REVIEW SUMMARY

CLIMATE PROJECTION

Assessing ExxonMobil's global warming projections

G. Supran*, S. Rahmstorf, N. Oreskes

BACKGROUND: In 2015, investigative journalists discovered internal company memos indicating that Exxon oil company has known since the late 1970s that its fossil fuel products could lead to global warming with "dramatic environmental effects before the year 2050." Additional documents then emerged showing that the US oil and gas industry's largest trade association had likewise known since at least the 1950s, as had the coal industry since at least the 1960s, and electric utilities, Total oil company, and GM and Ford motor companies since at least the 1970s. Scholars and journalists have analyzed the texts contained in these documents, providing qualitative accounts of fossil fuel interests' knowledge of climate science and its implications. In 2017, for instance, we demonstrated that Exxon's internal documents, as well as peer-reviewed studies published by Exxon and ExxonMobil Corp scientists, overwhelmingly acknowledged that climate change is real and human-caused. By contrast, the majority of Mobil and ExxonMobil Corp's public communications promoted doubt on the matter.

ADVANCES: Many of the uncovered fossil fuel industry documents include explicit projections of the amount of warming expected to occur over time in response to rising atmospheric greenhouse gas concentrations. Yet, these numerical and graphical data have received little attention. Indeed, no one has systematically reviewed climate modeling projections by any fossil fuel interest. What exactly did oil and gas companies know, and how accurate did their knowledge prove to be? Here, we address these questions by reporting and analyzing all known global warming projections documented by—and in many cases modeled by—Exxon and ExxonMobil Corp scientists between 1977 and 2003.

Our results show that in private and academic circles since the late 1970s and early 1980s, ExxonMobil predicted global warming correctly and skillfully. Using established statistical techniques, we find that 63 to 83% of the climate projections reported by ExxonMobil scientists were accurate in predicting subsequent global warming. ExxonMobil's average projected warming was 0.20° ± 0.04°C per decade, which is, within uncertainty, the same as that of independent academic and government projections published between 1970 and 2007. The average "skill score" and level of uncertainty of ExxonMobil's climate models (67 to 75% and ±21%, respectively) were also similar to those of the independent models.

Moreover, we show that ExxonMobil scientists correctly dismissed the possibility of a coming ice age in favor of a "carbon dioxide induced 'super-interglacial'"; accurately predicted that human-caused global warming would first be detectable in the year 2000 ± 5; and reasonably estimated how much CO_2 would lead to dangerous warming.

OUTLOOK: Today, dozens of cities, counties, and states are suing oil and gas companies for their "longstanding internal scientific knowledge of the causes and consequences of climate change and public deception campaigns." The European Parliament and the US Congress have held hearings, US President Joe Biden has committed to holding fossil fuel companies accountable, and a grassroots social movement has arisen under the moniker #ExxonKnew. Our findings demonstrate that ExxonMobil didn't just know "something" about global warming decades ago—they knew as much as academic and government scientists knew. But whereas those scientists worked to communicate what they knew, ExxonMobil worked to deny it—including overemphasizing uncertainties, denigrating climate models, mythologizing global cooling, feigning ignorance about the discernibility of human-caused warming, and staying silent about the possibility of stranded fossil fuel assets in a carbon-constrained world. ■

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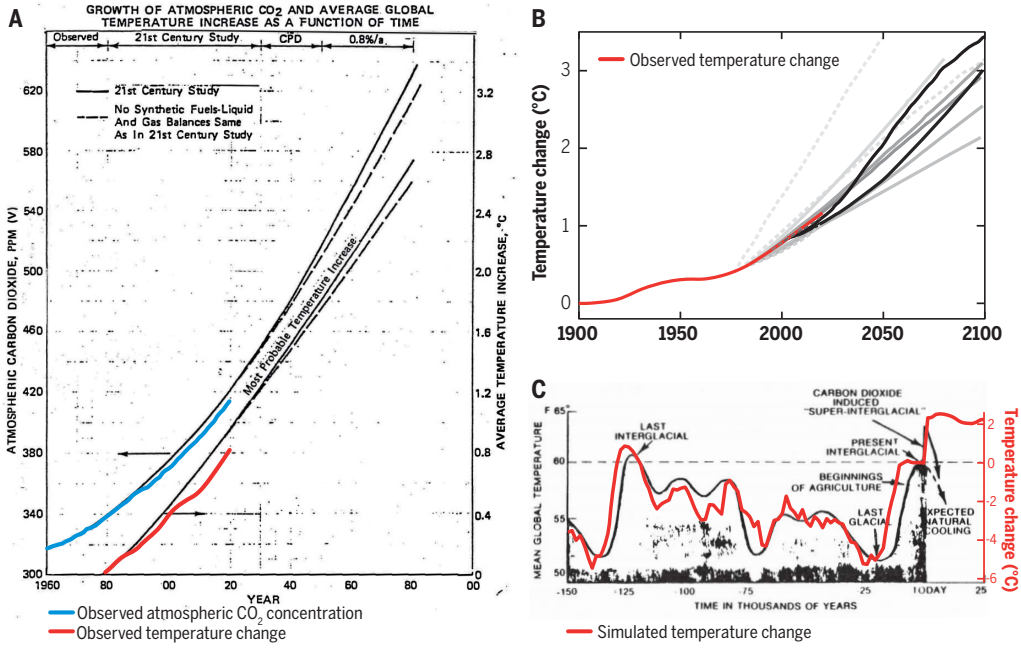

Historically observed temperature change (red) and atmospheric carbon dioxide concentration (blue) over time, compared against global warming projections reported by ExxonMobil scientists. (**A**) "Proprietary" 1982 Exxon-modeled projections. (**B**) Summary of projections in seven internal company memos and five peer-reviewed publications between 1977 and 2003 (gray lines). (**C**) A 1977 internally reported graph of the global warming "effect of CO_2 on an interglacial scale." (A) and (B) display averaged historical temperature observations, whereas the historical temperature record in (C) is a smoothed Earth system model simulation of the last 150,000 years.

