Drawing the Causal Chain: The Detection and Attribution of Climate Change

by Michael F. Wehner

This module describes the detection of human induced climate and its attribution to causal factors. This rigorous body of scientific literature has provided the evidence that human activities, principally the burning of coal, oil, and natural gas for energy, have changed climate. This module will discuss two broad aspects of detection and attribution science. The first part describes the human influence on long-term trends in the climate system. The second part describes the human influence on specific extreme weather events and their impacts.

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I. Introduction

The central issue in both climate science and the law is the attribution of effects to causes. In climate science, this is a two-step process. The first step is to detect that the climate has changed by demonstrating an observable change in a particular climate measure. The second step is to attribute that change to causal factors. Commonly known as D&A, the detection and attribution of climate change constitute an exercise in causality.

Complex phenomena such as climate change have many potential causal influences. Of principal concern today is the increase in atmospheric carbon dioxide (CO_2) resulting from the burning of fossil fuels for energy. While this powerful greenhouse gas makes up a small fraction of the atmosphere, its concentration has increased substantially since the Industrial Revolution. This increased concentration has been accompanied by an unprecedented increase in global temperatures and by other climatic changes. D&A analyses attempt to determine whether changes in the composition of the atmosphere are linked to observed changes in the climate system.

Carbon dioxide is not the only atmospheric pollutant with the potential to alter the climate. Methane (CH_4) from both natural and anthropogenic sources also acts to trap heat in the atmosphere, and its concentration in the atmosphere also has been increasing due to human activities. Various combinations of nitrogen and oxygen (known as nitrous oxides, or NO_x), as well as the chlorofluorocarbons and bromocarbons now banned by the Montreal Protocol, are also greenhouse gases with the similar heat-trapping properties. Some D&A studies attempt to separately quantify the individual warming effect of these various pollutants, but most studies aggregate all greenhouse gases as a "CO_2 equivalent", or the amount of carbon dioxide that would be needed to produce the warming of all greenhouse gases combined.

Aerosols are another important atmospheric pollutant. Not to be confused with hair spray, aerosols are small atmospheric particles or liquid droplets, either natural or man-made. Some of these aerosols, such as sulfate caused by burning high-sulfur coal and oil or by large volcanic eruptions, reflect sunlight back to outer space and can have a cooling effect that counteracts the effect of increased greenhouse gases.[1] Other aerosols, such as the soot or "black carbon" caused by forest fires or the burning of wood or dung for energy, can have a warming effect, thus exacerbating the effects of increased greenhouse gases.[2] Dust blown off the deserts can be transported long distances and also can have complex interactions with aspects of the climate system.[3]

In addition to changing the composition of the atmosphere, humans have changed the surface of the earth for tens of thousands of years if not longer. Deforestation and subsequent reforestation change the amount of light reflected from the earth's surface back into space, which in turn

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[1] N. Bellouin et al., *Bounding Global Aerosol Radiative Forcing of Climate Change*, 58 Reviews of Geophysics 1 (2019), https://doi.org/10.1029/2019RG000660.

[2] T.C. Bond et al., *Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment*, 118 JGR Atmospheres 5380 (2013), https://doi.org/10.1002/jgrd.50171.

[3] Kevin A. Reed et al., *Exploring the Impact of Dust on North Atlantic Hurricanes in a High-Resolution Climate Model*, 46 Geophysical Rsch. Letters 1105 (2019).

affects temperature. Forests tend to be darker than farmland and reflect less sunlight back to outer space, warming the earth's surface, while snow-covered land is white and reflects more sunlight back to space than do areas covered with vegetation. Urbanization also affects the planet's reflectivity, also known as albedo. For example, asphalt and dark roofs absorb more solar energy than do concrete or light-colored roofs. While the effects of urbanization are usually localized, D&A analyses have been used to quantify their consequences for climate change.

Variations in the intensity of sunlight received at the top of the earth's atmosphere can also cause the climate to change. Long-term variations in the Earth's orbit are known to have caused massive swings in climate over long time periods, ranging from very cold ice ages to conditions warmer than today's. However, these orbital changes and their associated climate effects occur very slowly compared with the global warming that has occurred in recent decades and are not generally part of D&A analyses.

Of more relevance on human timescales is the variability in the Sun's luminosity. With a period of approximately 13 years, these solar variations have been well studied and will be discussed later in this module.Add something here to acknowledge ENSO too.

II. How are D&A Analyses Done?

The causal factors described above are often referred to as external "forcing" factors. While these factors can be of both natural and anthropogenic origin, they are described as external because they are imposed upon the climate system rather than being an intrinsic part of it. Changes in climate due to these causal factors are the effects or "signals" being sought in D&A analyses.

However, the climate system also has a complicated internal variability. Some of these modes of internal variability are well known. For example, *El Niño* is part of a periodic redistribution of heat in the Pacific Ocean that occurs every few years. This natural variation in Pacific Ocean temperatures has far-reaching effects, such as modulating winter temperatures in North Dakota and influencing the number of North Atlantic hurricanes.

Other quasi-regular natural oscillations are not so well known to the public. For example, both the Atlantic and Pacific oceans undergo regular changes over periods of years to decades that can influence temperature and rainfall patterns on land. While some aspects of these natural changes within the climate system are not thoroughly understood, enough is known about their mechanisms and effects to rule out their being responsible for the warming and associated climatic changes observed in recent decades.

Climatic measures such as average global temperature also vary from year to year due to "noise" or apparently random variations within the climate system. These variations are much more difficult to predict because they are the result of initially small influences that are magnified by the mechanisms of the climate system. The total internal variability of the climate system is therefore a mixture of known natural oscillations and this unpredictable chaotic noise.

The challenge in a D&A analysis is to extract the external signal of human-produced forcing factors from the natural variation of the climate system. This sort of problem arises in other areas of science and technology, such as in certain electrical engineering applications, and climate scientists have adapted techniques from that discipline.

However, unlike electrical engineers or other physical scientists and as was noted in the module on How Climate Science Works, climate scientists have only a single experimental planet to study. Lacking alternate planets to test a hypothesis, they must rely on climate models to determine how external forcing factors are changing the climate. But the basic methodologies involved in using climate models are similar to those used in many other areas of science.

As an example, consider the most well-established aspect of the climate system, the global average surface temperature. The first step of a D&A analysis is to detect a change in the observed record, usually expressed as a trend. Fortunately, extensive observations of air temperatures over the land and in the ocean surface go back well into the 19th century. The black line in Figure 1 shows these measurements averaged over the entire globe each year from 1850 to 2020. These temperatures are shown as a difference from the average over the 1850–1900 period, which is centered around zero. The internal variability of climate is evident by the short-term ups and down in the black line. Around 1930, the observed global average surface temperature begins to increase above the previous average. By the 1980s, a detectable trend or change is obvious.

