improved ability does not necessarily imply enhanced implementation of effective preparation and response measures. While absolute numbers tend to overestimate populous or economically capable countries, relative values give more prominence to smaller and poorer countries. In order to consider both effects, the analysis of the CRI is based on absolute (indicators 1 and 3) as well as on relative (indicators 2 and 4) scores. Being double weighted in the average ranking of all indicators generating the CRI Score, more emphasis and therefore higher importance is given to the relative losses.

The Indicator "Losses in Purchasing Power Parity" Allows for a More Comprehensive Estimation of How Different Societies are Actually Affected

The indicator "absolute losses in US$" is identified by purchasing power parity (PPP) because using this figure expresses more appropriately how people are actually affected by the loss of US$ 1 than by using nominal exchange rates. Purchasing power parity is a currency exchange rate, which permits a comparison of, for instance, national GDPs, by incorporating price differences between countries. This means that a farmer in India can buy more crops with US$ 1 than a farmer in the USA with the same amount of money. Thus, the real consequences of the same nominal damage are much higher in India. For most countries, US$ values according to exchange rates must therefore be multiplied by a factor bigger than one.

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Annexes

CRI = Climate Risk Index; GDP = gross domestic product; PPP = purchasing power parity

Table 3: Climate Risk Index for 2018

CRI Rank	Country	CRI score	Fatalities in 2018 (Rank)	Fatalities per 100 000 inhab-itants (Rank)	Losses in mil-lion US$ (PPP) (Rank)	Losses per unit GDP in % (Rank)
125	**Albania**	108.00	102	87	124	124
109	**Algeria**	93.83	47	76	110	127
80	**Angola**	76.00	52	72	82	89
135	**Antigua and Barbuda**	125.00	115	115	135	135
40	**Argentina**	48.33	61	101	5	11
135	**Armenia**	125.00	115	115	135	135
43	**Australia**	49.50	62	86	11	26
49	**Austria**	56.00	88	89	20	25
135	**Azerbaijan**	125.00	115	115	135	135
135	**Bahrain**	125.00	115	115	135	135
98	**Bangladesh**	85.50	18	79	97	120
135	**Barbados**	125.00	115	115	135	135
130	**Belarus**	111.83	115	115	102	112
90	**Belgium**	81.83	102	112	39	63
135	**Belize**	125.00	115	115	135	135
101	**Benin**	88.00	77	77	109	94
135	**Bhutan**	125.00	115	115	135	135
59	**Bolivia**	63.50	71	66	62	58
129	**Bosnia and Herzegovina**	109.67	115	115	113	100
135	**Botswana**	125.00	115	115	135	135
91	**Brazil**	82.83	38	105	43	103
135	**Brunei Darussalam**	125.00	115	115	135	135
116	**Bulgaria**	101.00	115	115	85	88
135	**Burkina Faso**	125.00	115	115	135	135
25	**Burundi**	36.33	50	32	72	16
38	**Cambodia**	47.67	29	17	79	72
122	**Cameroon**	105.83	64	91	129	130
9	**Canada**	21.83	13	19	12	34
135	**Cape Verde**	125.00	115	115	135	135
73	**Central African Republic**	71.17	77	51	116	66
135	**Chad**	125.00	115	115	135	135
87	**Chile**	81.17	115	115	36	53
33	**China**	45.17	5	94	4	37
75	**Chinese Taipei**	72.33	53	65	55	98
53	**Colombia**	61.00	20	39	70	99
135	**Comoros**	125.00	115	115	135	135
96	**Costa Rica**	84.67	93	82	87	82
106	**Côte d'Ivoire**	89.50	46	55	125	128
126	**Croatia**	108.33	115	115	101	102
76	**Cyprus**	73.50	81	13	120	107
35	**Czech Republic**	46.83	71	63	28	28
68	**Democratic Republic of Congo**	69.83	24	69	91	83
135	**Democratic Republic of Timor-Leste**	125.00	115	115	135	135
55	**Denmark**	61.33	93	88	33	33
31	**Djibouti**	44.67	93	27	81	20
135	**Dominica**	125.00	115	115	135	135
99	**Dominican Republic**	86.50	81	84	84	93
112	**Ecuador**	97.00	62	73	122	126
131	**Egypt**	113.67	115	115	93	122

CRI Rank	Country	CRI score	Fatalities in 2018 (Rank)	Fatalities per 100 000 inhabitants (Rank)	Losses in million US$ (PPP) (Rank)	Losses per unit GDP in % (Rank)
30	**El Salvador**	44.33	71	49	49	24
135	**Eritrea**	125.00	115	115	135	135
108	**Estonia**	90.50	115	115	76	61
111	**Eswatini**	96.67	102	54	128	121
57	**Ethiopia**	62.83	26	70	63	74
10	**Fiji**	22.50	64	6	47	6
135	**Finland**	125.00	115	115	135	135
34	**France**	46.17	32	62	13	54
135	**Gabon**	125.00	115	115	135	135
113	**Georgia**	97.83	115	115	92	75
3	**Germany**	13.83	3	1	6	36
65	**Ghana**	68.33	22	24	108	116
11	**Greece**	23.67	14	4	38	41
70	**Grenada**	70.50	102	5	127	92
83	**Guatemala**	77.33	102	113	46	45
135	**Guinea**	125.00	115	115	135	135
37	**Guinea-Bissau**	47.50	55	7	112	52
135	**Guyana**	125.00	115	115	135	135
104	**Haiti**	88.67	81	85	111	85
45	**Honduras**	51.67	48	25	78	67
123	**Hungary**	107.17	81	81	134	133
135	**Iceland**	125.00	115	115	135	135
5	**India**	18.17	1	34	2	19
64	**Indonesia**	68.17	11	74	42	104
66	**Iraq**	68.50	41	58	64	95
81	**Ireland**	76.50	93	80	54	76
24	**Islamic Republic of Afghanistan**	36.00	15	21	61	49
60	**Islamic Republic of Iran**	64.83	48	100	21	60
106	**Israel**	89.50	60	41	131	132
21	**Italy**	33.67	28	56	8	27
128	**Jamaica**	109.50	115	115	118	97
1	**Japan**	5.50	2	2	3	12
50	**Jordan**	56.33	38	16	94	87
115	**Kazakhstan**	98.50	115	115	66	90
7	**Kenya**	19.67	12	23	26	17
135	**Kiribati**	125.00	115	115	135	135
81	**Korea, Republic of**	76.50	34	57	75	118
135	**Kosovo**	125.00	115	115	135	135
57	**Kuwait**	62.83	102	102	25	23
134	**Kyrgyz Republic**	117.50	102	106	133	129
22	**Lao People's Democratic Republic**	35.50	26	8	69	51
44	**Latvia**	50.00	102	75	32	8
62	**Lebanon**	67.17	50	18	105	106
56	**Lesotho**	61.50	58	11	121	84
135	**Liberia**	125.00	115	115	135	135
135	**Libya**	125.00	115	115	135	135
19	**Lithuania**	29.33	77	28	23	10
95	**Luxembourg**	84.33	115	115	65	48
4	**Madagascar**	15.83	17	20	30	4
93	**Malawi**	83.67	77	96	95	69
97	**Malaysia**	84.83	45	61	96	123
118	**Maldives**	103.33	115	115	119	78
135	**Mali**	125.00	115	115	135	135
135	**Malta**	125.00	115	115	135	135

CRI Rank	Country	CRI score	Fatalities in 2018 (Rank)	Fatalities per 100 000 inhabitants (Rank)	Losses in million US$ (PPP) (Rank)	Losses per unit GDP in % (Rank)
135	**Marshall Islands**	125.00	115	115	135	135
116	**Mauritania**	101.00	115	115	107	77
84	**Mauritius**	78.83	115	115	68	30
26	**Mexico**	37.67	10	44	14	57
135	**Micronesia**	125.00	115	115	135	135
135	**Moldova**	125.00	115	115	135	135
17	**Mongolia**	26.67	64	22	34	9
114	**Montenegro**	98.17	115	115	104	70
135	**Morocco**	125.00	115	115	135	135
54	**Mozambique**	61.17	56	78	71	42
48	**Myanmar**	53.83	20	43	59	79
85	**Namibia**	79.17	88	40	115	96
20	**Nepal**	29.67	8	10	56	47
62	**Netherlands**	67.17	81	99	24	50
46	**New Zealand**	53.17	88	68	37	29
52	**Nicaragua**	60.17	64	42	83	65
27	**Niger**	39.67	31	26	77	39
18	**Nigeria**	28.83	7	31	16	44
135	**North Macedonia**	125.00	115	115	135	135
94	**Norway**	84.00	102	104	48	73
13	**Oman**	24.33	71	30	9	3
100	**Pakistan**	87.83	19	90	90	119
92	**Panama**	83.33	75	37	117	117
135	**Papua New Guinea**	125.00	115	115	135	135
127	**Paraguay**	109.33	102	107	114	113
110	**Peru**	94.00	64	97	86	110
2	**Philippines**	11.17	4	14	7	14
41	**Poland**	49.00	42	60	22	55
72	**Portugal**	70.67	88	92	40	56
124	**Puerto Rico**	107.67	115	115	99	101
135	**Qatar**	125.00	115	115	135	135
135	**Republic of Congo**	125.00	115	115	135	135
28	**Republic of Yemen**	41.33	35	38	57	40
89	**Romania**	81.67	58	67	80	109
79	**Russia**	75.50	44	103	31	86
8	**Rwanda**	21.17	16	9	51	21
70	**Samoa**	70.50	115	115	74	2
103	**Saudi Arabia**	88.50	37	48	130	134
120	**Senegal**	104.50	115	115	100	91
61	**Serbia**	65.50	93	93	44	35
135	**Seychelles**	125.00	115	115	135	135
135	**Sierra Leone**	125.00	115	115	135	135
135	**Singapore**	125.00	115	115	135	135
102	**Slovak Republic**	88.33	64	36	132	131
51	**Slovenia**	57.83	93	52	58	46
29	**Solomon Islands**	43.17	88	12	103	22
47	**South Africa**	53.33	53	95	15	31
133	**South Sudan**	116.00	115	115	123	114
38	**Spain**	47.67	33	53	19	64
6	**Sri Lanka**	19.00	36	29	10	5
135	**St. Kitts and Nevis**	125.00	115	115	135	135
135	**St. Lucia**	125.00	115	115	135	135
135	**St. Vincent and the Grenadines**	125.00	115	115	135	135
42	**Sudan**	49.33	30	45	52	62
135	**Suriname**	125.00	115	115	135	135
105	**Sweden**	89.00	102	111	50	80

CRI Rank	Country	CRI score	Fatalities in 2018 (Rank)	Fatalities per 100 000 inhabitants (Rank)	Losses in million US$ (PPP) (Rank)	Losses per unit GDP in % (Rank)
77	**Switzerland**	73.67	93	98	35	59
73	**Tajikistan**	71.17	75	64	88	68
68	**Tanzania**	69.83	42	71	73	81
67	**Thailand**	68.83	25	59	60	105
135	**The Bahamas**	125.00	115	115	135	135
135	**The Gambia**	125.00	115	115	135	135
135	**Togo**	125.00	115	115	135	135
15	**Tonga**	25.17	102	3	41	1
88	**Trinidad and Tobago**	81.33	115	115	67	38
35	**Tunisia**	46.83	56	47	45	43
85	**Turkey**	79.17	40	83	53	108
135	**Tuvalu**	125.00	115	115	135	135
14	**Uganda**	24.67	23	35	29	13
121	**Ukraine**	105.33	93	114	89	111
135	**United Arab Emirates**	125.00	115	115	135	135
78	**United Kingdom**	73.83	64	110	17	71
12	**United States**	23.83	6	50	1	18
23	**Uruguay**	35.67	81	46	27	7
135	**Uzbekistan**	125.00	115	115	135	135
31	**Vanuatu**	44.67	102	15	106	15
119	**Venezuela**	104.17	81	108	98	115
16	**Vietnam**	26.17	9	33	18	32
135	**Zambia**	125.00	115	115	135	135
132	**Zimbabwe**	114.50	93	109	126	125

Table 4: Climate Risk Index for 1999–2018

Exemplary calculation: Albania ranks 137th in fatalities among all countries analysed in this study, 130th in Fatalities per 100 000 inhabitants, 114th in losses and 87th in losses per unit GDP. Hence, its CRI Score is calculated as follows:

CRI Score = 137 x 1/6 + 130 x 1/3 + 114 x 1/6 + 87 x 1/3 = 114.17

CRI Rank	Country	CRI score	Fatalities 1999-2018 (Rank)	Fatalities per 100 000 inhabitants 1999-2018 (Rank)	Losses in million US$ (PPP) 1999-2018 (Rank)	Losses per unit GDP in % 1999-2018 (Rank)
129	**Albania**	114.17	137	130	114	87
99	**Algeria**	92.50	35	66	84	152
103	**Angola**	97.00	53	69	101	145
47	**Antigua and Barbuda**	58.00	160	39	98	6
84	**Argentina**	79.50	62	116	23	80
157	**Armenia**	145.17	172	172	133	111
33	**Australia**	50.17	44	63	11	60
44	**Austria**	55.67	63	48	33	71
146	**Azerbaijan**	133.67	127	155	99	133
179	**Bahrain**	171.83	168	168	175	176
7	**Bangladesh**	30.00	9	37	17	40
151	**Barbados**	141.67	171	159	157	102
152	**Belarus**	142.00	109	134	143	166
55	**Belgium**	63.83	26	13	63	134
32	**Belize**	48.50	131	25	96	7
149	**Benin**	141.00	113	140	153	150
103	**Bhutan**	97.00	134	59	154	88
28	**Bolivia**	45.33	50	35	58	47

CRI Rank	Country	CRI score	Fatalities 1999-2018 (Rank)	Fatalities per 100 000 inhabitants 1999-2018 (Rank)	Losses in million US$ (PPP) 1999-2018 (Rank)	Losses per unit GDP in % 1999-2018 (Rank)
66	**Bosnia and Herzegovina**	70.17	125	115	40	13
145	**Botswana**	132.33	151	150	125	109
88	**Brazil**	83.17	21	108	16	123
175	**Brunei Darussalam**	169.17	168	154	179	180
67	**Bulgaria**	70.83	85	89	48	57
106	**Burkina Faso**	99.33	92	125	110	72
71	**Burundi**	73.67	81	82	119	39
12	**Cambodia**	35.33	40	34	52	26
147	**Cameroon**	133.83	87	135	138	154
95	**Canada**	88.17	76	133	15	86
155	**Cape Verde**	143.50	162	126	169	139
159	**Central African Republic**	149.33	139	151	167	144
110	**Chad**	100.83	106	128	105	69
93	**Chile**	87.83	83	121	36	83
43	**China**	55.50	5	104	2	59
41	**Chinese Taipei**	54.83	33	45	28	89
44	**Colombia**	55.67	24	49	32	90
140	**Comoros**	122.67	144	73	174	136
95	**Costa Rica**	88.17	94	74	97	95
153	**Côte d'Ivoire**	142.67	91	143	151	164
31	**Croatia**	48.33	55	19	65	66
144	**Cyprus**	129.67	150	101	146	140
85	**Czech Republic**	79.67	90	107	34	70
141	**Democratic Republic of Congo**	125.83	46	118	149	162
177	**Democratic Republic of Timor-Leste**	170.33	168	167	176	172
126	**Denmark**	112.83	147	162	44	81
64	**Djibouti**	69.50	113	31	140	51
10	**Dominica**	32.33	116	2	72	1
50	**Dominican Republic**	58.50	52	36	69	79
100	**Ecuador**	92.83	69	84	86	117
156	**Egypt**	143.67	77	158	121	174
25	**El Salvador**	42.50	65	41	54	27
122	**Eritrea**	109.17	164	170	107	22
158	**Estonia**	148.83	155	148	144	149
115	**Eswatini**	103.50	151	119	124	54
56	**Ethiopia**	64.67	29	91	53	62
13	**Fiji**	37.17	89	15	80	12
166	**Finland**	155.67	163	169	113	160
15	**France**	38.00	4	8	12	98
174	**Gabon**	167.33	155	153	181	181
102	**Georgia**	94.17	115	96	106	76
17	**Germany**	38.67	10	23	6	85
113	**Ghana**	102.50	56	81	115	141
82	**Greece**	78.83	71	70	50	106
21	**Grenada**	39.83	128	7	91	3
16	**Guatemala**	38.33	31	27	45	50
170	**Guinea**	161.33	132	161	172	171
124	**Guinea-Bissau**	111.33	140	103	158	82
120	**Guyana**	107.17	160	142	127	36
3	**Haiti**	13.83	15	4	42	9
42	**Honduras**	55.00	66	52	76	42
61	**Hungary**	69.00	59	47	59	101
177	**Iceland**	170.33	172	172	170	168
17	**India**	38.67	3	55	3	58
77	**Indonesia**	76.83	16	92	21	120

CRI Rank	Country	CRI score	Fatalities 1999-2018 (Rank)	Fatalities per 100 000 inhabitants 1999-2018 (Rank)	Losses in million US$ (PPP) 1999-2018 (Rank)	Losses per unit GDP in % 1999-2018 (Rank)
150	**Iraq**	141.33	96	157	108	165
136	**Ireland**	119.17	137	149	64	108
24	**Islamic Republic of Afghanistan**	41.83	13	14	82	64
83	**Islamic Republic of Iran**	79.00	42	113	22	92
139	**Israel**	120.50	111	124	90	137
26	**Italy**	43.67	6	9	18	110
57	**Jamaica**	64.83	112	80	71	23
62	**Japan**	69.33	23	93	7	100
133	**Jordan**	116.00	110	122	104	119
154	**Kazakhstan**	142.83	99	147	126	169
37	**Kenya**	53.67	39	71	43	49
134	**Kiribati**	116.17	172	172	159	11
87	**Korea, Republic of**	82.83	48	98	25	114
163	**Kuwait**	152.00	155	165	109	159
123	**Kyrgyz Republic**	109.33	78	53	160	156
76	**Lao People's Democratic Republic**	76.33	86	77	92	63
89	**Latvia**	83.83	107	64	100	84
138	**Lebanon**	120.00	118	110	118	132
118	**Lesotho**	106.50	148	138	129	43
165	**Liberia**	155.33	159	166	165	138
168	**Libya**	158.83	143	160	150	170
109	**Lithuania**	100.50	121	97	94	97
105	**Luxembourg**	97.17	95	12	148	158
11	**Madagascar**	32.83	32	38	51	19
80	**Malawi**	77.83	82	112	95	33
114	**Malaysia**	103.33	64	102	66	143
175	**Maldives**	169.17	172	172	173	163
135	**Mali**	116.67	98	136	122	104
164	**Malta**	152.83	164	145	161	151
172	**Marshall Islands**	165.00	172	172	180	147
81	**Mauritania**	78.50	104	75	111	53
116	**Mauritius**	104.67	145	106	117	77
54	**Mexico**	61.83	25	95	10	73
46	**Micronesia**	56.67	124	5	164	21
92	**Moldova**	86.17	134	129	75	25
53	**Mongolia**	61.67	93	51	83	46
107	**Morocco**	100.00	73	127	67	103
14	**Mozambique**	37.50	28	32	77	28
2	**Myanmar**	10.33	1	1	19	20
60	**Namibia**	66.67	80	28	116	74
9	**Nepal**	31.50	17	17	56	41
68	**Netherlands**	71.83	30	30	57	142
90	**New Zealand**	84.17	116	105	49	65
38	**Nicaragua**	53.83	67	40	88	44
73	**Niger**	74.00	67	85	103	52
117	**Nigeria**	104.83	27	114	68	153
107	**North Macedonia**	100.00	123	83	123	94
148	**Norway**	138.83	140	156	89	146
23	**Oman**	41.17	84	44	27	24
5	**Pakistan**	28.83	11	46	8	31
118	**Panama**	106.50	101	79	120	130
98	**Papua New Guinea**	91.33	72	54	136	116
70	**Paraguay**	73.50	108	111	47	32
47	**Peru**	58.00	34	60	38	78

