Global warming in the pipeline

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ABSTRACT

Improved knowledge of glacial-to-interglacial global temperature change implies that fast-feedback equilibrium climate sensitivity is at least ~4°C for doubled CO_2 ($2{\times}CO_2$), with likely range 3.5-5.5°C. Greenhouse gas (GHG) climate forcing is 4.1 W/m^2 larger in 2021 than in 1750, equivalent to $2{\times}CO_2$ forcing. Global warming in the pipeline is greater than prior estimates. Eventual global warming due to today's GHG forcing alone – after slow feedbacks operate – is about 10°C. Human-made aerosols are a major climate forcing, mainly via their effect on clouds. We infer from paleoclimate data that aerosol cooling offset GHG warming for several millennia as civilization developed. A hinge-point in global warming occurred in 1970 as increased GHG warming outpaced aerosol cooling, leading to global warming of 0.18°C per decade. Aerosol cooling is larger than estimated in the current IPCC report, but it has declined since 2010 because of aerosol reductions in China and shipping. Without unprecedented global actions to reduce GHG growth, 2010 could be another hinge point, with global warming in following decades 50-100% greater than in the prior 40 years. The enormity of consequences of warming in the pipeline demands a new approach addressing legacy and future emissions. The essential requirement to "save" young people and future generations is return to Holocene-level global temperature. Three urgently required actions are: 1) a global increasing price on GHG emissions, 2) purposeful intervention to rapidly phase down present massive geoengineering of Earth's climate, and 3) renewed East-West cooperation in a way that accommodates developing world needs.

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ACRONYMS

AR4, AR5, AR6: Assessment reports 4, 5, 6 of IPCC

CCN: cloud condensation nuclei

CERES: Clouds & Earth's Radiant Energy System (satellite observation, Earth's energy budget)

CLIMAP: Climate: Long range Investigation, Mapping and Prediction (research project in the 1970s and 80s to produce a map of climate conditions during the Last Glacial Maximum)

CMIP: climate model intercomparison project

ECS: equilibrium climate sensitivity (for idealized case that excludes "slow" climate feedbacks)

EEI: Earth's energy imbalance

ESS: Earth system sensitivity

GCM: global climate model

GHG: greenhouse gas

GISS: Goddard Institute for Space Studies (New York division of Goddard Space Flight Center)

IPCC: Intergovernmental Panel on Climate Change

LGM: last glacial maximum (approximately 20,000 years ago)

MARGO: Project to assess ocean cooling in LGM, *Nat. Geosci*. **2**, 127-132, 2009.

MPTGs & OTGs: Montreal Protocol Trace Gases & Other Trace Gases

MyBP: million years before present

PDO: Pacific Decadal Oscillation

PETM: Paleocene Eocene Thermal Maximum, a period about 56 million years ago when a rapid global warming by~6°C occurred in response to CO_2 increase comparable to doubling CO_2 today

PGM: Prior or penultimate glacial maximum (preceded Eemian interglacial period)

SRM: solar radiation management (usually reflection of sunlight to cool Earth)

INTRODUCTION

It has been known since the 1800s that infrared-absorbing (greenhouse) gases (GHGs) warm Earth's surface and that the abundance of GHGs changes naturally as well as from human actions.[1,2] Roger Revelle wrote in 1965 that we are conducting a "vast geophysical experiment" by burning fossil fuels that accumulated in Earth's crust over hundreds of millions of years.[3] Carbon dioxide (CO_2) in the air is now increasing and already has reached levels that have not existed for millions of years, with consequences that have yet to be determined. Jule Charney led a study in 1979 by the United States National Academy of Sciences that concluded that doubling of atmospheric CO_2 was likely to cause global warming of $3 \pm 1.5°C$.[4] Charney added: "However, we believe it is quite possible that the capacity of the intermediate waters of the ocean to absorb heat could delay the estimated warming by several decades."

After U.S. President Jimmy Carter signed the 1980 Energy Security Act, which included a focus on unconventional fossil fuels such as coal gasification and rock fracturing ("fracking") to extract shale oil and tight gas, the U.S. Congress asked the National Academy of Sciences again to assess potential climate effects. Their *Changing Climate* report has a measured tone on energy policy – amounting to a call for research.[5] Was not enough known to caution lawmakers against taxpayer subsidy of the most carbon-intensive fossil fuels? Perhaps the equanimity was due in part to a major error: the report assumed that the delay of global warming caused by the ocean's thermal inertia is 15 years, independent of climate sensitivity. With that assumption, they concluded that climate sensitivity for $2 \times CO_2$ is near or below the low end of Charney's 1.5-4.5°C range. If climate sensitivity was low and the lag between emissions and climate response was only 15 years, climate change would not be nearly the threat that it is.

Simultaneous with preparation of *Changing Climate*, a symposium was held 25-27 October 1982 at Columbia University's Lamont Doherty Geophysical Observatory, with papers published in January 1984 as *Climate Processes and Climate Sensitivity,* a monograph of the American Geophysical Union.[6] The symposium focused on the ocean's role in climate change and on climate change information contained in the paleoclimate record. Paleoclimate data showed that climate sensitivity is in the range 2.5-5°C for $2 \times CO_2$, thus at the upper end of Charney's range. In turn, this implied that the climate response time to a forcing is of the order of a century, not 15 years. Thus, the concept that a large amount of additional human-made warming is already "in the pipeline" was introduced.[7] E.E. David, Jr., President of Exxon Research and Engineering, in his keynote talk at the symposium insightfully noted: "The critical problem is that the environmental impacts of the CO_2 buildup may be so long delayed. A look at the theory of feedback systems shows that where there is such a long delay, the system breaks down, unless there is anticipation built into the loop."[8]

Thus, the danger caused by climate's delayed response and the need for anticipatory action to alter the course of fossil fuel development was apparent to scientists and the fossil fuel industry 40 years ago.[9] Yet industry chose to long deny the need to change energy course,[10] and now, while governments and financial interests connive, most industry adopts a "greenwash" approach that threatens to lock in perilous consequences for humanity. Scientists will share responsibility, if we allow governments to rely on goals for future global GHG levels as if targets had meaning

in the absence of policies required to achieve them. In the final section of this perspective article, we discuss actions required to slow down and reverse global warming.

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 to provide policymakers with regular scientific assessments on the current state of knowledge about climate change[11] and almost all nations agreed to the 1992 United Nations Framework Convention on Climate Change[12] with the objective to avert "dangerous anthropogenic interference with the climate system," The current IPCC Working Group 1 report[13] describes shutdown of the overturning ocean circulations and large sea level rise on the century time scale as "high impact, low probability" even under extreme GHG growth scenarios. This contrasts with "high impact, high probability" assessments reached in a paper – hereafter abbreviated *Ice Melt* – that several of us published in 2016.[14] Recently, the first author (JEH) of our present paper published a qualitative description of the decade-long investigation that led to the conclusion that most climate models are unrealistically insensitive to freshwater injected by melting ice and also that ice sheet models are unrealistically lethargic in the face of rapid, large climate change.[15]

Eelco Rohling, editor-in-chief of Oxford Open Climate Change, invited one of us (JEH) to write a perspective article on these scientific issues. We had noted in our papers that global warming in the past century does not imply a unique climate sensitivity because warming at Earth's surface depends on three major unknowns with only two fundamental constraints. Unknowns are equilibrium climate sensitivity(ECS), net climate forcing (because aerosol forcing is unmeasured), and ocean mixing of heat. Constraints are observed global temperature change and Earth's energy imbalance (EEI). In our investigation noted above, we assumed the canonical climate sensitivity 3°C for 2×CO_2, thus leaving two unknowns and two constraints. This allowed us to confirm that most climate models mix heat excessively into the deeper ocean and compensate for this by using a less strong aerosol forcing (less negative) than real-world aerosols.

A fresh look at this problem is demanded by two recent developments. First, improved analyses of global temperature during the last glacial maximum and during the prior (Eemian) interglacial period allow inference that ECS is higher than the canonical estimate. Second, although aerosol climate forcing remains unmeasured, there is evidence that human-made aerosol amount is on the decline, implying that acceleration of global warming may be in the offing. We clarify the physics by use of "response functions" for both global temperature and EEI, which reveal that climate response time is not simply a function of ocean mixing. We infer that ultrafast cloud feedbacks affect global temperature and EEI in opposite senses – slowing the warming of the ocean while speeding up partial restoration of planetary energy balance. We will describe implications in two papers. This first paper – *Global Warming in the Pipeline* – focuses on climate sensitivity, climate response time, and aerosols. The second paper – *Sea Level Rise in the Pipeline* – presents evidence that continued warming and increasing ice melt can cause shutdown of the overturning ocean circulations within decades and large sea level rise within a century.

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CLIMATE SENSITIVITY

Charney defined an equilibrium climate sensitivity (ECS): the eventual global temperature change caused by doubled CO_2 in the idealized case in which ice sheets, vegetation and long-lived GHGs are fixed (except for the specified CO_2 doubling). All other quantities are allowed to change. The ones deemed most significant – clouds, aerosols, water vapor, snow cover and sea ice – change rapidly in response to climate change. Thus, the Charney ECS is also called the "fast feedback" climate sensitivity. Feedbacks can interact in many ways, so their changes are usually calculated in global climate models (GCMs) that can simulate such interactions. Charney implicitly assumed that change of the ice sheets on Greenland and Antarctica – which we will categorize as a "slow feedback" – was not important on the time scale of most public interest.

ECS defined by Charney is a useful concept that helps us understand how human-made and natural climate forcings affect climate. We must also consider an Earth system sensitivity,[16] ESS, in which all feedbacks are allowed to respond to a climate forcing. ECS and ESS both depend on the initial climate state[17,18] and direction (warming or cooling) of climate change, but at the present climate state – with ice sheets on Antarctica and Greenland – climate should be about as sensitive in the warmer direction as in the cooler direction. Paleoclimate data indicate that ESS substantially exceeds ECS, i.e., when feedbacks that Charney kept fixed are allowed to change, climate sensitivity increases. As Earth warms, ice sheets shrink and the atmosphere contains more CO_2, CH_4 and N_2O, at least on glacial-interglacial time scales.

The time scale of climate feedbacks is crucial, but poorly understood, especially for the unique human-made forcing. As quantified below, the human-made GHG climate forcing is already 4 W/m^2, equivalent to $2\times CO_2$, and a GHG forcing as large as 8 W/m^2 (equivalent to $4\times CO_2$) is possible, perhaps likely, within a century. Such forcing is larger than estimates of the forcing that drove the largest known rapid global warming, the Paleocene Eocene Thermal Maximum (PETM),[19] which occurred ~56 MyBP. The CO_2 increase that drove PETM global warming was introduced over a few thousand years.[20] The net human-made climate forcing has been growing rapidly only since about 1970, i.e., for about half a century, but within another century it could match or exceed the PETM forcing, while being introduced 20 times faster. There is no known paleoclimate analogue of such a forcing. In *Sea level rise in the Pipeline* it will be argued that such a large, rapid forcing will cause nonlinear growth of ice melt, that excessive small-scale ocean mixing in most GCMs has caused underestimate of the effect of ice melt on overturning ocean circulations, that the world is nearing ice melt rates that will affect these circulations, that increasing ice melt increases Earth's energy imbalance thus accelerating ice melt and creating the danger of collapse of the West Antarctic ice sheet on a century time scale. Such increased ice melt and shutdown of ocean circulations, if they occur, will cool the North Atlantic and Southern Oceans. That type of cooling is not helpful, as it increases Earth's energy imbalance and thus the rate at which energy is pumped into the ocean. The cooling needed to slow and stop global warming and ice melt requires reducing and eliminating Earth's energy imbalance caused by the human-made climate forcing. Despite the danger of transitioning into nonlinear climate change – indeed, because of that danger – improved understanding of ECS is important. High ECS increases climate response time and the amount of global warming presently "in the pipeline" without further increase of climate forcing.

If knowledge of ECS was based only on models, it would be difficult to narrow the range of estimated climate sensitivity – or to have high confidence in any range – because we do not know how well feedbacks are modeled or even if the models include all significant real-world feedbacks. Cloud and aerosol interactions are complex, and even small cloud changes can have a substantial effect. That is why data on Earth's paleoclimate history are so valuable; they allow us to compare different equilibrium climate states, knowing that all feedbacks were in operation.

Climate sensitivity estimated at Ewing Symposium

In our paper[7] for the AGU *Geophysical Monograph* we compared the Last Glacial Maximum (LGM) with the current interglacial period (the Holocene). We ran GCM simulations introducing one-by-one LGM surface conditions provided by the CLIMAP project[21] and analyzed the effect of individual feedbacks on global change. With all CLIMAP surface conditions incorporated in the GCM – including ice sheet sizes and sea surface temperature (SST) – the calculated global mean surface temperature was 3.6°C colder in the LGM than in the Holocene. From analysis of the strength of individual feedbacks, we estimated ECS for $2\times CO_2$ as 2.5-5°C.

We recognized the potential to get a more certain and accurate evaluation of ECS by using the fact that Earth had to be in energy balance during the LGM. With CLIMAP surface conditions, we found that the model Earth was out of energy balance by 2.1 W/m^2, radiating more energy to space than it receives from the Sun. Such a large energy imbalance is impossible; averaged over millennia, the planet had to be in energy balance within less than 0.1 W/m^2. Earth (i.e., the climate model with CLIMAP SSTs) was trying to cool off; it would need to cool at least 1-2°C to achieve energy balance. When we employed CLIMAP's "maximal extent" ice sheet area – assuming that maximum ice sheet size was obtained simultaneously on all continents in both hemispheres – the increased reflection of sunlight only reduced the imbalance to 1.6 W/m^2.

Something was wrong with either CLIMAP surface conditions or our assumed change of atmospheric composition between the LGM and today. Indeed, we did not realize that – in addition to reduced CO_2 – CH_4 and N_2O were less abundant in the LGM than today. However, the effect of that change is moderate and the sense is to make the energy imbalance even larger. A likely explanation was that CLIMAP SSTs were unrealistically warm. We noted independent evidence for that conclusion, including a then-ongoing study of proxy temperature data by Rind and Peteet that indicated low latitude CLIMAP SSTs were too warm by as much as 2-3°C.[22]

Colder SSTs during the LGM implied a higher climate sensitivity. Our calculated climate forcing for the Holocene relative to the LGM (due to ice sheet, vegetation and CO_2 change) was almost 6 W/m^2. Forcing by $2\times CO_2$ is ~4 W/m^2, two-thirds of the LGM-to-Holocene forcing, so CLIMAP's estimate of 3.6°C temperature change implied an ECS at the low end of the 2.5-5°C range estimated from our feedback analysis. But if the LGM was cooler – as implied by the calculated energy imbalance – ECS would be in the upper part of the 2.5-5°C range.

CLIMAP project members would not concede such large errors in LGM SSTs. Therefore, we concluded only that climate sensitivity was 2.5-5°C for $2\times CO_2$. Even so, that range was more precise and reliable than climate models alone can ever provide. Today, advanced techniques for analysis allow more definitive assessment of climate sensitivity. Tierney et al.[23] used a large collection of geochemical proxies for SST constrained by isotope measurements and climate

change patterns defined by GCMs to find cooling of 6.1°C (95% confidence: 5.7-6.5°C) for the interval 23-19 ky BP. A further dynamically-constrained full-field analysis of climate evolution since the LGM by Osman, Tierney, et al.[24] sets LGM cooling at 21-19 ky BP as 6.8 ± 1°C with 95% confidence.[25] Seltzer et al.[26] use the temperature-dependent solubility of dissolved noble gases in ancient groundwater to find that global land areas between 45°S and 35°N cooled by 5.8 ± 0.6°C in the LGM; given the polar amplification of LGM cooling due in part to enhanced ice sheet extent, this supports global LGM cooling of at least 6°C.

Here we accept the conclusion that the LGM was at least 6°C cooler than the preindustrial Holocene and infer implications for climate sensitivity. First, however, we must clarify the definitions of climate sensitivity and climate forcings that we employ.

IPCC and independent climate sensitivity estimates

Progress in narrowing the uncertainty in climate sensitivity was slow in the first five assessment reports of the IPCC. The fifth assessment report[27] (AR5) in 2014 concluded only – with 66% probability – that ECS was in the range 1.5-4.5°C, the same as Charney's report 35 years earlier. Actually, much progress was being made in understanding of climate change. We estimate that thousands of papers on relevant climate processes were published that affect estimates of climate sensitivity. The broad spectrum of information – especially constraints imposed by paleoclimate data – at last affected the AR6 estimate of ECS. AR6[13] concludes with 66% probability that ECS is 2.5-4°C with 3°C as their best estimate for ECS (AR6 Fig. TS.6).

We avoid review of the literature on climate sensitivity by relying on the recent comprehensive review by Sherwood and 24 co-authors,[28] who used multiple lines of evidence to infer that climate sensitivity to doubled CO_2 is 2.6-3.9°C with 66% probability. This range refers to an "effective sensitivity," S, that the authors anticipate will differ from ECS by only several percent. S is intended to be relevant to the 150-year time scale. We focus on the equilibrium climate sensitivity (ECS) to allow us to evaluate climate sensitivity and climate response time independently. Understanding of response time is needed for the sake of assessing the urgency and the nature of actions required to maintain a propitious climate. Also, ECS can potentially be derived precisely from data on past stable climate states that were necessarily in near energy balance. Over the LGM-to-Holocene transition, which required energy to melt ice equivalent to 130 m of sea level and raise ocean temperature several degrees, energy imbalance averaged only about +0.2 W/m^2.[29] Thus during the LGM and Holocene, when global ocean temperature and sea level were relatively stable, EEI averaged over several ky was much less than 0.1 W/m^2.

We will estimate ECS using pairs of equilibrium climate states that bound glacial-to-interglacial climate changes. First, though, we need to discuss climate forcing definitions and comment on major processes involved in glacial-to-interglacial climate transitions.