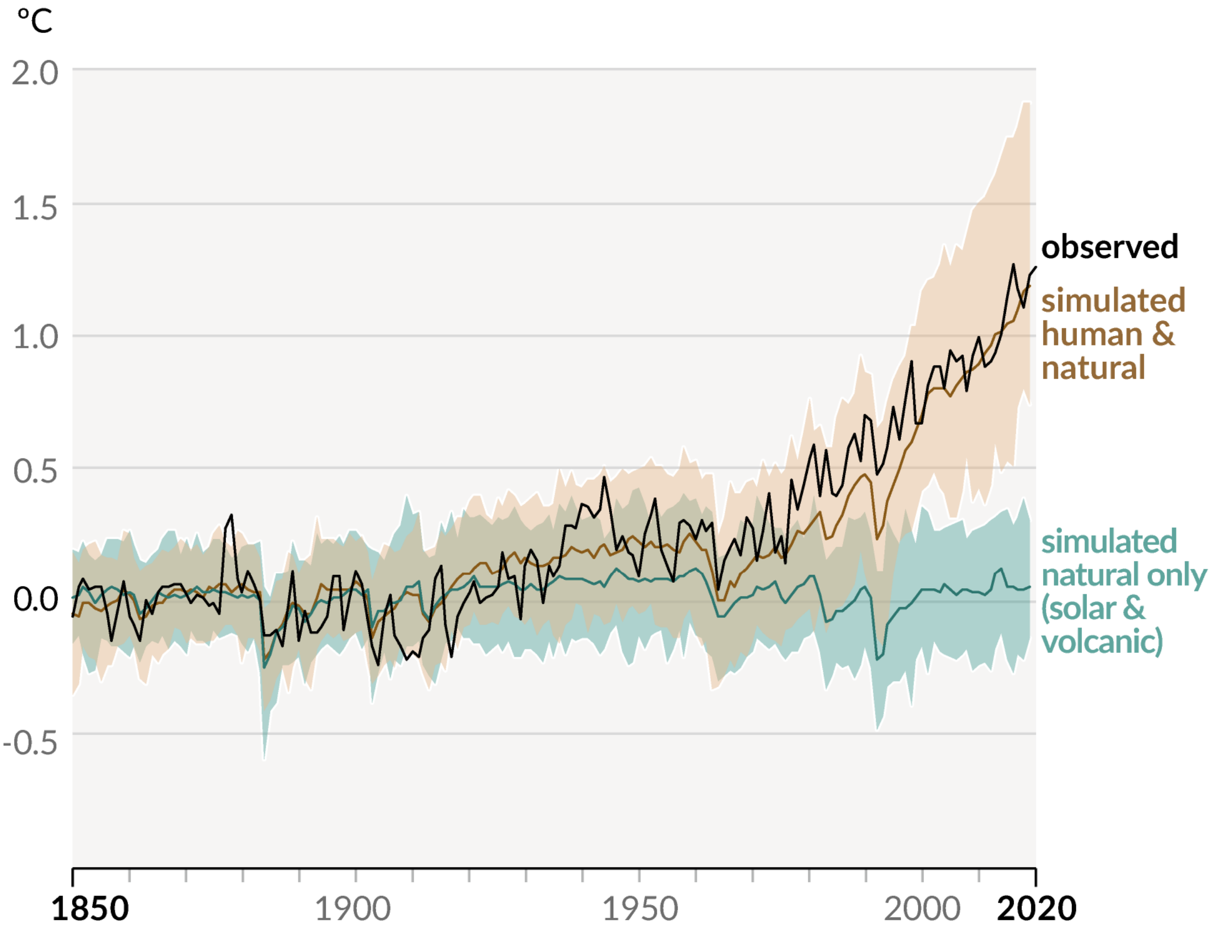

Figure 1: The observed global mean surface air temperature (black line) tracks with climate models containing human and natural influences (brown line) and not with models that include only natural influences (green line). Confidence intervals of the model simulations are shown by the shaded regions. Units: ºC. Source: IPCC, CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, SUMMARY FOR POLICYMAKERS (2021) (Figure SPM.1(b)).

If a trend has been detected, the next D&A step is the attribution of the observed change to a causal factor. To do that, D&A analyses typically compare the observations both with models that include a particular set of causal factors and with models that do not include them. The variations in simulations that do not include the causal factors reveal how much internal variability is present in the system, and this variability can be compared with the variability in the observations. The simulations that do include the causal factors then can be compared with an observation to determine whether an observed change can be attributed to that factor.

Correspondence between a simulation and an observed change does not necessarily mean that the change can be attributed to the causal factor included in the model. A model may not be "fit for purpose," meaning that it does not accurately simulate the system being modeled. Determining whether a model is fit for purpose is done through a process called model evaluation, which is a well-established science that has been discussed extensively in many reports and papers.[4] Model evaluation involves such steps as comparing model outputs, contrasting simpler with more complex models, combining models, and quantifying uncertainties. This process increases the confidence with which attributions and projections based on models can be made.

Figure 1 demonstrates many aspects of this D&A process. The brown line represents the global mean surface temperature from climate model simulations with five external forcing agents: greenhouse gases, anthropogenic aerosols, anthropogenic ozone, volcanic aerosols, and solar variability. The curve is smoother than the observations (black line) because an ensemble of different climate models yields results that have been averaged together, which reduces internal variability. The range of different model results is shown by the brown-shaded region. Agreement of the averaged model simulations with the observed change leads to the conclusion that the detected observed change is externally forced and not an internal variation.

Figure 1 also compares the "all forcings" simulations with simulations that include only the volcanic and solar variability forcings, as shown in green. These simulations clearly do not contain the observed change. Furthermore, when comparing the range of natural simulations (shaded green) to the range of "all forcings" simulations (shaded brown), it is clear that the "all forcings" signal emerged from the noise of natural variability in the 1990s. Applying formal statistical tools to these datasets can quantify these statements in a rigorous manner.[5]

The conclusions of a D&A study are often made in attribution statements, which are constructed not to overstate the link between a cause and the observed effect. From Figure 1, such a conservative statement would be "It is *very likely* that at least half of the observed warming is due to human influences." The italicized "very likely" is a reference to the IPCC calibrated language denoting a 95% statistical confidence interval.[6] The "at least" part of the statement refers to the lower bound of the brown shaded region, which is about half of the observed warming (in black).

This very conservative language belies the actual level of confidence in the attribution of global warming to greenhouse gases. An equally correct statement is "Our best estimate is that the observed warming is due to human influences." This statement is true because "best estimate" means that the central value (i.e., the average of the values predicted by multiple independent models) is equal to the observed change.

III. D&A Analyses Beyond Temperature

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[4] Zeke Hausfather et al., *Evaluating the Performance of Past Climate Model Projections*, 47 Geophysical Rsch. Letters 1 (2020), https://doi.org/10.1029/2019GL085378.

[5] *See, e.g.*, Gabriele C. Hegerl & Gerald R. North, *Comparison of Statistically Optimal Approaches to Detecting Anthropogenic Climate Change*, 10 J. of Climate 1125 (1997), https://doi.org/10.1175/1520-0442(1997)010%3C1125:COSOAT%3E2.0.CO;2.

[6] IPCC, CLIMATE CHANGE 2021: The Physical Science Basis, SUMMARY FOR POLICYMAKERS (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

D&A analyses consider many aspects of the climate system other than global mean temperature, including precipitation, ocean temperature, sea ice extent, and sea level. Figure 2 shows aspects of climate that have been subjected to D&A analyses.

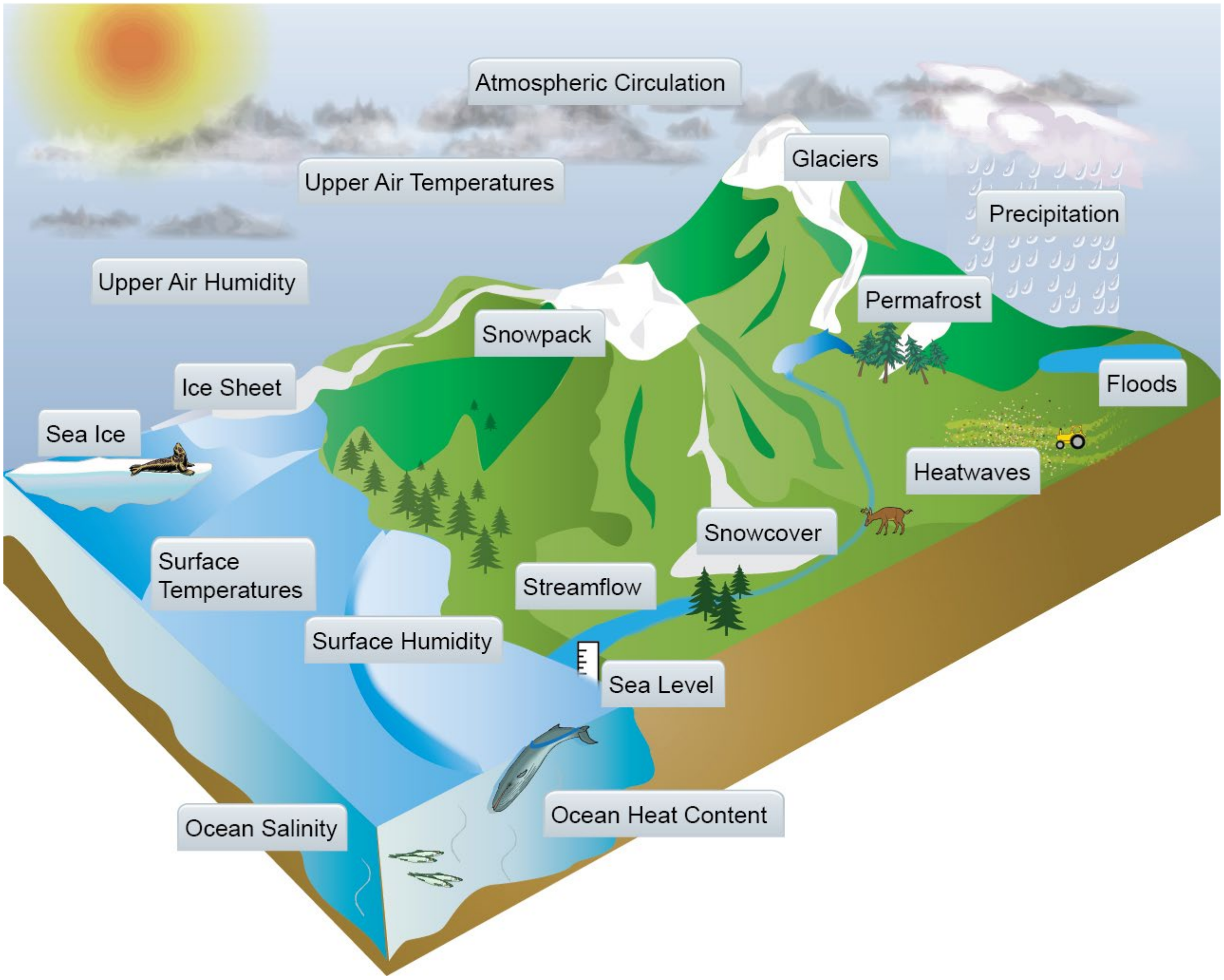

Figure 2: Studies in the peer-reviewed science literature have attributed changes in many aspects of climate to human emissions of heat-trapping gases and aerosols. Many natural factors have affected climate in the past and continue to do so today, but human activities are the dominant contributor to recently observed climate changes[7]

The first challenge in a D&A study is acquiring long-term observational records, which can be inadequate even for temperature, much less other quantities of interest. Observational coverage is incomplete over the globe and varies with time. Many parts of the southern hemisphere are poorly observed, as are the portions of the oceans outside of shipping lanes. Satellites provide uniform global coverage, but the earliest satellites with relevant instrumentation were launched

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[7] John Walsh et al., Appendix 3: Climate Science Supplement, in Climate Change Impacts in the United States: The Third National Climate Assessment (2014), https://nca2014.globalchange.gov/report/appendices/climate-science-supplement.

just in 1979. Furthermore, these early satellites' primary mission was weather prediction, not climate monitoring.