CRI Rank	Country	CRI score	Fatalities 1999-2018 (Rank)	Fatalities per 100 000 inhabitants 1999-2018 (Rank)	Losses in million US$ (PPP) 1999-2018 (Rank)	Losses per unit GDP in % 1999-2018 (Rank)
4	**Philippines**	17.67	7	16	9	29
78	**Poland**	77.17	43	88	30	107
19	**Portugal**	38.83	20	11	41	75
1	**Puerto Rico**	6.67	19	3	5	5
181	**Qatar**	173.67	172	172	168	179
162	**Republic of Congo**	151.50	130	123	177	178
74	**Republic of Yemen**	74.67	49	68	81	91
35	**Romania**	53.17	51	67	24	55
30	**Russia**	47.67	2	6	14	129
111	**Rwanda**	102.00	75	72	145	124
71	**Samoa**	73.67	155	57	141	16
112	**Saudi Arabia**	102.17	60	94	55	155
142	**Senegal**	129.50	102	139	135	131
69	**Serbia & Montenegro & Kosovo**	73.33	97	117	35	37
169	**Seychelles**	159.50	172	172	171	135
91	**Sierra Leone**	85.67	57	29	155	122
180	**Singapore**	172.17	172	172	163	177
121	**Slovak Republic**	108.00	119	120	79	105
40	**Slovenia**	54.33	79	26	73	61
65	**Solomon Islands**	70.00	128	33	156	35
79	**South Africa**	77.33	47	100	31	93
125	**South Sudan**	112.50	87	109	128	121
29	**Spain**	47.33	8	10	26	115
22	**Sri Lanka**	40.17	36	43	29	45
127	**St. Kitts and Nevis**	113.50	172	172	137	14
51	**St. Lucia**	59.33	142	24	132	17
52	**St. Vincent and the Grenadines**	59.83	148	21	139	15
101	**Sudan**	93.00	45	87	87	126
173	**Suriname**	166.00	164	152	178	175
142	**Sweden**	129.50	136	163	61	127
34	**Switzerland**	52.33	41	22	37	96
49	**Tajikistan**	58.17	74	65	85	30
130	**Tanzania**	114.33	70	132	102	125
8	**Thailand**	31.00	22	62	4	18
20	**The Bahamas**	39.67	122	18	60	10
86	**The Gambia**	81.00	103	50	147	68
160	**Togo**	149.67	126	146	166	157
75	**Tonga**	75.67	164	76	130	4
161	**Trinidad and Tobago**	150.17	153	137	152	161
130	**Tunisia**	114.33	105	131	93	113
132	**Turkey**	115.17	61	144	46	148
128	**Tuvalu**	113.67	172	172	162	2
62	**Uganda**	69.33	54	90	70	56
94	**Ukraine**	88.00	38	86	62	128
167	**United Arab Emirates**	158.33	145	164	131	173
58	**United Kingdom**	65.00	18	58	20	118
27	**United States**	44.17	12	78	1	48
97	**Uruguay**	88.33	120	99	78	67
171	**Uzbekistan**	162.00	154	171	142	167
38	**Vanuatu**	53.83	133	20	134	8
59	**Venezuela**	66.00	37	61	39	99
6	**Vietnam**	29.83	14	42	13	34
137	**Zambia**	119.67	100	141	112	112
36	**Zimbabwe**	53.33	58	56	74	38

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Germanwatch – Bonn Office
Kaiserstrasse 201
D-53113 Bonn, Germany
Phone: +49 (0)228 / 60492-0
Fax: +49 (0)228 / 60492-19

Germanwatch – Berlin Office
Stresemannstr. 72
D-10963 Berlin, Germany
Phone: +49 (0)30 / 2888 356-0
Fax: +49 (0)30 / 2888 356 -1

E-mail: info@germanwatch.org

or visit our website:

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Observing. Analysing. Acting.
For Global Equity and the Preservation of Livelihoods.

EXHIBIT 11

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

[redacted]

Final Report

February 1968

SOURCES, ABUNDANCE, AND FATE OF GASEOUS ATMOSPHERIC POLLUTANTS

Prepared for:

AMERICAN PETROLEUM INSTITUTE
1271 AVENUE OF THE AMERICAS
NEW YORK, N.Y. 10020

ATTN: MR. W. A. BURHOUSE
ASSISTANT DIRECTOR

By: E. ROBINSON AND R. C. ROBBINS

SRI Project PR-6755

B4007

Approved: N. K. HIESTER, DIRECTOR
CHEMICAL DEVELOPMENT AND ENGINEERING DIVISION

18 μ. As such CO_2 prevents the loss of considerable heat energy from the earth and radiates it back to the lower atmosphere, the so-called "greenhouse" effect. Thus the major changes which are speculated about as possibly resulting from a change in atmospheric CO_2 are related to a change in the earth's temperature.

The latest data available for estimating CO_2 temperature effects are those of Moller (1963). From Möller's data a CO_2 increase of 25% would result in an increase in temperature at the earth's surface of between 1.1 and 7°F, depending on the assumption made regarding the likely humidity changes accompanying this temperature change. If the amount of water vapor in the atmosphere remained unchanged, the smaller increase would occur, but if the relative humidity were to remain constant then the larger calculated increase would prevail. If, instead of a 25% increase, the CO_2 content were to double, the expected change would be about three times this figure. For atmospheric calculations, Möller's model is still a relatively simple one and has not included all of the possible major interactions occurring in the atmosphere. For this reason it is likely that Möller's calculations overestimate the effects on temperature of an increase in CO_2. More comprehensive models are under development and should be available shortly.

If the earth's temperature increases significantly, a number of events might be expected to occur, including the melting of the Antarctic ice cap, a rise in sea levels, warming of the oceans, and an increase in photosynthesis. The first two items are of course related since the increase in sea level would be mainly due to the added water from the ice cap. Estimates of the possible rate at which the Antarctic ice cap might melt have been made. If the poleward heat flux were increased 10%, the ice cap could disappear in about 4000 years. A shorter time, about 400 years, is estimated if it is considered that half the energy associated with a 2% increase in radiation were used to melt the polar ice cap. A 2% increase might result from a 25% increase in CO_2 by the year 2000.

With regard to sea level changes, if 1000 years were required to melt the Antarctic ice cap, the resulting 400 foot rise in sea level would occur at a rate of 4 feet per 10 years. This is 100 times greater than presently observed changes.

Changes in ocean temperature would change the distribution of fish and cause a retreat in the polar sea ice. This has happened in recent time on a very limited scale.

Changes in CO_2 might also bring about increased photosynthesis in areas where CO_2 might be a limiting factor in present growth patterns. Where temperature has been a limiting factor to growth and development, an increase in biological activity might be expected.

Although there are other possible sources for the additional CO_2 now being observed in the atmosphere, none seems to fit the presently observed situation as well as the fossil fuel emanation theory.

C. Summary of Carbon Dioxide in the Atmosphere

In summary, Revelle makes the point that man is now engaged in a vast geophysical experiment with his environment, the earth. Significant temperature changes are almost certain to occur by the year 2000 and these could bring about climatic changes.

Since Revelle's report, McCormick and Ludwig (1966) have studied the possible world-wide change of atmospheric fine particles. An increase in fine particulate material will have the effect of increasing the reflectivity of the earth's atmosphere and reducing the amount of radiation received from the sun. Thus this effect would be the opposite of that caused by an increase in CO_2. The argument has been made that the large-scale cooling trend observed in the northern hemisphere since about 1955 is due to the disturbance of the radiation balance by fine particles and that this effect has already reversed any warming trend due to CO_2.

It is clear that we are unsure as to what our long-lived pollutants are doing to our environment; however, there seems to be no doubt that the potential damage to our environment could be severe. Whether one chooses the CO_2 warming theory as described in detail by Revelle and others or the newer cooling prospect indicated by McCormick and Ludwig, the prospect for the future must be of serious concern.

It seems ironic that in our view of air pollution technology we take such a serious concern with small-scale events such as the photochemical reactions of trace concentrations of hydrocarbons, the effect on vegetation of a fraction of a part per million of SO_2, when the abundant pollutants which we generally ignore because they have little local effect, CO_2 and submicron particles, may be the cause of serious world-wide environmental changes.

the ambient atmosphere should be carefully checked, but probably the most important feature as far as atmospheric chemistry is concerned is to determine the source of the nitrate in the atmosphere. The source, on the basis of our analysis of the atmospheric nitrogen cycle, seems to be by the oxidation of NH_3. The oxidation mechanism for atmospheric NH_3 is unknown. This is a very difficult problem which has been evaded or ignored for several years. If NH_3 cannot be shown to be the source of the nitrate, then it will be necessary to find a sufficient natural source of NO or NO_2 to provide the nitrate.

In the area of atmospheric organic gases the almost complete absence of information on all the possible components except CH_4 should be remedied. Proven analytical techniques are available for such studies. While there may be some doubt in the cases of SO_2, H_2S, and other compounds that available techniques are sufficiently sensitive for use in the ambient atmosphere, this is not the case for the low molecular weight organics. Here, gas chromatography is presently capable of detecting the trace levels of many atmospheric organics present in the fractional part-per-billion range. Although the ambient concentrations are known, methane is in the same category as CO in that there is a major need to determine the sink or scavenging mechanism. At present this can only be guessed at.

Past and present studies of CO_2 are detailed and seem to explain adequately the present state of CO_2 in the atmosphere. What is lacking, however, is an application of these atmospheric CO_2 data to air pollution technology and work toward systems in which CO_2 emissions would be brought under control.

Another point which has been made in our discussion is that N_2O, CO, CH_4, and CO_2 have essentially the same atmospheric residence times because, we believe, vegetation plays a major role in the scavenging cycle for each of the materials. This postulate should obviously be carefully checked by

EXHIBIT 12

EXXON RESEARCH AND ENGINEERING COMPANY

P.O. BOX 8, LINDEN, N. J. 07036

GOVERNMENT RESEARCH LABORATORIES
W. M. COOPER, JR.
Director

December 7, 1978

Dr. Edward E. David, Jr.
General Administration
FP #101/Room G-119

Dear Ed:

A set of highly visible programs has been developed to help clarify the mechanisms associated with storage of carbon dioxide, and thus help predict the likelihood of a greenhouse effect. The programs will make use of Exxon facilities such as tankers and drilling ships to measure the rate of CO_2 uptake by the various layers of the ocean. Sophisticated techniques involving measurements of changes in isotopic ratios of carbon and the distribution of radon in the ocean will be used in conjunction with state-of-the-art techniques to measure CO_2 concentration in the atmosphere and in the oceans.

In addition to the ocean related work, a program is proposed to determine the source of the annual atmospheric CO_2 increment that has been increasing since the Industrial Revolution (1860). Researchers have attributed the CO_2 increment to varying combinations of fossil fuel burning and forest clearing. The program would measure the concentration of C-13 (stable) and C-14 (radioactive) in wines from sources that have well documented histories of temperature, weather, and location as a function of the time the wines were produced. By taking into account the relative absence of C-14 in wines, we will be able to estimate the contribution of fossil fuels (in which C-14 has decayed over the thousands of years of storage), and thus determine the relative concentration of fossil fuel derived CO_2 that was present in the atmosphere at the time the grapes were grown. Similarly, by analyzing the wine for the relative depletion of C-13 (this isotope is less reactive in photosynthesis than the predominant C-12), we will be able to estimate the contribution of forest clearing to the growth of CO_2 in the atmosphere. The wine measurement program would provide a unique and novel method to unravel the historical source of the incremental growth of CO_2 in the atmosphere.

We propose to implement our programs by May 1, 1979 in order to begin to assess the real meaning of the greenhouse effect to Exxon. We would start by equipping a tanker on the Persian Gulf to Aruba and Houston run with continuous instrumentation to measure CO_2 in the atmosphere and

in the ocean. A number of batch ocean samples will be taken and stored for measurement of C-14. This measurement will be used to estimate the penetration of CO_2 into the ocean. The equipment will be manned by two ER&E technicians. We expect to conduct measurements for at least a year, and this will involve 5 round trips. Preliminary discussions with Esso International tanker personnel on the feasibility of using Exxon tankers have been favorable.

The drilling ship program which is designed to measure the mass transfer coefficient for CO_2 between the atmosphere and the ocean as a function of weather conditions would probably be started in Exxon drilling operations off the coast of Australia. The program would involve a month or two of Rn-222 on-board measurement using conventional equipment for α-counting. The program would get underway towards the end of the Summer of 1979. The wine measurement program would procure some 100 bottles of wine that have well documented histories, probably from a single chateau in France. These wines would be analyzed for C-13 using the highly sophisticated facilities at EPRCo., and for C-14 using the unique equipment at the University of Miami (School of Marine and Atmospheric Science). The program would start in May 1979.

We expect to conduct these programs in two phases over the period 1979-1984 (inclusive). Phase I would start May 1, 1979 and be conducted entirely with Exxon funding over the first year. Phase II would start as soon as Government (DOE) funding can be obtained. We visualize the drilling ship operations and the wine measurements programs to be entirely funded by Exxon and the tanker measurements program funded by the DOE. Our screening-type estimates in 1979 $ indicate the Phase I programs will cost 0.5 M$ and the total programs (Phase I and Phase II) 8 M$. Personnel costs account for over 70% of the cost, so methods of automating the tanker sampling program will be sought during Phase I.

In view of the highly complex nature of the programs, and the need to integrate the Exxon results into the global weather modeling programs, we intend to work closely with a university and the Government. We are currently considering a cooperative program with Columbia University's Lamont-Doherty Geological Observatory because two of the oustanding oceanographers and experts on the CO_2 problem, W. S. Broecker and T. Takahashi are associated with that institution.

The rationale for Exxon's involvement and commitment of funds and personnel is based on our need to assess the possible impact of the greenhouse effect on Exxon business. Exxon must develop a credible scientific team that can critically evaluate the information generated on the subject and be able to carry bad news, if any, to the corporation. This team must be recognized for its excellence in the scientific community, the government, and internally by Exxon management. We see no better method to acquire the necessary reputation than by attacking one of the major uncertainties in the global CO_2 balance, i.e., flux to the oceans and providing the necessary data. In addition, the international significance of the proposed programs will enhance the Exxon image in the public domain and provide great public relations value. As a consequence of the above, these programs are prime candidates for early implementation under the National Impact Program charter.

We have attached to this letter two appendices which assess the state-of-the-art on the greenhouse effect and provide details of the proposed programs. We are looking to you and the management council for guidance.

Very truly yours,

Henry Shaw

Henry Shaw

HS/jep

Attachments

cc: J. F. Black
W. M. Cooper, Jr.
R. T. Craig
F. J. Feely
W. Glass
E. J. Gornowski, Jr.
P. J. Lucchesi
R. E. Lyon, Jr.
J. K. Patterson
B. T. Richards, Jr.
L. E. Swabb, Jr.
R. L. Weeks
H. N. Weinberg
N. R. Werthamer

EXHIBIT 13

EXXON RESEARCH AND ENGINEERING COMPANY

P.O. BOX 51, LINDEN, N.J. 07036

PRODUCTS RESEARCH DIVISION
J.F. BLACK
Scientific Advisor

June 6, 1978

The Greenhouse Effect

Ref. No: 78PR 461

Mr. F. G. Turpin, Vice President
Exxon Research and Engineering Co.
Petroleum Staff
P. O. Box 101
Florham Park, NJ 07932

Dear Frank:

The review of the Greenhouse Effect which I presented to the Exxon Corporation Management Committee last July used only vu-graphs, without a prepared text. Last month, I had the opportunity to present an updated version of this talk to PERCC. The attached text was dictated shortly afterward to satisfy requests for a written version of the talk from people who had not heard the presentation last July. Also attached is a summary.

Sincerely,

Jim

J. F. BLACK

JFB/mbh
Attachments: Summary
Text
Vugraphs

CC: Messrs. N. Alpert
W. M. Cooper, Jr.
E. E. David
E. J. Gornowski
R. L. Hirsch
F. A. L. Holloway
P. J. Lucchesi
L. E. Swabb, Jr.

THE GREENHOUSE EFFECT

J. F. Black, Products Research Division
Exxon Research and Engineering Co.

SUMMARY

The earth's atmosphere presently contains about 330 ppm of CO_2. This gas does not absorb an appreciable amount of the incoming solar energy but it can absorb and return part of the infrared radiation which the earth radiates toward space. CO_2, therefore, contributes to warming the lower atmosphere by what has been called the "Greenhouse Effect."

The CO_2 content of the atmosphere has been monitored since 1957 at two locations, the Mauna Loa Observatory, Hawaii and the South Pole. These and other shorter studies show that CO_2 is increasing. If the increase is attributed to the combustion of fossil fuels, it can be calculated that the CO_2 content of the atmosphere has already been raised by about 10 to 15% and that slightly more than half of the CO_2 released by fossil fuel combustion is remaining in the atmosphere. Assuming that the percentage of the CO_2 remaining in the atmosphere will stay at 53% as fossil fuel consumption increases, one recent study predicts that in 2075 A.D., CO_2 concentration will peak at a level about twice what could be considered normal. This prediction assumes that fossil fuel consumption will grow at a rate of 2% per year until 2025 A.D. after which it will follow a symetrical decrease. This growth curve is close to that predicted by Exxon's Corporate Planning Department.

Mathematical models for predicting the climatic effect of a CO_2 increase have not progressed to the point at which all the feedback interactions which can be important to the outcome can be included. What is considered the best presently available climate model for treating the Greenhouse Effect predicts that a doubling of the CO_2 concentration in the atmosphere would produce a mean temperature increase of about 2°C to 3°C over most of the earth. The model also predicts that the temperature increase near the poles may be two to three times this value.

The CO_2 increase measured to date is not capable of producing an effect large enough to be distinguished from normal climate variations. As an example of normal variations, studies of meteorological and historical records in England indicate that the mean temperature has varied over a range of about ±0.7°C in the past 1000 years. A study of past climates suggests that if the earth does become warmer, more rainfall should result. But an increase as large as 2°C would probably also affect the distribution of the rainfall. A possible result might be a shift of both the desert and the fertile areas of the globe toward higher latitudes. Some countries would benefit but others could have their agricultural output reduced or destroyed. The picture is too unclear to predict which countries might be affected favorably or unfavorably.