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G. Supran[1]*†, S. Rahmstorf[2,3], N. Oreskes[1,4]

Climate projections by the fossil fuel industry have never been assessed. On the basis of company records, we quantitatively evaluated all available global warming projections documented by—and in many cases modeled by—Exxon and ExxonMobil Corp scientists between 1977 and 2003. We find that most of their projections accurately forecast warming that is consistent with subsequent observations. Their projections were also consistent with, and at least as skillful as, those of independent academic and government models. Exxon and ExxonMobil Corp also correctly rejected the prospect of a coming ice age, accurately predicted when human-caused global warming would first be detected, and reasonably estimated the "carbon budget" for holding warming below 2°C. On each of these points, however, the company's public statements about climate science contradicted its own scientific data.

In 2015, investigative journalists uncovered internal company documents showing that Exxon scientists have been warning their executives about "potentially catastrophic" anthropogenic (human-caused) global warming since at least 1977 (*1*, *2*). Researchers and journalists have subsequently unearthed additional documents showing that the US oil and gas industry writ large—by way of its trade association, the American Petroleum Institute—has been aware of potential human-caused global warming since at least the 1950s (*3*); the coal industry since at least the 1960s (*4*); electric utilities, Total oil company, and General Motors and Ford motor companies since at least the 1970s (*5*–*8*); and Shell oil company since at least the 1980s (*9*).

This corpus of fossil fuel documents has attracted widespread scholarly, journalistic, political, and legal attention, leading to the conclusion that the fossil fuel industry has known for decades that their products could cause dangerous global warming. In 2017, we used content analysis to demonstrate that Exxon's internal documents, as well as peer-reviewed studies authored or coauthored by Exxon and ExxonMobil Corp scientists, overwhelmingly acknowledged that global warming is real and human-caused (*10*). By contrast, we found that the majority of Mobil and ExxonMobil Corp's public communications promoted doubt on the matter. Cities, counties, and states have accordingly filed dozens of lawsuits variously accusing ExxonMobil Corp and other companies of deceit and responsibility for climate damages (*11*). The attorney general of Massachusetts, for instance, alleges that ExxonMobil has had a "long-standing internal scientific knowledge of the causes and consequences of climate change" and waged "public deception campaigns" that misrepresented that knowledge (*12*). Civil society campaigns seeking to hold fossil fuel interests accountable for allegedly misleading shareholders, customers, and the public about climate science have emerged under monikers such as #ExxonKnew, #ShellKnew, and #TotalKnew (*13*–*15*) (see Box 1 for more examples).

But what exactly did the fossil fuel industry understand about the role of fossil fuels in causing global warming, and how accurate did their understanding prove to be? Several of the documents in question include explicit projections of the amount of warming that could be expected to occur over time in response to rising atmospheric greenhouse gas concentrations. Yet, whereas the text of these documents has been interrogated in detail, the numerical and graphical data in them have not. Indeed, no one has systematically reported climate modeling projections by any fossil fuel interest, let alone assessed their accuracy and skill. This contrasts with academic climate models, whose performance has been extensively scrutinized (*16*–*24*).

In this Review, we report and analyze all known projections of global mean surface temperature (hereafter "temperature") change reported by company scientists working for Exxon and/or for ExxonMobil Corp after Exxon's merger with Mobil Oil Corp in 1999. (Hereafter, we collectively refer to Exxon and ExxonMobil Corp as "ExxonMobil" or the "company.") Some projections resulted from models built or run in-house by ExxonMobil scientists, sometimes in collaboration with independent researchers. Others were produced by third parties and then discussed by ExxonMobil scientists in internal reports. Where relevant, we distinguish these provenances, but otherwise we collectively refer to these projections as "reported" by ExxonMobil scientists.

We test the accuracy and modeling skill of ExxonMobil's global warming projections by retrospectively comparing them against subsequent observed temperature changes. We also compare their performance against assessments of models published in independent scientific literature. [Here and throughout, we use the term "climate models" to generically refer to computer simulations of Earth's climate system. All of the models investigated here—both from ExxonMobil and from independent academic and government scientists—are variants of Energy Balance Models, rather than the higher-resolution, more comprehensive General Circulation Models that succeeded them in the late 1980s (*25*–*27*).] Having quantified ExxonMobil's early understanding of climate science, we contrast it with public claims made by the company and its allies. We then offer three illustrations of how quantitative historical analysis of the fossil fuel industry's documents can yield further historical insights into the disconnect between its private understanding of climate science and its public climate denial.

We focus on global mean surface temperature changes because they are a primary driver of climate impacts, are central to climate policy-making, are the most common output of early climate models, and are accurately captured by observational records. We limit our analysis to global warming projections reported by scientists at ExxonMobil, as compared to other companies, for several reasons. First, ExxonMobil's extensive climate research program is well documented. Second, ExxonMobil documents contain the largest public collection of global warming projections recorded by a single company, allowing us to develop a coherent picture of the early understanding of climate science by a specific industry actor. Third, the company has been active in challenging climate science in general and climate models specifically, such that its work on the matter may be of particular interest to researchers, reporters, advocates, shareholders, fund managers, politicians, and legal investigators examining corporate responsibility for climate change (Box 1).

Materials and methods

We analyzed 32 internal documents produced in-house by ExxonMobil scientists and managers between 1977 and 2002, and 72 peer-reviewed scientific publications authored or coauthored by ExxonMobil scientists between 1982 and 2014. The internal documents were collated from public archives provided by ExxonMobil Corp (*28*), *InsideClimate News* (*29*), and Climate Investigations Center (*30*).

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Box 1. Mounting calls for fossil fuel industry accountability

There are an increasing number of lawsuits, political investigations, and civil society campaigns seeking to hold ExxonMobil Corp and other companies accountable for allegedly misleading shareholders, customers, and the public about climate science.

Lawsuits

Cities, counties, and states have filed dozens of lawsuits accusing ExxonMobil Corp and others of deceptive marketing, misleading shareholders, and culpability for climate damages (two of the authors, G.S. and N.O., have provided expert input to some of these cases) (*11*).