Satellites nevertheless offer a good example of opportunities for D&A analyses. For example, one use of satellites is to compare temperatures close to the surface (in the troposphere) with those in the upper atmosphere. Microwave sounding unit satellites do not measure air temperature at different levels above the ground directly, but temperatures at different levels can be inferred from a retrieval and calibration algorithm.[8] The human influence on these temperatures is very clear in D&A analyses. Figure 3 shows, on the left, the vertical profile of air temperature aloft over the 1979–99 period. The troposphere, from the ground up to about 200 mb of pressure, has clearly been warming while the stratosphere, above about 100 mb of pressure, has been cooling both in the observations and in three models.[9] More importantly, a series of model simulations with external forcing agents individually imposed (Figure 3, right) reveals that only greenhouse gases and ozone (panels A and C) can produce a cooling of the stratosphere. These studies also demonstrate that solar variations are not responsible for the observed climate change, because they would be expected to warm the stratosphere rather than cool it as observed (figure 3, right panel E).

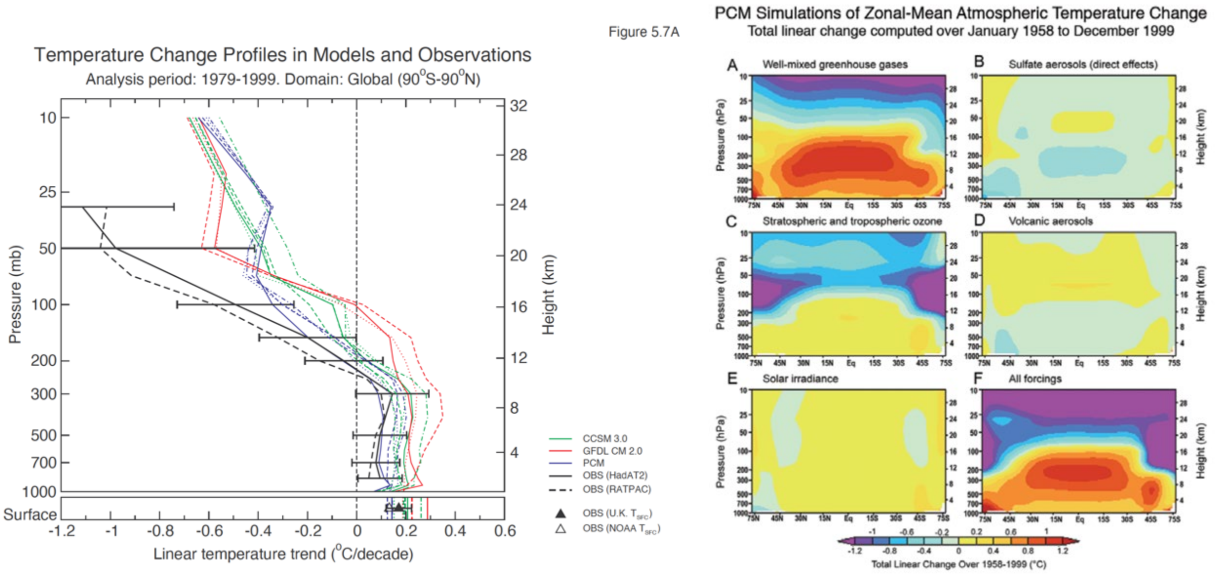

Figure 3: Left: Over the 1979–99 period, air temperature averaged over both latitude and longitude has increased in the lower atmosphere and has declined in the upper atmosphere. Observations are the solid and dashed black lines. Results from climate models are shown as colored lines. Right: Simulations of external forcing factors produce different predictions of changes in vertical air temperature. Note that changes in solar luminosity (lower left panel) do

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[8] Benjamin D. Santer et al., *Identifying Human Influence on Atmospheric Temperature*, 110 PNAS 26 (2013), https://www.pnas.org/doi/full/10.1073/pnas.1210514109; Benjamin D. Santer et al., *Influence of Satellite Data Uncertainties on the Detection of Externally Forced Climate Change*, 300 Science 1280 (2003), https://doi.org/10.1126/science.1082393.

[9] Benjamin D. Santer et al., *How Well Can the Observed Vertical Temperature Chang es Be Reconciled With our Understanding of the Causes of These Changes?*, in Temperature Trends in the Lower Atmosphere (T.R. Karl et al., eds.) (2006).

not reproduce the observed vertical changes but that the all forcings simulation (lower right panel), which includes human greenhouse gas increases, does. Source: Benjamin D. Santer et al., *How Well Can the Observed Vertical Temperature Changes Be Reconciled With our Understanding of the Causes of These Changes?*, in Temperature Trends in the Lower Atmosphere (T.R. Karl et al., eds.) (2006).

Because of the optical properties of water vapor, it can be remotely observed very accurately over the oceans. Although satellite observations of water vapor started only in 1989, the detected signal quickly rose above the noise and could be attributed readily to external forcing factors.[10] These studies demonstrated the validity of D&A analyses, as the measured moisture changes were shown to be consistent with observed temperatures and could be predicted from well-established physical laws.

Changes in average precipitation have also been subjects of D&A analyses. As the atmosphere warms, when fully saturated it can hold more water vapor, and precipitation might be expected to increase. However, the D&A problem for precipitation is complicated as changeds in atmospheric circulation can cause precipitation to increase or decrease spatially depending on location, and season and natural variability is high.[11] Hence, confidence in attribution of precipitation changes is lower than it is for temperature.[12] In addition, frequent and accurate precipitation observations are mostly limited to North America and Europe, which imposes some conditions on the published attribution statements[13] As discussed later in this module, potential changes in *extreme* temperature and precipitation due to global warming are expected to be more robust, and D&A studies are more confident in these areas.[14]

Climate models require many long computations, and such simulations require substantial human and machine resources. Fortunately, climate science has matured to the point where a great deal of simulation data from the international climate modeling community is now publicly available. (refs) Collections of simulations are one way to evaluate whether models are fit for purpose. Other times, more specialized analyses may be required to make this determination. [I would leave this statement in but add in John's observation as well.]

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[10] Carl A. Mears et al., *Relationship Between Temperature and Precipitable Water Changes Over Tropical Oceans*, 34 Geophysical Rsch. Letters 1 (2007), https://doi.org/10.1029/2007GL031936; Benjamin D. Santer er al., *Idnetification of Human-Induced Changes in Atmospheric Moisture Content*, 104 Proc. of the Nat'l Acad. of Sci's 15248 (2007), https://www.pnas.org/doi/full/10.1073/pnas.0702872104.

[11] D.R. Easterling et al., Precipitation Change in the United States, Chapter 7 in U.S. GLOBAL CHANGE RES. PROGRAM, CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT VOL. 1 (2017).

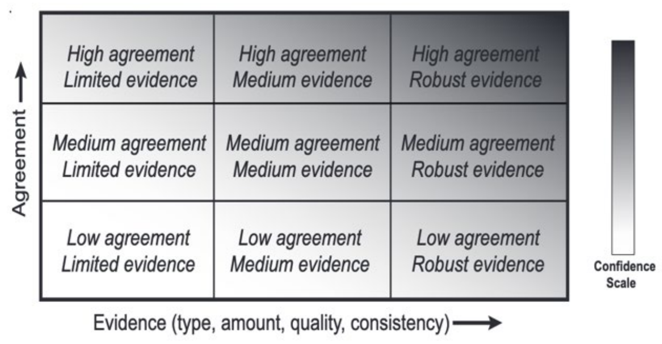
[12] IPCC, CLIMATE CHANGE 2021: The Physical Science Basis, SUMMARY FOR POLICYMAKERS (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

[13] Seung-Ki Min et al., *Human Contribution to More-intense Precipitation Extremes*, 470 Nature 378 (2011), https://www.nature.com/articles/nature09763; Xuebin Zhang et al., *Attributing Intensification of Precipitation Extremes to Human Influence*, 40 Geophysical Rsch. Letters 5252 (2013), https://doi.org/10.1002/grl.51010.

[14] Yeon-Hee Kim et al., *Attribution of Extreme Temperature Changes During 1951-2010*, 46 Climate Dynamics 1769 (2016), https://doi.org/10.1007/s00382-015-2674-2; Seung-Ki Min et al., *Multimodal Detection and Attribution f Extreme Temperature Changes*, 26 J. of Climate 7430 (2013), https://doi.org/10.1175/JCLI-D-12-00551.1.

IV. Assessing Confidence in Attribution Statements

Assessing confidence in attribution statements is critically important for decision and policy makers. Most attribution statements are framed in the calibrated language developed by the Intergovernmental Panel on Climate Change of an objective "likelihood" and a subjective "confidence" (Table 1).[15] As noted earlier, the IPCC's phrasing tends to be conservative because of the focus on the lower bounds of statistical confidence intervals.