It seems likely that any general temperature increase would be accentuated in the polar regions, possibly as much as two- or three-fold as mentioned above. Any large temperature increase at high latitudes would be associated with a reduction in snow cover and a melting of the floating ice-pack. Present thinking suggests that there would be little or no melting of the polar ice-caps in response to warmer temperatures on a time scale over which the Greenhouse Effect is predicted to apply.

A number of assumptions and uncertainties are involved in the predictions of the Greenhouse Effect. The first is the assumption that the observed CO_2 increase can be attributed entirely to fossil fuel combustion. At present, meteorologists have no direct evidence that the incremental CO_2 in the atmosphere comes from fossil carbon. The increase could be at least partly due to changes in the natural balance. There is considerable uncertainty regarding what controls the exchange of atmospheric CO_2 with the oceans and with carbonaceous materials on the continents.

Models which predict the climatic effects of a CO_2 increase are in a primitive stage of development. The atmosphere is a very complicated system, particularly on a global scale. In existing models, important interactions are neglected, either because they are not completely understood or because their proper mathematical treatment is too cumbersome. Substantial efforts are being expended to improve existing models. But there is no guarantee that better knowledge will lessen rather than augment the severity of the predictions.

The Greenhouse Effect has been the subject of a number of international scientific conferences during the past two years. These meetings have identified the information needed to definitely establish the source and ultimate significance of the CO_2 increase in the atmosphere. Present thinking holds that man has a time window of five to ten years before the need for hard decisions regarding changes in energy strategies might become critical. The DOE is presently seeking Congressional support for a research program which will produce the necessary information in the required time. This program is described.

THE GREENHOUSE EFFECT

By

J. F. BLACK

Transcript of a Talk
Delivered Before the PERCC Meeting
May 18, 1978

The Greenhouse Effect refers to a warming of the earth's atmosphere due to an increase in the concentration of carbon dioxide. As a background for the discussion today, the first vugraph outlines the basis for the Greenhouse Effect.

The earth receives energy in the form of both visible and ultraviolet radiation from the sun. Some of this radiation is reflected back into space, some is absorbed by the atmosphere but most is absorbed at the earth's surface. The earth in turns reemits energy in the form of infrared radiation toward space. Carbon dioxide and other atmospheric constituents absorb part of the infrared radiation. This absorbed energy warms the atmosphere. Therefore, higher carbon dioxide concentrations result in a more rapid absorption of the outgoing infrared radiation and warmer temperatures near the earth's surface. In my talk today I am planning to discuss:

I. The Source and Projected Magnitude of the CO_2 Increase in the Atmosphere

II. The Global Temperature Increase Which Can Be Expected From Higher CO_2 Concentrations

III. The Potential Problems Arising From a Global Temperature Increase

IV. Research Needed to Establish the Validity and Significance of Projected Increases of CO_2 in the Atmosphere.

My information is derived from following recent literature in this area and from talks with some of the leading research people in the field.

I. <u>The Source and Projected Magnitude of the CO_2 Increase in the Atmosphere</u>

Since 1958, CO_2 has been monitored at a number of remote sites which are free from local inputs (Vugraph 2). These are Point Barrow, Alaska; some Swedish aircraft flights; Mauna Loa, Hawaii; American Samoa and the South Pole. The carbon dioxide concentration has been found to be increasing rather uniformly at all locations with the South Pole measurements rather lagging those in the Northern Hemisphere.

Atmospheric scientists generally attribute this growth in CO_2 to the combustion of fossil fuel. A principal reason for this is that fossil fuel combustion is the only readily identifiable source which is (1) growing at the same rate, (2) large enough to account for the observed increases, and (3) capable of affecting the Northern Hemisphere first. If this assumption regarding the origin of carbon dioxide is true, it can be calculated that a little over 50% of the CO_2 entering the atmosphere is remaining there and the rest is being absorbed in surface sinks on the continents or in the ocean. Extrapolating backwards in time to follow the history of fossil fuel combustion, it can be estimated that since 1850 the concentration of this gas in the atmosphere has increased by about 13%. This increase amounts to about 75 billion metric tons of carbon dioxide.

It is also possible to extrapolate into the future. One of the most commonly quoted extrapolations is that of the Oak Ridge National Laboratory which was published in 1976[1]. This study produced two scenarios for the growth of fossil fuel consumption (Vugraph 3). Prior to 1973, fossil fuel use had been growing exponentially at about 4.3% per year. The scenario for most rapid growth assumed that this growth rate would continue, modified by a depletion factor which reduced the exponent in proportion to the amount of fossil fuel which remained unburned. Their second and more conservative assumption presumed that fossil fuel utilization would grow with a 2% growth rate out to 2025 A.D. followed by a symetrical decrease. This latter scenario is close to that developed independently by the Coordination and Planning Department of the Exxon Corporation.

Vugraph 4 presents the predicted atmospheric carbon dioxide levels which would result from each of these scenarios. The vertical axis in this vugraph presents the atmospheric carbon dioxide concentration relative to that which was calculated to have existed in 1850, prior to the combustion of appreciable amounts of fossil fuel. It can be seen that the scenario based upon very rapid growth predicts that by 2075 the atmospheric carbon dioxide concentration will be about 4 to 5 times that which existed prior to the industrial revolution. Moreover, at that time, the carbon dioxide concentration will still be increasing. The more conservative assumption, shown in the lower curve, predicts that carbon dioxide concentrations will level out about a century from now at a value which is about twice that in existence in 1850 and then would decline at a very slow rate.

Although carbon dioxide increase is predominantly attributed to fossil fuel combustion, most scientists agree that more research is needed to definitely establish this relationship. The possibility that the increasing carbon dioxide in the atmosphere is due to a change in the natural balance has not yet been eliminated. In fact, a look at the magnitude of the natural interchanges, as shown in Vugraph 5, shows that this possibility should be taken seriously.

The data in Vugraph 5 are taken from a Scientific Workshop on Atmospheric CO_2 sponsored by the World Meteorological Organization in December 1976. The vugraph shows the fluxes of CO_2 into and out of the atmosphere in units of billions of metric tons of carbon per year. It can be seen that fossil fuels are estimated to contribute five billion tons of carbon per year to the atmosphere and that about half of this is reabsorbed by the oceans or by the biosphere. The conclusion that fossil fuel combustion represents the sole source of incremental carbon dioxide involves assuming not only that the contributions from the biosphere and from the oceans are not changing but also that these two sources are continuing to absorb exactly the same amount as they are emitting. The World Meteorological Organization recognized the need to validate these assumptions, particularly in view of the fact that the rate of carbon dioxide increase represents less than 2% of the rate at which the atmosphere is exchanging carbon dioxide with the biosphere and the oceans.

The biologists have been claiming that deforestation and associated biogenic effects on the continents represent an important input of carbon dioxide to the atmosphere. Vugraph 6 summarizes the results from recent papers by a number of biologists on the contribution of the biosphere to the growth of CO_2 in the atmosphere relative to the contribution of fossil fuel combustion. Their estimates for this ratio are presented in the first column. In April of 1977, Adams[2] estimated that the ratio of the weight of carbon from net wood burned to the weight of carbon from fossil fuel burned in this century has been at least 0.1 and may have approached 1.0. The following month, Bolin[3] claimed that the increase in carbon dioxide due to the expansion of forestry and agriculture was at least half that due to fossil fuel combustion. In August of 1977, the National Academy of Sciences issued a report[4] which attributed the Greenhouse Effect to fossil fuel combustion and which received a considerable amount of sensational publicity. This has produced a rash of papers by the biologists to support their position. In January of this year, Woodwell[5] and a number of other authors from academic and oceanographic centers published a paper claiming that the terrestrial biomass appears to be a net source of carbon dioxide for the atmosphere which is possibly greater than that due to fossil fuel combustion. The following week, Stuiver[6] published results based upon C^{13}/C^{12} ratios which reported that the net release of carbon dioxide from the biosphere in the century prior to 1950 was twice as great as that from fossil fuel combustion. Even if it is assumed that the biospheric release stopped in 1950, the contribution of the biosphere up to the present time would still be 1.2 that from fossil fuel. The last four articles which I have quoted were all published in Science. In the present month, Wilson[7] published an article in Nature which supports the claim that deforestation has produced at least half as much carbon dioxide in the atmosphere as can be attributed to fossil fuel.

Now, you will remember that earlier in this talk it was pointed out that if the increase in carbon dioxide in the atmosphere is due to fossil fuel combustion, about 50% of the CO_2 being released remains in the atmosphere and the rest is absorbed in either the oceans or the continents. If there have been substantial releases of carbon dioxide in addition to that which can be attributed to fossil fuels, the natural sinks for carbon dioxide must be larger and more efficient than previously estimated. This would reduce the levels to which carbon dioxide has been projected to increase. This possibility is vehemently denied by the oceanographers,who claim that the oceans cannot possibly absorb much more carbon dioxide. However, it is my impression that the science of oceanography has not as yet reached a state of development which can justify such a positive claim.

The current status of scientific opinion regarding the carbon cycle is summarized in Vugraph 7. First, current scientific opinion overwhelmingly favors attributing atmospheric carbon dioxide increase to fossil fuel combustion. However, most scientists feel that more research is needed to support an unqualified conclusion. Finally, some scientists, particularly the biologists, claim that part or all of the CO_2 increase arises from the destruction of forests and other land biota.

II. The Global Temperature Increase Which Can Be Expected From Higher CO_2 Concentrations

Predictions on the significances of increases in atmospheric CO_2 must be based upon climate modeling. Modeling climatic effects is currently handicapped by an inability to handle all the complicated interactions which are important to predicting the climate. Some of these are shown in Vugraph 8.

One interaction which has not has yet been included with any degree of sophistication in climate models is the effect of cloudiness. Clouds can reflect incoming visible and ultraviolet radiation back into space with greater efficiency than would occur at the ground. On the other hand, at their bottom surface they absorb outgoing radiation and the cloud tops also emit infrared radiation, depending upon the temperature (that is altitude) at which the top is located. The effect of a cloud will therefore depend upon its size, its shape, and the altitude at which it is located.

Another uncertainty which has not, as yet, been handled in any great detail is the atmosphere - ocean circulation - sea surface temperature interaction. How should the heat capacity of the oceans be handled in view of the turbulence at the surface and to what depths are the oceans involved in interacting with the atmosphere? These are important questions because the entire heat content of the atmosphere is equal to the heat content of just the first three meters of the oceans. A third uncertainty in modeling is the interaction between the seasons and long-term climate trends. In present models, the changes which are predicted for increasing carbon dioxide concentrations are calculated with respect to a constant climate, that is a perpetual spring or summer season. It is quite possible that this assumption is inadequate. For example, the best accepted explanation for the on-set of the ice ages is that orbital and other changes result in the earth entering a period in which summers are cooler and winters are warmer than normal. Thus, this produces more precipitation and faster glacier growth during the winter and less melting during the summer.

Finally, a serious question has been raised as to whether climate is really predictable. This possibility was raised by Lorenz[8] in 1970. He drew an analogy to mathematical modeling. Many mathematical models of complicated phenomena are based upon a large number of non-linear equations with a variety of complex feedback interactions. If the mathematician is fortunate, when a model of this type is run on the computer, it will converge and give him a definite answer. Such a model is called transitive. On the other hand, when a complicated model is tested, it is not at all unusual to find that the solution will not converge but will oscillate back and forth without producing a stable answer. Such a model is called intransitive. There is also an intermediate condition. Occasionally, a model is found to converge initially upon a definite answer but after a short period to jump off this solution and settle down upon another one. After a second indefinite period, it will jump up and converge again upon a third solution and so on producing a number of apparent solutions in a random manner. Such a model is called almost transitive (or almost intransitive). Lorenz pointed out that the climate is a system which is the result of a large number of non-linear energy inputs between which there are many complicated feedback interactions. He therefore suggested that the climate may be a natural example of an almost transitive system which does not have a stable solution. It will settle down into an apparently stable condition but then after a random period will jump over to another apparent stability, etc.

It is not certain, however, that such a pessimistic outlook is justified and it has not stopped the development of many models of the Greenhouse Effect and other climate phenomena. The simplest of these are the one-dimensional models in which the input at the earth's surface is averaged over the globe and detailed calculations are carried out to predict vertical variations. Such models do not require much computer time and can include detailed treatment of vertical phenomena such as radiative transfer. They suffer, however, from the fact that the influence of latitudinal variations is completely ignored.

The next more complicated models are so-called zonally averaged models in which various latitude regions are treated separately in a two-dimensional manner. These take more computer time but are still short enough to permit considerable sophistication in the calculations. They still suffer, however, from an incomplete treatment of latitudinal interactions. In spite of this, many modelers feel that they are the most valuable type of model upon which to work.

The most complicated models are the so-called general circulation models which are three-dimensional in character. These take very long times to compute and the ratio of real to machine time can be as low as 10 to 1. A great deal of the computer time is spent in moving large masses of air around the globe and recalculating the snyoptic profiles every 10 to 15 minutes. Their advantage is that latitudinal effects are completely included but the sophistication with which vertical effects can be treated is limited due to the time and expense associated with running the model.

One of the best general circulation models of the Greenhouse Effect, and the one which is most frequently quoted, is that developed by Manabe and Wetherald[9]. Their predictions for the climatic effect of a doubling of CO_2 are presented in Vugraph 9. This vugraph predicts that a doubling of the atmospheric CO_2 concentration would produce a temperature rise at lower altitudes and a temperature decrease above twenty kilometers. At the surface the temperature rise would be about 2 to 3°C from the equator up to about 60° latitude, with a much greater increase predicted for the poles. The larger increase at the poles results from two effects. First, vertical mixing at the poles is reduced due to a natural decrease in the height of the inversion layer in these regions. Second, the model contains a temperature - ice and snow cover - reflectivity interaction by which increases in atmospheric temperature melt the snow and ice cover and reduce the amount of heat reflected back into space.

Simplifications incorporated in this model include fixed cloudiness, a "swamp" ocean which has zero heat capacity, and idealized treatment of the topography. The model also contains a simplified treatment of the infrared radiation transfer in the atmosphere. In a separate calculation, Manabe[10] calculated that the use of a more sophisticated treatment, developed by Rodgers and Walshaw[11], would reduce the indicated temperature increases at the surface by about 0.5°C. In the light of this and other models, it is generally accepted by climatologists that a doubling of the carbon dioxide concentration in the atmosphere would produce from 1.5°C-3.0°C warming at the earth's surface in the lower and mid-latitudes with about 2 to 3 times greater effect at the poles.

The next natural question is the significance of such a temperature rise compared to the magnitude of the natural temperature changes which have been observed to occur in the past. A comparison with respect to historical temperature changes since 1850, according to Kellogg[12], is presented in Vugraph 10. In this figure, the observed mean Northern Hemisphere temperature is plotted as the solid line. It can be seen that this has varied less than ±1°C over the last century. The extrapolations past 1977 result from the application of Manabe and Wetherald's model[9] with the assumption that the carbon dioxide levels will double by 2050 A.D. The lower dashed line in the figure represents an estimate of what the recent temperature trends would have been if the CO_2 increase had not occurred.

The significance of a temperature increase of the magnitude predicted by Manabe and Wetherald with respect to the long term record of climate is presented in Vugraph 11 which was prepared by Mitchell[13]. This figure shows that the expected temperature increase would be large even compared to the temperatures at the time of the last interglacial. As this temperature increase decayed, however, it would represent an amelioration of an expected natural cooling trend.

III. The Potential Problems Arising from a Global Temperature Increase

The implications arising from Manabe and Wetherald's predictions for the temperature effects resulting from a doubling of carbon dioxide concentrations in the atmosphere are outlined in Vugraph 12. It appears fairly certain that if the high increases they predict in the polar regions do occur, the permanent snow cover and floating sea ice will be reduced or possibly eliminated. This will have a negligible effect on sea level, however, since the snow cover does not represent an appreciable amount of water and the floating ice is already in equilibrium with the sea.

There will probably be no effect on the polar ice sheets. These are three in number. The Greenland ice sheet in the Northern Hemisphere represents an amount of water equivalent to a five meter rise in sea level. If the floating sea ice is removed, the Greenland ice cap would be surrounded by water. This might produce increased precipitation and actually result in the growth of this ice sheet.

The world's largest ice sheet is the East Antarctic sheet which contains water equivalent to a rise of 70 meters in the world's oceans. It is estimated that the temperature effects produced by doubling the atmospheric CO_2 concentration would not affect this very large glacier and that it too might increase in size.

The area on which most uncertainty exists is with respect to the West Antarctic ice sheet. The water in this glacier is equivalent to about a seven meter rise in the world's oceans. The West Antarctic ice sheet extends out over the ocean floor. Warmer oceans might result in an intrusion of the ocean waters underneath this ice sheet and a decrease in its size might occur. If this happens, an oceanic rise of some fraction of the maximum amount (7 meters) might take place.

With a warmer climate around the world, it seems fairly certain that precipitation would increase. On a global basis, this should result in a lengthening of the growing season. Growing seasons are estimated to increase about ten days for each 1°C rise in temperature.

The changing precipitation patterns, however, would benefit some areas and would harm others. It is not possible, on the basis of present information, to predict just where these effects would occur. As a first estimate, one might say that the climatic zones in the world would move northward. The effect of this on the agriculture of the U.S. and Russia is indicated in Vugraph 13.

The broadening of the equatorial regions might result in a northward migration of the desert areas in the United States. Our present corn and wheat belts would also move northward and migrate into Canada. It can be seen that Russia, which is indicated by the crossed hatched area, lies considerably farther north than does the United States. The very dark areas indicate the agricultural regions of Russia. If climatic zones migrate northward, the Russians have plenty of room to adopt to the change. Even those nations which are favored, however, would be damaged for a while since their agricultural and industrial patterns have been established on the bais of the present climate.

IV. Research Needed to Establish the Validity and Significance of Projected Increases of CO_2 in the Atmosphere

The Greenhouse Effect has been attracting a large amount of scientific attention. Some of the more important recent meetings on this subject are presented in Vugraph 14. The World Meteorological Organization held a scientific workshop on atmospheric CO_2 in Washington, DC, in December 1976. ERDA held a workshop on the Environmental Effect of CO_2 from Fossil Fuel Combustion at Miami in March of 1977. This meeting was organized by their Advisory Committee for research on the Greenhouse Effect, the Chairman of which is Dr. Alvin Weinberg. DOE's present research effort on the Greenhouse Effect is a direct result of this workshop and I will be saying more about their program later. SCOPE (Standing Committee on the Planetary Environment), a West European organization, held a workshop on the world carbon budget in March of 1977 in Hamburg, Germany. The most recent major meeting was that organized in Luxenburg, Austria, this past February by IIASA (International Institute for Applied Systems Analysis) for the World Meteorological Organization, the U.N. Committee on the Environment and SCOPE.

The conclusions from this last meeting summarize the present world scientific opinion with respect to the Greenhouse Effect. The IIASA meeting was organized into three working groups. Some of the more significant recommendations of these working groups are presented in Vugraph 15.