Political mobilizations

- In 2019, the European Parliament held a first-of-its-kind hearing on climate change denial by ExxonMobil Corp and other actors (to which one author, G.S., testified) (*64*).
- In 2019, hearings were held in the House and Senate of the United States (US) Congress regarding "oil industry efforts to suppress the truth about climate change" and "dark money and barriers to climate change," respectively (one author, N.O., testified to both) (*65*, *66*).
- In 2021, the US House Committee on Oversight and Reform requested documents and testimony from ExxonMobil Corp and other oil and gas companies and trade associations as part of an ongoing investigation into the fossil fuel industry's "coordinated effort to spread disinformation" about climate change (*67*).
- US President Joe Biden has issued repeated commitments to hold fossil fuel companies accountable, including a 2020 environmental justice plan to "strategically support ongoing plaintiff-driven climate litigation against polluters" (*68*); a 2020 statement that "We should go after" the fossil fuel industry "just like we did the drug companies, just like we did with the tobacco companies" (*69*); and a 2021 Executive Order "to hold polluters accountable" (*70*).
- In 2022, the Commission on Human Rights of the Philippines (to which one author, G.S., testified) ruled that the "Carbon Majors," including ExxonMobil Corp, "engaged in willful obfuscation [of climate science] and obstruction to prevent meaningful climate action" and that all such acts "may be bases for liability" (*71*).

Civil society campaigns

- International fossil fuel divestment movement, including specific calls for—and institutional commitments to—divestment from climate denying fossil fuel companies (two of the authors, G.S. and N.O., have supported these campaigns) (*72*–*74*).
- "Pay Up Climate Polluters" campaign (*75*).
- Array of distributed activism under the moniker #ExxonKnew (*13*).

The peer-reviewed publications were obtained by identifying all peer-reviewed documents among ExxonMobil Corp's lists of "Contributed Publications," except for three articles discovered independently during our research (*31*) [see supplementary materials (SM) section S2 for details on the assembly of the corpus]. These constitute all publicly available internal ExxonMobil documents concerning anthropogenic global warming of which we are aware, and all ExxonMobil peer-reviewed publications concerning global warming disclosed by the company.

Using manual content analysis, we identify all documents that reported climate model outputs of (i) a time series of projected future temperature, and (ii) future external radiative forcings [including at least atmospheric carbon dioxide (CO_2) concentration] (see SM section S1.1 for coding details). For models driven by more than one forcing time series (i.e., for high- and low-CO_2 scenarios as well as a central, "nominal" one), each resulting temperature time series is treated as a separate and individual projection. Our figures and tables therefore distinguish between "nominal," "high," and "low" model projections. By contrast, for a given CO_2 scenario, temperature time series accompanied by uncertainty bars (corresponding, for example, to different model climate sensitivities) are treated as single projections with uncertainty bounds given by those uncertainty bars. This yields 12 documents published between 1977 and 2003, which contain 16 distinct temperature projections presented in the form of 12 unique graphs and one table (summarized in SM section S2.2). The 12 documents comprise seven internal memos (1977 to 1985) and five peer-reviewed papers (1985 to 2003). Twelve of the 16 temperature projections came from models built or run in-house by ExxonMobil scientists, typically in collaboration with independent researchers. Once identified, all original temperature and forcing projections are converted for analysis by digitizing graphs and extracting tables.

We assess each model projection over the period from the publication year of its containing document through 2019 (or through the final projected year, if earlier). First, we overlay all original temperature time series with observed temperature changes. Observations are aligned with respect to the earliest reference year(s) for which model projection data are available and, unless noted otherwise, reflect the smoothed annual average of five historical time series. Following Hausfather *et al.* (2020) and the Intergovernmental Panel on Climate Change (IPCC), we compare observations to model projections in two quantitative ways: (i) change in temperature versus time; and (ii) change in temperature versus change in radiative forcing (the "implied transient climate response," or iTCR) (*16*, *24*). The iTCR metric enables us to assess model performance while accounting for any differences in the assumptions about future radiative forcings driving the models. For each projected and observed temperature time series, per-decade temperature changes are calculated by fitting an ordinary least squares model over the projection period and multiplying the resulting gradient coefficient by 10. Analogously, iTCR is calculated by regressing temperature against anthropogenic radiative forcing over the projection period and multiplying the result by the forcing associated with doubled atmospheric CO_2 concentrations, $F_{2x} = 3.7\mathrm{W/m^2}$ (*16*):

$$iTCR = F_{2x}\Delta T/\Delta F_{\mathrm{anthro}}$$

For model projections, $\Delta F_{\mathrm{anthro}}$ was based on explicit external forcing values when provided and was otherwise estimated from model CO_2 concentration scenarios as

$$\Delta F_{\mathrm{anthro}} = 5.35 \cdot \ln\left(\frac{p'_{\mathrm{CO_2}}}{p_{\mathrm{CO_2}}}\right)$$

where $p_{\mathrm{CO_2}}$ is the initial CO_2 concentration (in parts per million) at the start of the projection period and $p'_{\mathrm{CO_2}}$ is the CO_2 concentration during each subsequent year through 2019 (*16*). In the real world, of course, global temperature changes are driven by multiple natural and anthropogenic factors, including but not limited to CO_2. Nevertheless, even when model projections are driven by CO_2-only anthropogenic forcing scenarios, retrospectively comparing projections to observations offers a robust, independent, and established test of model skill. This is because (i) global warming has been almost entirely human-caused since the late 19th century (*32*, *33*) and (ii) total anthropogenic forcing over the past 150 years has been, to first order, similar to the forcing of CO_2 alone, because the warming effects of other greenhouse gases and the cooling effects of other sources cancel one another out (*34*). For further discussion of the implications and limitations of model-versus-observation comparisons, see SM section S1.2.7. Observed

ΔF_{anthro} values, meanwhile, were based on a 1000-member ensemble of observationally informed forcing estimates reported by Dessler and Forster (2018) (*35*).

Evaluated in terms of each of the above metrics, we deem model projections and historical observations to be consistent if and only if the 95% confidence intervals of the differences between the two include zero. As detailed in SM sections S1.2.2 and S1.2.3, these confidence intervals were calculated to reflect two sources of uncertainty: (i) statistical uncertainty in regression coefficients and (ii) structural uncertainty due to different model climate sensitivities, as and when indicated by error bars in projections reported by ExxonMobil scientists.

As an additional measure of performance, we calculate the "skill score" of each model by comparing the root-mean-squared errors of a model projection with those of a zero temperature change null hypothesis (*20*). For each projection, we calculate skill scores with respect to (i) each of the five observational temperature records for the temperature-versus-time metric and (ii) the 5000 estimates of $\Delta T/\Delta F_{anthro}$ for the iTCR metric. (See SM section 1.2 for details on graphical overlays and on calculation of consistency and skill scores and their accompanying uncertainties.)