Climate forcing definitions

Equilibrium global surface temperature change, at least nominally, is related to ECS by

$$\Delta T_S \sim F \times ECS = F \times \lambda, \tag{1}$$

where λ is a widely-used abbreviation of ECS, ΔT_S is the global mean equilibrium surface temperature change in response to climate forcing F, which is an imposed perturbation of the planet's energy imbalance measured in W/m^2 averaged over the entire planetary surface. There are alternative ways to define F, as discussed in Chapter 8[30] of AR5 and in a paper[31] hereafter called *Efficacy*. Objectives are to find a definition of F such that different forcing mechanisms of the same magnitude yield a similar global temperature change, but also a definition that can be computed easily and reliably. The first four IPCC reports used adjusted forcing, F_a, which is Earth's energy imbalance after stratospheric temperature adjusts to presence of the forcing agent. F_a usually yields a consistent response among different forcing agents, but there are exceptions such as black carbon aerosols; F_a exaggerates their impact. Also, F_a is awkward to compute and depends on definition of the tropopause, which varies among models. F_s, the fixed SST forcing (including fixed sea ice), is much more robust than F_a as a predictor of climate response,[31,32] but a GCM is required to compute F_s. In *Efficacy*, F_s is defined as

$$F_s = F_o + \delta T_o/\lambda \tag{2}$$

where F_o is Earth's energy imbalance after atmosphere and land surface adjust to the presence of the forcing agent with SST fixed. A GCM run of about 100 years is needed to accurately define F_o because of unforced atmospheric variability. The GCM run also defines δT_o, the global mean surface air temperature change caused by the forcing with SST fixed. λ is the model's ECS in °C per W/m^2. $\delta T_o/\lambda$ is the portion of the total forcing (F_s) that is "used up" in causing the δT_o warming; radiative flux to space increases by $\delta T_o/\lambda$ due to warming of the land surface and global air. The term $\delta T_o/\lambda$ is usually less than 10% of F_o, but not necessarily negligible.

IPCC AR5 and AR6 define effective radiative forcing ERF as ERF = F_o. Omission of $\delta T_o/\lambda$ was intentional[30] and is not a major issue because uncertainty in most forcings is as large as $\delta T_o/\lambda$. However, if the forcing is used to calculate global surface temperature response, the forcing to use is F_s, not F_o. It would be useful if both F_o and δT_o were reported for all climate models.

A further refinement of climate forcing is suggested in *Efficacy*: an effective forcing (F_e) defined by a long GCM run with calculated ocean temperature. The resulting global surface temperature change, relative to that for an equal CO_2 forcing, defines the efficacy of the forcing. Effective forcings, F_e, were found to be within a few percent of F_s for most forcing agents, i.e., the results confirmed that F_s is a robust forcing definition. This support, strictly, is for F_s, not for F_o = ERF, which is systematically at least several percent smaller than F_s.

Another issue was exposed by climate simulations of the Goddard Institute for Space Studies (GISS) GCM for the CMIP6[33] and AR6 studies. This newer GISS model,[34,35] which we label the GISS (2020) model,[36] has higher resolution (2°×2.5° and 40 atmospheric layers) and other changes that yield a moister upper troposphere and lower stratosphere, relative to the GISS model used in *Efficacy* and earlier papers. The fixed SST simulation for 2×CO_2 with the GISS (2020) model yields F_o = 3.59 W/m^2, δT_o = 0.27°C and λ = 0.9 °C per W/m^2. Thus F_S = 3.59 + 0.30 = 3.89 W/m^2, which is 5.4% smaller than the F_S = 4.11 W/m^2 for the GISS model used in *Efficacy*. The GISS (2020) authors[34,35] attribute reduced CO_2 forcing to infrared blanketing by increased water vapor. We agree with the sense of this impact of increased water vapor, but changes introduced in the GISS (2020) cloud parameterization also may be a relevant factor. Introduction of F_s in AR5 to quantify climate forcing is a valuable advance, but it allows rapid feedbacks to come into play in assessed forcings. In a later section, we find evidence of rapid adjustments in GISS (2020) that are likely related to the cloud parameterization.
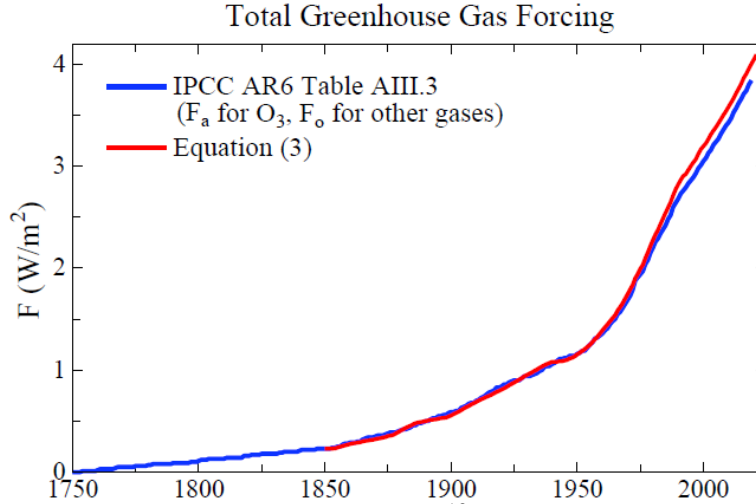
Fig. 1. IPCC AR6 Annex III greenhouse gas forcing,[13] which employs F_a for O_3 and F_o for other GHGs, compared with the effective forcing, F_e, from Eq. (3). See discussion in text.

Meanwhile, we use existing data to construct and make available formulae for GHG forcing as a function of gas amounts. Our original formulae,[37] included in Supporting Material, are adjusted GHG forcing, F_a, obtained as numerical fit to calculations with the GISS GCM radiation code, which uses the correlated k-distribution method[38] based on high spectral resolution laboratory data.[39] The laboratory data have changed little, so we convert these F_a to effective forcings (F_e) via efficacy factors (E_a) from Table 1 of *Efficacy*. The total GHG forcing is then

$$F_e = F_a(CO_2) + 1.45 \, F_a(CH_4) + 1.04 \, F_a(N_2O) + 1.32 \, F_a(MPTGs + OTGs) + 0.45 \, F_a(O_3). \qquad (3)$$

F_a forcings were calculated with a global-mean 1-dimensional (1-D) radiative convective model; thus coefficients in (3) include effect of conversion to 3-D atmosphere (see Supporting Material). The coefficient for CH_4 (1.45) includes the effect of changing CH_4 on stratospheric water vapor and O_3, as well as the efficacy of CH_4 per se (1.10). Following Prather and Ehhalt,[40] we assume that CH_4 is responsible for 45% of the O_3 change. Forcing caused by the remaining 55% of the O_3 change is based on the IPCC AR6 O_3 forcing ($F_a = 0.47$ W/m² in 2019); we multiply this AR6 O_3 forcing by $0.55 \times 0.82 = 0.45$, where 0.82 is the efficacy of O_3 forcing from Table 1 of *Efficacy*. Thus, the non-CH_4 portion of the O_3 forcing is 0.21 W/m² in 2019. MPTGs and OTGs are Montreal Protocol Trace Gases and Other Trace Gases.[41] An updated list of these gases and a table of their annual forcings since 1992 are available as well as the earlier data.[42]

The climate forcing from our formulae is slightly larger than IPCC AR6 forcings (Fig. 1). For example, in 2019, the final year of AR6 data, our GHG forcing is 4.00 W/m², while the AR6 forcing is 3.84 W/m². Our forcing is expected to be larger, because the IPCC forcings are F_o for all gases except O_3, for which they provide F_a (AR6 section 7.3.2.5). Table 1 in *Efficacy* allows accurate comparison: δT_o for $2 \times CO_2$ for the GISS model used in *Efficacy* is 0.22°C, λ is 0.67°C per W/m², so $\delta T_o / \lambda = 0.33$ W/m². Thus, the conversion factor from F_o to F_e (or F_s) is 4.11/(4.11-0.33). The non-O_3 portion of the AR6 2019 forcing (3.84 – 0.47 = 3.37) W/m² increases to 3.664 W/m². The O_3 portion of the AR6 2019 forcing (0.47 W/m²) decreases to 0.385 W/m² because the efficacy of $F_a(O_3)$ is 0.82. The AR6 GHG forcing in 2019 is thus ~ 4.05 W/m², expressed as $F_e \sim F_s$, which is about 1% larger than follows from our formulae.
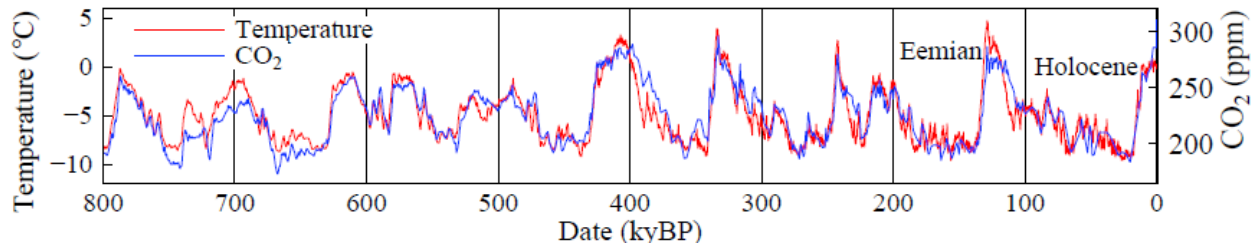
Fig. 2. Antarctic Dome C temperature for past 800 ky from Jouzel et al.(2007)[43] relative to the mean of the last 10 ky and Dome C CO_2 amount from Luthi et al. (2008).[44]

This nearly precise agreement is not indicative of the true uncertainty in the GHG forcing, which IPCC AR6 estimates as 10%, thus about 0.4 W/m^2. In Supporting Materials, we show that our CH_4 forcing is larger than that of IPCC AR6, while our MPTG + OTG forcing is smaller than that of IPCC AR6; these differences approximately offset. The forcing calculation is difficult because it must account for the complex spectral variability of gaseous absorption and the four-dimensional variability of water vapor and clouds, but modern computer capability makes more accurate assessment possible via systematic model intercomparisons. Improved knowledge of atmospheric radiative properties is needed as humanity works to limit GHGs and otherwise affect Earth's energy balance so as to limit undesirable climate change.

The stunning conclusion is that the GHG increase since 1750 now produces a climate forcing equivalent to that of 2×CO_2 (our formulae yield $F_e \sim F_s = 4.09$ W/m^2 for 2021; IPCC's AR6 $F_s = 4.14$ W/m^2). The human-made 2×CO_2 climate forcing imagined by Charney, Tyndall and other greenhouse giants[1] is no longer imaginary. At this moment, humanity is taking its first steps into the period of consequences. Earth's paleoclimate history helps us assess potential outcomes.

Glacial-to-interglacial climate oscillations

Air bubbles in Antarctic ice cores – trapped as snowfall piled up and compressed into ice – preserve a record of long-lived GHGs for at least the past 800,000 years. Isotopic composition of the ice provides a measure of temperature change in and near Antarctica.[43] In general, CO_2, CH_4 and N_2O were more abundant in interglacial periods than in glacial periods.

Changes of Antarctic temperature and GHGs, especially CO_2, are highly correlated (Fig. 2). This does not imply that GHGs were the primal cause of the climate oscillations. Hays, Imbrie and Shackleton[45] showed that small changes of Earth's orbit about the Sun and the tilt of Earth's spin axis relative to the orbital plane are pacemakers of the ice ages. These orbital changes alter the seasonal and geographical distribution of insolation, which initiates change of ice sheet size and GHG amounts. Both of these are mechanisms for glacial-interglacial climate change, but the reason long-term climate is so sensitive is the further role of ice sheets and GHGs as amplifying feedbacks. As Earth warms, ice sheets shrink, thus exposing a darker surface that absorbs more sunlight and warms Earth; this effect works in the opposite sense as Earth cools. Also, as Earth warms, the ocean and continents release GHGs to the air, which amplifies the warming; as Earth cools, the ocean and continents take up these gases, which amplifies the cooling.[46]

The weak orbital forcings oscillate slowly over tens and hundreds of thousands of years.[47] The picture of how Earth orbital changes drive millennial climate change was first painted clearly in the 1920s by Milutin Milankovitch, who built on 19th century hypotheses of James Croll and

Joseph Adhémar. Paleoclimate changes of ice sheet size and GHG amount in response to global temperature change are sometimes described as slow feedbacks.[48] They change slowly in the paleoclimate record, because they are paced by the slowly changing Earth orbital forcing. However, this does not mean that these feedbacks cannot operate more rapidly in response to a rapid climate forcing. Indeed, we will conclude that GHG and ice sheet feedbacks partially respond well before the fast-feedback response to a climate forcing is complete.

Today it is possible to evaluate ECS precisely via comparison of stable climate states before and after a glacial-to-interglacial climate transition. GHG amounts are known from ice cores and ice sheet sizes can be inferred from sea level and other geologic data. A warm LGM suggested by CLIMAP and MARGO[49] data (~3°C cooler than the Holocene) can be firmly rejected, because it is now certain that their SST data yield a planet out of energy balance by more than 2 W/m^2, as discussed above. An energy imbalance of +2 W/m^2 is enough to raise the temperature of the upper kilometer of the ocean 2.2°C or melt ice to raise sea level 22 m in a century[50] – and 10 times those amounts in a millennium. Such change rates did not occur, so the LGM was more than 3°C cooler than today. As discussed above, we accept the recent paleo analyses concluding that the LGM was at least ~6°C cooler than the Holocene.

The Holocene is an unusual interglacial. It began as expected: the maximum glacier melt rate was at 13.2 kyBP (kiloyears before present)[51] and, after peaking early in the Holocene, GHG amounts began to decline as in most interglacials. However, several ky later, CO_2 and CH_4 began to increase, which raised a question of whether humans were beginning to affect GHG amounts. Ruddiman[52] suggested that CO_2 began to be affected by deforestation 8 ky ago and CH_4 by rice irrigation 5 ky ago. That issue does not prevent us from using the LGM-Holocene comparison to estimate ECS, but for the sake of clarity we compare the LGM with both the early and late Holocene. In addition, we compare the prior glacial maximum (PGM)[53] with the subsequent interglacial (Eemian, about 130-118 kyBP). Based on a review[54] of Eemian data, we estimate that the Eemian was about +1°C warmer than the average Holocene temperature. The review includes a robust estimate of peak Eemian SSTs of +0.5 ± 0.3°C relative to 1870-1889,[55] which is +0.65 ± 0.3°C relative to our base period 1880-1920 and is consistent with our estimate of +1°C for land plus ocean Eemian peak warmth.

LGM-Holocene and PGM-Eemian evaluation of ECS

CO_2, CH_4 and N_2O amounts in the Holocene, LGM, Eemian and PGM are known accurately from ice cores, with the exception of N_2O in the PGM when N_2O reactions with dust in the ice core corrupt the data.[56] We take PGM N_2O as the mean of the smallest reported PGM amount and the LGM amount. The resulting potential error in the N_2O forcing is of order 0.01 W/m^2.

We calculate CO_2, CH_4, and N_2O forcings using Eq. (3) and formulae for each gas in Supporting Material. We provide[57] GHG amounts and calculated forcings for the periods shown by green bars in Fig. 3. The period chosen in the Eemian avoids the early spike of CO_2 and temperature to assure that it is a period with Earth in energy balance. Between the LGM (18-24 kyBP) and late Holocene (1-5 kyBP), GHG forcing increased 2.5 W/m^2 with 2.0 W/m^2 (80%) from CO_2. Between the LGM and early Holocene, GHG forcing increased 2.15 W/m^2 with 80% from CO_2. Between the PGM and Eemian, GHG forcing increased 2.3 W/m^2 with 79% from CO_2.
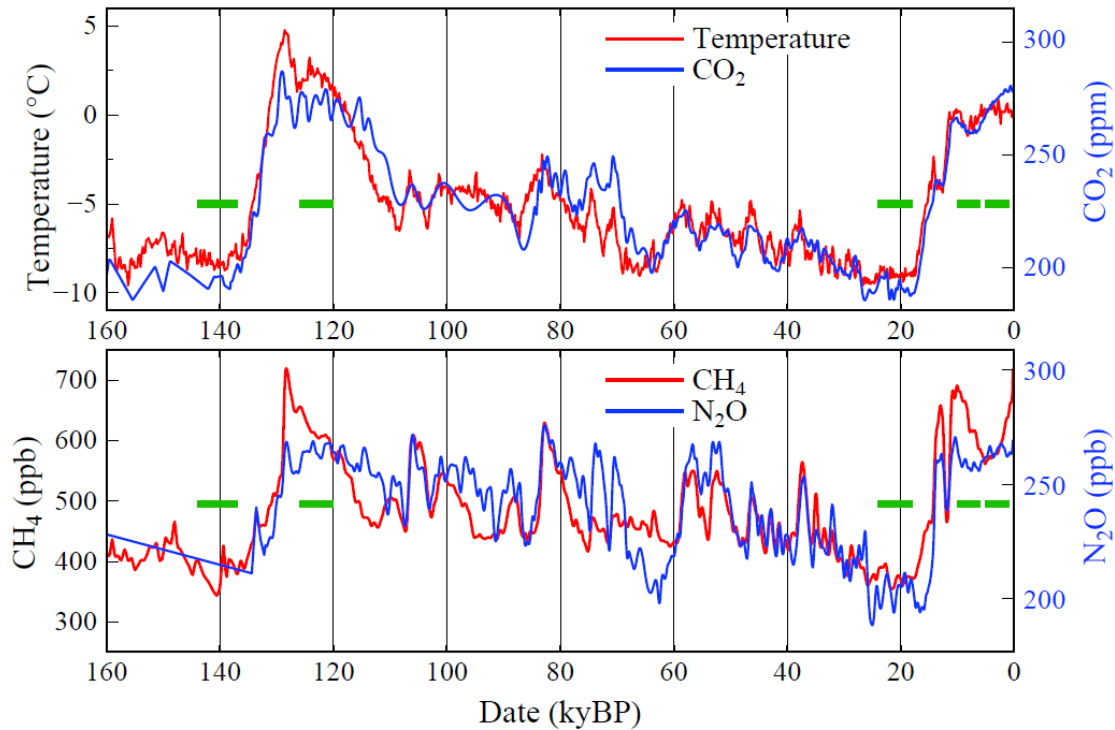
Fig. 3. Antarctic (dome C) temperature (Jouzel et al.[43]) and multi-ice core GHG amounts (Schilt et al.).[56] Green bars (1-5, 6-10, 18-24, 120-126, 137-144 kyBP) are periods of calculations.