The working group on the carbon cycle concluded that scientific confidence in models of that cycle is considerably less than it was ten years ago. What is necessary to instill greater confidence is to provide a better understanding of the flux from the biosphere as reported by the biologists. The working group also recommended that more information be obtained on the interchange of CO_2 into the ocean and how it is transported to greater depths.

The second working group, on the climatic impact of a doubling of CO_2, reached conclusions close to those which have been summarized in the present talk. They felt that a doubling of atmospheric carbon dioxide would produce a 2-3 degree centigrade increase in temperature depending upon the influence of clouds.

The third working group was concerned with the impact of the Greenhouse Effect on energy strategies. They recommended that man can afford a 5-10 yr. time window to establish the validity and significance of the Greenhouse Effect. They said that it is premature to limit the use of fossil fuels at present but that their use should not be encouraged. This group went on to recommend more research and greater effort on the development of energy sources which would not result in CO_2 release.

The DOE has initiated a major research program on the Greenhouse Effect under the leadership of David Slade. Detailed recommendations for this effort have been prepared by an Advisory Committee. These recommendations would have the DOE research program concentrate principally upon obtaining better information regarding the carbon cycle while research on climatic effects, including climate modeling, would be left up NOAA. Six programs for research on the carbon cycle are being recommended for immediate funding. These are presented in order of priority in Vugraph 16.

This immediate program would cost \$1.56 $\overline{MM}$ in the first year and would soon grow to about \$10 $\overline{MM}$ per year. The program to receive highest priority, is obtaining a better estimate of fossil fuel CO_2 output. This would involve a worldwide study of how fossil fuel combustion might be expected to increase and what would limit this increase in both the under-developed and developed countries. The second project relates to the use of carbon isotopes to obtain a better estimate of the input of carbon dioxide from the biosphere. It is hoped that C^{13}/C^{12} ratios as well as C^{14}/C^{12} ratios can be used for this purpose.

The third project is to obtain a direct assessment of the biosphere input by observing the growth or depletion of vegetated areas around the world from the Landstat satellites. High resolution radar and aerial photography will probably be required in some instances to identify vegetation types. The global vegetation map provided by these methods would be used to identify sample areas for 1) further analysis using photographs of higher resolution and 2) ground validation of vegetation and soil type to define the relationship between image characteristics and desired ground information. Two hundred to a thousand such areas would be identified and would be resurveyed at 2 to 5 year intervals in a program which would be expected to be able to detect a 2% change in the vegetation. This is an expensive program and would require about \$3 $\overline{MM}$ per year when it is running in full force.

The fourth project is to expand and improve the carbon dioxide monitoring network. This would involve adding 10 to 15 additional monitoring stations at suitably remote areas and expanding the instrumentation at all stations so that it could determine carbon isotope ratios.

The fifth project is to obtain better information on the transfer of carbon dioxide from surface waters into the deeper ocean. This would involve not only studies of CO_2 but also of tracers such as tritium, helium-3 and radiocarbon. This would require research with oceanographic ships and, when completely under way, would cost about $5 MM/year. The last of the high priority programs for immediate funding is to obtain better information on the buffering of CO_2 absorption in the ocean.

After the initial programs are under way, the Advisory Committee is recommending that an additional effort involving seven more programs be established. These are listed, in order of priority, in Vugraph 17. The entire program would cost $1.26 MM in the planning phase and would rise to $5 MM/year when under way.

The first item in this program, and the seventh in the overall priority list, is to determine whether shallow water carbonates are dissolving because of CO_2 levels. The second item would be to obtain a better estimate of the response of the biota as a sink for additional carbon dioxide. The third in this program is to develop better models for the carbon cycle. Although modeling is an extremely important undertaking, it is placed ninth on the overall list because information from the earlier programs is needed for better model development.

Item number ten recommends a study and a better definition of the rate of carbon dioxide exchange across the interface between the air and the ocean. The next project would be to study the flux of organic carbon into and within the sea. Item number twelve is to develop improved carbon dioxide measurement techniques, while the final item on this list is to study the dissolution of deep sea calcium carbonate as a final sink for atmospheric carbon dioxide.

V. Summary

A summary of my talk is presented in Vugraph 18. In the first place, there is general scientific agreement that the most likely manner in which mankind is influencing the global climate is through carbon dioxide release from the burning of fossil fuels. A doubling of carbon dioxide is estimated to be capable of increasing the average global temperature by from 1° to 3°C, with a 10°C rise predicted at the poles. More research is needed, however, to establish the validity and significance of predictions with respect to the Greenhouse Effect. It is currently estimated that mankind has a 5-10 yr. time window to obtain the necessary information. A major research effort in this area is being considered by the U.S. Department of Energy.

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THE GREENHOUSE EFFECT

J. F. BLACK

TALK BEFORE

PERCC MEETING

MAY 18, 1978

VUGRAPH 1

BASIS FOR THE GREENHOUSE EFFECT

I. EARTH RECEIVES VISIBLE & UV RADIATION FROM SUN

A. Some Reflected Into Space
B. Some Absorbed By Atmosphere
C. Most Absorbed At Earth's Surface

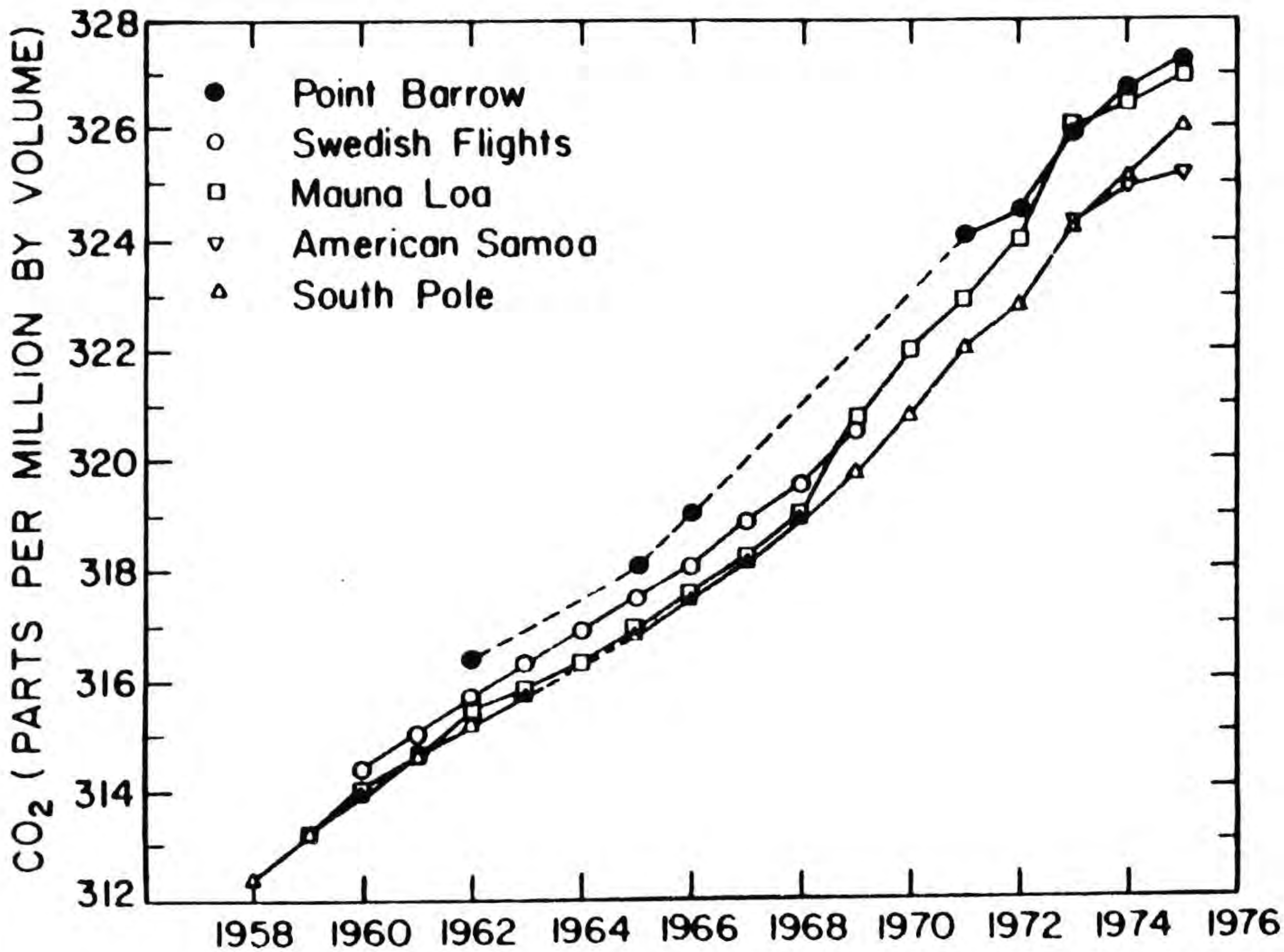
II. EARTH EMITS INFRARED RADIATION TOWARD SPACE

A. Carbon Dioxide And Other Atmospheric Constituents Absorb Part Of The Infrared Radiation
B. Absorbed Energy Warms The Atmosphere

III. THEREFORE HIGHER CO_2 CONCENTRATIONS WARM THE LOWER ATMOSPHERE

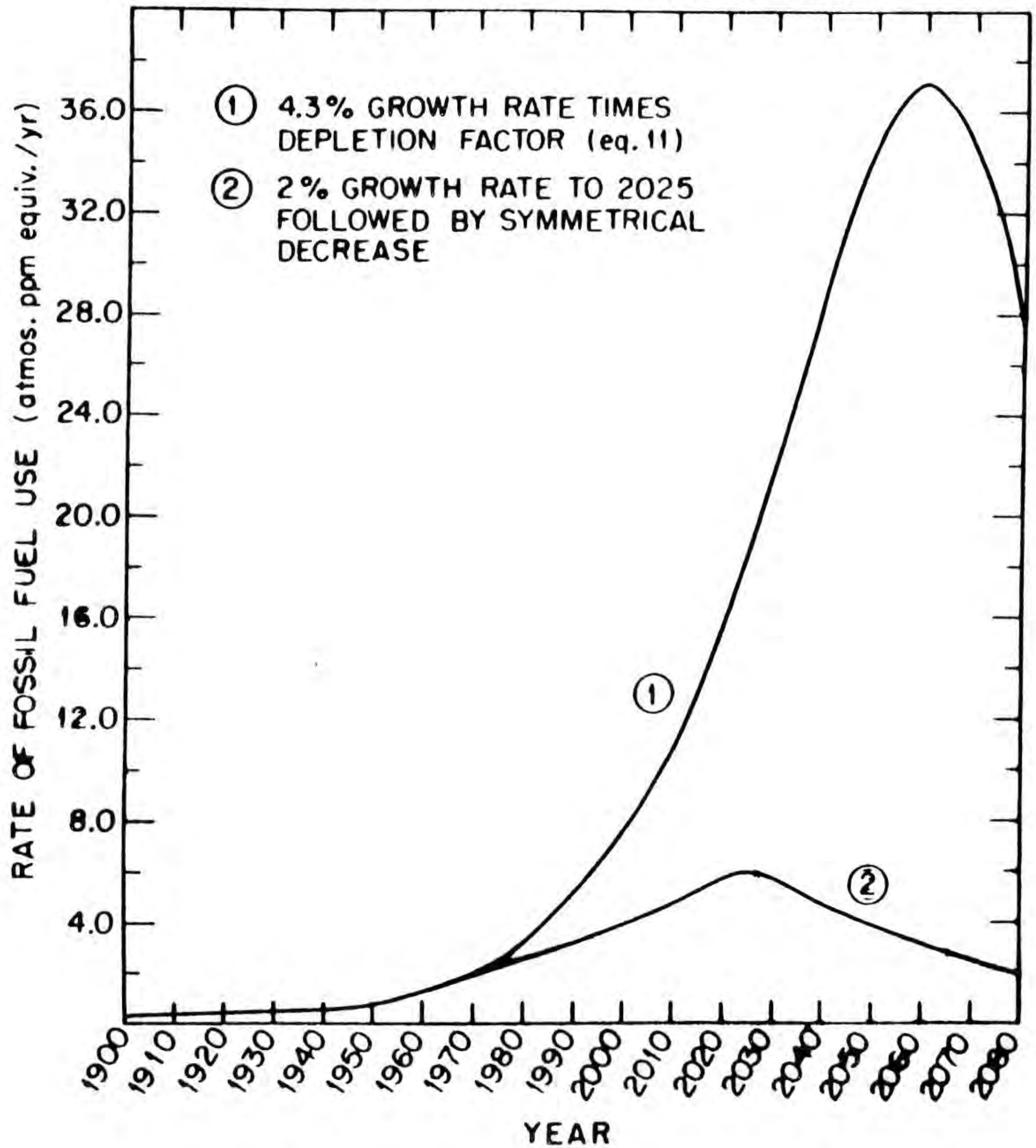
VUGRAPH 2

CO_2 MEASURED AT REMOTE SITES



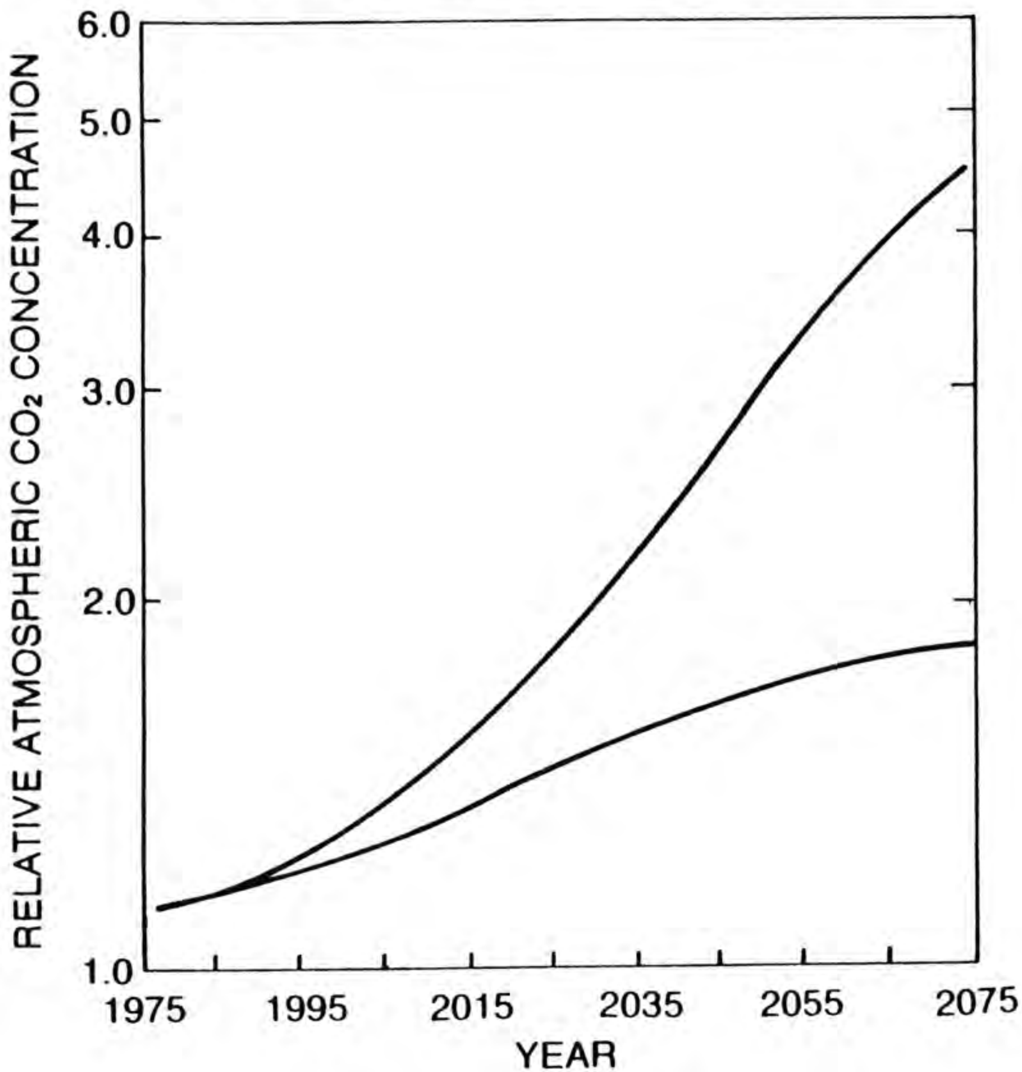
VUGRAPH 3

POSSIBLE LIMITING SCENARIOS FOR THE USE OF FOSSIL FUELS

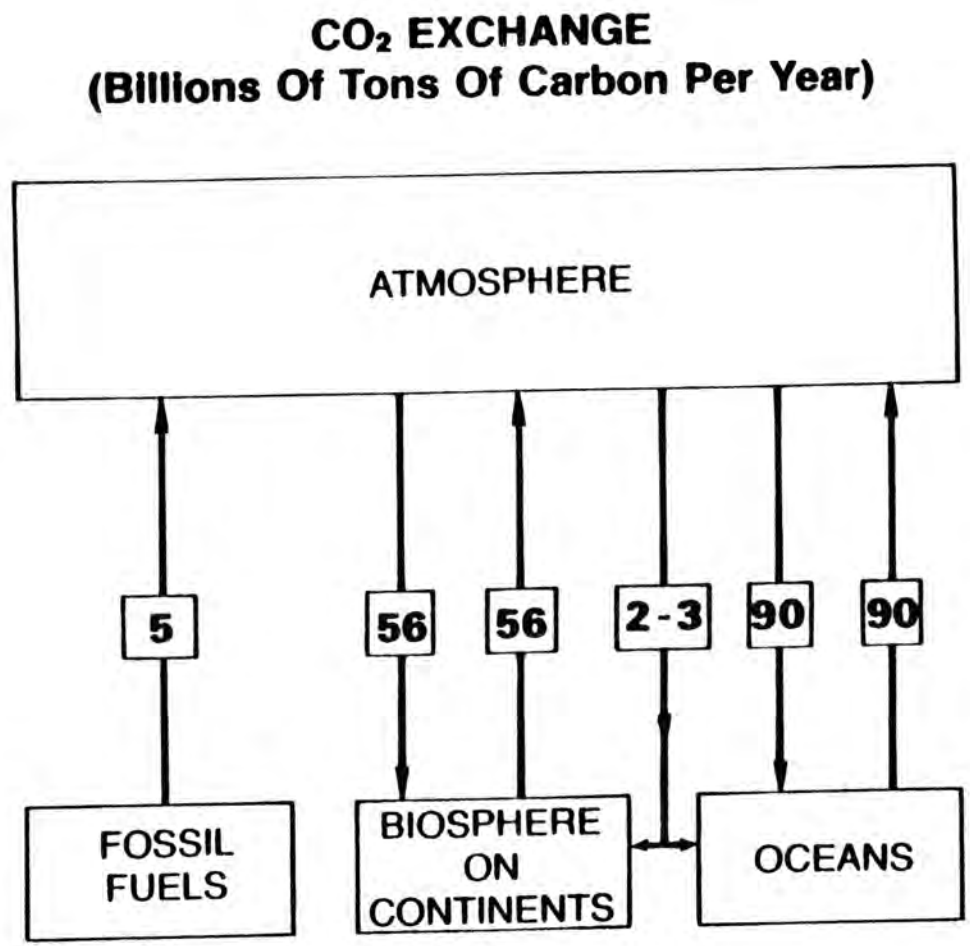


VUGRAPH 4

PROJECTED ATMOSPHERIC CO_2 CONCENTRATIONS RELATIVE TO 1860



VUGRAPH 5


CO2 EXCHANGE
(Billions Of Tons Of Carbon Per Year)
ATMOSPHERE
5
56
56
2-3
90
90
FOSSIL FUELS
BIOSPHERE ON CONTINENTS
OCEANS

VUGRAPH 6

RATIO OF CO_2 DERIVED FROM BIOSPHERE VS FOSSIL FUEL

RATIO	1st AUTHOR	JOURNAL	DATE
0.1-1.0	ADAMS	SCIENCE	4/1/77
0.5	BOLIN	SCIENCE	5/6/77
0.8-1.6 (1)	WOODWELL	SCIENCE	1/13/78
2.0 (2)	STUVIER	SCIENCE	1/19/78
0.5	WILSON	NATURE	5/4/78

(1) PRESENT RATE (2) 1850-1950

VUGRAPH 7

CURRENT STATUS OF SCIENTIFIC OPINION

I. Current Opinion Overwhelmingly Favors Attributing Atmospheric CO_2 Increase To Fossil Fuel Combustion

II. Most Scientists Feel More Research Is Needed To Support An Unqualified Conclusion

III. Some Scientists Claim That Part Or All Of The CO_2 Increase Arises From The Destruction Of Forests And Other Land Biota.