Accurate and skillful climate modeling

Overall, ExxonMobil's global warming projections closely track subsequent observed temperature increases.

Figure 1 reproduces all 12 identified unique graphs, which contain 15 of the 16 identified temperature projections (the 16th was reported as a table). For example, panel 3 of Fig. 1 is a graph showing "an estimate of the average global temperature increase" under the "Exxon 21st Century Study–High Growth scenario" for CO_2. It was included in a 1982 internal briefing on the "CO_2 'Greenhouse' Effect" prepared by Exxon Research and Engineering Company and circulated widely to Exxon management

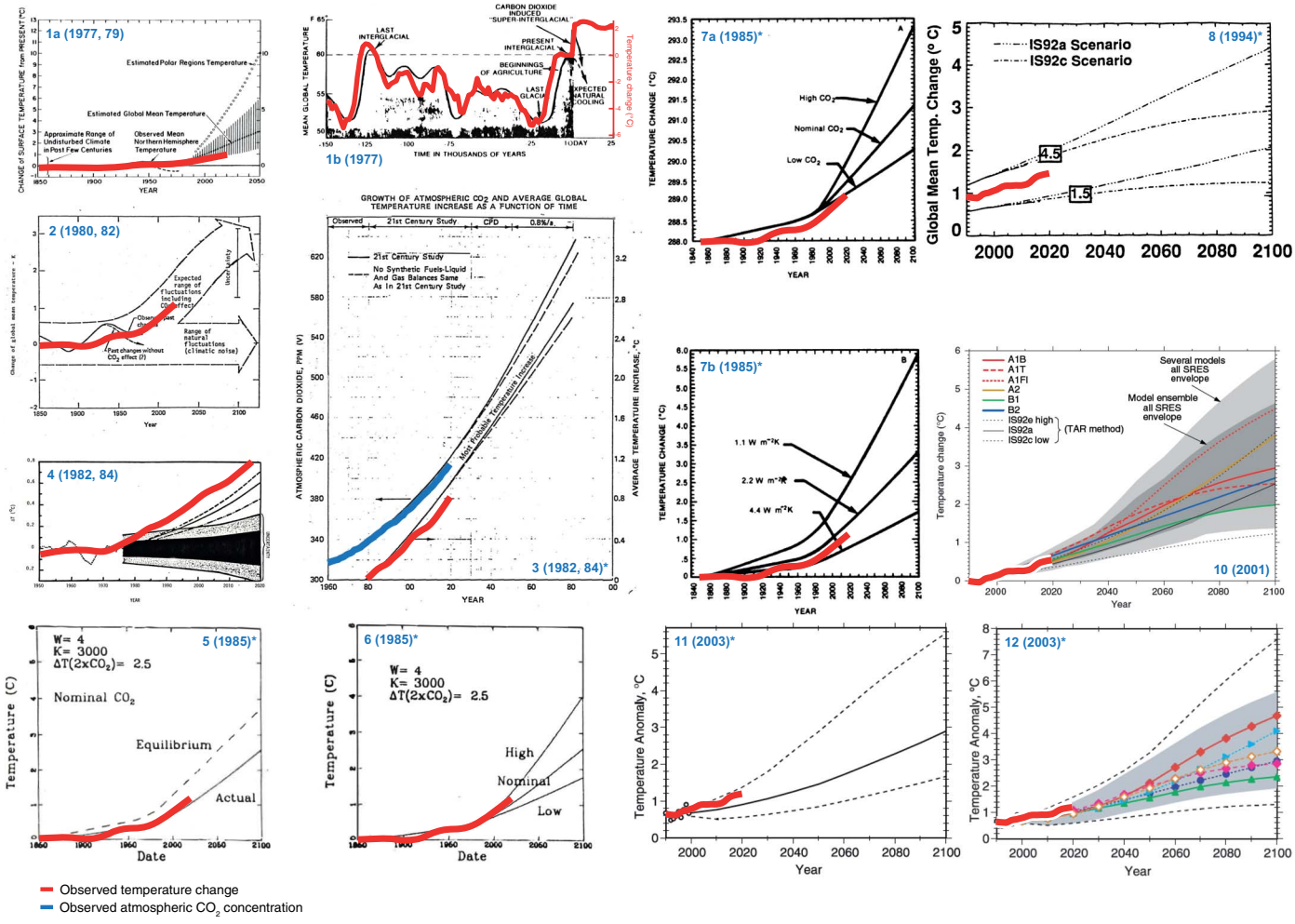

Fig. 1. Historically observed temperature change versus time (red) compared against global warming projections reported by ExxonMobil scientists in internal documents and peer-reviewed publications. Panel numbers indicate projections reported in internal documents: (1a, b) Black (1977, vugraphs 10 and 11, respectively) (*54*) and Mastracchio (1979) (*88*), (2) Shaw (1980) (*89*) and Glaser (1982, fig. 9) (*36*), (3) Glaser (1982, fig. 3) (*36*) and Shaw (1984) (*37*), (4) Weinberg *et al*. (1982) (*42*) and Callegari (1984) (*41*), (5, 6) Flannery (1985, pages 23 and 24, respectively) (*39*); and in peer-reviewed publications: (7a, b) Hoffert and Flannery (1985, figs. 5.16A and B, respectively) (*38*), (8) Jain *et al*. (1994) (*40*), (10) Albritton *et al*. (2001) (*90*), (11, 12) Kheshgi and Jain (2003, figs. 7c and 8c, respectively) (*91*). Asterisks indicate global warming projections modeled by ExxonMobil scientists themselves. Panels have been numbered to match the labels in Fig. 2; this means that (9) Kheshgi *et al*. (1997) (*92*), which reports projections in tabulated rather than graphical form, is represented in Fig. 2 but is not included here. Temperature observations reflect the smoothed annual average of five historical time series. The only exception to this is the historical temperature record in (1b), which reflects a smoothed Earth system model simulation of the last 150,000 years driven by orbital forcing only, with an appended moderate anthropogenic emissions scenario. Panel 3 additionally compares projected atmospheric carbon dioxide concentrations against annual mean observations (blue). For data sources and plotting details, see SM sections S1 and S2.