High agreement *Limited evidence*	*High agreement* *Medium evidence*	*High agreement* *Robust evidence*
Medium agreement *Limited evidence*	*Medium agreement* *Medium evidence*	*Medium agreement* *Robust evidence*
Low agreement *Limited evidence*	*Low agreement* *Medium evidence*	*Low agreement* *Robust evidence*

Table 1. Likelihood Scale

Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

Table 1: The calibrated uncertainty language developed by the IPCC treats both the nature of the evidence (left) and the likelihood of outcomes (right). Left: Confidence increases towards the top-right corner as suggested by the increasing strength of shading. Generally, evidence is treated with greater confidence when multiple independent lines of high-quality evidence are consistent. Right: Objective likelihood statements range from virtually certain to exceptionally unlikely.

Source: MICHAEL D. MASTRANDREA ET AL., INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, GUIDANCE NOTE FOR LEAD AUTHORS OF THE IPCC FIFTH ASSESSMENT REPORT ON CONSISTENT TREATMENT OF UNCERTAINTIES 3 (2010).

The IPCC has also developed a method for assigning confidence to attribution statements regarding long-term changes in climate, as shown in Figure 4.[16] This method can be used to assess contrasting studies when developing a weighted likelihood of particular events.

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[15] Sophie C. Lewis et al., *Toward Calibrated Language for Effectively Communicating the Results of Extreme Event Attribution Studies*, 7 Earth's Future 1020 (2019), https://doi.org/10.1029/2019EF001273; MICHAEL D. MASTRANDREA ET AL., INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, GUIDANCE NOTE FOR LEAD AUTHORS OF THE IPCC FIFTH ASSESSMENT REPORT ON CONSISTENT TREATMENT OF UNCERTAINTIES (2010).

[16] Friederike E.L. Otto et al., *Toward an Inventory of the Impacts of Human-Induced Climate Change*, 101 Bull. Of Am. Meteorological Soc'y E1972 (2020), https://doi.org/10.1175/BAMS-D-20-0027.1; Sonia I. Seneviratne et al., Weather and Climate Extreme Events in a Changing Climate, Chapter 11 in IPCC, CLIMATE CHANGE 2021: The Physical Science Basis (2021).

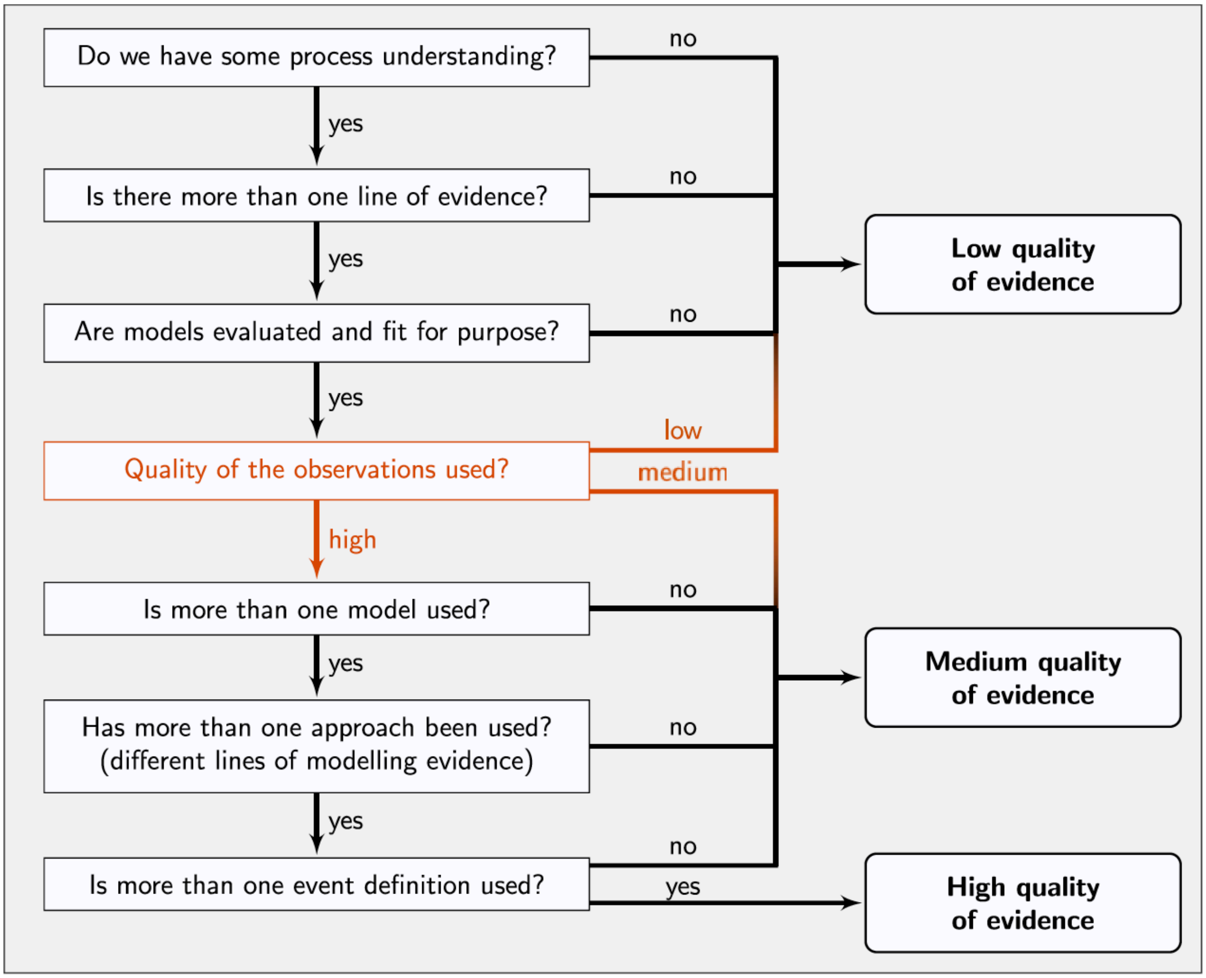

Figure 4: Confidence (low, medium, or high) in attribution statements can be assessed by answering a series of yes-no questions. Source: Friederike E.L. Otto et al., *Toward an Inventory of the Impacts of Human-Induced Climate Change*, 101 Bull. Of Am. Meteorological Soc'y E1972, E1975 (2020).

Confidence in an attribution statement is highest when multiple, independent teams arrive at similar conclusions using different observational datasets, different climate models, and different attribution techniques. This has occurred in only a few cases, in part because the attribution community remains small and much D&A work remains to be done.

Early attribution statements often relied on single climate models, and some rather specialized attribution efforts still do. But confidence increases with the number of climate models used, and the widespread and centralized availability of climate model output data increasingly makes the use of multiple models possible. Using multiple observational datasets also increases confidence, though many of these datasets are not independent, limiting the increase in confidence. As a proxy for multiple observations, some attribution studies use reanalyses products. These datasets are produced by specialized weather prediction models that are highly constrained by observations. Their principal advantage is that they provide a physically justified way of constructing spatially and temporally complete fields. In addition, reanalysis products include constrained estimates of physically unobservable quantities that may be of interest. However, confidence in attribution statements based on reanalyses depends on the uncertainties inherent to the renanalysis procedures.

V. Attributing Extreme Events to Climate Change

Traditional attribution statements have focused on long-term observed changes in climate. In contrast, extreme event attribution statements generally focus on the influence of human activities on a single event (or sometimes a single class of events).

In 2003, after his house in Oxford, England, was flooded by an exceptionally rainy storm, climate scientist Myles Allen proposed that the human influence on severe weather events could be quantified.[17] Prior to that, climate scientists tended not to say much about the human influence on individual extreme weather events. Instead, they would say something like "While no individual event can be tied to climate change, what happened is consistent with expectations."

Today, some kinds of individual events can be linked to climate change. Extreme event attribution techniques now make it possible under certain circumstances to formulate quantitative statements, with confidence intervals, about the human influence on many kinds of individual extreme weather and climate events. For example, in 2003, shortly after Allen's proposal, central Europe experienced a disastrous heatwave that caused over 70,000 excess deaths. Using the high-quality observational record of European temperatures and a single climate model, scientists estimated that climate change *likely* at least doubled the chances of the measured maximum daytime temperatures. Since then, the field of extreme event attribution has expanded to include many types of extreme weather in addition to heatwaves—including heavy precipitation, floods, droughts, and some extreme storms such as hurricanes.[18]

The ability to quantify the human influence on a particular event such as a flood or heat wave is of direct relevance for judges. Extreme event attribution statements are of two equivalent types. The first is "Did global warming change the magnitude of this event given its estimated rarity?" The second is "Did global warming change the chances of an event of this magnitude?" These two questions are not independent, as illustrated by Figure 5. In this figure, the likelihood of a given temperature in Washington, D.C., as calculated by models is plotted as a function of its return time. Return time—the period in which we might expect an event to recur on average—is a key term for stating the likelihood of an event. The black line averages the model simulations under present-day conditions of global warming. The red line averages the simulations under preindustrial climate conditions. The intersection of the vertical line with the black line indicates that, if the current climate were unchanging, temperatures would reach 41°C about once every 20 years on average over a long period of time. But the climate is changing, so a better way of describing current conditions is to say that there is a 1-in-20 or 5% chance of reaching 41°C this year. In a preindustrial climate, the 20-year event would have been at about 39°C , as indicated

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[17] Myles Allen, *Liability for Climate Change*, 421 Nature 891 (2003), https://doi.org/10.1038/421891a.