VUGRAPH 8

UNCERTAINTIES WHICH LIMIT CLIMATE MODELING

I. CLOUDINESS

A. Effect Of A Cloud Depends On Size, Shape and Position.

II. ATMOSPHERE — OCEAN INTERACTIONS

A. How Should Heat Capacity Be Handled
B. To What Depth Is The Ocean Involved

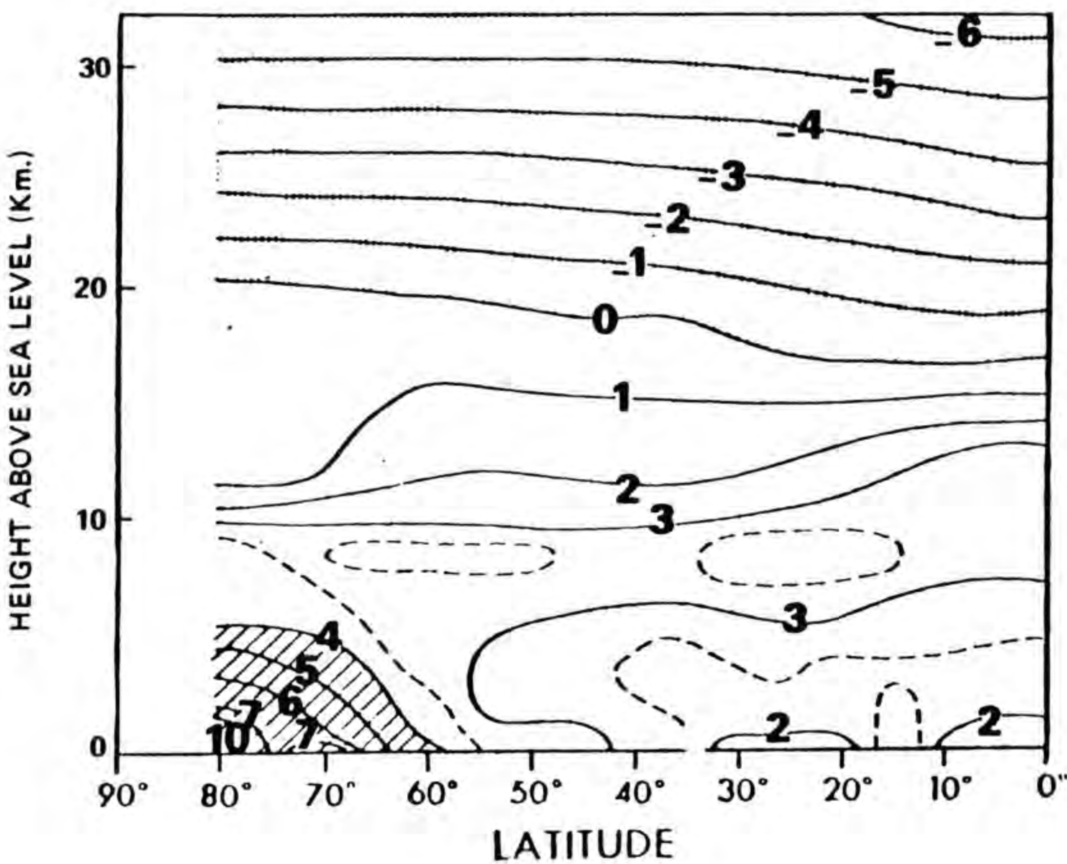
III. THE INTERACTION BETWEEN SEASONS AND LONG TERM TRENDS

IV. IS CLIMATE REALLY PREDICTABLE

A. Could Be An "Almost Transitive" System Which Fluctuates Between Stable States.

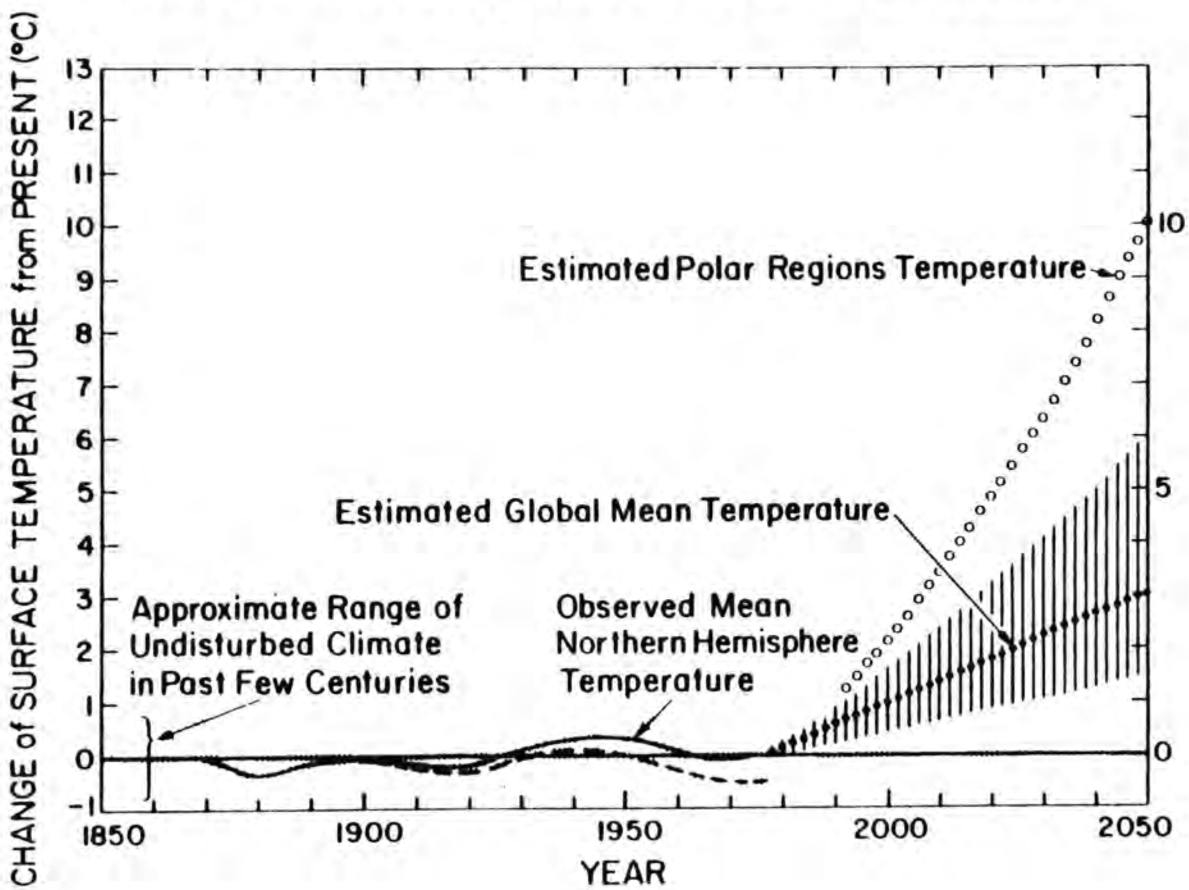
VUGRAPH 9

TEMPERATURE EFFECT OF DOUBLING CO_2



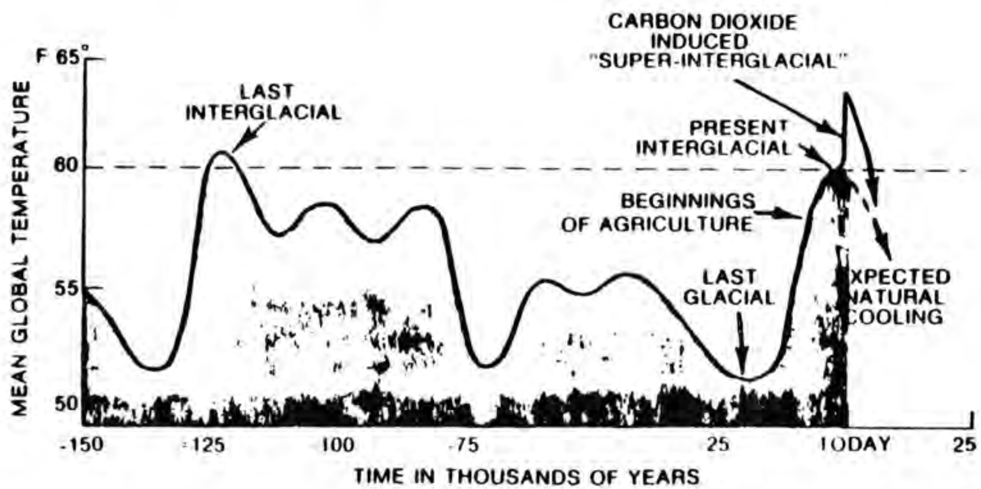
VUGRAPH 10

HOW PREDICTED ΔT COMPARES WITH RECENT TEMPERATURES



VUGRAPH 11

EFFECT OF CO_2 ON AN INTERGLACIAL SCALE



VUGRAPH 12

IMPLICATION OF PREDICTED GREENHOUSE EFFECT

I. **PERMANENT SNOW COVER AND FLOATING SEA ICE WILL BE REDUCED**
   - A. Negligible Effect On Sea Level

II. **PROBABLY NO EFFECT ON POLAR ICE SHEETS**
   - A. West Antarctic Ice Sheet Most Critical

III. **LENGTH OF GROWING SEASON WOULD INCREASE**
   - A. 1°C Temperature Rise Adds 10 Days

IV. **CHANGES IN PRECIPITATION PATTERNS WILL BENEFIT SOME AREAS AND HARM OTHERS.**
   - A. Models Can Not Predict These Effects
   - B. Can Study Evidence From Climatic Optimum 4000-8000 Years Ago.

MOST OF THE USSR'S VAST AGRICULTURAL LAND BASE LIES LATITUDINALLY NORTH OF THE UNITED STATES
Fairbanks
Leningrad
Kiev
Moscow
Arctic Circle
60
40
40
Minneapolis
San Francisco
Philadelphia
Washington
Denver
Springfield
SOVIET AGRICULTURAL LANDS

VUGRAPH 13

VUGRAPH 14

RECENT MEETINGS ON GREENHOUSE EFFECT

I. WORLD METEOROLOGICAL ORGANIZATION

SCIENTIFIC WORKSHOP ON ATMOSPHERIC CO_2

NOV. 28 - DEC. 3, 1976, WASHINGTON, D. C.

II. ERDA - WORKSHOP

ENVIRONMENTAL EFFECT OF CO_2 FROM FOSSIL FUEL COMBUSTION

MARCH 7-11, 1977, MIAMI BEACH, FLA.

III. SCOPE

WORKSHOP ON WORLD CARBON BUDGET

MARCH 21-26, 1977, HAMBURG, GERMANY

IV. IIASA

CARBON DIOXIDE, CLIMATE AND SOCIETY

FEB. 21-24, 1978, LAXENBURG, AUSTRIA

VUGRAPH 15

WORKING GROUP REPORTS - IIASA WORKSHOP

I. THE CARBON CYCLE

A. CONFIDENCE IN MODELS CONSIDERABLY LESS THAN 10 YEARS AGO

B. BIOSPHERE FLUX MUST BE ESTABLISHED

II. WHAT WILL BE CLIMATE IMPACT OF 2 X CO_2

A. 2-3°C INCREASE DEPENDING ON HOW CLOUDS ACT

III. CO_2 QUESTION VS. ENERGY STRATEGIES

A. MAN CAN AFFORD 5-10 YR. TIME WINDOW TO ESTABLISH WHAT MUST BE DONE.

B. IT IS PREMATURE TO LIMIT USE OF FOSSIL FUELS BUT THEY SHOULD NOT BE ENCOURAGED.

VUGRAPH 16

ERDA PROPOSALS FOR IMMEDIATE FUNDING

($1.56 $\overline{MM}$ TO START - SOON UP TO $9.8 $\overline{MM}$/YR.)

1. BETTER ESTIMATE OF FOSSIL FUEL CO_2 OUTPUT
2. USE CARBON ISOTOPES TO GET INPUT FROM BIOSPHERE
3. DIRECT ASSESSMENT OF BIOSPHERE INPUT ($3 $\overline{MM}$)
4. EXPAND AND IMPROVE MONITORING NETWORK
5. TRANSFER OF CO_2 INTO DEEPER OCEAN ($5 $\overline{MM}$)
6. BUFFERING OF CO_2 ABSORPTION IN OCEAN

VUGRAPH 17

PROJECTS STARTING AFTER INITIAL PROGRAMS ARE UNDER WAY

($1.26 $\overline{MM}$ TO START - RISES TO $5.0 $\overline{MM}$/YR)

7. ARE SHALLOW WATER CARBONATES DISSOLVING
8. RESPONSE OF BIOTA TO CO_2 INCREASE
9. BETTER MODELS OF CARBON CYCLE
10. CO_2 EXCHANGE ACROSS AIR-SEA INTERFACE
11. FLUX OF ORGANIC CARBON INTO & WITHIN SEA
12. IMPROVE CO_2 MEASUREMENT TECHNIQUES
13. DISSOLUTION OF DEEP SEA $CaCO_3$ AS FINAL SINK

VUGRAPH 18

SUMMARY

I. CO_2 RELEASE MOST LIKELY SOURCE OF INADVERTENT CLIMATE MODIFICATION.

II. PREVAILING OPINION ATTRIBUTES CO_2 INCREASE TO FOSSIL FUEL COMBUSTION.

III. DOUBLING CO_2 COULD INCREASE AVERAGE GLOBAL TEMPERATURE 1°C TO 3°C BY 2050 A.D. (10°C PREDICTED AT POLES).

IV. MORE RESEARCH IS NEEDED ON MOST ASPECTS OF GREENHOUSE EFFECT

V. 5-10 YR. TIME WINDOW TO GET NECESSARY INFORMATION

VI. MAJOR RESEARCH EFFORT BEING CONSIDERED BY DOE

EXHIBIT 14

Central Files

PROPRIETARY INFORMATION

For Authorized Company Use Only

EXXON RESEARCH AND ENGINEERING COMPANY

P.O. BOX 101, FLORHAM PARK, NEW JERSEY 07932

EXXON ENGINEERING PETROLEUM DEPARTMENT
Planning Engineering Division

Cable: ENGREXXON, N.Y.

R. L. MASTRACCHIO
Manager
L. E. Hill
Senior Eng. Assoc.

October 16, 1979

Controlling Atmospheric CO_2

79PE 554

Dr. R. L. Hirsch:

The attached memorandum presents the results of a study on the potential impact of fossil fuel combustion on the CO_2 concentration in the atmosphere. This study was made by Steve Knisely, a summer employee in Planning Engineering Division.

The study considers the changes in future energy sources which would be necessary to control the atmospheric CO_2 concentration at different levels. The principle assumption for the CO_2 balance is that 50% of the CO_2 generated by fossil fuels remains in the atmosphere. This corresponds to the recent data on the increasing CO_2 concentration in the atmosphere compared to the quantity of fossil fuel combusted.

Present climatic models predict that the present trend of fossil fuel use will lead to dramatic climatic changes within the next 75 years. However, it is not obvious whether these changes would be all bad or all good. The major conclusion from this report is that, should it be deemed necessary to maintain atmospheric CO_2 levels to prevent significant climatic changes, dramatic changes in patterns of energy use would be required. World fossil fuel resources other than oil and gas could never be used to an appreciable extent.

No practical means of recovering and disposing of CO_2 emissions has yet been developed and the above conclusion assumes that recovery will not be feasible.

It must be realized that there is great uncertainty in the existing climatic models because of a poor understanding of the atmospheric/terrestrial/oceanic CO_2 balance. Much more study and research in this area is required before major changes in energy type usage could be recommended.

W. L. Ferrall

W. L. FERRALL

WLF:ceg
Attachment

c: J. F. Black
J. W. Herrmann
L. E. Hill
E. D. Hooper
F. J. Kaiser
R. L. Mastracchio
W. H. Mueller
H. Shaw
G. O. Wilhelm

Exxon Engineering — Petroleum Department

79PE 554 October 16, 1979

EXXON RESEARCH AND ENGINEERING COMPANY

CONTROLLING THE CO_2 CONCENTRATION IN THE ATMOSPHERE

The CO_2 concentration in the atmosphere has increased since the beginning of the world industrialization. It is now 15% greater than it was in 1850 and the rate of CO_2 release from anthropogenic sources appears to be doubling every 15 years. The most widely held theory is that:

- The increase is due to fossil fuel combustion
- Increasing CO_2 concentration will cause a warming of the earth's surface
- The present trend of fossil fuel consumption will cause dramatic environmental effects before the year 2050.

However, the quantitative effect is very speculative because the data base supporting it is weak. The CO_2 balance between the atmosphere, the biosphere and the oceans is very ill-defined. Also, the overall effect of increasing atmospheric CO_2 concentration on the world environment is not well understood. Finally, the relative effect of other impacts on the earth's climate, such as solar activity, volcanic action, etc. may be as great as that of CO_2.

Nevertheless, recognizing the uncertainty, there is a possibility that an atmospheric CO_2 buildup will cause adverse environmental effects in enough areas of the world to consider limiting the future use of fossil fuels as major energy sources. This report illustrates the possible future limits on fossil fuel use by examining different energy scenarios with varying rates of CO_2 emissions. Comparison of the different energy scenarios show the magnitude of the switch from fossil fuels to non-fossil fuels that might be necessary in the future. Non-fossil fuels include fission/fusion, geothermal, biomass, hydroelectric and solar power. The possible environmental changes associated with each scenario are also discussed.