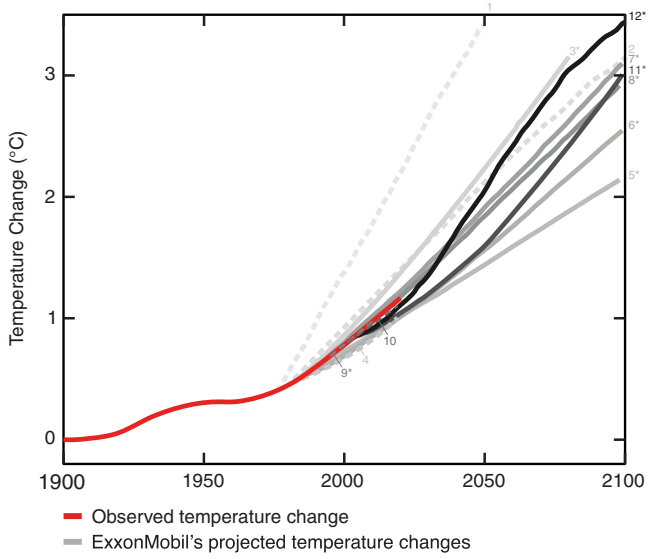

Fig. 2. Summary of all global warming projections (nominal scenarios) reported by ExxonMobil scientists in internal documents and peer-reviewed publications (gray lines), superimposed on historically observed temperature change (red). Solid gray lines (and asterisked numerical labels) indicate global warming projections modeled by ExxonMobil scientists themselves; dashed gray lines indicate projections internally reproduced by ExxonMobil scientists from third-party sources. Shades of gray and numerical labels scale with model start dates, from earliest (1977: lightest, "1") to latest (2003: darkest, "12"). Numerical labels correspond to panels in Fig. 1, which displays all original graphical projections reported by ExxonMobil scientists. Observations reflect the smoothed annual average of five historical time series. For data sources and plotting details, see SM sections S1 and S2.

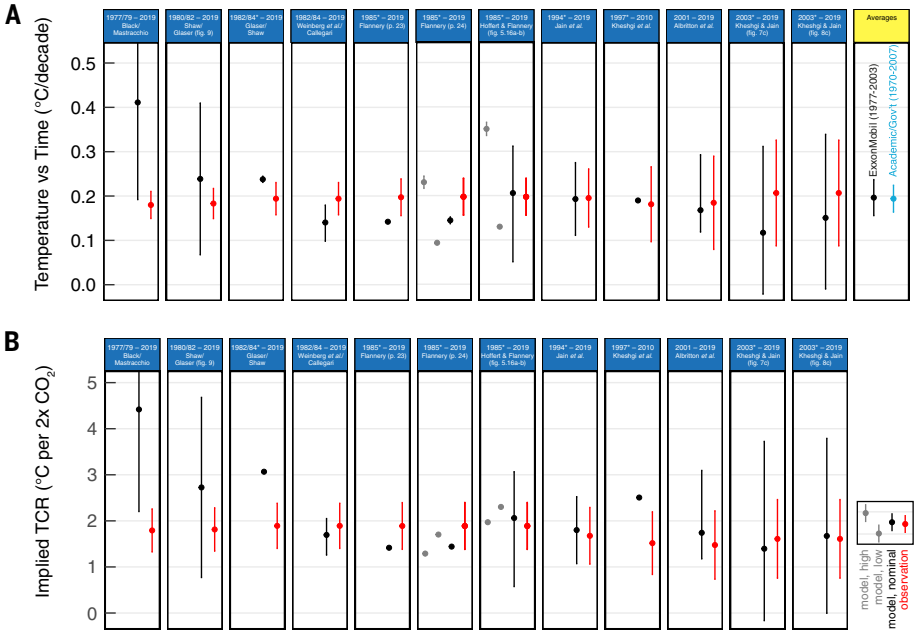

Fig. 3. Comparison of (red) historical temperature observations and (gray or black) global warming projections reported by ExxonMobil scientists in internal documents and peer-reviewed publications, as illustrated in Figs. 1 and 2. Observed and projected trends are compared in terms of (**A**) temperature change versus time and (**B**) temperature change versus change in radiative forcing ("implied TCR"). iTCR is defined as the change in temperature versus change in radiative forcing (see materials and methods and SM section S1.2.3 for details). The left-to-right order of panels corresponds to the numbering of projections ("1" to "12") in Figs. 1 and 2. Trends are computed over model projection periods indicated in the blue boxes above each panel. Asterisks indicate global warming projections modeled by ExxonMobil scientists themselves. The yellow-labeled box in (A) displays averages and bootstrapped standard errors of (black) the 16 projections reported by ExxonMobil scientists spanning 1977 to 2003 and (cyan) 18 academic and government climate model projections spanning 1970 to 2007 reported by Hausfather *et al*. (2020) (*16*).

(*36*). The briefing was labeled as "proprietary information for authorized company use only." The graph appeared a second time in an Exxon manager's presentation on "CO_2 greenhouse and climate issues" at an internal company environmental conference in 1984 (*37*).

Panel 3 of Fig. 1 displays one of 12 unique temperature projections (out of a total of 16 projections) that were output by models built or run in-house by ExxonMobil scientists (the 12 projections are indicated by asterisks in Figs. 1 to 3 and Table 1). To our knowledge, the temperature projection in panel 3 was independently produced by Exxon scientists as part of "technology forecasting activities in 1981" operated by the company's Corporate Planning Department (*37*). The temperature projection was based on "calculations" of future atmospheric CO_2 concentrations "recently completed at Exxon Research and Engineering Company" (*36*). The remaining 11 temperature projections were produced by models developed by ExxonMobil scientists in collaboration with academic coauthors. Specifically, the seven unique temperature projections shown in panels 5 to 7b in Fig. 1 derived from a one-dimensional upwelling-diffusion Energy Balance Model to study how the "climatic transient response from fossil fuel burning is damped…by heat storage in the world's oceans…" (*38*). The Exxon scientist leading the collaboration internally described their climate modeling as "sophisticated" and "state of the art" (*39*). The remaining four unique temperature projections (three in panels 8, 11, and 12 in Fig. 1 and the fourth designated by "9" in Fig. 2) were generated by an "Integrated Science Model which consists of coupled modules for carbon cycle, atmospheric chemistry of other trace gases, radiative forcing by greenhouse gases, energy balance model for global temperature, and a model for sea level response" (*40*).