Earth's surface changes are the other forcing required to evaluate ECS: (1) change of surface albedo (reflectivity) and topography due to ice sheets, (2) vegetation change, e.g., interglacial boreal forests replaced by brighter tundra, and (3) continental shelves exposed by lower sea level in glacial times. The forcing caused by all three changes can be evaluated at once with a global climate model. Accurate assessment requires realistic simulation of clouds, which reduce surface albedo effects. Clouds are the most important and difficult fast feedback (rapid response) in global climate models.[58] Thus, evaluation of the surface forcing is ideal for PMIP[59] (Paleoclimate Modelling Intercomparison Project) collaboration with CMIP[60] (Coupled Model Intercomparison Project); a joint study could provide valuable model intercomparisons as well as assessment of the most important climate characteristic: climate sensitivity.

Aerosols are a final issue to address before estimating climate sensitivity. Human-made aerosols, including their effect on clouds, are a climate forcing (an imposed perturbation of Earth's energy balance). Natural aerosol changes are, like clouds and water vapor, a fast climate feedback. Indeed, aerosols and clouds form a continuum and distinction becomes arbitrary as humidity approaches 100 percent. There are many aerosol types, including VOCs (volatile organic compounds) produced by trees, sea salt produced by wind and waves, black and organic carbon produced by forest and grass fires, dust produced by wind and drought, and marine biologic dimethyl sulfide and its secondary aerosol products. All of these vary geographically and in response to climate change. We cannot accurately specify their properties in prior eras, and there is no need to do so, because their changes are feedbacks included in the climate response.

Sherwood et al.[28] review studies of LGM ice sheet forcing and settle on –3.2 ± 0.7 W/m², the same as the IPCC AR4 estimate.[61] However, some GCMs yield efficacies for ice sheet forcings as low as ~0.75[62] or even ~0.5,[63] i.e., the response to the ice sheet forcing is a fraction of the

response to an equal CO_2 forcing. For LGM vegetation, we[7] found a forcing of -0.9 W/m² by using the Koppen[64] scheme to relate vegetation to local climate. Kohler et al.[65] estimate a continental shelf forcing of -0.6 W/m². We estimate the net LGM-Holocene surface forcing as 3-5 W/m², with the wide range due to the uncertain efficacy of the surface forcing. For the time being – until more accurate assessment of surface forcing is available – let's use the mean Holocene GHG forcing of 2.3 W/m², which makes the total LGM-Holocene forcing 5.3-7.3 W/m². Taking the LGM-Holocene warming as 6.1°C[23] and 2×CO_2 forcing as 4 W/m² yields ECS = 3.3-4.6°C for 2×CO_2. Osman, Tierney et al. LGM cooling of 6.8°C for 23-19 ky BP yields ECS = 3.7-5.1°C.

PGM-Eemian climate change provides a check. PGM-Eemian GHG forcing was 2.3 W/m². PGM sea level was ~10 m higher than LGM sea level.[66] The North American ice sheet was smaller than in the LGM and the Eurasian ice sheet was probably larger.[53] Redistribution of ice mass between the two major ice sheets has little effect on their combined climate forcing, but less ice mass by the equivalent of 10 m of sea level reduces the surface forcing by ~0.3 W/m²; see Fig. S4 in *Target CO_2* paper.[67] PGM-Eemian global warming was at least as great as LGM-Holocene global warming. The PGM was probably slightly warmer than the LGM, as suggested by the higher PGM sea level and the temperature inferred at Dome C in Antarctica (Fig. 2). However, temperature at Dronning Maud Land in Antarctica seems to have been cooler in the PGM than in the LGM.[68] The global Eemian temperature was about 1°C warmer than the Holocene, as discussed above. In summary, PGM-Eemian warming was several tenths of a degree greater than the LGM-Holocene warming, while the forcing maintaining Eemian warmth was a few tenths of a W/m² smaller than the Holocene forcing. Thus, while the LGM-Holocene climate change implies ECS =3.3-5.1°C for 2×CO_2, the PGM-Eemian implies ECS ~ 4-6°C.

We conclude ECS is at least approximately 4°C and is almost surely in the range 3.5-5.5°C. The IPCC AR6 conclusion that 3°C is the best estimate for ECS is inconsistent with paleoclimate data. Our conclusion also applies for transition to warmer climates, as discussed in the Summary below. Charney's estimate of 3°C for 2×CO_2, thus ¾°C per W/m² forcing, stood as the canonical ECS estimate for more than 40 years. Precise data for equilibrium paleo climate states point to a new canonical ECS: 1°C per W/m² forcing. The one major caveat is uncertainty in the glacial surface climate forcing. A well-designed PMIP/CMIP study could narrow that uncertainty.

High climate sensitivity has implications for climate response time and the amount of warming in-the-pipeline. Slow climate response – delayed climate response – has policy implications.

CLIMATE RESPONSE TIME

Climate response time was surprisingly long in our climate simulations[7] for the 1982 Ewing Symposium. The e-folding time – the time for surface temperature to reach 63% of its equilibrium response – was about a century. The only published atmosphere-ocean GCM – that of Bryan and Manabe[69] – had a response time of 25 years, while several simplified climate models referenced in our Ewing paper had even faster responses. The longer response time of our climate model was largely a result of high climate sensitivity – our model had an ECS of 4°C for 2×CO$_2$ while the Bryan and Manabe model had an ECS of 2°C.

The physics is straightforward. If the delay were a result of a fixed source of thermal inertia, say the ocean's well-mixed upper layer, response time would increase linearly with ECS because most climate feedbacks come into play in response to temperature change driven by the forcing, not in direct response to the forcing. Thus, a model with ECS of 4°C takes twice as long to reach full response as a model with ECS of 2°C, if the mixed layer provides the only heat capacity. However, while the mixed layer is warming, there is exchange of water with the deeper ocean, which slows the mixed layer warming. The longer response time with high ECS allows more of the ocean to come into play. If mixing into the deeper ocean is approximated as diffusive, surface temperature response time is proportional to the square of climate sensitivity.[70]

Slow climate response accentuates need for the "anticipation" that E.E. David, Jr. spoke about. If ECS is 4°C, more warming is in the pipeline than widely assumed. The greater warming could eventually make much of the planet inhospitable for humanity and cause the loss of coastal cities to sea level rise. We will argue that these fates can still be avoided via a reasoned policy response, but we must understand climate response time to define effective policies.

Temperature response function

In the Bjerknes lecture[71] at the 2008 American Geophysical Union meeting, the first author (JEH) argued that the ocean in many[72] GCMs has excessive, unrealistic mixing, and he suggested that GCM modeling groups report and make available the global temperature response function of their models. The response function is global temperature response to instantaneous doubling of carbon dioxide (2×CO$_2$) with the model run long enough to approach equilibrium. The response function characterizes a climate model and allows rapid (Green's function) estimate of the global mean surface temperature history in response to any climate forcing:

$$T_G(t) = \int [dT_G(t)/dt]\, dt = \int \lambda \times R(t)\, [dF_e/dt]\, dt. \tag{4}$$

T_G is the Green's function estimate of global temperature at time t, λ (°C per W/m^2) the model's 2×CO$_2$ equilibrium sensitivity, R the dimensionless temperature response function (% of equilibrium response), and dF_e the forcing change per unit time, dt. The integration over time begins when Earth is in near energy balance, e.g., in preindustrial time. The response function yields an accurate estimate of global temperature change for any climate forcing history, with nearly the same result as that of the global GCM that produced the response function (see Chart 15 of the Bjerknes presentation).[71] This approximation is expected to be good for any forcing unless and until the forcing causes a fundamental reorganization of the global ocean circulation.
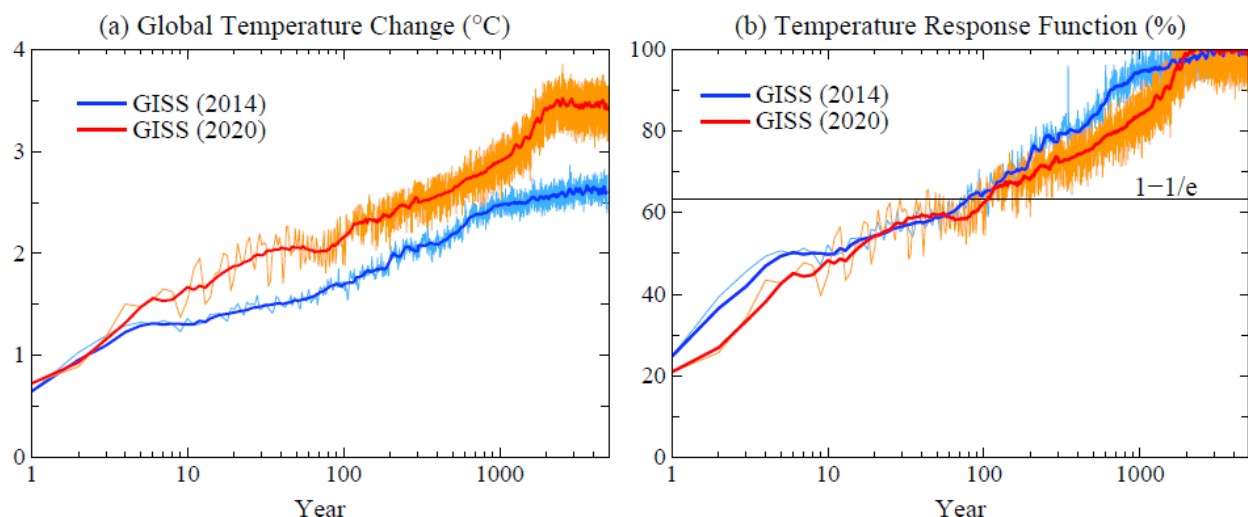
Fig. 4. (a) Global mean surface temperature response to instant CO_2 doubling and (b) normalized response function (percent of final change). Thick lines in Figs. 4 and 5 are smoothed[73] results.

Ocean mixing is addressed by comparison of two versions of the GISS GCM: GISS (2014)[74] and GISS (2020).[35] Both models[75] are described by Kelley et al. (2020).[34] Ocean mixing is markedly improved in GISS (2020) by use of a high-order advection scheme,[76] finer upper-ocean vertical resolution (40 layers), updated mesoscale eddy parameterization, and correction of errors in the ocean modeling code.[34] The GISS (2020) model has improved internal variability, including the Madden-Julian Oscillation (MJO), El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), although the spectral signature of the ENSO-like variability is unrealistic and its amplitude is excessive, as shown by the magnitude of oscillations in Fig. 4a. Ocean mixing in GISS (2020) may still be a bit excessive in the North Atlantic, where the model's simulated penetration of CFCs is greater than observed.[77]

Despite reduced ocean mixing, the response time of surface temperature in the GISS (2020) model is no faster than the GISS(2014) model (Fig. 4b): it takes 100 years to reach within 1/e of the equilibrium response. Slow response is partly explained by the larger ECS of the GISS (2020) model, which is 3.5°C versus 2.7°C for the GISS (2014) model, but something more is going on in the newer model, as exposed by the response function of Earth's energy imbalance.

Earth's energy imbalance

When Earth's climate is perturbed by a forcing, the resulting Earth energy imbalance (EEI) drives warming or cooling that tends to restore balance. Increasing GHGs and decreasing aerosols at present cause a positive EEI – more energy coming in than going out – by about +1 W/m^2 averaged over several years.[78] Highest absolute accuracy of EEI is obtained by tracking ocean warming – the primary repository for excess energy – and by adding the heat stored in warming of continents and the heat used in net melting of ice.[78] Heat storage in air adds a small, almost negligible, amount. Observations of radiation balance from Earth-orbiting satellites by themselves cannot measure EEI to the needed accuracy, but, when calibrated with the *in situ* data, satellite Earth radiation budget observations provide invaluable EEI data on finer temporal and spatial scales than the *in situ* data.[79]
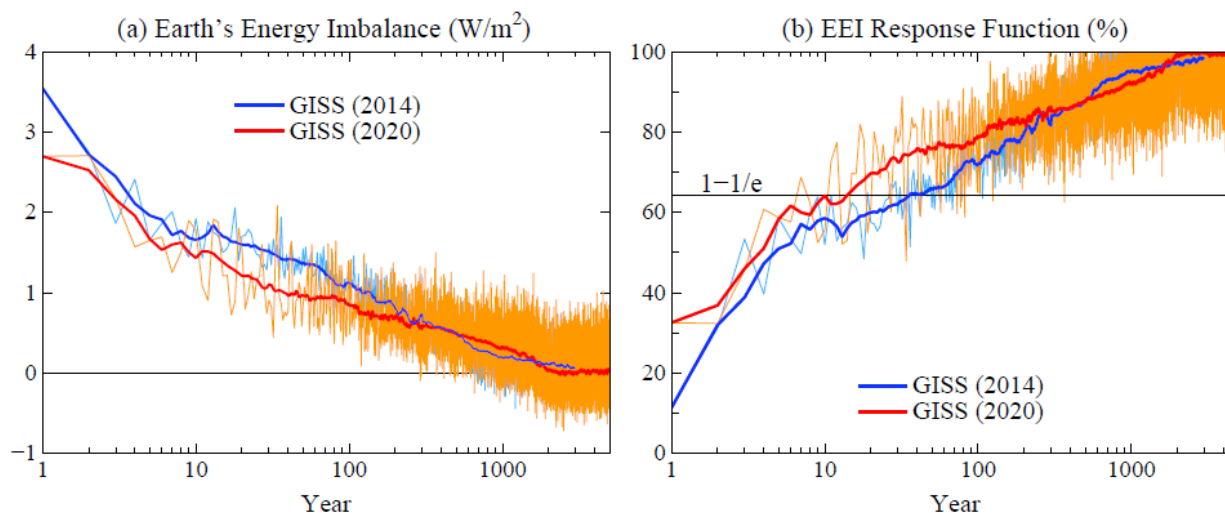
Fig. 5. (a) Earth's energy imbalance (EEI) for 2×CO₂, and (b) EEI normalized response function.

After a step-function forcing is imposed, EEI and global surface temperature must each approach a new equilibrium, but EEI does so more rapidly, especially for the GISS (2020) model (Fig. 5). EEI in the GISS (2020) model needs only a decade to reach within $1/e$ of full response (Fig. 5b), while global surface temperature requires a century (Fig. 4b). Rapid decline of EEI – to half the forcing within 5 years (Fig. 5a) – has practical implications, if it is realistic. First, EEI defines the rate that heat is pumped into the ocean, so if EEI is reduced, ocean surface temperature response time increases. Second, rapid EEI decline – if it is realistic – implies that the assumption that global warming and pumping of heat into the ocean can be stopped if humanity reduces climate forcing by an amount equal to EEI may be wrong. Instead, the required reduction of forcing is probably larger than EEI. In any scenario to stabilize climate, the difficulty in finding additional reduction in climate forcing of even a few tenths of a W/m^2 is substantial.[54] Calculations that can help quantify this issue are discussed in Supporting Material.

What is the physics behind the fast response of EEI? The 2×CO₂ forcing and initial EEI are both nominally 4 W/m^2. In the GISS (2014) model, the decline of EEI averaged over the first year is 0.5 W/m^2 (Fig. 5a), a moderate decline that might be largely caused by warming continents and increased heat radiation to space. In contrast, EEI declines 1.3 W/m^2 in the GISS (2020) model (Fig. 5a). Such a huge, immediate decline of EEI implies existence of an ultrafast climate feedback. Climate feedbacks are the heart of climate change and warrant discussion.

Slow, fast and ultrafast feedbacks

Charney et al.[4] described climate feedbacks without discussing time scales. At the 1982 Ewing Symposium, water vapor, clouds and sea ice were described as "fast" feedbacks[7] presumed to change promptly in response to global temperature change, as opposed to "slow" feedbacks or specified boundary conditions such as ice sheet size, vegetation cover, and atmospheric CO₂ amount, although it was noted that some specified boundary conditions, e.g., vegetation, in reality may be capable of relatively rapid change.[7]

Large response of EEI in one year (Fig. 5a) implies a third feedback time scale: ultrafast. Ultrafast feedbacks are not a new concept. When atmospheric CO₂ is doubled, the added infrared

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opacity causes the stratosphere to cool. Instantaneous EEI upon CO_2 doubling is only $F_i = +2.5$ W/m^2, but stratospheric cooling quickly increases EEI to +4 W/m^2.[80] This quick adjustment led to the choice of adjusted forcing, F_a, as superior to F_i as a measure of climate forcing.

Physics behind ultrafast change in the GISS model likely involves cloud change. Indeed, Kamae et al.[81] review rapid cloud adjustments separate from surface temperature-mediated changes. Clouds respond to radiative forcing, e.g., via effects on cloud particle phase, cloud cover, cloud albedo and precipitation.[82] The GISS (2020) model alters glaciation in stratiform mixed-phase clouds, which increases the amount of supercooled water in stratus clouds, especially over the Southern Ocean [Fig. 1 in GISS (2020) GCM description[34]]. The portion of supercooled cloud water drops changes from too little in GISS (2014) to too much in GISS (2020). Although neither model realistically simulates stratocumulus clouds – which are important for accurate simulation of Earth's albedo and climate sensitivity – that modeling deficiency does not affect our assessment of climate sensitivity and it does not prevent use of the two GISS models to help expose real-world physics affecting climate sensitivity and climate response times.

Cloud modeling is now a focus in GCM development. Several models in CMIP6 comparisons find high ECS.[82] It would be informative if the models defined their temperature and EEI response functions (Figs. 4 and 5). Failing that, model runs of even a decade could define the most crucial portion of Figs. 4a and 5a. In addition, if many short (e.g., 2-year) 2×CO_2 climate simulations were made with each run beginning at a different point in the model's control run, ultrafast feedbacks including cloud changes could be defined to an arbitrary accuracy by averaging the responses and subtracting the same years in the control run. As noted in our Supporting Material, definition of response functions for just a few forcings – say CO_2, aerosols and solar irradiance – would help assess the physical mechanisms causing ultrafast feedbacks and the physics behind high climate sensitivity.