[18] (Herring et al., 2022, 2019, 2018, 2016, 2015, 2014; Peterson et al., 2013, 2012).

by the intersection of the vertical line with the red curve. Therefore, climate change caused the 20-year event to be about 2ºC warmer.

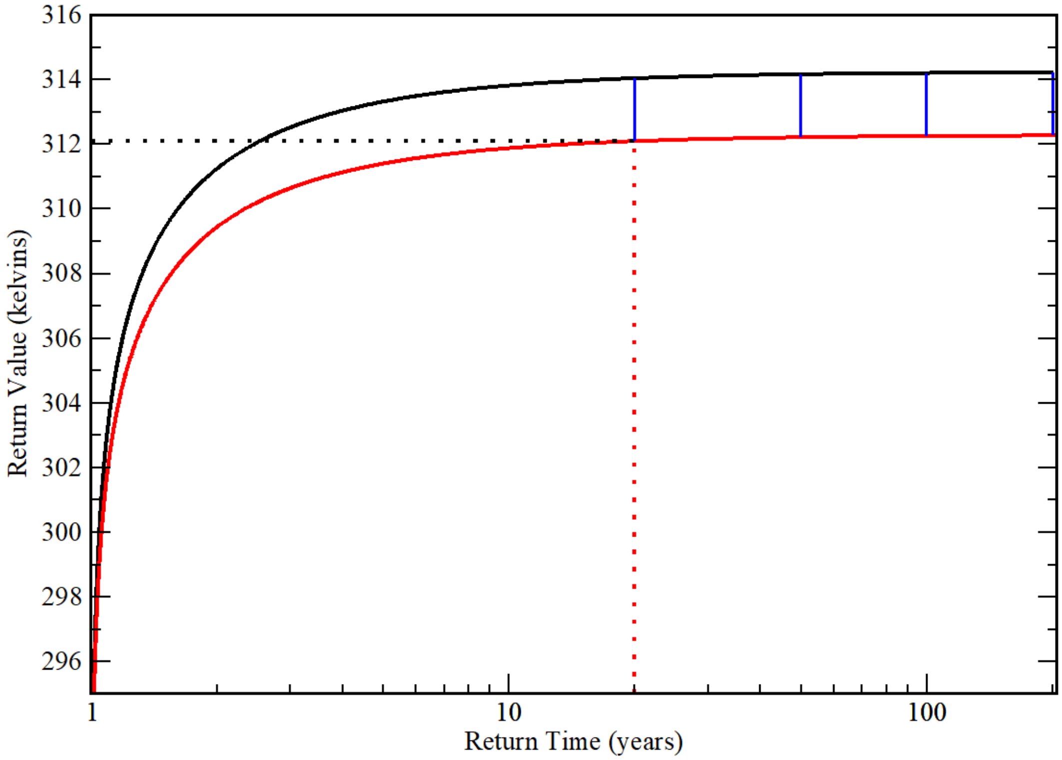

Figure 5: A 20-year event of surface air temperature near Washington, D.C., is about 2ºC (3.6ºF) higher in a realistic climate (black line) than in a cooler counterfactual climate without anthropogenic climate change (red line). Units: Kelvins. Source: Michael Wehner et al., *Early 21st Century Anthropogenic Changes in Extremely Hot Days As Simulated by the C20C+ Detection and Attribution Multi-model Ensemble*, 20 Weather & Climate Extremes 1, 6 (2018). [Need to redraw graph with degrees Celsius as units.]

The second question regarding likelihood is more nuanced. The horizontal dashed line drawn at 39ºC intersects the black curve at a return time of about 2.5 years under present-day climate conditions. It intersects the red line at a return time of 20 years under preindustrial conditions. Hence, the chances of reaching 39ºC have been increased by climate change by a factor of 20/2.5 or eight times.

Hence, the questions about human caused changes in probability and magnitude of individual extreme weather events are two sides of the same coin. However, changes in magnitude are often more easily interpreted when considering changes in the impacts of extreme events as described below.

Confidence in individual extreme event attribution statements is increased if D&A studies have produced more general statements about the relevant variables or regions. However, this is not strictly necessary, and extreme event attribution statements can be made even if trends in similar events have not been detected (Knutson, 2017).

Extreme heat Figure 5 also demonstrates some of the issues associated with attribution statements involving extreme heat. The high temperature curves without climate change (red) and with climate change (black) approach values of 39ºC and 41ºC, respectively, and appear never to go higher. Was a temperature of 106ºF impossible without climate change, as this curve would suggest? Most attribution statements would likely not make such a strong claim from this model calculation but would say that the likelihood of the temperature rising that high is very low but not absolutely zero because of statistical uncertainty. Quantifying the uncertainty in this upper bound is an ongoing topic in statistical research.

Figure 5 shows that the temperature change attributable to human activities in the once in 50- or 100-year heatwave is not very different than the once in 20-year event. This consequence of the distribution of extreme heat events in the atmosphere over time, in which high-temperature events of any kind are extremely rare, permits confidence in attribution statements about heatwaves in advance of their occurrence. Figure 6 applies this analysis to the continental United States, which shows one model's estimate of the change in 20-year temperatures attributable to climate change. This change is nearly identical in pattern and magnitude to the model's changes in 50-year temperatures. A confident attribution statement is therefore that almost any heatwave that occurs now in the United States is about 3.5ºF to 4.5ºF warmer than it would have been without climate change. This attribution statement can be made without estimating the probability of the heatwave temperature as long as it is thought to be rare. It would even extend to record temperatures, as long as the existing records are not broken by a large amount. However, in the case of far outliers, such as the 2021 Pacific Northwest heatwave, certain assumptions of this theory are violated and only less definitive statements can be made.

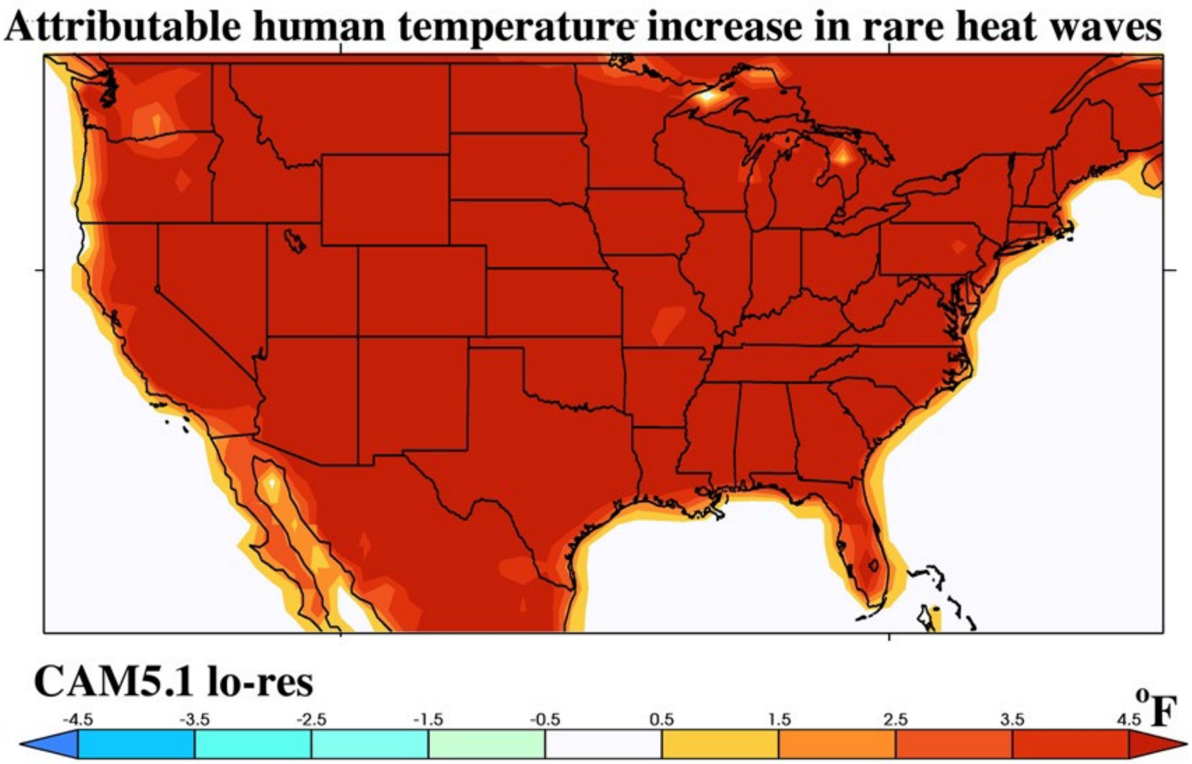

Figure 6: High temperatures during rare heatwaves in much of the United States are estimated to be 3.5ºF to 4.5ºF higher due to changes humans have made in the composition of the atmosphere. Adapted from Michael Wehner et al., *Early 21st Century Anthropogenic Changes in Extremely Hot Days As Simulated by the C20C+ Detection and Attribution Multi-model Ensemble*, 20 Weather & Climate Extremes 1 (2018).