CONCLUSIONS

As stated previously, predictions of the precise consequences of uncontrolled fossil fuel use cannot be made due to all of the uncertainties associated with the future energy demand and the global CO_2 balance. On the basis that CO_2 emissions must be controlled, this study examined the possible future fuel consumptions to achieve various degrees of control. Following are some observations and the principle conclusions from the study:

- The present trends of fossil fuel combustion with a coal emphasis will lead to dramatic world climate changes within the next 75 years, according to many present climatic models.

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- The CO_2 buildup in the atmosphere is a worldwide problem. U.S. efforts to restrict CO_2 emission would delay for a short time but not solve the problem.

- Warming trends which would move the temperate climate northward may be beneficial for some nations (i.e., the USSR, see Figure 1) and detrimental for others. Therefore, global cooperation may be difficult to achieve.

- Removal of CO_2 from flue gases does not appear practical due to economics and lack of reasonable disposal methods.

- If it becomes necessary to limit future CO_2 emissions without practical removal/disposal methods, coal and possibly other fossil fuel resources could not be utilized to an appreciable extent.

- Even with dramatic changes in current energy resource use, it appears unlikely that an increase of 50% over the pre-industrial CO_2 level can be avoided in the next century. This would be likely to cause a slight increase in global temperatures but not a significant change in climate, ocean water level or other serious environmental efforts.

The potential problem is great and urgent. Too little is known at this time to recommend a major U.S. or worldwide change in energy type usage but it is very clear that immediate research is necessary to better model the atmosphere/terrestrial/oceanic CO_2 balance. Only with a better understanding of the balance will we know if a problem truly exists.

Existing Data and Present Models

Since the beginning of industrialization, the atmospheric carbon dioxide concentration has increased from approximately 290 ppm in 1860 to 336 ppm today. Atmospheric CO_2 concentrations have been recorded on a monthly basis by C. D. Keeling since 1958 at Mauna Loa Observatory in Hawaii (see Figure 2). Seasonal variations are clearly shown with the CO_2 concentrations lowest during the North American and Eurasian summers, due to increased photosynthetic activities. Over the last ten years, the atmospheric concentration has been increasing at an average rate of about 1.2 ppm/year.

The present consumption of fossil fuels releases more than 5 billion tons of carbon as CO_2 into the atmosphere each year. Data to date indicate that of the amount released approximately one-half is absorbed by the oceans. The other half remains in the atmosphere. There is some question as to whether the terrestrial biosphere is a sink, absorbing atmospheric CO_2, or a source of CO_2 emissions, due to man's land clearing activities. Current opinion attributes the atmospheric CO_2 increase to fossil fuels and considers the biosphere input to be negligible.

Figure 3 shows the carbon cycle with the ocean and the biosphere as sinks for approximately 50% of the fossil fuel emissions. Most models show the ocean to be a major sink while the biosphere appears to be a much smaller sink if it absorbs any CO_2 at all. It is clear from Figure 3 that the net atmospheric increase in CO_2 is quite small compared to the quantities of CO_2 exchanged between the atmosphere and the earth. This makes it very difficult to analyze the fossil fuel impact on the overall carbon cycle.

The fossil fuel resource is very large compared to the quantity of carbon in the atmosphere. Therefore, if one half of the CO_2 released by combustion of fossil fuels remains in the atmosphere, only about 20% of the recoverable fossil fuel could be used before doubling the atmospheric CO_2 content.

The concern over the increasing CO_2 levels arises because of the radiative properties of the gas in the atmosphere. CO_2 does not affect the incoming short-wave (solar) radiation to the earth but it does absorb long-wave energy reradiated from the earth. The absorption of long-wave energy by CO_2 leads to a warming of the atmosphere. This warming phenomenom is known as the "greenhouse effect."

A vast amount of speculation has been made on how increased CO_2 levels will affect atmospheric temperatures. Many models today predict that doubling the 1860 atmospheric CO_2 concentration will cause a 1^{o} to $5^{o}C$ global temperature increase (see Figure 4). Extrapolation of present fossil fuel trends would predict this doubling of the CO_2 concentration to occur about 2050. A temperature difference of $5^{o}C$ is equal to the difference between a glacial and an interglacial period. The temperature increases will also tend to vary with location being much higher in the polar region (see Figure 5). These temperature predictions may turn out too high or low by several fold as a result of many feedback mechanisms that may arise due to increased temperatures and have not been properly accounted for in present models.

These mechanisms include:

- A decrease in average snow and ice coverage. This is a positive feedback mechanism since it would result in a decrease of the earth's albedo (reflectivity) which would produce an added warming effect.

- Cloud Cover. This is considered the most important feedback mechanism not accounted for in present models. A change of a few percent in cloud cover could cause larger temperature changes than those caused by CO_2. Increased atmospheric temperature could cause increased evaporation from the oceans and increased cloud cover.

- Ocean and Biosphere Responses. As the CO_2 level is increased and the ambient temperature rises, the ocean may lose some of its capacity to absorb CO_2 resulting in a positive feedback. However, increased CO_2 levels could increase photosynthetic activities which would then be a negative feedback mechanism.

As evidenced by the balance shown in Figure 3, the atmospheric carbon exchange with the terrestrial biosphere and the oceans is so large that small changes due to these feedback mechanisms could drastically offset or add to the impact of fossil fuel combustion on the earth's temperature.

Appendix A gives one, but not unanimous, viewpoint of how the environment might change if the feedback mechanisms are ignored. The contribution that will ultimately be made by these feedback mechanisms is unknown at present.

Energy Scenarios for Various CO_2 Limits

Using the CO_2 atmospheric concentration data recorded to date, the correlation of these data with fossil fuel consumption and the proposed "greenhouse effect" models, this study reviews various world energy consumption scenarios to limit CO_2 atmospheric buildup. The concentration of CO_2 in the atmosphere is controlled in these studies by regulating the quantity of each type of fossil fuel used and by using non-fossil energy sources when required. The quantity of CO_2 emitted by various fuels is shown in Table 1. These factors were calculated based on the combustion energy/carbon content ratio of the fuel and the thermal efficiency of the overall conversion process where applicable. They show the high CO_2/energy ratio for coal and shale and the very high ratios for synthetic fuels from these base fossil fuels which are proposed as fuels of the future.

The total world energy demand used in these scenarios is based upon the predictions in the Exxon Fall 1977 World Energy Outlook for the high oil price case for the years 1976 to 1990. It is assumed that no changes in the sources of supply of energy could be made during this period of time. Case A, which has no restrictions on CO_2 emissions, follows the high oil price predictions until 2000.

Petroleum production and consumption is the same in each scenario. The high oil price case predictions are followed until 2000. After 2000 petroleum production continues to increase until a reserve to production ratio (R/P) equals ten to one. Production peaks at this point and then continues at a ten to one R/P ratio until supplies run out.

The consumption of coal, natural gas and non-fossil fuels (fission/fusion, geothermal, biomass, hydroelectric and solar power) vary with each scenario. Shale oil makes small contributions past the year 2000. It is not predicted to be a major future energy source due to environmental damage associated with the mining of shale oil, and also due to rather large amounts of CO_2 emitted per unit energy generated (see Table 1). If more shale oil were used, it would have the same effect on CO_2 emissions as the use of more coal. The fossil fuel resources assumed to be recoverable are tabulated in Appendix B.

A. No Limit on CO_2 Emissions

In this scenario no limitations are placed upon future fossil fuel use. The use of coal is emphasized for the rest of this century and continues on into the next century. The development and use of non-fossil fuels continue to grow but without added emphasis. Natural gas production continues at a slowly increasing rate until an R/P ratio of 7/1 is reached around 2030. Production after 2030 continues at a 7/1 ratio until reserves run out. Figure 6 shows the future energy demand for this scenario.

Figure 7 shows that the CO_2 buildup from this energy strategy is quite rapid. The yearly atmospheric CO_2 increase rises from 1.3 ppm in 1976 to 4.5 ppm in 2040. Noticeable temperature changes would occur around 2010 as the concentration reaches 400 ppm. Significant climatic changes occur around 2035 when the concentration approaches 500 ppm. A doubling of the pre-industrial concentration occurs around 2050. The doubling would bring about dramatic changes in the world's environment (see Appendix A). Continued use of coal as a major energy source past the year 2050 would further increase the atmospheric CO_2 level resulting in increased global temperatures and environmental upsets.

B. CO_2 Increase Limited to 510 ppm

This energy scenario is limited to a 75% increase over the pre-industrial concentration of 290 ppm. No limitations are placed on petroleum production. Natural gas production is encouraged beginning in 1990 to minimize coal combustion until non-fossil fuels are developed. Production of natural gas would increase until 2010 when an R/P ratio of 7/1 would be reached. Production would then continue at a R/P of 7/1 until supplies ran out. The development and use of nonfossil fuels are emphasized beginning the 1990's. Non-fossil fuels start to be substituted for coal in 1990's. Figure 8 shows the future energy demand by fuel for this scenario.

Figure 9 shows the atmospheric CO_2 concentration trends for this scenario. The lower graph shows the maximum yearly atmospheric CO_2 increase allowable for the 510 ppm limit. The yearly CO_2 increase peaks in 2005 when it amounts to 2.3 ppm and then steadily decreases reaching 0.2 ppm in 2100. A 0.2 ppm increment is equivalent to the direct combustion of 5.1 billion B.O.E. of coal. This would be approximately 2 to 3% of the total world energy demanded in 2100. (For more detail on the construction of Figure 9, see Appendix C.)

A comparison of the Exxon year 2000 predictions and this scenario's year 2000 requirements shows the magnitude of possible future energy source changes. The Exxon predictions call for nonfossil fuels to account for 18 billion B.O.E. in 2000. This scenario requires that 20 billion B.O.E. be supplied by non-fossil fuels by

2000. This difference of 2 billion B.O.E. is equivalent to the power supplied by 214-1000 MW nuclear power plants operating at 60% of capacity. If it were supplied by methane produced from biomass, it would be equivalent to 80,000 square miles of biomass at a yield of 50 ton/acre, heat value of 6500 Btu/dry pound and a 35% conversion efficiency to methane. Therefore even a 20% increase in non-fossil fuel use is a gigantic undertaking.

The magnitude of the change to non-fossil fuels as major energy sources is more apparent when scenarios A and B are compared in the year 2025. Scenario B requires an 85 billion B.O.E. input from non-fossil fuels in 2025. This is almost double the 45 billion B.O.E. input predicted in scenario A. This 35 billion B.O.E. difference is approximately equal to the total energy consumption for the entire world in 1970.

The environmental changes associated with this scenario wouldn't be as severe as if the CO_2 concentration were allowed to double as in scenario A. Noticeable temperature changes would occur around 2010 when the CO_2 concentration reaches 400 ppm. Significant climate changes would occur as the atmospheric concentration nears 500 ppm around 2080. Even though changes in the environment due to increased atmospheric CO concentrations are uncertain, an increase to 500 ppm would probably bring about undesirable climatic changes to many parts of the earth although other areas may be benefitted by the changes. (See Appendix A, part 1).

C. <u>CO_2 Increase Limited to 440 ppm</u>

This scenario limits future atmospheric CO_2 increases to a 50% increase over the pre-industrial concentration of 290 ppm. As in the previous case, no limitations are placed on petroleum production and increased natural gas production is encouraged. Much emphasis is placed on the development and use of non-fossil fuels. Non-fossil fuels are substituted for coal beginning in the 1990's. By 2010 they will have to account for 50% of the energy supplied worldwide. This would be an extremely difficult and costly effort if possible. In this scenario coal or shale will never become a major energy source. Figure 10 shows the future world energy demand by fuel for this scenario.

The atmospheric CO_2 concentration trends for this scenario are shown in Figure 11. To satisfy the limits of this scenario the yearly CO_2 emissions would have to peak in 1995 at 2.0 ppm,

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and then rapidly decrease reaching a value of 0.04 ppm in 2100. A 0.04 ppm maximum allowable increase means that unless removal/disposal methods for CO_2 emissions are available only one billion B.O.E. of coal may be directly combusted in 2100 (or 1.4 billion Barrels of Oil). This would be less than 1% of the total energy demanded by the world in 2100.

To adhere to the 440 ppm limit, non-fossil fuels will have to account for 28 billion B.O.E. in 2000 as compared to 20 billion B.O.E. in scenario B and 18 billion B.O.E. in scenario A. This difference between scenarios A and C of 10 billion B.O.E. is equivalent to over 1000, 1000 MW nuclear power plants operating at 60% of capacity. Ten billion B.O.E. is also approximately equivalent to 400,000 square miles of biomass at 35% conversion efficiency to methane. This is equivalent to almost one-half the total U.S. forest land.

By 2025 the 110 billion B.O.E. input from non-fossil fuels called for in this scenario is more than twice as much as the 45 billion B.O.E. input predicted in scenario A. This difference of 65 billion is approximately equal to the amount of energy the entire world will consume in 1980. In terms of power plants, 65 billion B.O.E. is equivalent to almost 7000, 1000 MW nuclear power plants operating at 60% of capacity.

An atmospheric CO_2 concentration of 440 ppm is assumed to be a relatively safe level for the environment. A slight global warming trend should be noticeable but not so extreme as to cause major changes. Slight changes in precipitation might also be noticeable as the atmospheric CO_2 concentration nears 400 ppm.

S. KNISELY

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Table 1

CO_2 EMISSIONS

Fuel	lb CO_2 Emitted* / 1000 Btu Fuel	% of Present CO_2 Output
SNG from Coal	0.35	0
Coal Liquids	0.32	0
Methanol from Coal	0.38	0
H_2 from Coal Gasification	0.38	0
Shale Oil	0.23	0
Bituminous Coal	.21	38%
Petroleum	.15	49%
Natural Gas	.11	13%
Fission/Fusion	0	0
Biomass	0	0
Solar	0	0

* Includes conversion losses where applicable.

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APPENDIX A

ECOLOGICAL CONSEQUENCES OF INCREASED CO_2 LEVELS

From:

Peterson, E.K., "Carbon Dioxide Affects Global Ecology," Environmental Science and Technology 3 (11), 1162-1169 (Nov '69).

1. Environmental effects of increasing the CO_2 levels to 500 ppm. (1.7 times 1860 level)

   - A global temperature increase of 3°F which is the equivalent of a 1°-4° southerly shift in latitude. A 4° shift is equal to the north to south height of the state of Oregon.

   - The southwest states would be hotter, probably by more than 3°F, and drier.

   - The flow of the Colorado River would diminish and the southwest water shortage would become much more acute.

   - Most of the glaciers in the North Cascades and Glacier National Park would be melted. There would be less of a winter snow pack in the Cascades, Sierras, and Rockies, necessitating a major increase in storage reservoirs.

   - Marine life would be markedly changed. Maintaining runs of salmon and steelhead and other subarctic species in the Columbia River system would become increasingly difficult.

   - The rate of plant growth in the Pacific Northwest would increase 10% due to the added CO_2, and another 10% due to increased temperatures.

2. Effects of a doubling of the 1860 CO_2 concentration. (580 ppm)

   - Global temperatures would be 9°F above 1950 levels.

   - Most areas would get more rainfall, and snow would be rare in the contiguous states, except on higher mountains.

   - Ocean levels would rise four feet.

   - The melting of the polar ice caps could cause tremendous redistribution of weight and pressure exerted on the earth's crust. This could trigger major increases in earthquakes and volcanic activity resulting in even more atmospheric CO_2 and violent storms.

   - The Arctic Ocean would be ice free for at least six months each year, causing major shifts in weather patterns in the northern hemisphere.

- The present tropics would be hotter, more humid, and less habitable, but the present temperature latitude would be warmer and more habitable.

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APPENDIX B

FOSSIL FUEL RESOURCES

Oil	- Assume 1.6 trillion barrels of oil potentially recoverable as of 1975 (assuming the future recovery rate to be 40%). The minimum allowable Reserve to Production (R/P) ratio is ten one.
Shale Oil	- Potential of 3.0 trillion B.O.E. but assuming 1977 technology only 200 billion B.O.E. actually recoverable.
Natural Gas	- Approximately 1.6 trillion B.O.E. potentially recoverable. Minimum allowable R/P = 7.1.
Coal	- Potential recoverable reserves equal approximately 12 trillion B.O.E. assuming a conservative 25% recoverability.

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APPENDIX C

CONSTRUCTION OF SCENARIOS B AND C
(Scenario A requires no CO_2 emissions control)

1. Scenario B

The CO_2 concentration vs. year curve in Figure 9 was generated by the following equation:

after 1970 (t = 0), then

$$*C = 292 \text{ ppm} + 219 \text{ ppm}/[1 + 5.37 \exp. (-t/24 \text{ years})]$$

where C = concentration in ppm

The curve on the lower section of Figure 9, atmospheric CO_2 increase vs. years, is generated by finding the difference in the concentrations of successive years. This curve gives the maximum yearly increases allowable to stay within the limits placed on this scenario. The amount of fossil fuel that may be consumed in any given year can then be calculated by the lower curve. For example:

In 2100 the maximum allowable CO_2 increase equals 0.2 ppm.

This is equivalent to:

$$\frac{2 \text{ ppm}}{} \times \frac{2.1 \times 10^9 \text{ ton C}}{1 \text{ ppm}} \times \frac{2000 \text{ lb}}{\text{ton}} \times \frac{44 \text{ lb } CO_2}{12 \text{ lb C}} = 3.1 \times 10^{12} \text{ lb } CO_2$$

3.1×10^{12} lb CO_2 may be released by the combustion of:

for coal: $$\frac{3.1 \times 10^{12} \text{ lb } CO_2}{} \times \frac{1000 \text{ Btu}}{.21 \text{ lb } CO_2} \times \frac{1 \text{ B.O.E.}}{5.8 \times 10^6 \text{ Btu}}$$

= 2.5 billion B.O.E. of coal

This scenario is based on the assumption that 50% of CO_2 released each year will always be absorbed by the ocean and the rest will remain in the atmosphere.

*Derived from an equation presented by U. Siegenthaler and H. Oeschger (1978) (see references).

2. Scenario C

The equation for the generation of Figure 11 is derived to be,

after 1970 (t = 0), then

$$*C = 292 \text{ ppm} + 146 \text{ ppm}/[1 + 3.37 \exp. (-t/20 \text{ years})]$$

This scenario is the same as Scenario B only with different limits.