Zhu et al.[83] recently used the LGM climate to constrain the microphysics and ice nucleation cloud parameterization in the Community Earth System Model CESM2. The paleo constraint reduced the ECS of the model from >5°C to 4°C for 2×CO_2. This independent study with a model including cloud microphysics is consistent with our inferences and could be a vehicle to evaluate EEI response with more realistic cloud physics. If the EEI response is much faster than the temperature response, it implies that the climate forcing reduction required to stabilize climate is greater than measured EEI, as discussed in Supporting Material.

The ultrafast response of EEI in the GISS (2020) model also exists, although much smaller, in the GISS (2014) model, as shown in our Supporting Material. The need for further study of ultrafast feedbacks and the wide range of climate sensitivities among current GCMs does not alter the high ECS that we infer from paleoclimate data, as that inference has little dependence on GCMs. The main role of GCMs in the paleoclimate analyses is to define seasonal and geographical climate patterns, which allows more accurate assessment of global temperature change from limited paleo data samples.[23,24,26]

Understanding clouds requires understanding aerosols, which are involved in cloud feedbacks. Human-caused aerosol changes are also a major driver of climate change.
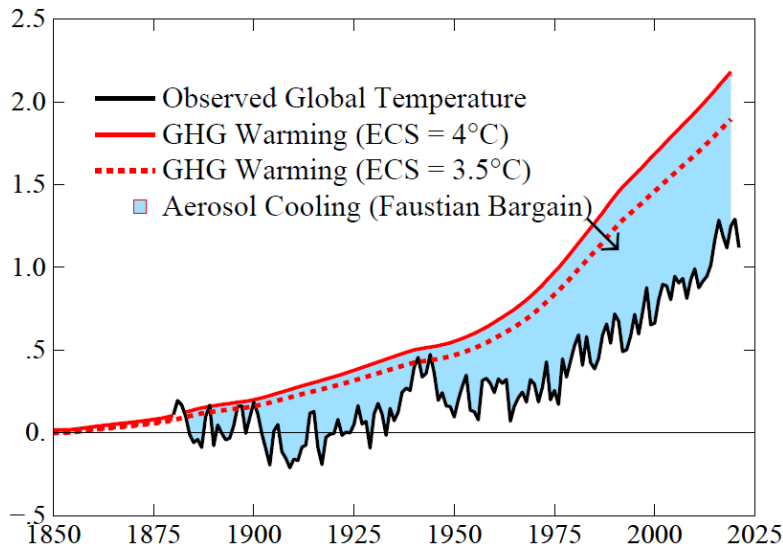
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Fig. 6. Observed global mean surface temperature (black line) and expected warming from observed GHG changes with two alternative choices for ECS. The difference (blue area) is an estimate of the cooling effect of the (unmeasured) aerosol forcing. The temperature peak in the World War II era is in part an artifact of inhomogeneous ocean data during that period.[54]

AEROSOLS

ECS near 4°C implies that expected warming for today's GHGs far exceeds observed warming. Expected GHG warming (Fig. 6) is calculated using equation (4) with the response function (Fig. 4b).[84] For ECS = 4°C, the expected GHG warming today (2.2°C) exceeds observed warming by about 1°C. If ECS is 3.5°C, the gap is about 0.7°C. The indicated expected warming does not include warming by slow feedbacks except for a small contribution in observed GHG amounts; potential further warming by slow feedbacks is discussed quantitatively below.

Human-made aerosols are the likely source of cooling that has partially offset GHG warming. An alternative source of cooling is human-made increase of Earth's surface albedo, which occurs via deforestation, agriculture, road-building, and other human developments, partially offset by decreased albedo due to deposition of soot on snow and ice surfaces. IPCC[13] (Chapter 7, Table 7.8) estimates the net forcing due to surface albedo change as -0.12 ± 0.1 W/m^2, which is an order of magnitude smaller than their estimated aerosol forcing. Thus, in our empirical evaluation of human-made cooling, we associate almost the entire cooling with aerosols.

Aerosol cooling is described as a Faustian bargain.[85] Payment comes due as we reduce pollution from shipping, vehicles, industry, and power plants, which we must do because ambient air pollution causes millions of deaths per year, with particulates most responsible.[86]

Aerosol climate forcing is difficult to measure because it occurs mainly via small induced cloud changes.[13] The absence of significant global warming over the period 1850-1920 (Fig. SPM.1 of the IPCC AR6 WG1 report) is a clue for the scale of aerosol forcing. GHG forcing increased +0.54 W/m^2 in 1850-1920, which causes an expected warming ~0.3°C by 1920, based on the climate response function with 3.5°C ECS (Fig. 4). Natural forcings – solar irradiance and volcanic aerosols – could contribute to lack of warming, but we are unaware of a persuasive case
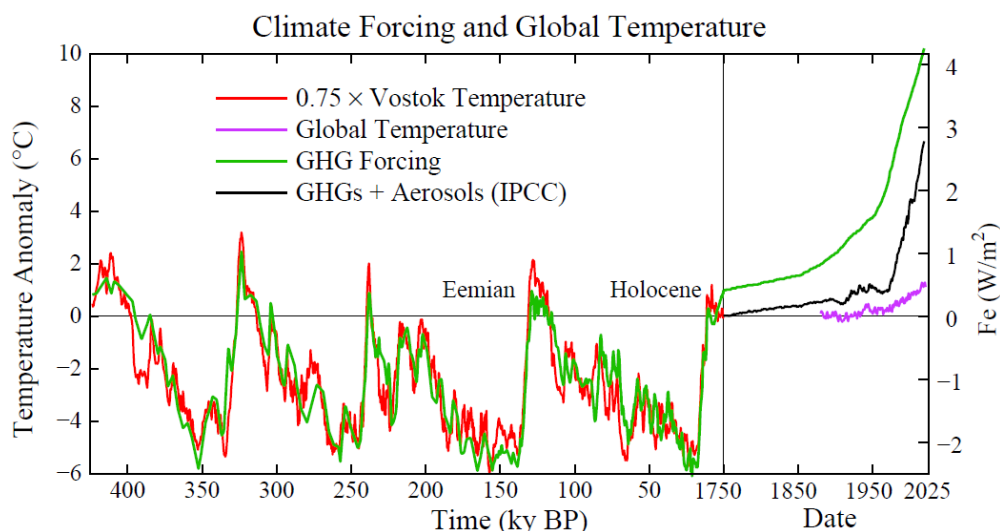
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Fig. 7. Global mean surface temperature (left scale) and climate forcings (right). Scale factor between temperature and forcings is 2.4°C per W/m^2 (see text). Antarctic (Vostok) temperature change based on water isotopes[87,88] is multiplied by 0.75. Time scale is expanded post 1750. Modern temperature is NASA GISS analysis.[89,90] Zero point for GHG forcing is the mean for 10-8 ky BP, a period expected to precede significant human effects. GHG + IPCC aerosol forcing is indistinguishable from IPCC[13] all-anthropogenic forcing (Supporting Material).

for the required downward trends of those forcings. Aerosols from increasing industrialization prior to most environmental protection laws are a more likely offset to GHG warming.

Paleoclimate evidence related to human-caused aerosols

Paleoclimate data provide ways to assess aerosol climate forcing. Natural paleo aerosol changes are fast feedbacks, as discussed above, but human-caused aerosols are a forcing – an imposed perturbation of Earth's energy balance. We will examine the continuity of modern climate data with the paleoclimate record to show the magnitude of warming in the pipeline, if today's level of GHGs – or a greater amount – long persists. Then we use the relative stability of Holocene global temperature to extract evidence that human-made aerosols were a significant climate forcing during the latter part of the preindustrial Holocene.

In the paper *Target CO$_2$*[67] the scale factor between equilibrium global temperature change and GHG forcing is 1.5°C per W/m^2 of GHG forcing based on an assumed ECS of 3°C for 2×CO$_2$ (0.75°C per W/m^2) and an assumption that GHG and ice sheets contributed about equally to the glacial-interglacial climate forcing (each 3 W/m^2). Our present assessment has ECS of 4°C (1°C per W/m^2) and more precise LGM-to-Holocene GHG forcing (2.5 W/m^2) and ice sheet forcing (3.5 W/m^2). Thus, the improved ΔT to F_{GHG} scale factor in Fig. 7 is $(F_{GHG} + F_{Ice})/ F_{GHG} \times 1°C$ per W/m^2 = 2.4°C per W/m^2 of GHG forcing. Temperature change in the paleo portion of Fig. 7 is the full observed change, which includes slow feedbacks. Modern temperature (purple curve) has not had time for the ocean to warm fully or for slow feedbacks to come fully into play.

Paleo GHG forcing in Fig. 7 is the first three terms in Eq. 3 with adjusted forcings for CO$_2$, CH$_4$ and N$_2$O from formulae in Supporting Material. The GHG forcings are a fit to radiative transfer calculations in a GCM[31] and agree well with the net IPCC GHG forcing, as shown above. Fig. 7
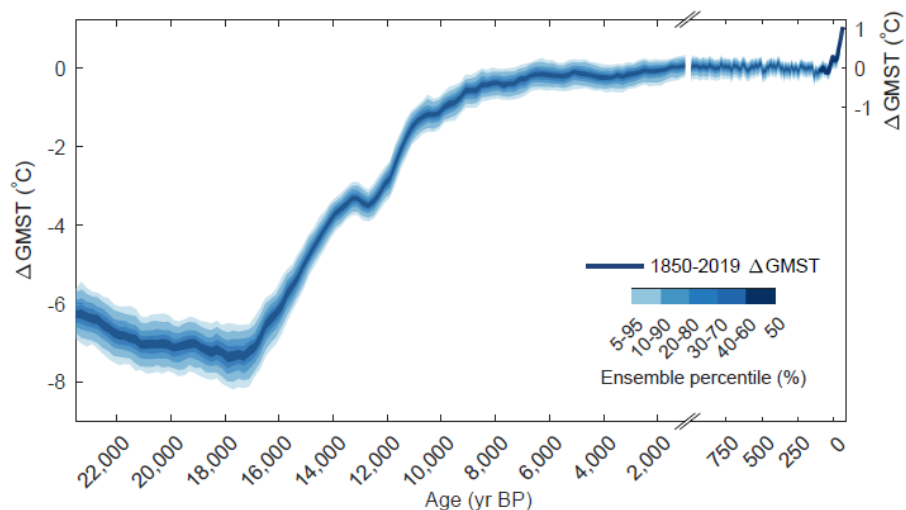
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Fig. 8. Global mean surface temperature change over the past 24 ky, reproduced from Fig. 2 of Osman et al.[24] including Last Millennium reanalysis of Tardif et al.[91]

also shows the GHG plus aerosol forcing using IPCC's estimated aerosol forcing history. There are gaps in the Vostok N_2O record prior to 132 ky BP, so we approximate the earlier N_2O forcing by increasing the $CO_2 + CH_4$ forcing by 12 percent. Good accuracy of this approximation is shown in Supporting Material for the past 132 ky, when N_2O data are available.

Paleo GHG climate forcing and Antarctic temperature change are nearly congruent (Fig. 7). A free parameter in Fig. 7 is the factor by which the Vostok temperature change is multiplied to obtain approximate congruence with the climate forcing. With the climate forcings and climate sensitivity assumed in *Target CO₂*, close congruence of forcing and temperature was achieved if Vostok temperature change was multiplied by 0.5, i.e., Southern Hemisphere polar amplification of temperature was a factor of two. With GHG forcing of 2.5 W/m^2 and ECS of 1°C per W/m^2, the factor by which Vostok temperature must be multiplied to achieve close congruence of temperature and forcing is 0.75 (Fig. 7). Reduced Southern Hemisphere polar amplification is consistent with recent estimates of LGM-Holocene global temperature change.[23,24,26]

Target CO₂ and Fig. 7 use the Vostok temperature derived from water isotopes.[87,88] Recent analysis[92] of LGM Antarctic cooling based on borehole thermometry and firn properties reveal that glacial cooling at the ice sheet surface is less than suggested by water isotopes, implying that the scale factor between Vostok and global temperature may be different from the value (0.75) in Fig. 7. Neither this specific scale factor for Vostok (where the temperature depends on changing ice surface height and other local factors) nor ice age polar amplification in general are important for our present paper. Here we only want to explain clearly the contents of Fig. 7.

A stunning result in Fig. 7 is that equilibrium global warming for today's GHG level is 10°C. Aerosols, at their maximum level in the early 21st century, reduce equilibrium warming to 7°C, but the aerosol amount is in decline The paleo temperature changes occurred over millennia, on the time scale of the climate forcing. Today's GHG forcing is rising faster than any known paleo case. In a following paper[93] we will use paleoclimate data, climate modeling and modern observations to assert that a large ice sheet response and several meters of sea level rise are likely on the century time scale in response to continued extraordinary human-made climate forcing.
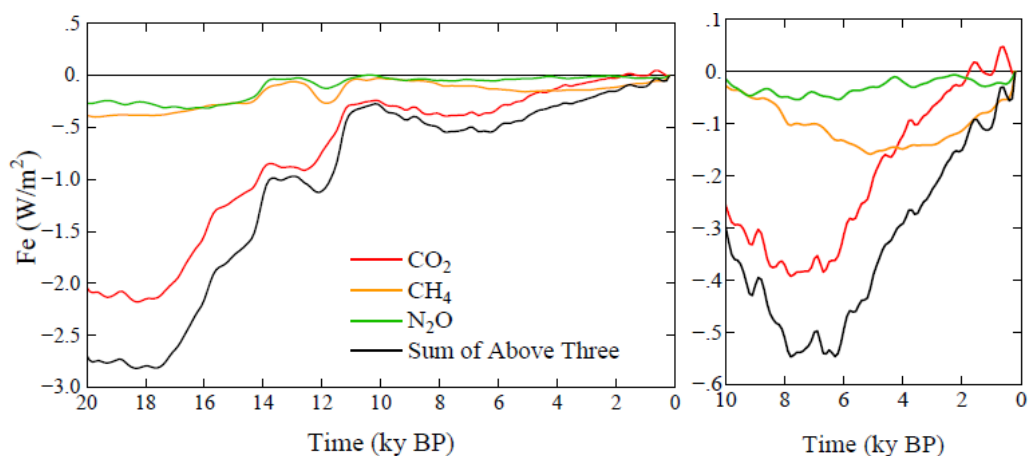
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Fig. 9. GHG climate forcing in past 20 ky with vertical scale expanded for the past 10 ky on the right. GHG amounts are from Schilt et al.[56] and formulae for forcing are in Supporting Material.

We focus here on the two forcings – human-caused changes of GHGs and aerosols – that are the dominant causes of ongoing climate change. Volcanic and solar irradiance forcings have notable short-term variation, but no significant long-term trend. Other human-made forcings estimated by IPCC have little net effect on total forcing history (see Supporting Material).

Several proxy-based analyses (e.g.) [94,95] found global cooling in the second half of the Holocene, but a recent analysis[24] that uses GCMs to overcome spatial and temporal biases in proxy data finds a rising global temperature in the first half of the Holocene followed by nearly constant global temperature in the last 6000 years until the past few centuries (Fig. 8, extracted from Fig. 2 of Osman *et al.*[24]). The deep ocean, tropical sea surface, and Antarctica all had stable temperature in the last 6000 years (Fig. S6 of *Target CO₂*).[67]

The final 6000 years of the Holocene are unusual. GHG forcing (Fig. 9) increased by 0.5 W/m², yet global temperature was stable, if not declining. Even the Osman et al.[24] analysis (Fig. 8), which shows Holocene warming over the last 9000 years, has no warming in the last 6000 years. Six thousand years is sufficient time for slow feedbacks to operate, as well as fast feedbacks. Global warming of about 1°C would be expected, based on climate sensitivity implied by Fig. 7. How can we interpret the absence of warming? Was another climate forcing at work?

Did humanity significantly affect preindustrial climate?

Ruddiman hypothesized[52] that humanity began to influence climate with the advent of land-clearing and agriculture. In a review[96] of his hypothesis, Ruddiman places the beginning of significant deforestation at 6500 yr BP and rice irrigation at 5000 yr BP, causing respective increases of atmospheric CO_2 and CH_4. In his analysis, Ruddiman seeks human-made sources of CO_2 and CH_4 of sufficient magnitude to compensate for large declines of those gases in the latter parts of prior interglacial periods. While we support Ruddiman's assertion that humans began to affect climate prior to the industrial revolution, we note that such large sources are unnecessary to account for Holocene GHG levels. Our principal interest is in preindustrial aerosols, but first we comment on why Ruddiman's thesis is more viable than it may have seemed.
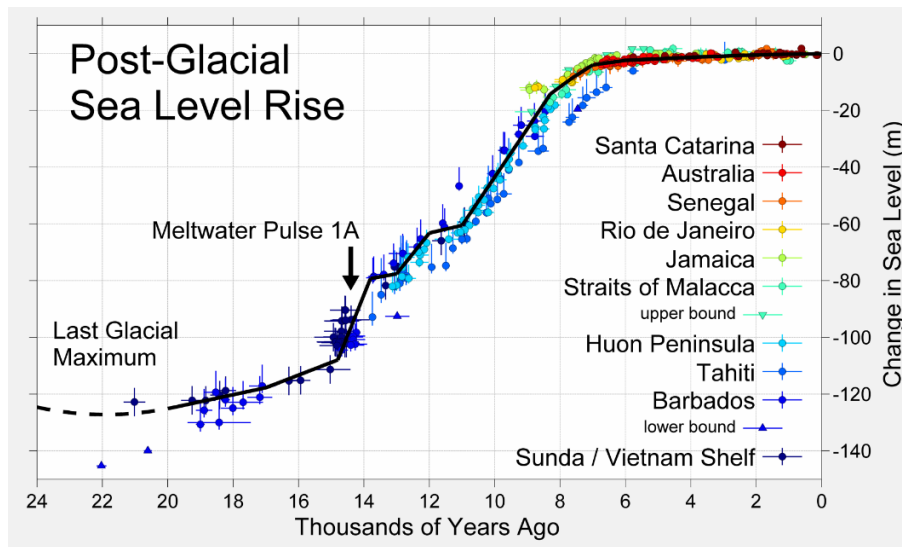
21

Fig. 10. Sea level since the last glacial period relative to present. Credit: Robert Rohde[97]

GHG decreases during a typical interglacial period are slow feedbacks that occur in concert with global cooling. However, global cooling did not occur in the past 6000 years, so the feedbacks did not occur. A principal mechanism in glacial-interglacial swings of atmospheric CO_2 and global temperature (Fig. 2) is the net rate of uptake of carbon by the deep ocean. Carbon sequestration in the deep ocean increases if ocean overturning slows because the rate of carbon return to the atmosphere is reduced. Maximum insolation at 60°S was in late-spring (mid-November) 6000 years ago; since then, the date of maximum insolation at 60°S slowly advanced through the year, recently passing mid-summer (Fig. 26b of Hansen et al.[14]). Maximum insolation from late-spring through mid-summer is optimum for direct warming of the Southern Ocean and for promoting early warm-season ice melt, which reduces surface albedo and magnifies regional warming.[48] Thus, Earth orbital parameters were optimum for keeping the Southern Ocean warm as needed to maintain a strong overturning ocean circulation.