In Fig. 1, we overlay the original graphs with observed atmospheric CO_2 concentrations and temperature changes, shown in blue and red, respectively. In general, observations closely track projections.

In Fig. 2, we digitize all of ExxonMobil scientists' temperature projections corresponding to "nominal" (i.e., central) CO_2 scenarios in all 12 graphs (and one table). These projections, shown in gray, are plotted from the observed temperature change, shown in red,

Table 1. Skill scores of global warming projections reported by ExxonMobil scientists in internal documents and peer-reviewed publications. Scores are shown for ($\Delta T/\Delta t$) temperature change versus time; and ($\Delta T/\Delta F$) temperature change versus change in radiative forcing ("implied TCR"). Average skill scores are summarized for (i) all projections and (ii) projections modeled by ExxonMobil scientists themselves (indicated by asterisks). A skill score of 100% indicates perfect agreement with observations; a score less than zero indicates worse performance than a zero temperature change null hypothesis. For each projection, median scores and 5th and 95th percentile confidence intervals are shown, all as percentages. For each average skill score, the mean and the 1σ standard error of the mean are shown. Confidence intervals for projections over short periods—such as Kheshgi *et al*. (1997), Albritton *et al*. (2001), and Kheshgi and Jain (2003)—are large, primarily owing to the substantial impact of interannual and subdecadal variability on short-term temperature trends.

Projection	Reference	Time frame	Skill $\Delta T/\Delta t$ (%)	Skill $\Delta T/\Delta F$ (%)
1977 Black (vugraph 10); 1979 Mastracchio | nominal	(*54*, *88*)	1977–2019	22 (−55 to −4)	−49 (−102 to 0)
1980 Shaw; 1982 Glaser (fig. 9) | nominal	(*36*, *89*)	1980–2019	73 (53 to 84)	49 (16 to 78)
1982* Glaser (fig. 3/table 4); 1984 Shaw | nominal	(*36*, *37*)	1982–2019	82 (61 to 92)	37 (1 to 68)
1982 Weinberg *et al*.; 1984 Callegari | nominal	(*41*, *42*)	1982–2019	70 (64 to 82)	90 (73 to 99)
1985* Flannery (page 23) | nominal	(*39*)	1985–2019	70 (63 to 83)	76 (61 to 92)
1985* Flannery (page 24) | high	(*39*)	1985–2019	87 (66 to 97)	69 (55 to 84)
1985* Flannery (page 24) | low	(*39*)	1985–2019	46 (42 to 55)	90 (73 to 99)
1985* Flannery (page 24) | nominal	(*39*)	1985–2019	71 (64 to 84)	77 (62 to 94)
1985* Hoffert and Flannery (fig. 5.16) | high	(*38*)	1985–2019	28 (−5 to 44)	92 (71 to 99)
1985* Hoffert and Flannery (fig. 5.16) | low	(*38*)	1985–2019	64 (58 to 76)	77 (49 to 97)
1985* Hoffert and Flannery (fig. 5.16) | nominal	(*38*)	1985–2019	99 (80 to 99)	89 (65 to 99)
1994* Jain *et al*. | nominal	(*40*)	1994–2019	97 (71 to 99)	89 (54 to 99)
1997* Kheshgi *et al*. | nominal	(*92*)	1997–2010	93 (49 to 98)	34 (−43 to 80)
2001 Albritton *et al*. | nominal	(*90*)	2001–2019	84 (60 to 98)	81 (18 to 98)
2003* Kheshgi and Jain (fig. 7c) | nominal	(*91*)	2003–2019	56 (41 to 85)	85 (55 to 98)
2003* Kheshgi and Jain (fig. 8c) | nominal	(*91*)	2003–2019	72 (51 to 95)	88 (37 to 99)
Average of all projections			67 (60 to 74)	67 (58 to 76)
Average of ExxonMobil models			72 (66 to 78)	75 (70 to 81)

Box 2. How ExxonMobil Corp exaggerated the uncertainties of climate science and modeling

- In 2000, ExxonMobil Corp CEO Lee Raymond wrote that "[W]e do not now have a sufficient scientific understanding of climate change to make reasonable predictions and/or justify drastic measures…the science of climate change is uncertain…." (*76*). The report speculated about a "natural period of warming," "solar activity," and "[v]olcanic eruptions, El Nino." "With all this natural climate 'noise' and the complexities of measurement," it said, "science is not now able to confirm that fossil fuel use has led to any significant global warming."
- In 2001, an ExxonMobil Corp press release said of the "Hockey Stick" graph showing anthropogenic global warming: "The error bars are huge, yet some prefer to ignore them" (*77*).
- In 2005, Lee Raymond said in a television interview: "There is a natural variability that has nothing to do with man…It has to do with sun spots…with the wobble of the Earth…[T]he science is not there to make that determination [as to whether global warming is human-caused]…[T]here are a lot of other scientists that do not agree with [the National Academy and IPCC]…[T]he data is [sic] not compelling" (*78*).
- In 2007, ExxonMobil Corp's website stated that "[G]aps in the scientific basis for theoretical climate models and the interplay of significant natural variability make it very difficult to determine objectively the extent to which recent climate changes might be the result of human actions" (*79*).
- In 2013, ExxonMobil Corp CEO Rex Tillerson said: "[T]he facts remain there are uncertainties around the climate…what the principal drivers of climate change are…[T]here are other elements of the climate system that may obviate this one single variable [of burning fossil fuels]…And so that's that uncertainty issue…" (*80*).

at the start of each projection period. The darkness of the projection lines scales with their start years, from 1977 (lightest gray) to 2003 (darkest gray). Solid gray lines indicate projections modeled by ExxonMobil scientists themselves, whereas dashed gray lines indicate projections reproduced from third-party peer-reviewed papers. With the exception of the earliest projection (designated by "1"), which overestimated future warming, projections lie close to and evenly distributed around observations.