Figure 1

MOST OF THE USSR'S VAST AGRICULTURAL LAND BASE LIES LATITUDINALLY NORTH OF THE UNITED STATES
Fairbanks
Leningrad
Kiev
Moscow
Arctic Circle
60
40
40
Minneapolis
San Francisco
Philadelphia
Washington
Denver
Springfield
SOVIET AGRICULTURAL LANDS

Figure 2

CONCENTRATION OF ATMOSPHERIC CO_2 AT MAUNA LOA OBSERVATORY, HAWAII

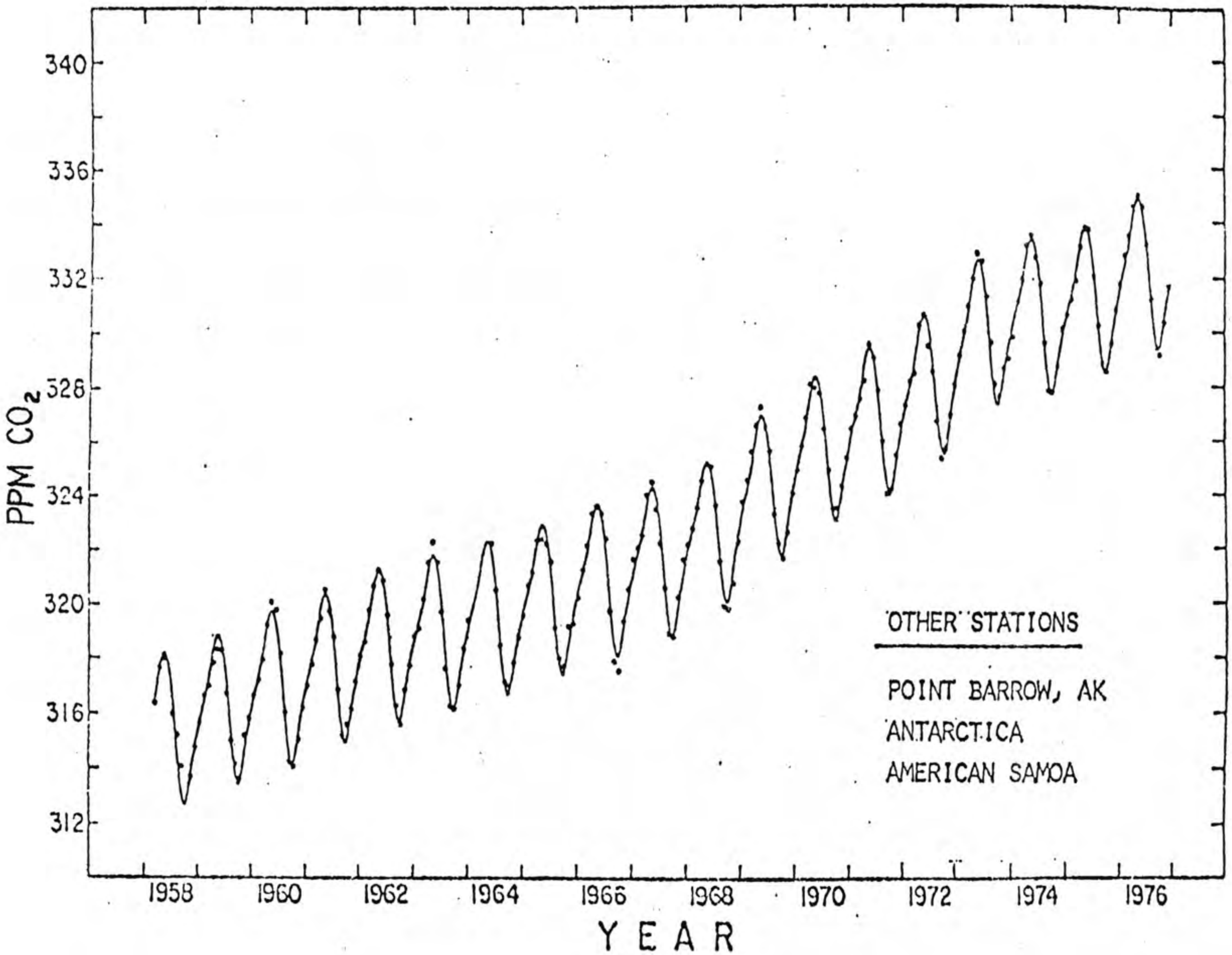

Figure 3

The Carbon Cycle

Current

Fluxes in Gt/a
Pool sizes in Gt

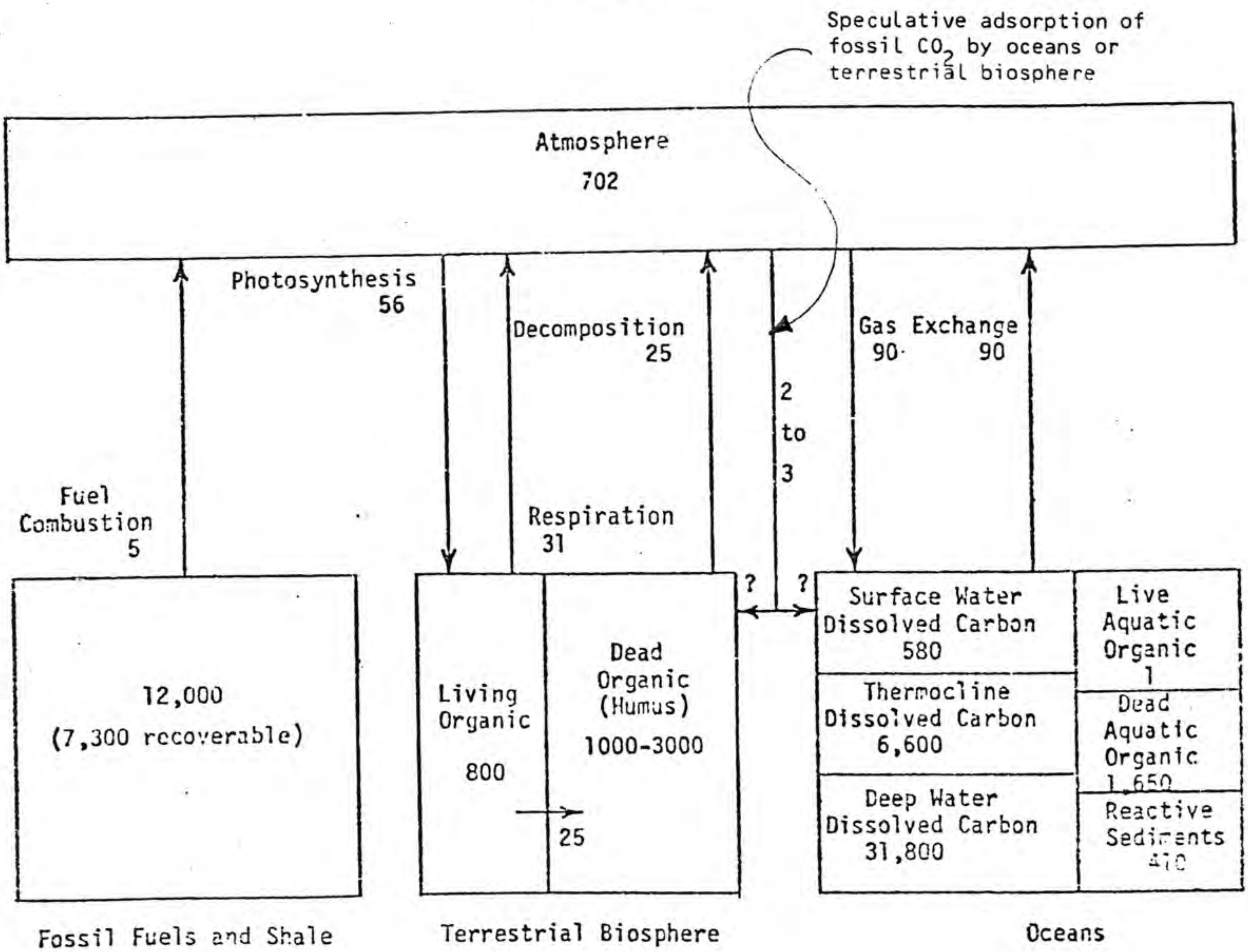

Figure 4

HOW PREDICTED ΔT COMPARES WITH RECENT TEMPERATURES

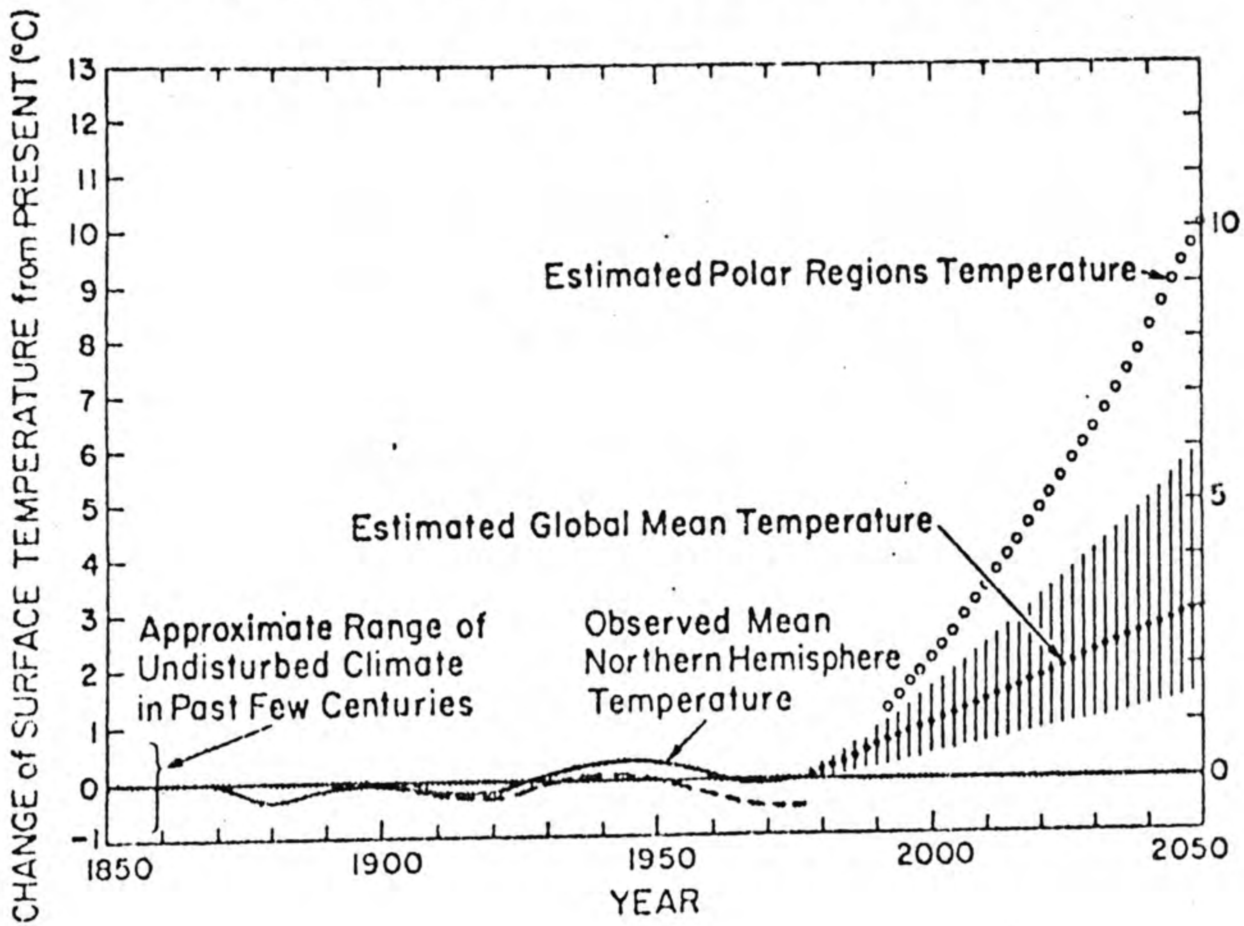

Figure 5

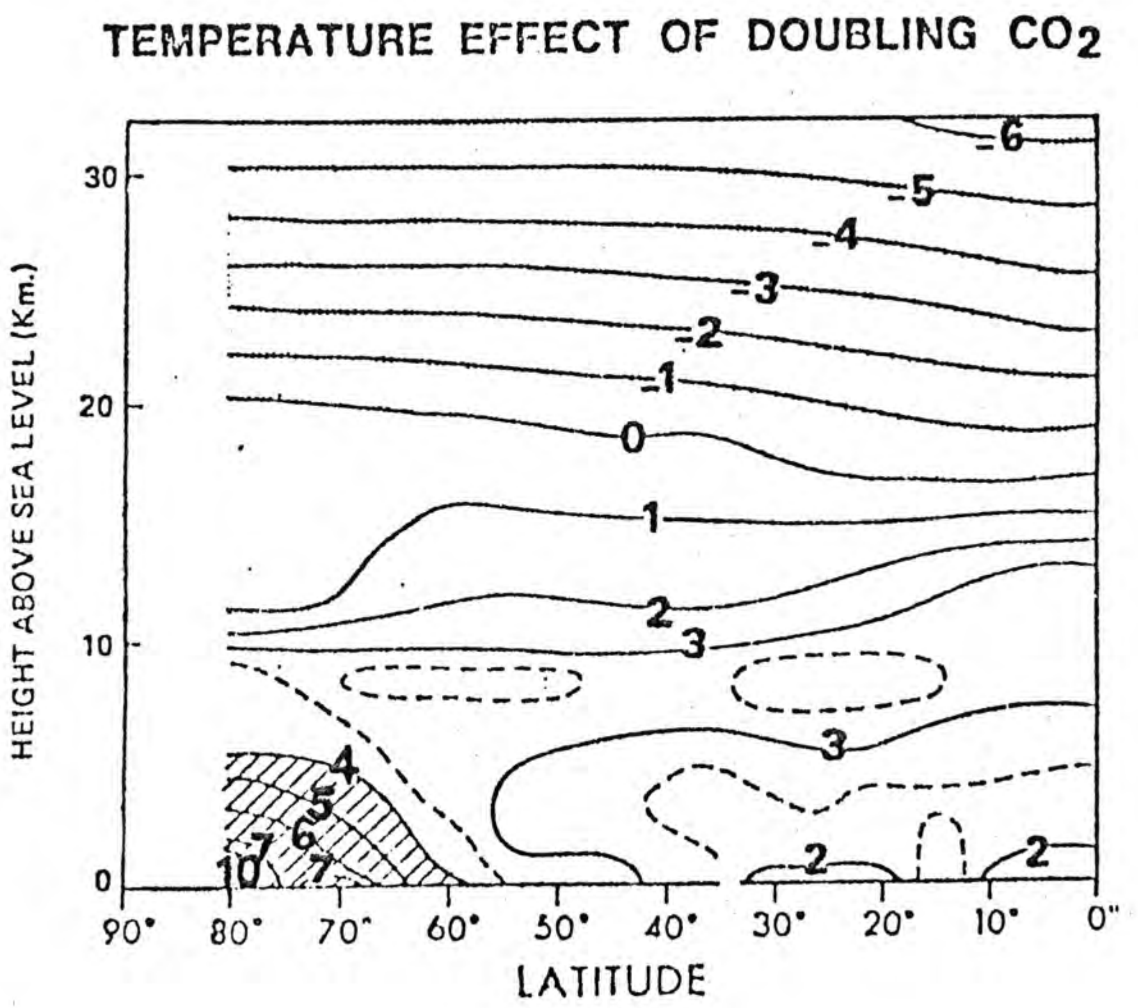
TEMPERATURE EFFECT OF DOUBLING CO2
HEIGHT ABOVE SEA LEVEL (Km.)
30
20
10
0
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
LATITUDE
-6
-5
-4
-3
-2
-1
0
1
2
3
3
2
2
4
5
6
7
10
7

Figure 6

WORLD ENERGY DEMAND BY FUEL

UNLIMITED CO_2 INCREASE
(COAL EMPHASIS)