Precipitation Estimating the human influence on heavy precipitation events is more complicated than for heatwaves. Precipitation is a sporadic event, and extreme precipitation even more so. Well-established physical laws indicate that the capacity of the atmosphere to hold water vapor increases by about 7% per degree Celsius of warming. However, recent attribution simulations suggest that this rate is a lower bound for precipitation increases in certain types of extreme storms and that the actual rate can exceed this lower bound by factors of two or three.[19]

The computational demands of models with resolutions fine enough to capture the processes and conditions of severe storms, including hurricanes, restrict the duration of simulations using current supercomputers. However, shorter but more constrained simulations using weather prediction models have proven to be useful in deriving more constrained attribution statements. These so-called "storyline" attribution statements can answer the first question above about the

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[19] Christina M. Patricola et al., *Future Changes in Extreme Precipitation Over the San Francisco Bay Area: Dependence on Atmospheric River and Extratropical Cyclone Events*, 36 Weather & Climate Extremes 1 (2022), https://doi.org/10.1016/j.wace.2022.100440; Kevin A. Reed et al., *Attribution of 2020 Hurricane Season Extreme Rainfall to Human-Induced Climate Change*, 13 Nature Commn's 1 (2022), https://doi.org/10.1038/s41467-022-29379-1.

human induced change in magnitude of an event but cannot inform about the human induced change in its probability. For instance using a version of the Weather Research and Forecasting model, the author and a colleague,[20] analyzed 15 different large tropical cyclones (that is, hurricanes) and were able to make robust predictions of precipitation increases. Other simulations of dozens of individual tropical cyclones suggest best estimates of anthropogenic increases in precipitation that are twice the typical rate of 7% for the most intense storms[21] In general, the human influence on hurricanes remains a topic of active research and public interest.

Other types of storms have received less attention from the attribution community. Recent research on atmospheric river storms, which carry intense plumes of moisture from the oceans onto land, impacting the San Francisco Bay Area has found that precipitation also can increase at about twice the 7% rate,[22] though the physical mechanisms of change are very different than for tropical cyclones.

Little is known about the increases in extreme extratropical storms such as occur in the winter, or about the intense summer mesoscale convective systems that can occur in continental interiors. Limited studies have analyzed the human influence on the environmental conditions that support tornadoes, and a consensus on the influence of climate change on them has not been reached.[23]

Drought Assessing the impact of global warming on drought can be complicated and is less certain. The National Oceanic and Atmospheric Administration (NOAA) categorizes drought as a hierarchy of four related conditions. The first, meteorological drought, is characterized by a deficit of precipitation compared to normal conditions. The second, agricultural (or ecological) drought, is characterized by a deficit of soil moisture compared with normal conditions. The third, hydrological drought, is characterized by a deficit of water runoff compared to normal conditions. The fourth, socioeconomic drought, occurs when demand for water exceeds the supply.

Agricultural drought depends both on the precipitation that falls on the ground and on the loss of moisture from plants and soils into the atmosphere. Evaporation from bare ground depends strongly on air temperature. As climate change increases temperature, evaporation also increases, leading to drier soils. Transpiration from plants depends even more strongly on air temperature. As temperature increases, plants cool themselves by evaporating water from their leaves and

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[20] Christina M. Patricola et al., *Future Changes in Extreme Precipitation Over the San Francisco Bay Area: Dependence on Atmospheric River and Extratropical Cyclone Events*, 36 Weather & Climate Extremes 1 (2022), https://doi.org/10.1016/j.wace.2022.100440.

[21] Kevin A. Reed et al., *Anthropogenic Influence on Hurricane Dorian's Extreme Rainfall*, 102 Bull. of Am. Meteorological Soc'y S9 (2021), https://doi.org/10.1175/BAMS-D-20-0160.1; Kevin A. Reed et al., *Attribution of 2020 Hurricane Season Extreme Rainfall to Human-Induced Climate Change*, 13 Nature Commn's 1 (2022), https://doi.org/10.1038/s41467-022-29379-1; Kevin A. Reed et al., *Forecasted Attribution of the Human Influence on Hurricane Florence*, 6 Sci. Advances 1 (2020), https://doi.org/10.1126/sciadv.aaw9253.

[22] Christina M. Patricola et al., *Future Changes in Extreme Precipitation Over the San Francisco Bay Area: Dependence on Atmospheric River and Extratropical Cyclone Events*, 36 Weather & Climate Extremes 1 (2022), https://doi.org/10.1016/j.wace.2022.100440.

[23] Emily Bercos-Hickey et al., *Anthropogenic Influences on Tornadic Storms*, 34 J. of Climate 8989 (2021), https://doi.org/10.1175/JCLI-D-20-0901.1; Noah S. Diffenbaugh, *Robust Increases in Severe Thunderstorm Environments in Response to Greenhouse Forcing*, 110 PNAS 16361 (2013).

stems. In very hot conditions, plants can draw moisture from their root system and release it into the atmosphere until there is very little soil moisture left. Because of these processes, many studies have attributed increases in agricultural drought conditions to human influences.[24]

Consensus on the effects of climate change on meteorological drought occurrences has not been reached in regions of the United States. Only in Mediterranean regions do studies demonstrate a consistent human influence on precipitation deficits, and even here confidence is low.[25] As climate continues to warm, meteorological drought conditions in Mexico and the Southwest United States are projected to become more common (Easterling et al., 2017), but a robust signal of this process has not yet been detected.

VI. The Impacts of Extreme Events

Attributions statements can also be made that link the extreme weather events influenced by human activities with the socioeconomic impacts of those events. As an example, consider Hurricane Harvey, which inundated much of the greater Houston area in 2017. What made Hurricane Harvey such an impactful event was that the storm stalled atop the Gulf Coast of Texas for about three days, dumping copious amounts of rain on land. Three independent analyses of Hurricane Harvey have quantified the increase in total rainfall that can be attributed to human-induced climate change.[26] The average finding of these analyses is that global warming increased the region's precipitation during Hurricane Harvey by about 19%, with a lower bound of 7 percent and an upper bound of 38 percent.

To evaluate the effect of a 19% increase in precipitation, researchers used a model that had demonstrated its ability to accurately simulate the flood caused by Hurricane Harvey given the available precipitation observations.[27] To construct a counterfactual "flood that might have been" without climate change, they decreased the observed precipitation uniformly by the range of the published precipitation attribution statements.[28] They found that climate change increased both

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[24] Sonia I. Seneviratne et al., Weather and Climate Extreme Events in a Changing Climate, Chapter 11 in IPCC, CLIMATE CHANGE 2021: The Physical Science Basis (2021); Michael F. Wehner et al., Droughts, Floods, and Wildfire, Chapter 8 in U.S. GLOBAL CHANGE RES. PROGRAM, CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT VOL. 1 (2017).

[25] Sonia I. Seneviratne et al., Weather and Climate Extreme Events in a Changing Climate, Chapter 11 in IPCC, CLIMATE CHANGE 2021: The Physical Science Basis (2021).

[26] Mark D. Risser & Michael F. Wehner, *Attributable Human-Indiced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation During Hurricane Harvey*, 44 Geophysical Rsch. Letters 12457 (2017), https://doi.org/10.1002/2017GL075888; Geert Jan van Oldenborgh et al., *Attribution of Extreme Rainfall From Hurricane Harvey, August 2017*, 12 Env't Rsch. Letters 1 (2017), https://doi.org/10.1088/1748-9326/aa9ef2; S-Y Simon Wang et al., *Quantitative Attribution of Climate Effects on Hurricane Harvey's Extreme Rainfall in Texas*, 13 Env't Rsch. Letters 1 (2018), https://doi.org/10.1088/1748-9326/aabb85.

[27] Michael Wehner & Christopher Sampson, *Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region During Hurricane Harvey*, 166 Climatic Change 1 (2021), https://doi.org/10.1007/s10584-021-03114-z; Oliver E.J. Wing et al., *A Flood Inundation Forecast of Hurricane Harvey Using a Continental-Scale 2D Hydrodynamic Model*, 4 J. of Hydrology X 1 (2019), https://doi.org/10.1016/j.hydroa.2019.100039.

[28] Michael Wehner & Christopher Sampson, *Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region During Hurricane Harvey*, 166 Climatic Change 1 (2021), https://doi.org/10.1007/s10584-021-03114-z.

the extent and depth of the flooding, with the magnitude of the increases depending on the amount of increased precipitation estimated to result from global warming.