GHG forcing decreased 0.2 W/m^2 between 10 and 6 ky BP, but the decrease was exceeded by a forcing due to shrinkage of ice sheets. Sea level 10 ky ago was 40 m below today (Fig. 10); loss of that ice causes a climate forcing of just over +1 W/m^2 (see Supporting Material of *Target CO₂*).[67] The net forcing was enough to produce the global warming of less than or about 1°C deduced from paleo data for the period 10-6 ky BP (Fig. 8). The mystery is the past 6000 years, when sea level and thus ice sheet volume were static. The 0.5 W/m^2 rise of GHG forcing over 6000 years must have been counteracted by a comparable negative forcing to yield the near constant global temperature deduced by Osman et al.[24] An even larger negative forcing is required, if there was global cooling in the past 6000 years.

Hansen et al.[48] suggested that human-made aerosol cooling offset or exceeded GHG warming in the past 6000 years. Growth of population, agriculture and land clearance[96] produced aerosols as well as CO_2. Wood was the principal fuel for cooking and heating. As today, the largest aerosol forcing would be via effects on cloud cover and cloud brightness. This aerosol indirect effect tends to saturate as aerosol amount increases, so aerosol effectiveness per aerosol amount was greatest as civilization developed. Thus, it is unsurprising that human-made global aerosol

(a) Greenhouse Gas and IPCC Aerosol Climate Forcings
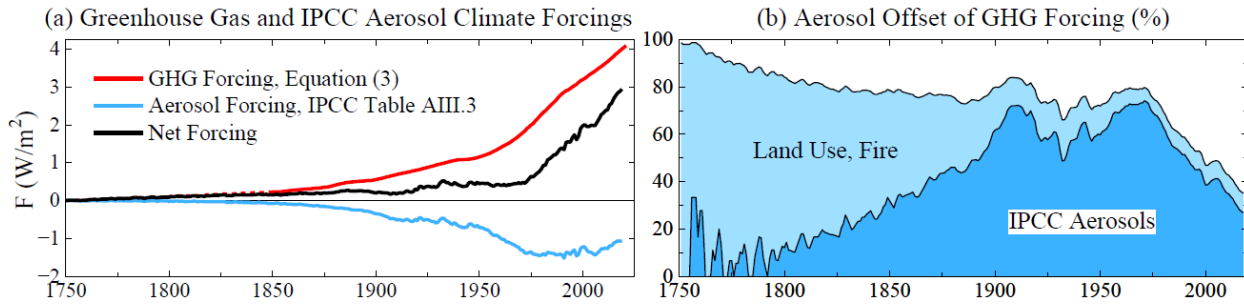
(b) Aerosol Offset of GHG Forcing (%)

Fig. 11. (a) Estimated greenhouse gas and aerosol climate forcings relative to 1750 values. (b) Aerosol climate forcing as percent of GHG forcing that it offsets. Aerosol and GHG forcings for dark blue area are relative to 1750 values. Light blue area is added when the GHG and aerosol forcings are defined relative to their values 6000 years ago, with GHG and aerosol forcings both reaching 0.5 W/m^2 by 1750.

forcing approximately offset human-made CO_2 forcing, as required to explain the absence of global warming in the past 6000 years of preindustrial climate.

Hemispheric differences provide a consistency check. GHG (mainly CO_2) forcing is global, while the aerosol forcing was mainly in the Northern Hemisphere. Global offset of the two forcings implies a net negative forcing in the Northern Hemisphere and positive forcing in the Southern Hemisphere. Therefore, human-made aerosols were likely a contributor to observed Northern Hemisphere cooling, which occurred on at least a regional scale, while GHG warming in the Southern Hemisphere helped orbital forcing keep the Southern Ocean warm.

Industrial era aerosols

Scientific advances often face early resistance from other scientists.[98] Examples are the snowball Earth hypothesis[99] and the role of an asteroid impact on extinction of non-avian dinosaurs,[100] which initially were highly controversial but are now more widely accepted. Ruddiman's hypothesis, right or wrong, is still controversial. Thus, we minimize this issue by showing aerosol effects with and without preindustrial human-made aerosols.

Global aerosol properties have not been monitored with the detail and accuracy needed to define the aerosol climate forcing,[101] but IPCC[13] estimates the aerosol forcing (Fig. 11a) based on assumed aerosol precursor emissions – mainly related to fossil fuel use – and aerosol models that are tested against a range of observations in recent decades. The task is difficult because of the multitude of aerosol types and the complex effects of aerosols on clouds. Uncertainty in aerosol forcing is at least 50 percent of the estimate in Fig. 11a[13] and probably is constrained more by observed global temperature change than by measurements of aerosols or precursor gases.

Using IPCC's best estimate aerosol forcing history (Fig. 11a) and the accurately known GHG history, we calculate the percent of GHG climate forcing offset by aerosol cooling – the dark blue area in Fig. 11b, which is simply the ratio of aerosol and GHG forcings. However, if human-made aerosol forcing was – 0.5 W/m^2 by 1750, offsetting the known +0.5 W/m^2 GHG forcing in 1750 (regardless of whether or not the GHG forcing was human-made), that aerosol forcing should be included in the total aerosol forcing and offset a 1750 GHG forcing of 0.5 W/m^2 (Fig. 9). This 1750 aerosol forcing – largely cloud effects of aerosols from land use, human-caused fires, and burning of biomass – is assumed to continue until today. The picture of the aerosol role in climate change, shown by both shades of blue in Fig. 11b, thus changes when
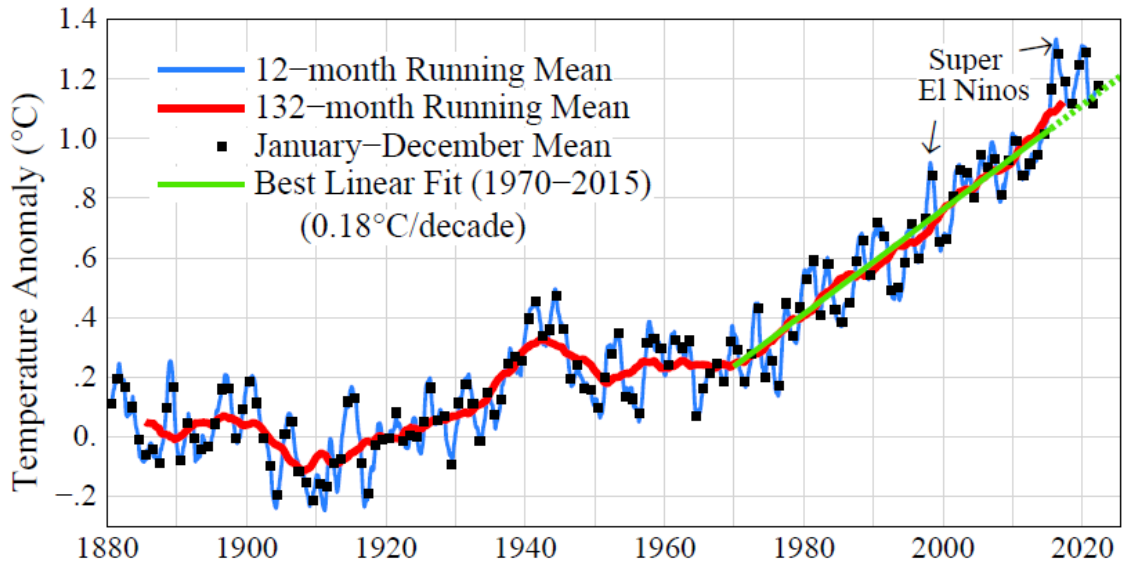
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Fig. 12. Observed global surface temperature change relative to 1880-1920 based on GISS analysis.[89,90] Data for 2022 is January-October mean. Monthly updates are available.[102]

the full effect of aerosols from land-use and human-caused fires is included. Aerosol offset of GHG warming was dominant until about 1970. The relative decline of aerosol forcing after 1970 (Fig. 11b) reflects the effect of clean air laws in parts of the world.

Fig. 11b, with and without the (light blue) preindustrial aerosols, encapsulates two alternative views of the historical role of human-caused aerosols. IPCC's aerosol history, with aerosol forcing gradually becoming important relative to GHG forcing, derives from aerosol simulations driven mainly by fossil fuel emissions. In the alternative view, civilization always produced aerosols as well as GHGs. Organized societies and rapid population growth began on coasts as stabilizing sea level increased coastal margin biologic productivity[103] and inland as agriculture developed. Wood was the main fuel; it would be surprising if the growing human population did not produce aerosols that affected clouds of a prior virgin atmosphere. Aerosols travel great distances, as shown by the presence of Asian aerosols in the United States and by satellite tracking of fire-produced aerosols. Small aerosol amounts in otherwise pristine marine air can produce a significant climate forcing. In our view, humans likely contributed to both rising GHG and aerosol climate forcings in the past 6000 years. No persuasive alternative explanation has been proffered for the absence of global warming in that period of increasing GHG amounts.

At face value, the steep decline in the aerosol offset of GHG forcing beginning in the early 1970s (Fig. 11b) – a result of stabilization of global aerosol forcing (Fig. 11a) – is a triumph of aerosol modeling, providing a partial explanation for the steep global temperature rise that began at that time (Fig. 12). However, we must bear in mind that the temperature record was known when the aerosol scenarios were developed. It is not a case of prediction and observational confirmation.

One implication of our alternative view of aerosol forcing history is that the human-caused negative aerosol climate forcing is 0.5 W/m^2 larger than obtained from models that deal with aerosol change only in the past century or two. Thus, the Faustian payment that will eventually come due is probably larger than usually assumed, as discussed below.

Global temperature and EEI constraints on aerosols and climate models

Global warming in the past 100 years (Fig. 12) is commonly used to estimate climate sensitivity, but by itself it is ill-suited for that purpose. Global warming does not yield a unique climate sensitivity because the warming depends on three major unknowns with only two fundamental constraints.[15] Unknowns are: ECS, net climate forcing (uncertain because aerosol forcing is unmeasured), and ocean mixing (uncertain based on evidence that many ocean models are too diffusive). Constraints are observed global temperature change (Fig. 12) and EEI.[78] Accurate knowledge of EEI began with the Argo float program,[104] which initiated well-calibrated measurements of ocean heat content globally in the first decade of the 21st century.

In an analysis[105] using early Argo data, we reduced unknowns to two by assuming ECS = 3°C. From EEI ~ 0.58 W/m^2 for the 2006-2010 solar minimum, we inferred a solar cycle mean EEI ~ 0.75 W/m^2. Our aerosol forcing versus time was from aerosol modeling of Koch[106] that incorporated changing technology factors defined by Novakov.[107] We solved for aerosol forcing in 2010, obtaining –1.63 ± 0.3 W/m^2 relative to 1880 – in the range estimated in the radiative forcing chapter of IPCC reports, but more negative than aerosol forcing used in most GCMs in CMIP and IPCC reports. Our interpretation – in agreement with Knutti[108] – was that most climate models compensate for excessive ocean mixing (which reduces surface warming) by using aerosol forcing less negative than the real world to achieve realistic global warming.

With ECS uncertain, we are back to an underdetermined system. Moreover, response functions for the GISS GCMs (Figs. 4 and 5) imply that climate response depends on more than ECS and ocean mixing; atmospheric processes also affect climate response time. We infer – for want of a likely alternative – that cloud changes are probably involved in the ultrafast feedbacks. Thus, a comprehensive analysis must include analysis of the role of cloud feedbacks in global climate change. A first step is to assess the mechanisms in ultrafast feedbacks, which can be done via many short (~2 year) GCM runs for 2×CO$_2$, as described above. If CMIP included such short simulations, it may identify observable feedbacks that produce high ECS in several GCMs.[82] A second step is to define response functions individually for CO$_2$, aerosols and solar irradiance. Aerosols, located mainly beneath clouds, may have a different response function than GHGs. The solar variability response is needed because the period with accurate EEI data is limited; solar change is a significant portion of the forcing change in that period.

Such an analysis would require many GCM runs and is beyond the scope of this paper. Instead, for the purpose of estimating today's aerosol climate forcing, we make the usual assumption that effective forcings defined by a primitive GCM[31] allow all forcings to be treated as equivalent and thus we use of a single response function in Eq. (4). This assumption is called into question by the indirect evidence that cloud feedbacks may be more complex and have a larger effect than in early GCMs, yet we may be able to draw some general conclusions with appropriate caveats.

Aerosol climate forcing and future warming estimates

Many combinations of climate sensitivity and aerosol forcing are consistent with observed global warming.[15] The response function for the GISS (2014) model yields a result (Fig. 13) typical of models in CMIP and IPCC reports: AR6 aerosol forcing yields good agreement with observed warming in the last half century – the period when human-made climate forcing overwhelms
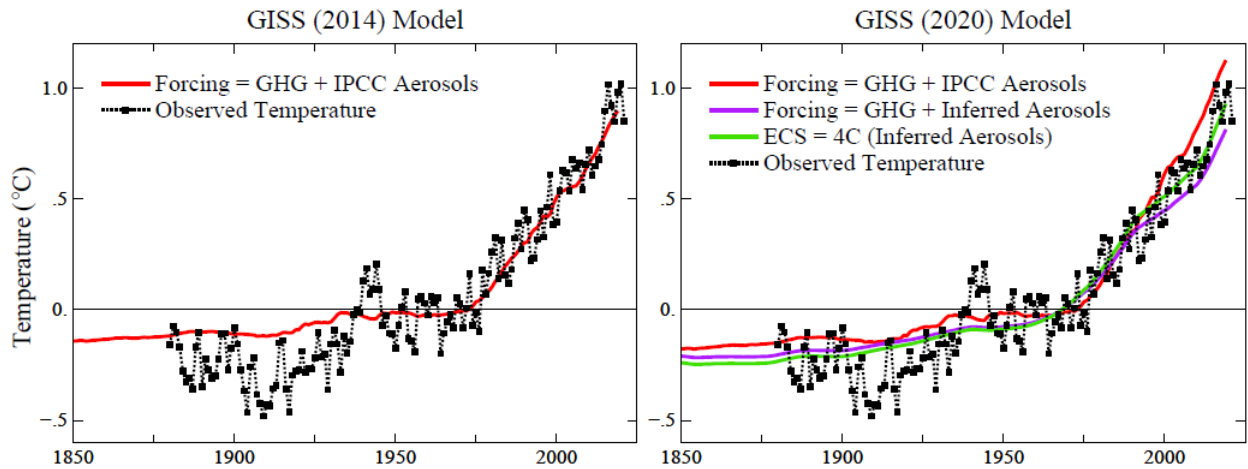
Fig. 13. Global temperature change T_G due to aerosols + GHGs calculated with Green's function Eq (4) using GISS (2014) and (2020) response functions (Fig. 4). Observed temperature is the NASA GISS analysis.[89,90] Base period: 1951-1980 for observations and model.

natural forcings, unforced climate variability, and flaws in observed warming due to inadequate data. However, agreement with observed temperature also can be achieved by climate models with high ECS. The GISS (2020) model, with ECS = 3.5°C, yields greater warming than observed if IPCC aerosol forcing is used (Fig. 13), but less warming than observed for the aerosol scenario inferred in our 2011 EEI study.[105] This latter aerosol scenario yields close agreement with observed warming if ECS ~ 4°C (green curve in Fig. 13).[109] Agreement also can likely be achieved with a still higher ECS by use of a larger (more negative) aerosol forcing.

IPCC AR6 WG1 best estimate aerosol forcing (Table AIII.3)[13] is near maximum (negative) value by 1975, then nearly constant until the 21st century, when it rises to –1.09 W/m² in 2019 (Fig. 14). This AR6 aerosol forcing is in the upper (less negative) portion of the range estimated in the radiative forcing chapter of AR6.[110] In contrast, some aerosol models, including those of Koch[106] and Bauer (Fig. 14), yield substantial growth of aerosol forcing after 1975.
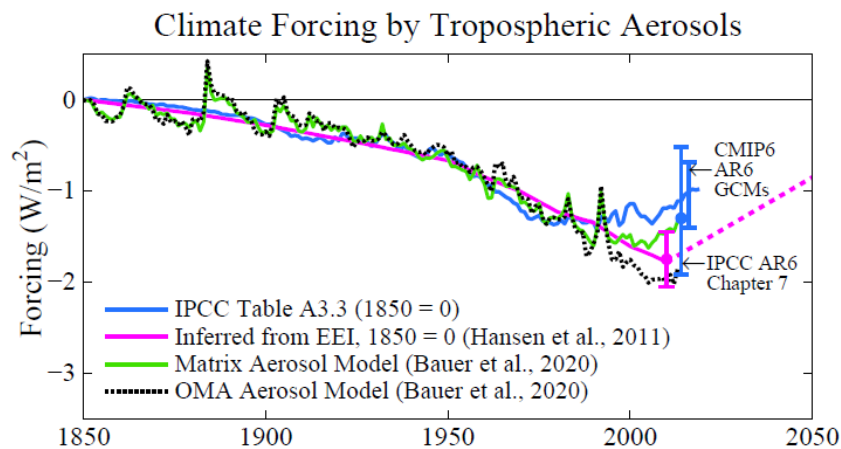

Fig. 14. Aerosol forcing relative to 1850 from Annex III of IPCC AR6, from two aerosol models of Bauer et al. (2020)[111] and as inferred in the EEI study of Hansen et al. (2011).[105]

The issue we raise is the magnitude of aerosol forcing. Aerosol forcing is unmeasured and hard to model because it involves complex aerosol effects on clouds. The result is wide latitude in the aerosol forcing used in climate simulations. Two GCM problems cause a tendency to minimize aerosol forcing: (1) excessive mixing of heat into the deep ocean, and (2) a too-small ECS, likely due to GCM failure to fully capture cloud feedbacks. An analysis based on observed EEI and global temperature, largely independent of GCMs, concluded[105] that aerosol forcing was about –1.6 W/m^2 in 2010 relative to 1880. Our present finding of ECS ~ 4°C favors a slightly larger aerosol forcing (Fig. 13) for consistency with observed global warming.[112] We conclude that the peak human-made aerosol forcing was likely in the (negative) range 1.5-2 W/m^2 relative to preindustrial and more negative relative to a pristine (pre-human) atmosphere.