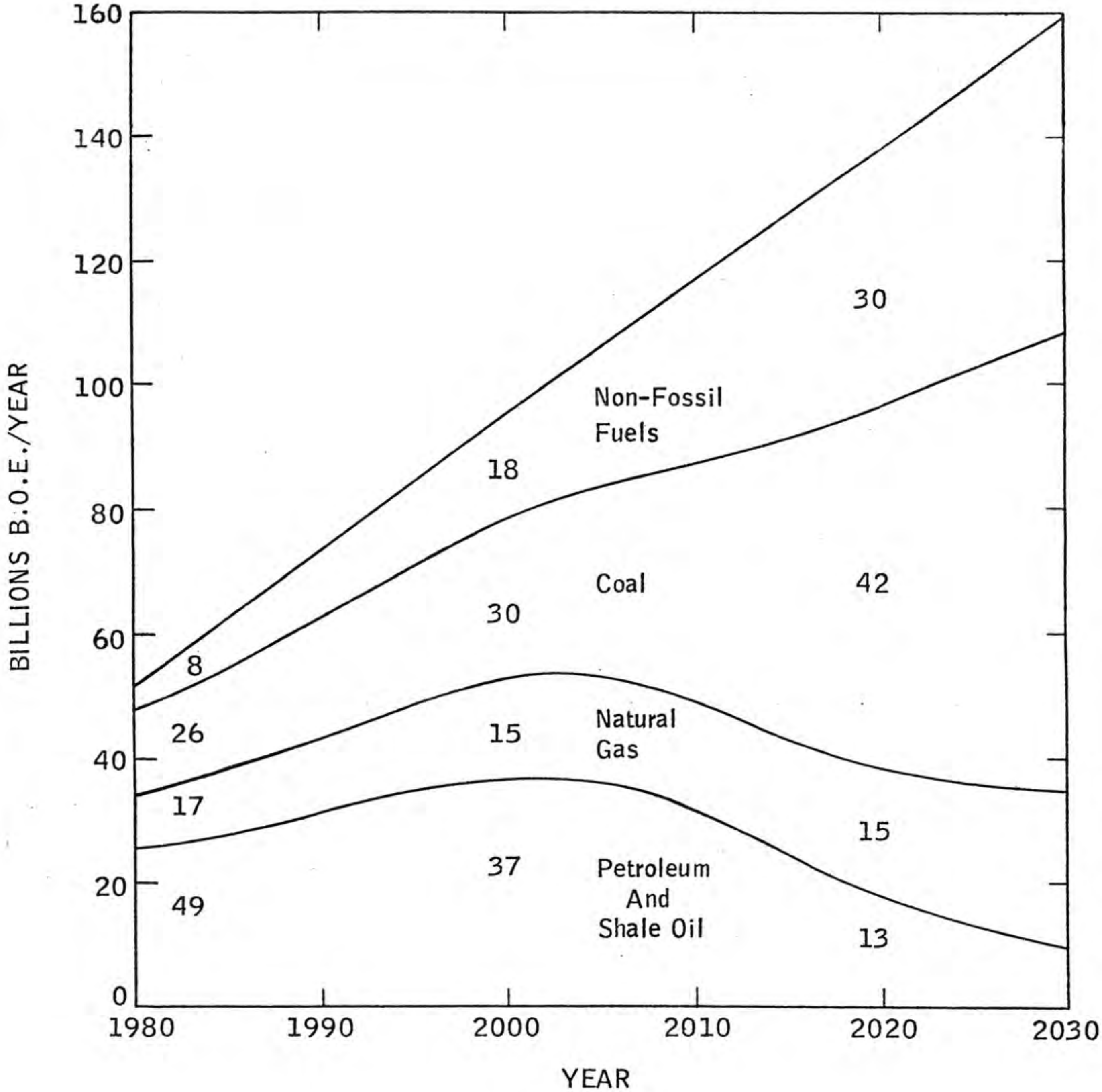

Figure 7

CO_2 IN ATMOSPHERE
RATE OF CO_2 BUILDUP
UNLIMITED INCREASE

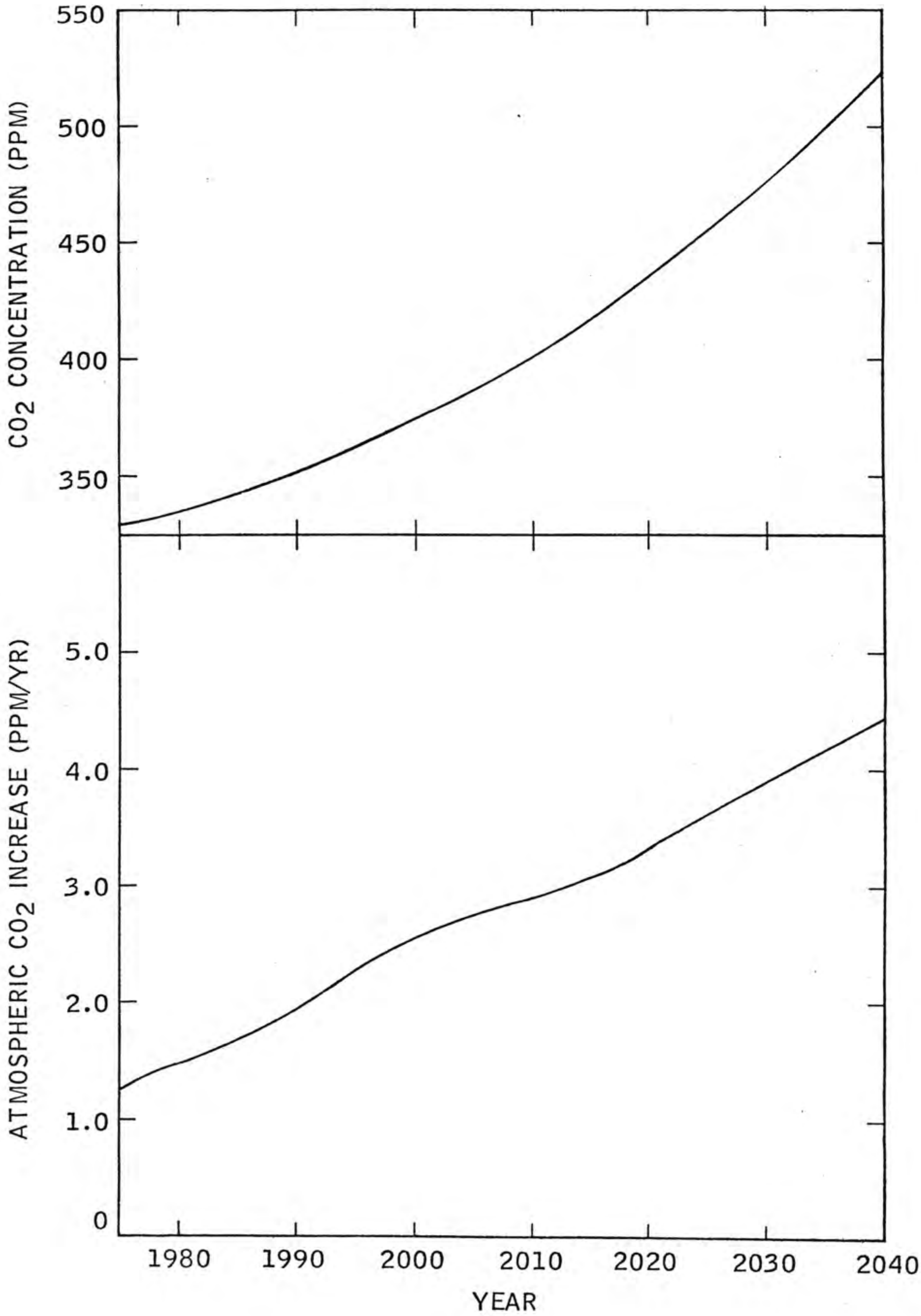

Figure 8

WORLD ENDERGY DEMAND BY FUEL
LIMITED TO A 75% CO_2 INCREASE

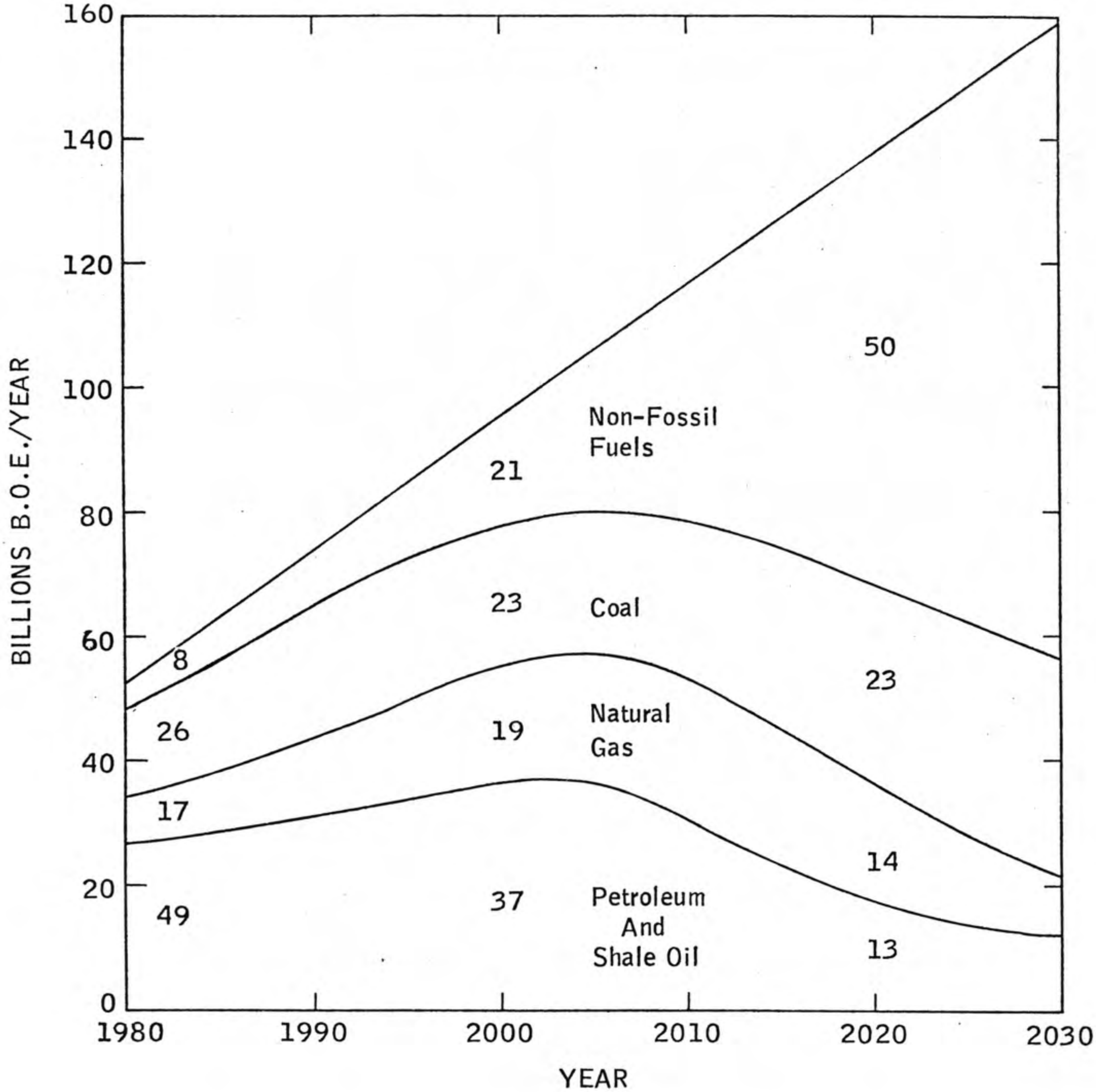

Figure 9

CO_2 IN ATMOSPHERE

RATE OF CO_2 BUILDUP
LIMITED TO 75% INCREASE

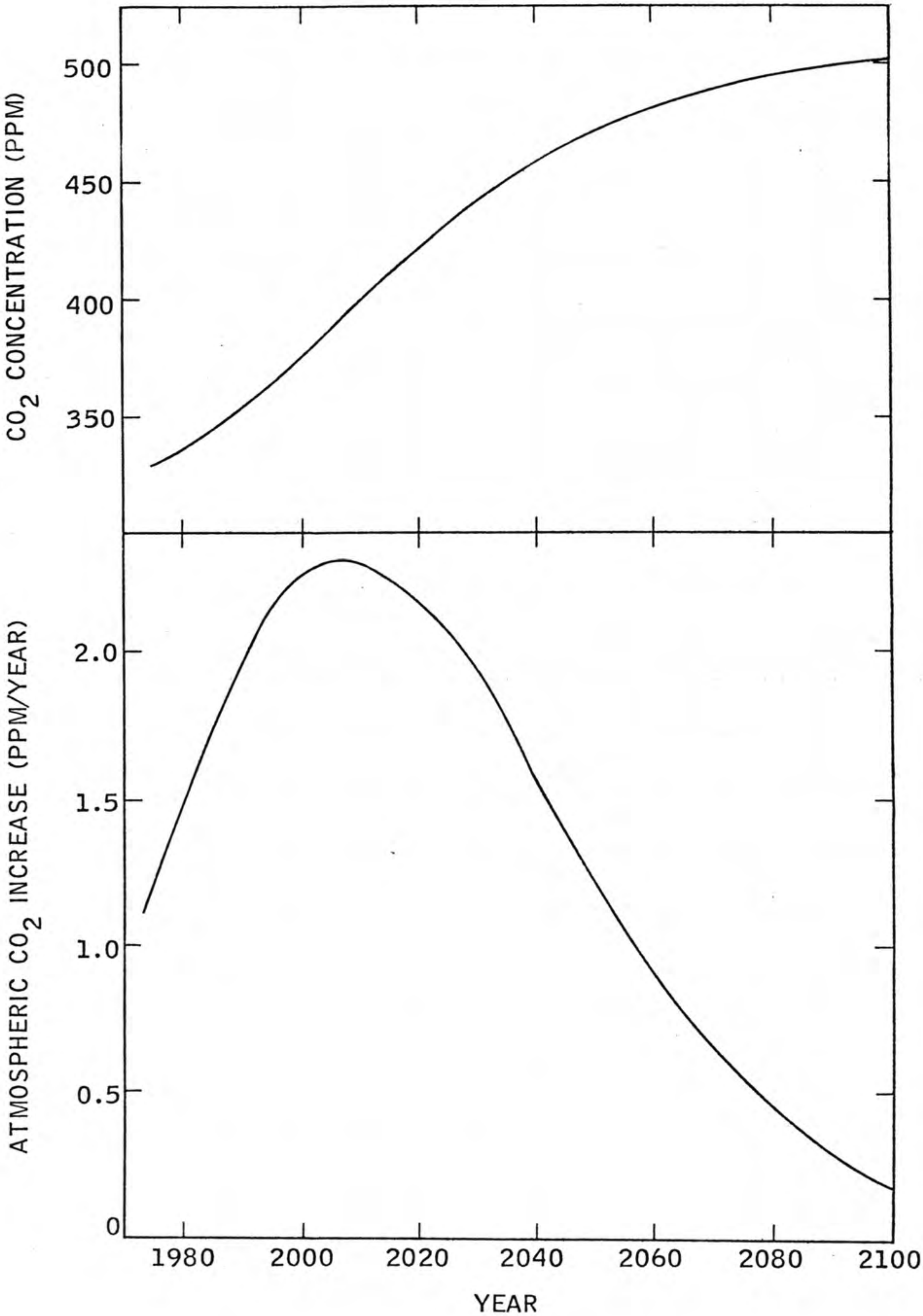

Figure 11

CO_2 IN ATMOSPHERE

RATE OF CO_2 BUILDUP

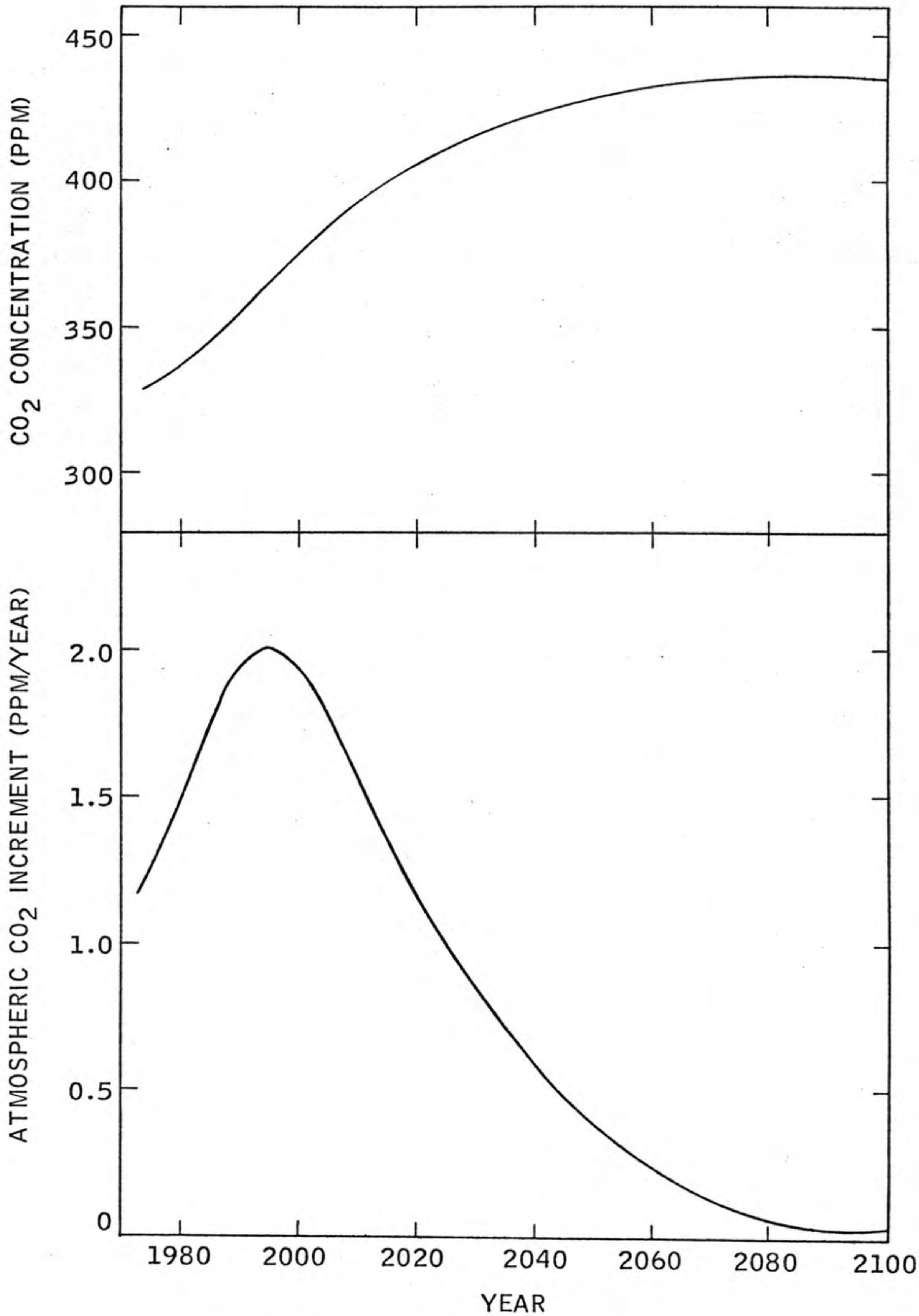

EXHIBIT 15

GENERAL – 154-1-1B

INTER-OFFICE CORRESPONDENCE

Greenhouse

DATE November 19, 1979

TO H. N. Weinberg

FROM H. Shaw

REFERENCE 79CR 184

SUBJECT Research in Atmospheric Science

Atmospheric Science will be of critical importance to Exxon in the next decade. This area emcompasses the complex interdisciplinary research that is needed for in-depth understanding of:

(1) the long range atmospheric transport of sulfates and nitrates across continents and oceans

(2) the impact of anthropogenic sources on climate

(3) the mechanism of acid rain formation

(4) the formation mechanism and dispersion of fine particulates

(5) the enhanced sorption of carcinogens and trace metals on fine particulates

(6) the effect of hydrocarbons, halocarbons and other components on atmospheric ozone depletion

(7) the effect of oxygen depletion in the oceans

(8) the potential greenhouse effect

H. N. WEINBERG

NOV 19 1979

All these critical ecological questions involve a number of disciplines which generally do not interact at Exxon Research, viz., dispersion modeling, climatology, oceanography, atmosphere chemistry, and environmental engineering. See attached articles on the subject.

why?

We should determine how Exxon can best participate in all these areas and influence possible legislation on environmental controls. It is important to begin to anticipate the strong intervention of environmental groups and be prepared to respond with reliable and credible data. Such groups have already attempted to curb the budding synfuels industry because it could accelerate the build-up of CO_2 in the atmosphere. In many respects, the potential environmental problems the energy industry may be facing are similar to those that affected the aircraft industry a decade ago. This industry was caught unprepared when confronted with atmospheric ozone depletion due to Supersonic Transports (SST). As it turned out, this rationale for discontinuing further development of the SST is currently believed to be erroneous by the scientific community. A well prepared aircraft industry should have been able to present data indicating that the ozone layer would not suffer irreparable harm due to the NO emissions from a projected fleet of SST's. On the other hand, the apparent damage that can be caused to the ozone layer by Freons is believed to be significant. When Freon based aerosol containers were baned, the chemical industry was also caught unprepared. If the industry had anticipated the problem, it could have been working on substitute propellants, and might have enhanced its image and public credibility by voluntarily stopping the use of Freons. Such a procedure could have avoided government intervention.

It behooves us to start a very aggressive defensive program in the indicated areas of atmospheric science and climate because there is a good probability that legislation affecting our business will be passed. Clearly, it is in our interest for such legislation to be based on hard scientific data. The data obtained from research on the global damage from pollution, e.g., from coal combustion, will give us the needed focus for further research to avoid or control such polutants. We should be prepared for, and ahead of the government in making the public aware of pollution problems.

Fall-out from intensive study of climate, oceanography, etc., could provide data to better plan fuel distribution systems, and possibly anticipate fuel needs. A first step in evaluating the importance of an atmospheric science program is to form a small task force of knowledgeable people to assess it. I would recommend that a team consisting of a gas phase kineticist, an environmental engineer, and an oceanographer or climatologist develop a list of specific research questions which would be of relevance to Exxon. We should also invite outstanding consultants to consider the possible impact of global ecological factors to Exxon. At some early point we will need to hire a scientist with a national reputation to provide leadership to the area and attract talent. This individual could head the part of the program that we are already committed to, viz., the greenhouse study. I suggest that Dr. Stephen H. Schneider, who will be visiting us on November 20th, may be such an individual, and we should take advantage of his visit here to begin to discuss the subject.

Henry

Henry Shaw

HS/lw

Attachment

cc: N. R. Werthamer