In Fig. 3A, we compare trends in temperature change versus time for historical observations (in red) and for all 16 projections reported by ExxonMobil scientists (in gray or black). Over the course of their respective projection periods (indicated in blue boxes at the top of each panel in Fig. 3), the average predicted warming was 0.20° ± 0.04°C per decade. Ten of the 16 projections are consistent with historical observations (differences between models and projections are shown in fig. S1A). Of the remaining six projections, two forecast more warming than observed and four forecast less. Treating each unique graph and table—rather than each forcing scenario—as independent, 10 out of the 12 unique projection datasets are consistent with observations. Of the remainder, one forecasts more warming than observed and one forecasts less. Notably, these two projections are among the only three (out of 12) that were reported without uncertainty bars. They therefore have less "room for uncertainty" in our consistency tests. Overall, the models perform very well.

When we account for mismatches between forecast and observed forcings by using the iTCR metric, 12 of the 16 projections reported by ExxonMobil scientists are consistent with observations. Figure 3B uses the iTCR metric to compare trends in observed and projected iTCRs, and fig. S1B shows their differences. Treating each unique graph and table as independent, 9 out of 12 datasets are consistent.

Box 3. How Mobil and ExxonMobil Corp cultivated the myth of a 1970s global cooling scientific consensus

- In 1997, Mobil CEO Lee Raymond questioned whether "the Earth [is] really warming" by claiming that "In the 1970s, some of today's prophets of doom from global warming were predicting the coming of a new ice age" (*81*).
- In 2001, an ExxonMobil Corp press release said: "[T]here is no consensus about long-term climate trends and what causes them...during the 1970's [sic], people were concerned about global cooling" (*82*).
- In 2003, US Senator James Inhofe, who has to date received $2.3 million in campaign contributions from oil and gas companies, including ExxonMobil, argued that the issue of human-caused global warming "is far from settled" by pointing to "those who warned us in the 1970s that the planet was headed for a catastrophic global cooling" (*56*, *83*–*85*).
- In 2004, a report published by the ExxonMobil Corp-funded Cato Institute stated that "Thirty years ago there was much scientific discussion among those who believed that humans influenced the... reflectivity [which would] cool the earth, more than...increasing carbon dioxide, causing warming. Back then, the 'coolers' had the upper hand...But nature quickly shifted gears...Needless to say, the abrupt shift in the climate caused almost as abrupt a shift in the balance of scientists who predictably followed the temperature" (*56*, *86*).

The three outliers forecast more warming than observed; two of them do not have uncertainty bars.

We also calculate skill scores for the temperature-versus-time and iTCR metrics (Table 1). A skill score of 100% indicates perfect agreement between projections and observations; a score between zero and 100% indicates some degree of skill; and a score less than zero indicates a performance worse than a zero-change null hypothesis (*16*, *20*).

With respect to temperature change versus time, we find the average of the median skill scores of all 16 reported projections to be 67 ± 7%. Across projections modeled by ExxonMobil scientists themselves, it is 72 ± 6%. These scores indicate highly skillful predictions. The highest-scoring projection was a 1985 peer-reviewed publication [Hoffert and Flannery (1985, nominal CO_2 scenario)], with a skill score of 99% (*38*). The 1982/1984 projection discussed earlier (Fig. 1, panel 3) has a skill score of 82% [although it marginally failed the consistency test (Fig. 3 and fig. S1)]. Only three of the 16 projections have skill scores below 50%. For comparison, NASA scientist James Hansen's global warming predictions presented to the US Congress in 1988 have been found to have skill scores ranging from 38 to 66% across the three different forcing scenarios that he reported (*16*, *20*).

Using the iTCR metric, the average skill of the 16 projections is 67 ± 9%. Among projections modeled by ExxonMobil scientists themselves, it is 75 ± 5%. Seven projections score 85% or above. Hoffert and Flannery (1985, high CO_2 scenario) is again the highest scorer (92%), closely followed by two projections scoring 90%, which are featured in three internal reports in 1982/1984 and 1985, respectively (*38*, *39*, *41*, *42*). Only four projections have skill scores below 50% for the iTCR metric. Again, for comparison, Hansen's 1988 projections had skill scores in terms of the iTCR metric ranging from 28 to 81% (*16*).

We can compare these metrics with Hausfather *et al.* (2020), who calculated the average skill scores of 18 academic and government climate model projections published between 1970 and 2007. They obtained a value of 69% for both temperature-versus-time and iTCR metrics (*16*). On average, therefore, global warming projections reported by ExxonMobil scientists were as skillful as those of independent scientists of their day, and their own models were especially skillful. (As described earlier, ExxonMobil scientists did not simply rerun existing models; they developed their own models, typically in collaboration with academic coauthors, which independently corroborated the findings of other climate scientists.) To the extent that these projections represented contemporary knowledge of the likely effects of fossil fuel burning on global temperature, we can conclude that Exxon knew as much in the 1970–1990s as academic and government scientists knew. The average warming projected by the 18 academic and government models was 0.19° ± 0.03°C per decade, which is, within uncertainty, the same as ExxonMobil's average of 0.20° ± 0.04°C per decade.

We note that 2 of the 18 projections analyzed by Hausfather *et al.* (2020) are among those reported by ExxonMobil scientists. However, excluding these two projections has negligible effect on the average warming predicted by ExxonMobil or on the average skill scores of all ExxonMobil projections with respect to both temperature change versus time and iTCR (see sensitivity analyses, SM section S1.2.5 and table S1). Our conclusions also hold true when considering only the 12 (of 16) temperature projections from models built or run in-house by ExxonMobil scientists, indicated by asterisks in Figs. 1 to 3 and Table 1 (see SM section S1.2.5 and table S1).

In summary, climate projections reported by ExxonMobil scientists between 1977 and 2003 were accurate and skillful in predicting subsequent global warming. Some projections suggested slightly too much warming and others not quite enough, but most (63 to 83%, depending on the metric used) were statistically consistent with subsequently observed temperatures, particularly after accounting for discrepancies between projected and observed changes in atmospheric CO_2 concentrations. ExxonMobil's projections were also consistent with, and as skillful as, those of academic and government scientists. All told, ExxonMobil was aware of contemporary climate science, contributed to that science, and predicted future global warming correctly. These findings corroborate and add quantitative precision to assertions by scholars, journalists, lawyers, politicians, and others that ExxonMobil accurately foresaw the threat of human-caused global warming, both prior and parallel to orchestrating lobbying and propaganda campaigns to delay climate action (*1*, *2*, *10*, *11*, *13*, *43*–*48*), and refute claims by ExxonMobil Corp and its defenders that these assertions are incorrect (*49*).