Declining aerosol amount implies acceleration of global warming above the 1970-2010 rate (0.18°C per decade). Just as 1970 was a hinge point for global warming (Fig. 12), so 2010 is another hinge point as it marks transition to declining aerosols from China (a decline not captured well in most CMIP6 models[113]), where emissions of SO_2 (a principal precursor of aerosols) declined 70 percent between 2006 and 2017,[114] and strengthening of regional and global regulations on ship emissions in 2015 and 2020 by the International Maritime Organization (IMO).[115] A review[116] of aerosol forcing estimates for 2000-2019 found a consensus that aerosol forcing decreased (became less negative), but the decrease among the estimates ranged from about 0.1 W/m^2 to about 0.3 W/m^2 for the 20-year period. Uncertainties in each case are substantial, but together they make a persuasive case that the change of aerosol forcing in that period is of the opposite sign from that in the 20th century, i.e., aerosol change no longer partly offsets growth of GHG climate forcing, rather it adds to the GHG forcing growth.

Expectation of continued decline in aerosol amount is based in part on growing concern about health effects of aerosol pollution that causes millions of deaths per year[86] and global trends toward renewable energy, nuclear power, and replacement of coal by gas. Reduction of human-made aerosols by half between 2010 and 2050 would contribute a climate forcing about +0.2 W/m^2 per decade. Although an aerosol reduction that rapid is uncertain, we expect some reduction and a forcing increase of at least +0.1 W/m^2 per decade for the reasons given here.

Average GHG climate forcing increase since 1970 is about 0.45 W/m^2 per decade, but about 0.5 W/m^2 in the past decade (Fig. 15). This graph includes all well-mixed GHGs and changes of O_3 and stratospheric H_2O associated with CH_4 change. It thus misses only about half of the O_3 change, which is estimated to cause a forcing of about 0.2 W/m^2 over 1750-2021, about 5% of the total GHG forcing (see Supporting Material). GHG climate forcing growth has continued unabated since the 1997 Kyoto Protocol and subsequent agreements of the Conference of the Parties (COP) meetings, such as the Paris Agreement of 2015, and the growth rate has even increased. For reasons given in the Discussion section below, we expect a similar growth rate to continue for the next few decades, at least as long as polices are based on goals and targets.

During 1970-2010 the drive for global warming increased ~0.3 W/m^2 per decade (+0.45 W/m^2 for GHGs, –0.15 W/m^2 for aerosols). Going forward from 2010 for a few decades, we expect this drive to be at least 0.5-0.6 W/m^2 per decade, for reasons given above. Global temperature responds reliably to climate forcing on decadal time scales, with about 50% of the response in the first decade, with about 15% more in the next 100 years (Fig. 4b). Thus, the rate of global
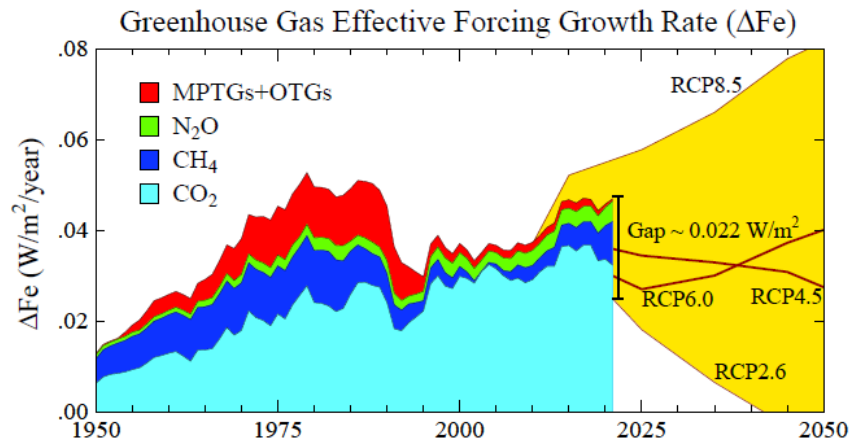
Fig. 15. Update[41] of annual growth of climate forcing by GHGs, including part of O₃ forcing via the efficacy of CH_4 forcing (cf. Supporting Material). MPTG and OTG are Montreal Protocol and Other Trace Gases. RCP2.6 is a scenario designed to keep global warming below 2°C.

temperature change in 2010-2040 should be nearly proportional to the multi-decadal growth rate of the climate forcing. Therefore, we estimate that the global warming rate in 2010-2040 will be at least 50% greater than in 1970-2010, i.e., at least 0.27°C per decade.

Interpretation of past climate change and prediction of the future could be more precise if aerosol climate forcing were monitored. Aerosol monitoring could be analogous to the method used for GHGs. The GHG forcing is obtained by measuring GHG changes accurately and making a radiative transfer calculation with a realistic global distribution of clouds. A similar approach for aerosols requires global monitoring of changes of aerosol and cloud particle microphysics with precision adequate to define their climate forcing.[117,118] In the absence of such Keeling-like global monitoring, progress has been made via limited satellite measurements of aerosol and cloud properties, field studies, and aerosol and cloud modeling. These data provide an estimate of the small direct aerosol forcing in cloud-free regions. The indirect forcing caused by aerosol-induced cloud changes must be extracted from natural (unforced) cloud variability and cloud changes caused by ongoing global warming. In the absence of precise global monitoring of aerosol and cloud particle microphysics, progress has relied heavily on modeling of aerosol-cloud physics and testing results against specific observations.

The great inadvertent aerosol experiment

Sulfate aerosols are a cloud condensation nuclei (CCN), so ship emissions result in a larger number of smaller cloud particles, affecting cloud albedo and cloud lifetime.[119] Ships provide a large percentage of sulfates in the North Pacific and North Atlantic regions (Fig. 16). Ship-tracks (cloud trails) produced by aerosol CCN are apparent, but it has been suggested that cooling by these clouds is overestimated because of cloud liquid water adjustments.[120] On the other hand, Manshausen et al.[121] present evidence that liquid water path (LWP) effects are mis-estimated, including regions without visible ship-tracks; they estimate a LWP forcing $- 0.76 \pm 0.27$ W/m², in stark contrast with the IPCC estimate of $+ 0.2 \pm 0.2$ W/m². Wall et al.[122] use satellite observations to quantify relationships between sulfates and low-level clouds; with help of the "opportunistic experiment" provided by decrease of air pollution downwind of eastern North
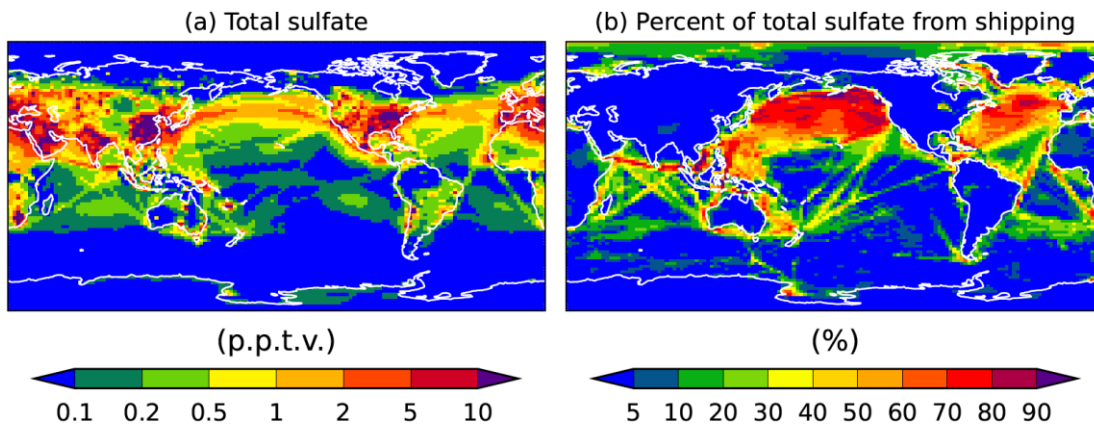
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(a) Total sulfate   (b) Percent of total sulfate from shipping

(p.p.t.v.)   (%)

0.1   0.2   0.5   1   2   5   10   5   10   20   30   40   50   60   70   80   90

Fig. 16. Total sulfate (parts per trillion by volume) and percentage of total sulfate provided by shipping in simulations of Jin et al.[123] prior to IMO regulations on sulfur content of fuels.

America, they infer a sulfate indirect aerosol forcing of -1.11 ± 0.43 W/m^2 over the global ocean, consistent with our inference of a large (negative) total aerosol forcing.

IMO emission regulations provide a great opportunity for insight into aerosol climate forcing. Sulfur content of fuels was limited to 1% in 2010 near the coasts of North America and in the North Sea, Baltic Sea and English Channel, and further restricted there to 0.1% in 2015.[115] In 2020 a limit of 0.5% was imposed worldwide. The 1% limit did not have a noticeable effect on ship-tracks, but a striking reduction of ship-tracks was found after the 2015 IMO regulations, especially in the regions near land where emissions were specifically limited.[124] Following the additional 2020 regulations,[125] global ship-tracks were reduced more than 50%.[126]

Earth's albedo (reflectivity) measured by CERES (Clouds and Earth's Radiant Energy System) satellite-borne instruments[79] over the 22-years March 2000 to March 2022 reveal a decrease of albedo and thus an increase of absorbed solar energy coinciding with the 2015 change of IMO emission regulations. Global absorbed solar energy is +1.01 W/m^2 in the period January 2015 through March 2022 relative to the mean for the first 10 years of data (Fig. 17). This increase is 4.7 times greater than the standard deviation (0.22 W/m^2) of annual absorbed solar energy in the
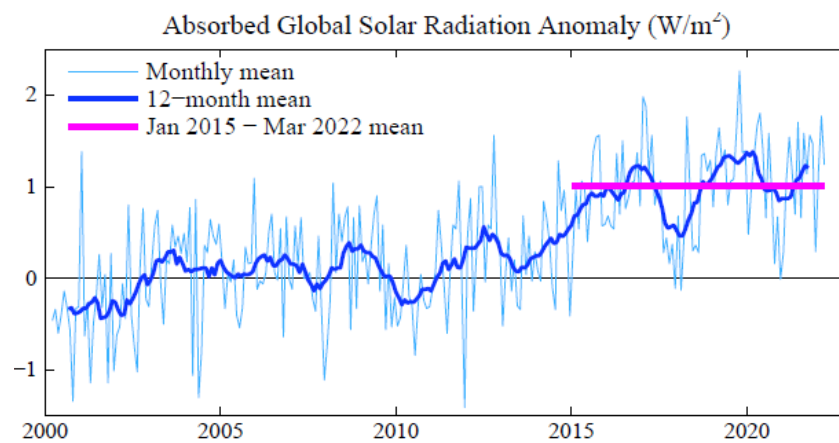

Fig. 17. Global absorbed solar radiation relative to mean of the first 120 months of CERES data. CERES data available at http://ceres.larc.nasa.gov/order_data.php
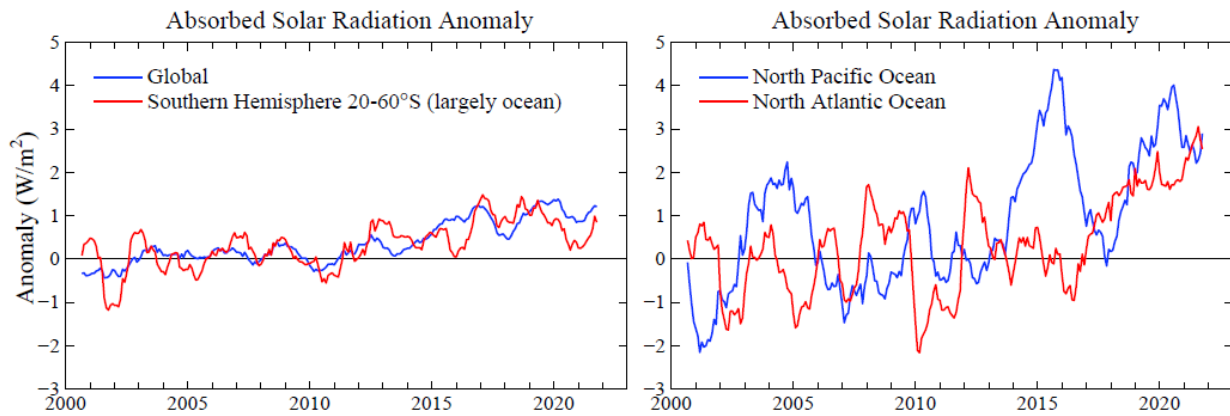
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Fig. 18. Absorbed solar radiation for indicated regions relative to first 120 months of CERES data. Southern Hemisphere 20-60°S is 89% ocean. North Atlantic is (20-60°N, 0-60°W) and North Pacific is (20-60°N, 120-220°W). Data source: http://ceres.larc.nasa.gov/order_data.php

first 10 years of data and 4.5 times greater than the standard deviation (0.23 W/m^2) of CERES data through December 2014. The increase of absorbed solar energy is notably larger than estimated potential CERES instrument drift, which is <0.085 W/m^2 per decade.[79] Increased solar energy absorption occurred despite 2015-2020 being the declining phase of the ~11-year solar irradiance cycle.[127] Nor can increased absorption be attributed to correlation of Earth's albedo (and absorbed solar energy) with the Pacific Decadal Oscillation (PDO): the PDO did shift to the positive phase in 2014-2017, but it returned to the negative phase in 2017-2022.[128]

Given the large magnitude of the solar energy increase, cloud changes are likely the main cause. Quantitative analysis[128] of contributions to the 20-year trend of absorbed solar energy show that clouds provide most of the change. Surface albedo decrease due to sea ice decline contributes to the 20-year trend in the Northern Hemisphere, but that sea ice decline occurred especially in 2007, with minimum sea ice cover reached in 2012; over the past decade as global and hemispheric albedos declined, sea ice had little trend.[129] Potential causes of the cloud changes include: 1) reduced aerosol forcing, 2) cloud feedbacks to global warming, 3) natural variability.[130] Absorbed solar energy was 0.78 W/m^2 greater in 2015-2021 than in the first decade of CERES data at latitudes 20-60°S (Fig. 18), a region of relatively little ship traffic. This change is an order of magnitude larger than the estimate of potential detector degradation.[79] Climate models predict a reduction of cloud albedo in this region as a feedback effect driven by global warming.[131] Continued monitoring of absorbed energy can confirm the reality of the change, but without global monitoring of detailed physical properties of aerosols and clouds,[101] it will be difficult to apportion observed change among the candidate causes.

The North Pacific and North Atlantic regions of heavy ship traffic are ripe for more detailed study of cloud changes and their causes, although unforced cloud variability is large in such sub-global regions. North Pacific and North Atlantic regions both have increased absorption of solar radiation after 2015 (Fig. 18). The 2014-2017 maximum absorption in the North Pacific is likely enhanced by reduced cloud cover during the positive PDO, but the more recent high absorption is during the negative PDO phase. In the North Atlantic. The persistence of increased absorption for the past several years exceeds prior variability, but longer records plus aerosol and cloud microphysical data are needed for interpretation.

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SUMMARY

Climate sensitivity

The equilibrium climate sensitivity (ECS) estimated by the 1979 Charney study – 3°C for $2\times CO_2$ – stood for more than 40 years. The current IPCC report[13] concludes that 3°C is their best estimate for ECS. We find, however, that ECS is at least near 4°C.

Earth's climate history provides reliable assessment of ECS because it allows comparison of equilibrium climate states. All feedbacks are included in comparisons of real-world equilibrium climate states. In contrast, transient climate change such as that occurring today is affected by innumerable, partially complete, climate feedback processes that occur on a range of time scales. The most accurate evaluation of ECS is from comparison of recent glacial and interglacial climates because atmospheric composition is known precisely from ice core data.

The fundamental constraint that forces a conclusion that ECS is at least approximately 4°C is the requirement that Earth was in energy balance during the ice ages. It was recognized almost 40 years ago that CLIMAP[21] (and later MARGO[49]) boundary conditions for the last ice age (LGM) implied[7] the impossible conclusion that Earth was out of energy balance during the LGM by about 2 W/m^2, equivalent to a (negative) forcing half that of $2\times CO_2$. However, at that time, a conclusion of high climate sensitivity needed to challenge the extensive, respected, CLIMAP analysis of climate conditions during the LGM. Resolution of that matter lay dormant until improved definition of LGM conditions became available.

Our assessment is that recently developed techniques of Tierney at al.[23] and Seltzer et al.[26] allow a firm conclusion that LGM global cooling relative to preindustrial conditions was much greater than the ~3.5°C implied by CLIMAP and MARGO. This leads to a $2\times CO_2$ equilibrium climate sensitivity (ECS) at least near 4°C. The Eemian/PGM (prior glacial maximum) climate change provides a valuable check because of the complex Holocene GHG history and the possibility that human-made aerosols contributed a negative climate forcing in the second half of the Holocene. The Eemian/PGM case confirms and strengthens the conclusion that ECS is at least near 4°C for $2\times CO_2$ and by itself would favor a best estimate near 5°C. ECS assessment could be tightened via a climate model intercomparison project to define accurately the surface climate forcing during the LGM and PGM.