The left side of Figure 7 shows the actual flood and two of the counterfactual floods in the South Houston and Pasadena neighborhoods, which represent a small subsection of the total region analyzed. The model has a resolution of 30 m, which is about the size of a suburban house and its yard. The top panel shows the simulated flood using observed precipitation data during Hurricane Harvey and is a close approximation of the flooding that actually occurred. The middle panel shows the counterfactual flood simulation corresponding to the lower bound (a 7% increase) of published precipitation attribution statements. The area flooded is not substantially different between the two simulations, but the flood that actually occurred is about a foot deeper than it would have been if climate change had not produced a 7% increase in total rainfall. The lower panel shows the counterfactual flood corresponding to the upper bound (a 38% increase) of published precipitation attribution statements. In this case, many homes that were flooded would not have been if climate change had not increased total rainfall by 38%. In addition, the actual flood was more than 3 feet deeper than the counterfactual flood because of climate change.

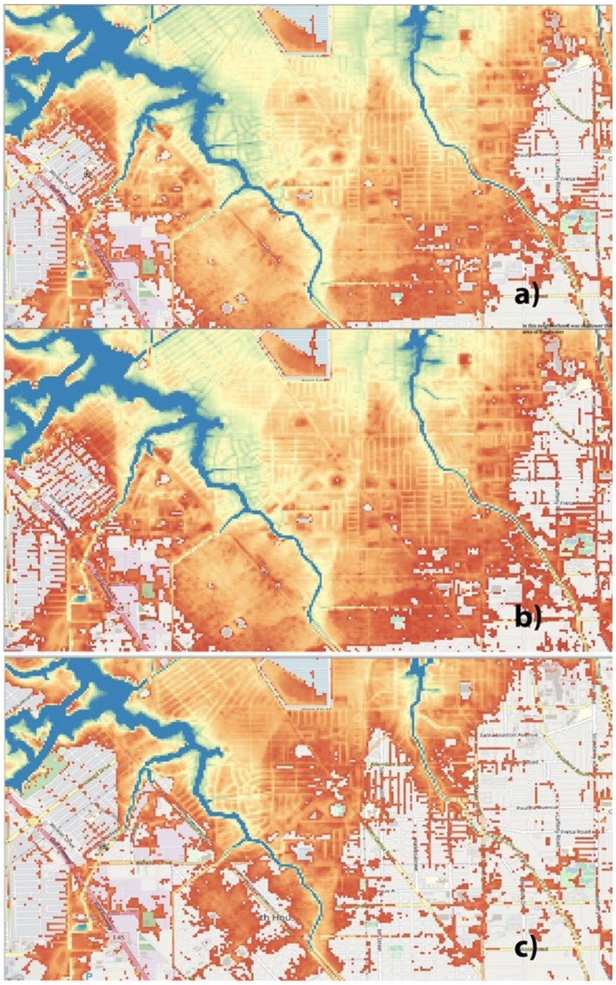

Figure 7: Simulations of the actual flood that occurred in the South Houston and Pasadena neighborhoods can be compared with the floods that would have occurred without climate change. a) The flood that was. b) The flood that would have occurred in the absence of climate change if human activities increased Harvey's storm total precipitation by 7%. c) The flood that would have occurred in the absence of climate change if human activities increased Harvey's precipitation by 38%. Source: Michael Wehner & Christopher Sampson, *Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region During Hurricane Harvey*, 166 Climatic Change 1, (2021) (Figure 2).

Over the greater Houston area, this analysis found that for the best estimate of a 19% human-induced increase in precipitation, the flood area was increased by 14%. The reinsurance companies estimate the insured losses of Hurricane Harvey to be about $90 billion. Assuming that damages were mostly from the flood and that properties were equally valued and distributed uniformly throughout the region yields a crude estimate of $13 billion for the insured loss due to climate change. The 19% precipitation attribution statement also corresponds to a four-fold human-induced increase in the probability of the actual flood. Thus, as a best estimate, the probability of an insured $90 billion hurricane loss in Texas was quadrupled due to climate change.

The very high resolution of the model and maps permits individuals to know if climate change flooded their own house. More generally, these maps permit much more detailed overall damage estimates. Projecting real estate value maps onto the flood maps reveals that, as a best estimate, 32% of flooded homes in Harris County would not have been flooded without climate change. Furthermore, regardless of climate change, 75% of the flooded homes were outside the federal 100-year floodplain and were thus uninsured, adding to the insured loss.[29] Figure 8 shows the upper bound on the distribution of homes that were flooded in Harris County due to climate change.

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[29] Kevin T. Smiley et al., *Social Inequalities in Climate Change-Attributed Impacts of Hurricane Harvey*, 13 Nature Comm's 1 (2021), https://doi.org/10.1038/s41467-022-31056-2.

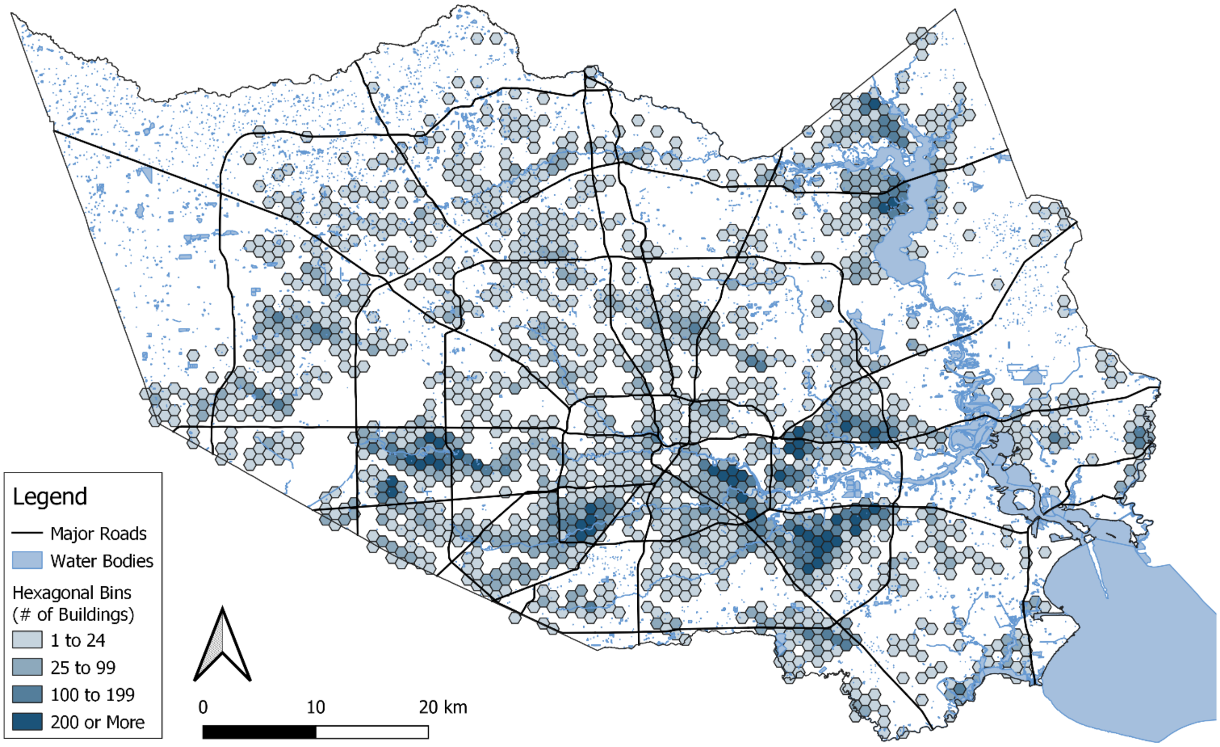

Figure 8: Each hexagonal bin symbolizes the number of residential buildings that would not have flooded without the added impact of climate change in Harris County, Texas, during Hurricane Harvey. These calculations were made using a 38% attributable precipitation increase from climate change. Source: Kevin T. Smiley et al., *Social Inequalities in Climate Change-Attributed Impacts of Hurricane Harvey*, 13 Nature Comm's 1 (2021) (Figure 1).

Census data reveals that Hurricane Harvey's flood damages were not distributed equally across socioeconomic groups. Figure 9 reveals that while Hispanic households comprise about 36% of the population Harris County, about half of the flooded homes were Hispanic households. The percentage was about the same whether or not climate change caused these homes to be flooded, as the percentage is relatively insensitive to which precipitation attribution statement is used. Additional analysis reveals that damages increased with wealth in white neighborhoods. In Hispanic neighborhoods, the situation was reversed, with damages increasing with poverty. With documentation of the relative contribution that wealthy households make to increases in greenhouse gases compared with poor households, such analyses can be used to quantify environmental and other social injustices[30]

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[30] Kevin T. Smiley et al., *Social Inequalities in Climate Change-Attributed Impacts of Hurricane Harvey*, 13 Nature Comm's 1 (2021).