What ExxonMobil knew versus what they said

Our findings about the company's early understanding of climate science contradict many of the claims that the company and its allies have made in public.

Emphasizing uncertainties

It has been established that, for many years, Exxon's public affairs strategy was—as a 1988 internal memo put it—to "emphasize the uncertainty in scientific conclusions regarding the potential enhanced greenhouse effect" (*10*, *44*, *50*). However, our analysis shows that in their reports and briefings to management, ExxonMobil's own scientists did not particularly emphasize uncertainty; on the contrary, the level of uncertainty indicated by their global warming projections (bootstrapped 2σ standard error of the mean = ±21%) was commensurate with that reported by independent academics (±16%). Crucially, it excluded the possibility of no anthropogenic global warming; at no point did company scientists suggest that human-caused global warming would not occur. Nor did they conclude that the uncertainties were too great to permit differentiation of human and natural drivers. Yet publicly, ExxonMobil Corp made these claims until at least the early 2010s (see Box 2).

Denigrating climate models

ExxonMobil has often specifically claimed or suggested in public that climate models are

"unreliable" (*51*). In 1999, for example, ExxonMobil Corp's chief executive officer (CEO) Lee Raymond said future climate "projections are based on completely unproven climate models, or, more often, sheer speculation." (*2*) In 2013, his successor, Rex Tillerson, called climate models "not competent" (*52*). In 2015, he stated: "We do not really know what the climate effects of 600 ppm versus 450 ppm will be because the models simply are not that good" (*53*). The company's own modeling contradicts such statements. Exxon's 1982 projection shown in Fig. 1 (panel 3), for example, suggests that 600 ppm of atmospheric CO_2 would lead to 1.3°C more global warming than 450 ppm.

Quantifying ExxonMobil's broader climate knowledge

We gain additional insights into how ExxonMobil misled the public and other stakeholders by further evaluating the company's climate projections and comparing them to its public communications.

Mythologizing global cooling

Panel 1b of Fig. 1 is a graph of the global warming "effect of CO_2 on an interglacial scale" originally published by climate scientist J. Murray Mitchell Jr. in March 1977 and reproduced by Exxon scientist James Black in a private briefing to the Exxon Corporation Management Committee 4 months later (*54*, *55*). This dataset was not included in our preceding analysis because its long time scale does not permit accurate digitization of its projected post-industrial anthropogenic global warming. Nonetheless, overlaying the original graph with the temperatures simulated by a modern Earth system model (in red) shows that Exxon scientists were accurate in warning their superiors of the prospect of a "carbon dioxide induced 'super-interglacial,'" as Mitchell Jr. termed it, that would render Earth hotter than at any time in at least 150,000 years (*56*). This shows that Exxon scientists correctly sided with the majority of the peer-reviewed literature in the 1970s that foresaw human-caused global warming overwhelming any possibility of global cooling and a (natural) ice age. [According to Peterson *et al.* (2008), only ~14% of the peer-reviewed literature between 1965 and 1977 anticipated global cooling (*56*).] It also shows that "the myth of the 1970s global cooling scientific consensus" cultivated in public by Mobil in the 1990s and ExxonMobil Corp in the 2000s (see Box 3) was false and contradicted the conclusion of their own scientists that global cooling was unlikely (*56*).

Claiming ignorance about discernibility

A second insight involves ExxonMobil's predictions as to when anthropogenic global warming would be discernible against the backdrop of natural climate fluctuations. Ten internal reports and one peer-reviewed publication spanning 1979–1985 offered quantitative estimates, with a median year of 2000 ± 5. (For each document, we infer the predicted year from its corresponding supporting quotations, summarized in table S4; see SM section S1.2.6 for method details.) This is consistent with what in fact occurred. In 1995, the IPCC declared that a human effect on global temperatures had been detected, a conclusion they reiterated with higher confidence in 2000 and in all subsequent IPCC assessment reports (*57*, *58*). In other words, ExxonMobil's understanding of climate science was sufficient not only to project long-term warming accurately but also to predict when it would be discernible. Yet, ExxonMobil publicly asserted that the science was too uncertain to know when—or if—human-caused global warming might be measurable. In 2004, for example, they stated that "scientific uncertainties continue to limit our ability to make objective, quantitative determinations regarding the human role in recent climate change," a claim that was contrary to the analysis of their own scientists (*59*).

Staying silent on stranded assets

A third insight concerns the "carbon budget"—the amount of CO_2 that can be added to the atmosphere—while holding anthropogenic global warming below 2°C. Five ExxonMobil studies published between 1982 and 2005 address the question. They conclude that to stabilize CO_2 concentrations below 550 ppm and/or limit warming to 2°C would impose a carbon budget of 251 to 716 gigatonnes of carbon (GtC) between 2015 and 2100 (*10*). For comparison, recent calculations have narrowed the uncertainty and place the figure at 442 to 651 GtC (*60*). Thus, ExxonMobil's calculations of the carbon budget were consistent with today's best estimates. Yet, to our knowledge, ExxonMobil did not alert investors, consumers, or the general public to this constraint.

Quantifying climate knowledge

The substantial body of literature documenting the history of climate lobbying and propaganda by fossil fuel interests has been described as a "vast blind spot" of major climate assessments—ignored, in particular, in all but the most recent IPCC assessment report (*61*–*63*). Yet bringing quantitative techniques from the physical sciences to bear on a discipline traditionally dominated by qualitative journalistic and historical approaches offers one path to remedying this blind spot. Here, it has enabled us to conclude with precision that, decades ago, ExxonMobil understood as much about climate change as did academic and government scientists. Our analysis shows that, in private and academic circles since the late 1970s and early 1980s, ExxonMobil scientists (i) accurately projected and skillfully modeled global warming due to fossil fuel burning; (ii) correctly dismissed the possibility of a coming ice age; (iii) accurately predicted when human-caused global warming would first be detected; and (iv) reasonably estimated how much CO_2 would lead to dangerous warming. Yet, whereas academic and government scientists worked to communicate what they knew to the public, ExxonMobil worked to deny it.

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SUPPLEMENTARY MATERIALS

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