ECS is the climate sensitivity defined by the Charney study, with ice sheets and GHGs fixed. Earth system sensitivity (ESS)[16,17,18] is the complete climate sensitivity in which the climate system – including GHGs and ice sheets, which we refer to (somewhat misleadingly) as slow feedbacks – responds to the imposed forcing. During the past 800,000 years, CO_2 provided ~80% of GHG climate forcing, i.e., the total GHG forcing is 25% larger than the CO_2 forcing. Thus, the climate sensitivity in which non-CO_2 GHG feedbacks are allowed to change increases from ~4°C to ~5°C. When all feedbacks, including ice sheets, are allowed to respond to the climate forcing, the equilibrium response is approximately doubled, i.e., ESS is ~ 10°C.

Earth warmed 1.2°C in the past century (Fig. 12) and is out of energy balance by about +1 W/m^2, so climate is headed toward a warmer state than existed in the period covered by ice cores. The Pliocene provides the best chance for empirical assessment of climate sensitivity for a warmer

Earth that still has ice sheets. The chief difficulty is uncertainty about Pliocene CO_2 amount, which is estimated to have been 300-450 ppm based on sediment-derived CO_2 proxies,[132] but CO_2 amounts from boron and alkenone proxies diverge strongly in the Pliocene.[133] Unless and until knowledge of Pliocene CO_2 is reliably sharpened, we can only conclude that the Pliocene data are not inconsistent with our assessed ECS.[28]

The Paleocene-Eocene Thermal Maximum (PETM) provides an opportunity to assess climate sensitivity in the absence of large ice sheets. PETM warming of about 5-6°C was driven by an approximate doubling of CO_2, which occurred over a period of 3,000-10,000 years.[19,20] Because there were no large ice sheets, this empirical estimate of ESS is converted to ECS by accounting for forcing by changes of non-CO_2 GHGs. If we assume that forcing by non-CO_2 GHGs increased in the same proportion (~25%) to CO_2 forcing as in the period covered by ice core data, we obtain an ECS estimate of 4-5°C for 2×CO_2. One review[19] of PETM data infers ECS ~3.6°C with 66% confidence that ECS is in the range 2.3-4.7°C, but a recent PETM study,[134] aided by GCM-guided analysis of the sparse data, estimates the PETM CO_2 increase as 86% of a CO_2 doubling, thus finding ECS ~6.5°C, if non-CO_2 gases are fixed. With the assumption that non-CO_2 gases amplified the CO_2 forcing by 25%, we obtain ECS ~ 5°C. High ECS in a warm ice-free climate may be a result of amplifying cloud feedbacks,[18,135] and a rising tropopause may also contribute to high ECS in warm climates.[136]

Other studies of ECS based on paleoclimate change yield a wide range of estimates, mainly because of the large uncertainty in CO_2 amount. Present knowledge of long-term CO_2 change is analogous to knowledge of LGM SST 40 years ago: at least some of the estimates of paleo CO_2 must be flawed. Sophisticated statistical treatments of the data do not eliminate effects of wrong data. Until accurate knowledge of long-term CO_2 history is achieved, the best analysis of ECS is that provided by the period with ice core GHG data.

Global warming in the pipeline

High climate sensitivity implies that there is more global warming in the pipeline – and greater climate impacts – than has been widely recognized. The poster child for warming in the pipeline is Fig. 7, showing that equilibrium warming for today's GHG level, including slow feedbacks, is about 10°C. Today's level of particulate air pollution reduces equilibrium warming to about 7°C.

How can the equilibrium warming be so large with today's CO_2 level of "only" 415 ppm, a level that might have been reached in the Pliocene? Many of today's GHGs, such as CFCs, did not exist in paleoclimate and others have increased by extraordinary amounts. With all trace gases included, the increase of GHG effective forcing between 1750 and 2021 is 4.09 W/m^2, which is equivalent to increasing the 1750 CO_2 amount (278 ppm) to 561 ppm (formulae in Supporting Material). We have already reached the GHG climate forcing level of doubled CO_2.

The 7-10°C global warming is the eventual response if today's level of GHGs is fixed and the aerosol amount is somewhere between its year 2000 amount and preindustrial amount. Given the time required for the ocean to warm and ice sheets to shrink to new equilibria, this is not a warming that will be experienced by today's public, but it is an indication of the path upon which we have set our planet. Moreover, we are in the process of setting the planet upon an even more extreme course as the net human-made climate forcing and global temperature are continuing to

rise, even at accelerating growth rates. As long as there is such a large gap between the present climate and the equilibrium climate, the climate system will drive hard toward hotter climate.

Doubled CO_2 is already a huge climate forcing that will have large impacts, if left in play for long. The large global warming in the pipeline today is not widely appreciated. Civilization and its infrastructure are not set up for a $2\times CO_2$ world. We need to reduce human-made climate forcing before it exerts its full influence on the climate system. It will take time to halt and reverse growth of GHGs, so it is important to understand response times of the climate system.

Climate response times

We expected climate response time – as simulated by an atmosphere-ocean GCM with fixed ice sheets – to become faster as ocean models reduced excessive downward mixing of heat.[71] This expectation was not met when we compared two generations of the GISS GCM. The GISS (2020) GCM is demonstrably improved[34,35] in its ocean simulation over the GISS (2014) GCM as a result of higher vertical and horizontal resolution, more realistic parameterization of sub-grid scale motions, and correction of errors in the ocean computer program.[34] Yet the time required for the model to achieve 63% of its equilibrium response remains about 100 years. There are two reasons for this, one that is obvious and one that is more interesting.

The surface in the newer model warms as fast as in the older model, but it must achieve greater warming to reach 63% of equilibrium because its ECS is higher, which is one reason that the response time stays long. The other reason is that Earth's energy imbalance (EEI) in the newer model decreases rapidly. EEI defines the rate that heat is pumped into the ocean, so a smaller EEI implies a longer time for the ocean to reach its new equilibrium temperature. Quick drop of EEI – in the first year after introduction of the forcing – implies existence of an ultrafast feedback in the GISS (2020) model. For want of an alternative with such a large effect on Earth's energy budget, we suspect a rapid cloud feedback and we suggested a set of brief GCM runs that could define cloud changes and other diagnostic quantities to an arbitrary accuracy.

The Charney report[4] recognized that clouds were a main cause of a wide range in ECS estimates. Today, clouds still cast uncertainty on climate predictions. Several CMIP6[33] GCMs have ECS of ~ 4-6°C for $2\times CO_2$,[137,138] with the high sensitivity caused by cloud feedbacks.[82] Even if the most extreme cloud feedbacks are exaggerated, these models draw attention to this large uncertainty in climate models. As cloud modeling progresses, it will aid understanding if climate models report their $2\times CO_2$ temperature and EEI response functions.

Fast EEI response – faster than global temperature response – has a practical effect: observed EEI understates the reduction of climate forcing required to stabilize climate. Although the magnitude of this effect is uncertain (see Supporting Material), it makes the task of restoring a hospitable climate and saving coastal cities more challenging. On the other hand, long climate response time implies a potential for educated policies to affect the climate outcome before undesirable consequences have occurred. For the purpose of avoiding unacceptable outcome, we need quantitative understanding of the major climate forcings and feedbacks.
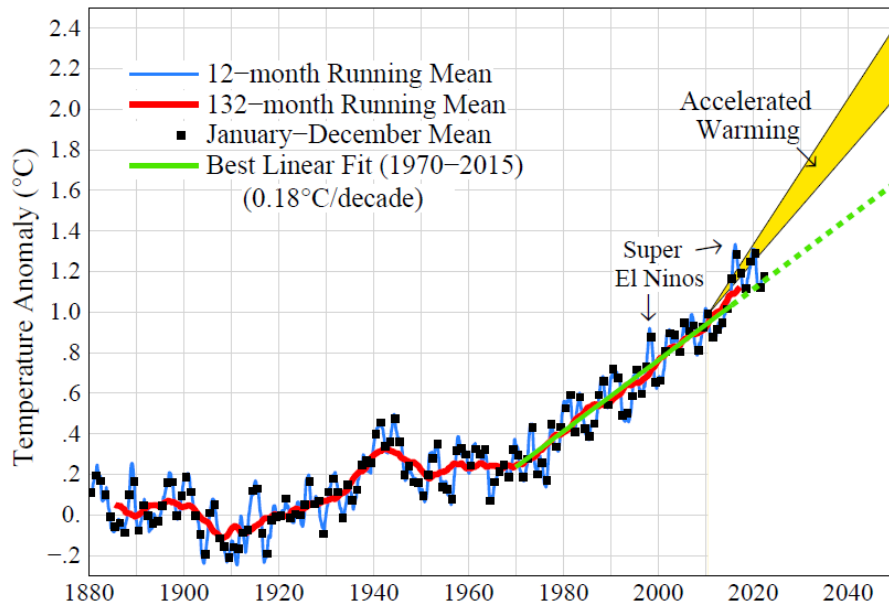
Fig. 19. Accelerated warming rate post-2010 (yellow area) if aerosol reductions approximately double the net (GHG + aerosol) climate forcing. Upper and lower edges of the yellow area are 0.36 and 0.27°C per decade warming rates.

Aerosol climate forcing

Aerosol climate forcing is larger than the recent (AR6) IPCC estimate. Aerosols probably provided a significant climate forcing prior to the industrial revolution. We know of no other persuasive explanation for the absence of significant global warming during the past 6000 years (Fig. 8), a period in which the GHG forcing increased 0.5 W/m^2. Climate models that do not incorporate a growing negative aerosol forcing yield significant warming in that period,[139] a warming that, in fact, did not occur. Negative aerosol forcing, increasing as civilization developed and population grew, should be expected. As humans burned fuels at a growing rate – wood and other biomass for millennia and fossil fuels in the industrial era – aerosols as well as GHGs were an abundant, growing, biproduct. The wood-burning aerosol source has continued in modern times.[140] GHGs are long-lived and accumulate, so their forcing eventually dominates unless aerosol emissions grow higher and higher – the Faustian bargain.[85]

We conclude that peak aerosol climate forcing – in the first decade of this century – was of a (negative) magnitude of at least 1.5-2 W/m^2. We estimate that the GHG plus aerosol climate forcing during the period 1970-2010 grew +0.3 W/m^2 per decade (+0.45 from GHG, – 0.15 from aerosols), which produced observed warming of 0.18°C per decade. With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 19).

Summary of present climate status

GHG climate forcing imagined by Charney, Tyndall and other greenhouse giants[1] is no longer imaginary: the GHG climate forcing increase since 1750 (~4.1 W/m^2) is equivalent to 2×CO$_2$. GHG forcing is now growing by almost 0.5 W/m^2 per decade (Fig. 15) and it is no longer partly

offset by increasing aerosols. The situation that E.E. David warned about is now coming into play. As David noted, a system with long delay and amplifying feedbacks can break down, unless "anticipation is built into the loop." Required anticipation was development of energies that produce no GHGs. Instead, the fossil fuel industry, subsidized by the government, developed fracking to enlarge the pool of available fossil fuels.

Climate's delayed response allowed policy procrastination, as the impacts of climate change were not glaringly apparent to the public. The designated scientific authority (IPCC), relying primarily on climate models, continued for decades to report a broad range for estimated global climate sensitivity: 1.5-4.5°C for $2\times CO_2$, with non-negligible possibility that it was less than 1.5°C. Meanwhile, Earth's paleoclimate history tells a clearer story: climate sensitivity is near the high end of that long-time estimated range. Another excuse for inaction was hope that large climate impacts will be delayed until humanity is wealthier and able to mitigate problems. Hope of lethargic climate was based in part on the millennial time scale of large paleoclimate changes (Fig. 2). However, the timescale of those paleoclimate changes results more from the timescale of the forcings, rather than an inherent lethargy of the climate system. Our second perspective article – *Sea Level Rise in the Pipeline*[93] – concludes, as outlined already,[15] that exponential increase of sea level rise to at least several meters is likely if high fossil fuel emissions continue. Specifically, it is concluded that the time scale for loss of the West Antarctic ice sheet and multimeter sea level rise would be of the order of a century, not a millennium. Eventual impacts would include loss of coastal cities and flooding of regions such as Bangladesh, the Netherlands, a substantial portion of China, and the state of Florida in the United States. For practical purposes, the losses would be permanent. Such outcome could be locked in soon, which creates an urgency to understand the physical system better and to take major steps to reduce the human-made drive of global warming.

Rapid human-made global warming that began in about 1970 (Fig. 12) has taken climate far out of the Holocene range, the climate to which civilization is adapted, but ocean and ice sheet inertia still allow reasoned policy response that may preserve a bright future for young people and future generations. The basic requirement to preserve shorelines is return to a climate no warmer than the mid-20th century, possibly a bit cooler. This cooler climate will also address other problems such as overheating of low latitudes and increasing regional climate extremes.

Policy implications

Climate science has exposed a crisis that the world is loath to fully appreciate. Delayed response of the climate system has allowed huge global warming to build up in the pipeline. Humanity is now entering the period of consequences. Scientists – as informed witnesses of ongoing efforts of the world to deal with climate change via the Framework Convention and IPCC processes – have the opportunity, indeed, the obligation, to assess the present course of those efforts.
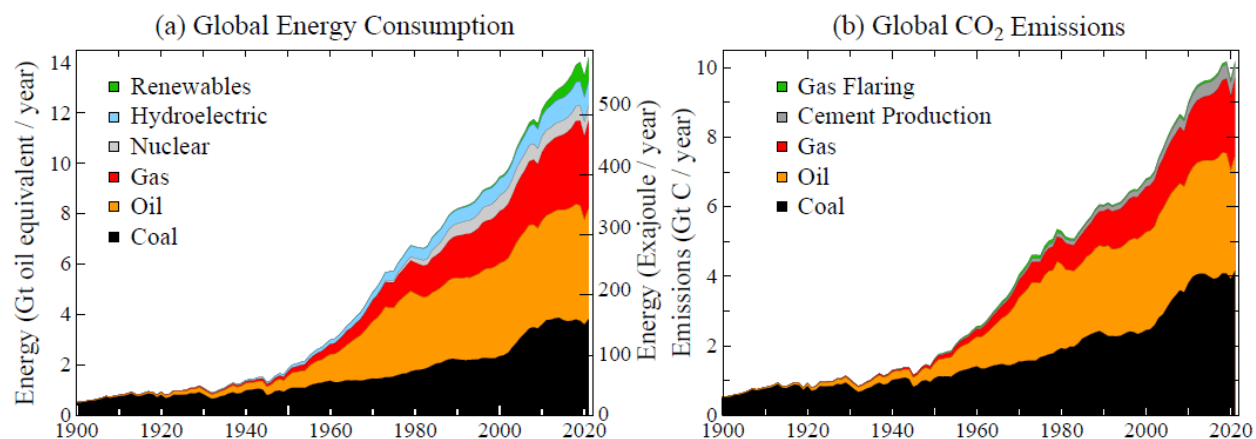
Fig. 20. Global energy consumption and CO_2 emissions (Hefner et al.[141] and BP[142]; see text).

Fossil fuels powered the industrial revolution as the energy source that raised living standards in much of the world. Fossil fuels continue to provide most of the world's energy (Fig. 20a) and produce most of the CO_2 emissions (Fig. 20b). Fossil fuel reserves and recoverable resources are more than enough to provide most of the world's energy for the rest of this century,[143] and barring new effective policies they will continue to do so – and they will continue to drive global warming at an unprecedented rate that we now understand is exceedingly dangerous.

Climate policy under the Framework Convention is demonstrably flawed. Empirical data (Fig. 20) confirm that as long as fossil fuel pollution can be dumped in the air free of charge, agreements such as the 1997 Kyoto Protocol and 2015 Paris Agreement have little effect on global emissions.[144] The reason is clear: much of the world is in early or middle stages of economic development. Energy is required to raise living standards, and fossil fuels continue to be the most convenient, affordable source for that energy. Thus growth of emissions is occurring in the developing world (Fig. 21a), while the developed world is still the larger source of the cumulative emissions (Fig. 21b) that drive climate change.[145,146] Thus, exhortations at annual COP meetings, imploring each nation to set tighter emission targets, have little effect on global emissions, as is blatantly apparent in the yawning gap between reality and the RCP2.6 scenario (Fig. 15) designed to keep global warming below 2°C.

Moreover, a 2°C (or 1.5°C) target is more politically-based or practically-based than science-based. The science-based target, we assert, should be return to Holocene climate, the climate in which civilization developed and is adapted to. We must avoid passing points-of-no-return with unacceptable consequences, such as loss of the West Antarctic ice sheet and thus loss of global cities. That goal should also suffice for other unacceptable consequences, such as avoiding unlivable conditions in the tropics and subtropics. A crucial issue that science must address is the magnitude and duration of Holocene-overshoot that can occur without passing points-of-no-return. We are already into overshoot territory and greater overshoot is in the offing.

Given the situation that we have allowed to develop, three actions now seem to be essential.