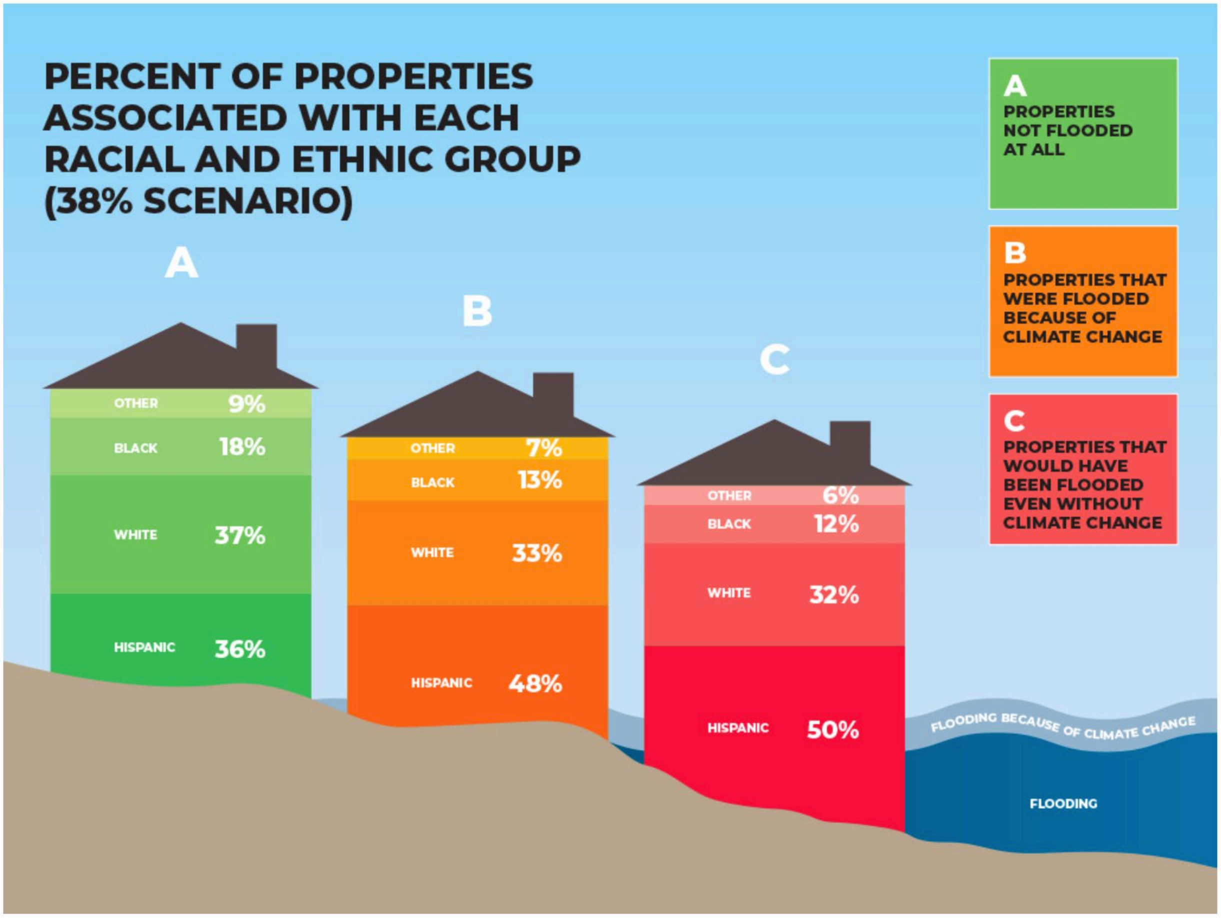

Figure 9. The average percentage of household properties flooded during Hurricane Harvey varied by ethnic group. Green: Not flooded. Red: Flooded without climate change. Orange: Flooded because of climate change (with a 38% human-induced precipitation increase). Source: Kevin T. Smiley et al., *Social Inequalities in Climate Change-Attributed Impacts of Hurricane Harvey*, 13 Nature Comm's 1 (2021) (Figure 2).

Other human impacts of extreme weather have been quantified. Of particular interest are the effects of climate change on deaths resulting from heatwaves, which are the deadliest of all extreme weather events.[31] Epidemiology studies have developed relationships between mortality risk and temperature.[32] These curves tend to steepen at very high temperatures, implying that small increases in temperature at the high end have large increases in mortality. By estimating the attributable human temperature increase during a heatwave and using the observed temperature, the change in mortality risk can be estimated.

Another method maps these mortality/temperature curves onto temperature changes to produce plots like Figure 5 of return periods for mortality risk. This makes it possible to estimate both the number of people who died because of the influence of climate change on a heatwave and the

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[31] World Meteorological Org., Atlas of Mortality and Economic Losses From Weather, Climate and Water Extremes (1970-2019) (2021).

[32] Michela Baccini et al., *Heat Effects on Mortality in 15 European Cities* 19 Epidemiology 711 (2008), https://doi.org/10.1097/EDE.0b013e318176bfcd.

change in probability of mortality.[33] However, many other factors also need to be considered when extending attribution statements to the human impacts of extreme events[34]

Finally, not all climate impacts come in the form of extreme weather events. Climate change also causes subtle shifts in weather, such as additional warm days per year or fewer cool days per year, that can have substantial human impacts. Climate scientists have developed an index to characterize the influence of climate change on the temperature on any given day and region in the United States, including both extreme and more modest temperatures.[35]

VII. Attribution of Climate Change to Sources

Who is responsible for climate change and its associated impacts? While this question extends beyond science and into the realm of ethics and philosophy, scientific research in the field of source attribution can inform thinking on this complex issue.

One of the first things to consider when assessing responsibility for climate change is the source and the emissions derived from that source. The source may be an actor such as a country or a company, an economic sector, or a human activity. A given source's contribution to climate change may be derived from observational data of greenhouse gas emissions, modeling, or corporate and governmental reports of emissions. Uncertainties in these estimates come from data gaps, the unknown climatic impacts of historical land-use changes, and the nonlinear behavior of greenhouse gases in the climate system, among other factors.[36] With these uncertainties in mind, a source's proportional contribution to climate change can be estimated by dividing the emissions associated with that source by the total of accumulated anthropogenic emissions.

To tie the emissions of a source to a specific climate impact, models must first be used to estimate the contribution of a source's emissions to the concentration of greenhouse gases in the atmosphere. That incremental change in atmospheric concentration then must be linked to a given impact of climate change, such as sea level rise or a heatwave.

The field of greenhouse gas accounting has important implications for climate law and governance. Notably, the methodological approach taken when conducting a greenhouse gas accounting survey can dramatically influence the results of that survey. Three such accounting methods have been devised for government-based accounting: 1) territorial accounting, which considers only emissions that are directly generated within a given country or territory, 2) consumption-based accounting, which considers additional emissions embodied in products that are imported into a country or territory, and 3) extraction-based accounting, which considers the emissions associated with the combustion of exported fossil fuels from the country or territory. While the United Nations Framework Convention on Climate Change currently uses the

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[33] Daniel Mitchell et al., *Attributing Human Mortality During Extreme Heat Waves to Anthropogenic Climate Change*, 11 Env't Rsch. Letters 1 (2016), https://doi.org/10.1088/1748-9326/11/7/074006.

[34] Sarah Perkins-Kirkpatrick et al., *On the Attribution of the Impacts of Extreme Weatehr Events to Anthropogenic Climate Change*, 17 Env't Rsch. Letters 1 (2021), http://doi.org/10.1088/1748-9326/ac44c8.

[35] The tool is available at https://www.climatecentral.org/tools/climate-shift-index.

[36] Michael Burger et al., *The Law and Science of Climate Change Attribution*, 45 COLUM. J. ENV'T L. 57 (2020).

territorial accounting approach, there is an ongoing push for countries to quantify additional indirect emissions.

A private sector analog to these government-based emissions accounting methods is the characterization of emissions into three "scopes." Scope 1 includes direct emissions associated with company operations. Scope 2 includes indirect emissions associated with purchasing energy such as electricity, steam, heat, or cooling. Scope 3 encompasses all indirect emissions throughout the full value chain of a company not already covered by scope 2, especially those generated by the consumption of products created through the burning of fossil fuels. The Securities and Exchange Commission recently proposed rules to make the reporting of scope 1 and 2 emissions, in addition to scope 3 emissions in some cases, mandatory. (ref EPA. SEC)

In litigation related to climate impacts, the first step in assessing responsibility is attributing the emissions of a particular country or entity to its proportional contribution to climate change. The second step is assigning to an impact that source's contribution to climate change. The first study to do this investigated the proportional contribution of the emissions of individual nation-states to global mean surface temperature. (ref Otto) Interestingly, the authors found that the framing of this question matters significantly to the outcome. Calculating a proportional contribution derived from quantifying the likelihood of the heatwave if a given region had been the only region to emit yields a different result than calculating a proportional contribution derived from the likelihood of the heatwave if that region had not emitted. [Does she say why, since a given concentration of CO2 equivalents should always yield the same effect regardless of who emitted them? Non-linearity?]

Judges are increasingly being asked to assign responsibility for climate change. Numerous states and several local governments have brought suit against the world's largest oil companies, their associations, and others for climate-related damages. One kind of lawsuit alleges that the companies worked to delay climate policies and are therefore responsible for some amount of the climate damages with which these governments are now burdened. If and when such cases come to trial, source attribution science will likely play a central role.

VIII. Conclusion

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred".[37] Such a statement could not have been made without the many D&A analyses that underlie it.

Developments in attribution science over the past two decades have made possible many robust statements about the human influence on climate. These statements extend to both long-term trends and extreme events, including heatwaves, floods, droughts, and storms. The extension of attribution science to socioeconomic damages and inequality is now underway and is likely to become an important factor in assigning responsibility in legal proceedings.

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[37] IPCC, CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, SUMMARY FOR POLICYMAKERS (2021).

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