First, a rising global price on GHG emissions must underly energy and climate policies, with enforcement by border duties on products from countries that do not have an internal carbon fee or tax. Public buy-in and maximum effectiveness require the collected funds to be distributed to
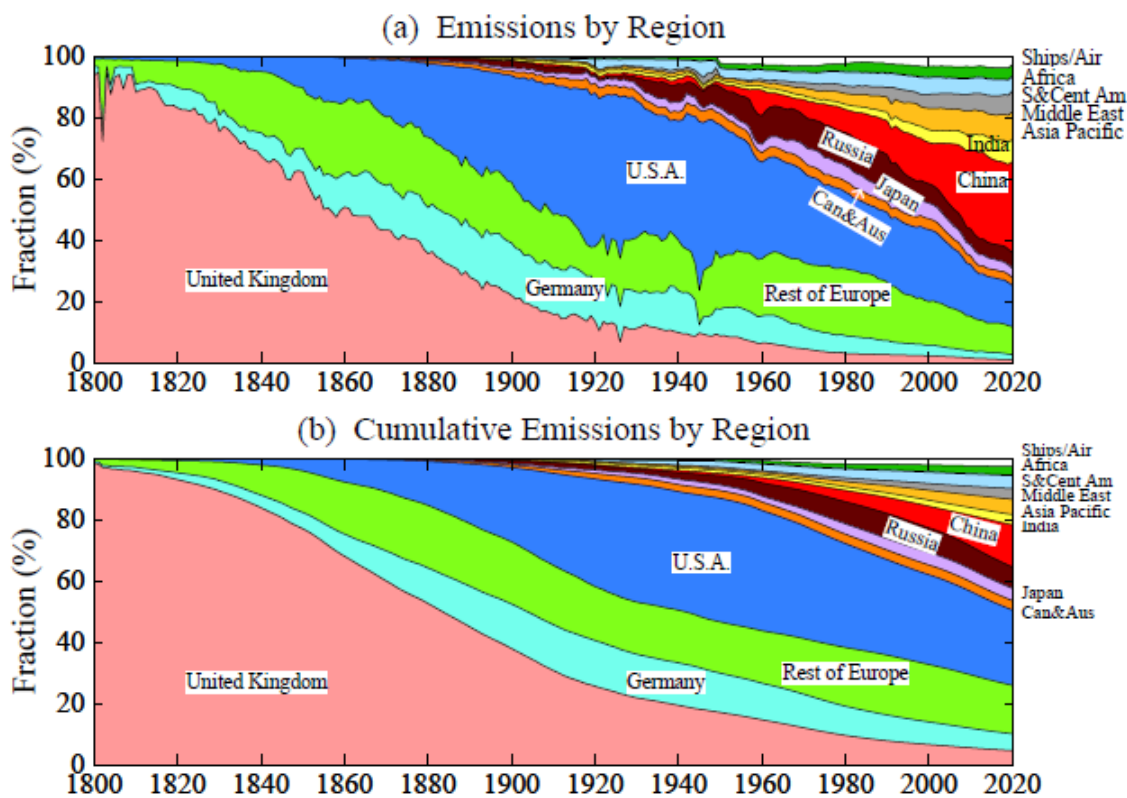
Fig. 21. Fossil fuel CO_2 emissions by nation or region as a fraction of global emissions. Data sources: Heffner et al.[141] for 1751-2017 concatenated with BP[142] for 2018-2020.

the public, an approach that helps address global wealth disparities. Economists in the U.S. overwhelming support such a carbon fee-and-dividend;[147] college and high school students, who have much at stake, join in advocacy.[148] The science rationale for a rising carbon price with a level playing field for energy efficiency, renewable energies, nuclear power, and all innovations has long been understood, but not achieved. Instead, fossil fuels and renewable energy are heavily subsidized, including use of "renewable portfolio standards" that allow utilities to pass added costs to consumers. Nuclear energy has thus been relatively disadvantaged and excluded as a "clean development mechanism" under the Kyoto Protocol, based in part on myths about damage caused by nuclear energy that are not supported by scientific facts.[149] A rising carbon fee is an underlying strategy to develop a mix of electricity sources needed to achieve rapid decarbonization, low cost, and reliability of the energy system.

Second, human-made geoengineering of Earth's climate must be rapidly phased out. The best measure of geoengineering is Earth's energy imbalance (EEI), which has reached a level of at least 0.9 W/m^2 averaged over the solar cycle (equivalent to the energy of 600,000 Hiroshima atomic bombs per day) with most of the excess energy heating the ocean and melting ice. Realistic phasedown of emissions alone cannot remove this imbalance in less than several decades (cf. Fig. 15 and discussion thereof), which may be too slow to avoid locking in loss of the West Antarctic ice sheet and sea level rise of several meters. Removal of human-made GHGs from the air will be spurred by a carbon price, but GHG removal sufficient to reduce EEI to zero may require decades, if it is even feasible. Given that GHG forcing is still rising rapidly, highest
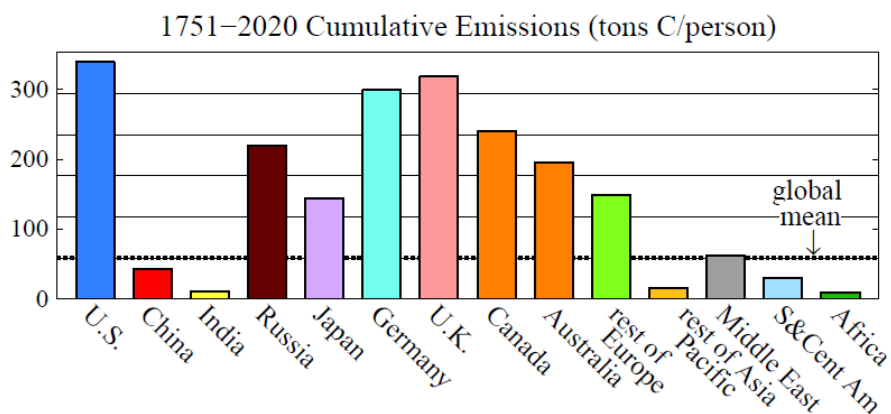
Fig. 22. Cumulative per capita national fossil fuel emissions.[150]

priority must be given to phasing down emissions. However, given that GHG forcing is already 4 W/m^2, it may be necessary to temporarily affect EEI via solar radiation management (SRM), if the world is to avoid disastrous consequences, including large sea level rise. Risks of such intervention must be defined, as well as risks of no intervention. Thus the U.S. National Academy of Sciences recommends research on SRM.[151] An example of SRM is injection of atmospheric aerosols at high southern latitudes, which global simulations suggest would cool the Southern Ocean at depth and limit melting of Antarctic ice shelves.[15,152] The most innocuous aerosols may be salt or fine salty droplets extracted from the ocean and sprayed into the air by autonomous sailboats.[153] This approach has been discussed for potential use on a global scale,[154] but even use limited to high latitudes in the Southern Hemisphere will require extensive research and forethought to avoid unintended adverse effects.[155] The present decade may be the last opportunity to develop the knowledge, technical capability, and political will for the actions that are needed to save global coastal regions from long-term inundation.

Third, effective global cooperation is needed to achieve the required reduction of GHG climate forcing over the next several decades. Higher income countries – most of them in the West – are responsible for most of the cumulative fossil fuel CO_2 emissions (Fig. 21b and Fig. 22), which are the main drive for global warming, [145,146] even though the West constitutes a small fraction of global population. De facto cooperation between the West and China drove down the price of renewable energy, especially solar power, and further cooperation is needed to develop emission-free technologies for the rest of the world that will be the source of most future GHG emissions (Fig. 21a). Given China's huge demand for carbon-free energy if its coal use is to be displaced, China-U.S. cooperation in development of modern nuclear power was proposed, but then stymied by U.S. prohibition of technology transfer.[156] Competition is normal, but if there is a will it can be managed, reaping the benefits of cooperation over confrontation.[157] Of late, priority seems to be given to economic and military hegemony, despite recognition of the long-term existential threat posed by climate change. It is important to not foreclose the possibility of return to a more ecumenical perspective of our shared future. In this situation, scientists can improve global prospects by maintaining and expanding international cooperation. Public and political awareness of the gathering climate storm will grow this decade as climate anomalies increase, so it is important to improve scientific understanding and lay groundwork for effective actions.
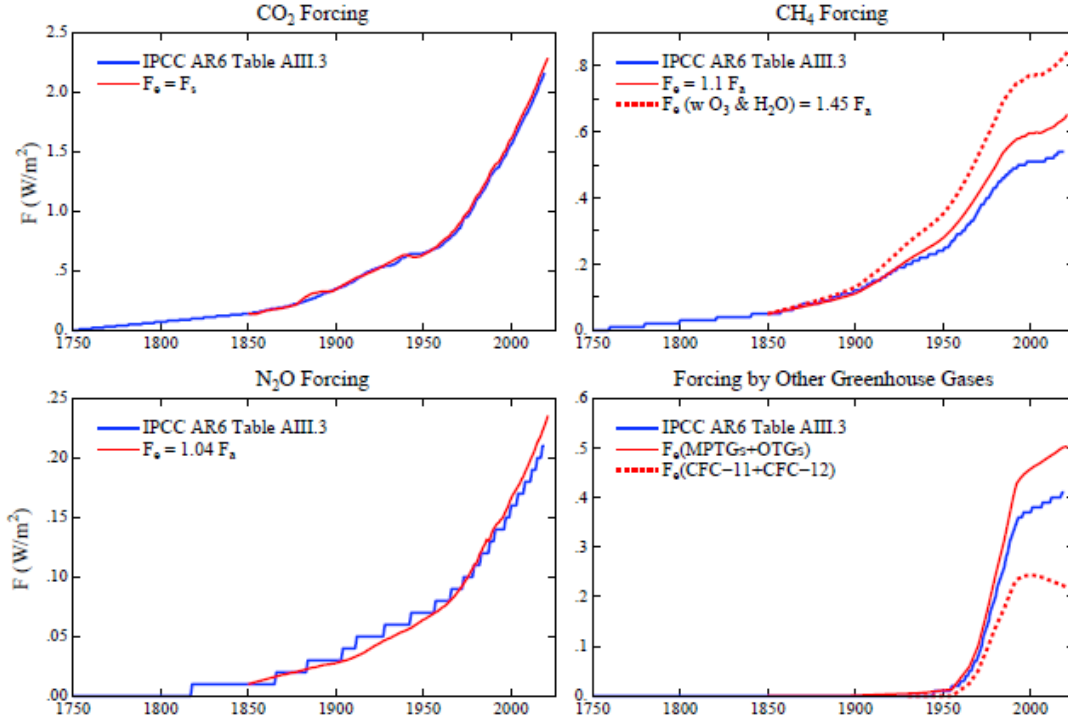
Fig. S1. GHG forcings. IPCC from AR6 Table AIII.3. Our forcings from Eq. (3) and Table 1.

SUPPORTING MATERIAL

1. GHG forcing formulae and comparison with IPCC forcings

Formulae (Table 1) for adjusted forcing, F_a, were numerical fits[37] to 1-D calculations with the GISS GCM radiation code using the correlated k-distribution method.[38] Gas absorption data were from high spectral resolution laboratory data.[39] These F_a were converted to F_e via GCM calculations that include 3-D effects, as summarized in Eq. (3), where the coefficients are from Table 1 of *Efficacy*.[31] The factor 1.45 for CH_4 includes the effect of CH_4 change on stratospheric H_2O and tropospheric O_3. We assume that CH_4 is responsible for 45% of the O_3 change.[40] The remaining 55% of the O_3 forcing is obtained by multiplying the IPCC AR6 O_3 forcing (0.47 W/m^2 in 2019) by 0.55 and by 0.82, where the latter factor is the efficacy that converts F_a to F_e. The non-CH_4 portion of the O_3 forcing is thus 0.21 W/m^2 in 2019. The time-dependence of this portion of the O_3 forcing is from Table AIII.3 in IPCC AR6. MPTGs and OTGs are Montreal Protocol Trace Gases and Other Trace Gases.[41] An updated list of these gases and a table of their annual forcings since 1992 are [available] as are [earlier data].[42]

Table 1. Greenhouse gas radiative forcings

Gas	Radiative forcing
CO_2	$F = f(c) - f(c_o)$, where $f(c) = 4.996 \ln (c + 0.0005c^2)$
CH_4	$F = 0.0406(\sqrt{m} - \sqrt{m_o}) - [g(m, n_o) - g(m_o, n_o)]$
N_2O	$F = 0.136(\sqrt{n} - \sqrt{n_o}) - [g(m_o, n) - g(m_o, n_o)]$,
	where $g(m, n) = 0.5 \ln [1 + 2 \times 10^{-5}(mn)^{0.75}]$
CFC-11	$F = 0.264(x - x_o)$
CFC-12	$F = 0.323(y - y_o)$

c, CO_2 (ppm); m, CH_4 (ppb); n, N_2O (ppb); x/y, CFC-11/12 (ppb).
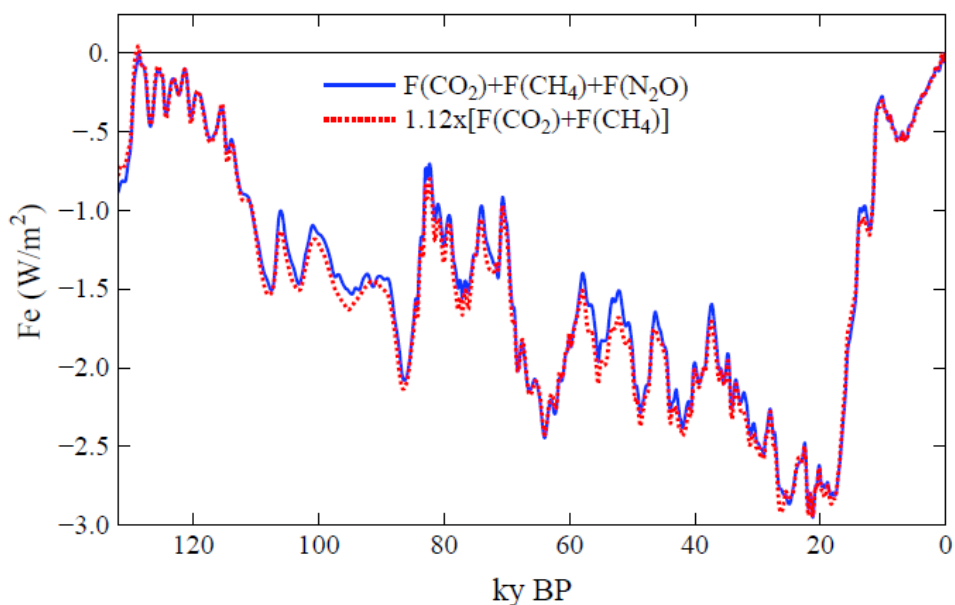
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Fig. S2. Test of accuracy of 2-term approximation for forcing by the three gases.

2. Approximation for N_2O forcing

CO_2 and CH_4 are well-preserved in ice cores. However, the N_2O record is corrupted in some time intervals by chemical reactions with dust particles in the ice core. For such intervals we approximate the N_2O forcing by increasing the sum of CO_2 and CH_4 forcings by 12%, i.e., we approximate the forcing for all three gases as $1.12\times[F(CO_2) + F(CH_4)]$. The accuracy of this approximation is checked in Fig. S2 via computations for the past 132 ky, when data are available for all three gases from the multi-core composite of Schilt et al.[56]
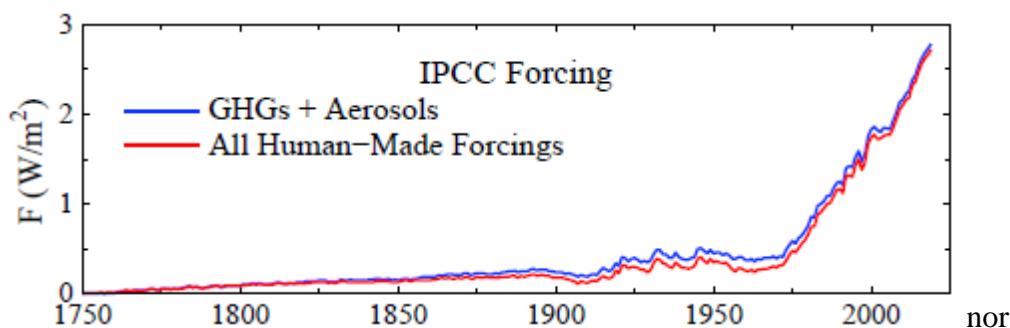

Fig. S3. Climate forcings provided in current IPCC report[13] for GHGs plus aerosols and for all human-made forcings, i.e., excluding only volcano and solar forcings.

3. Comparison of GHG + Aerosol forcing with All Human-Made forcing

IPCC all human-made forcings include land-use effects and contrails, which have large relative uncertainties. The forcings in Fig. S3 are those provided by IPCC (cf. Annex III of the current IPCC physical sciences report).[13]
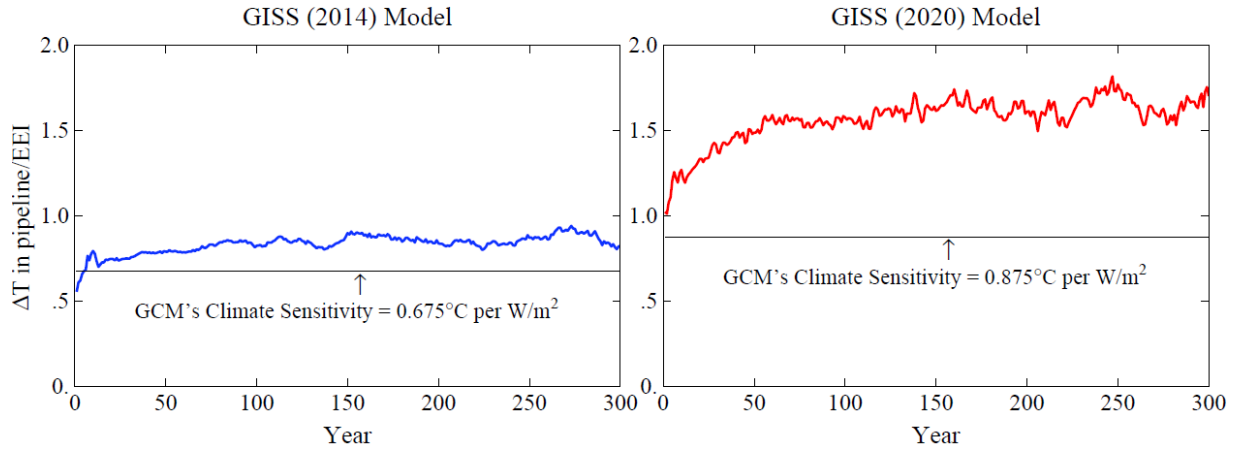
Fig. S4. Ratio of warming in the pipeline to EEI, (Teq – T)/EEI, for the first 300 years after instant doubling of CO_2 for (a) GISS (2014) model and (b) GISS (2020) model.

4. Global warming in the pipeline: Green's function calculations

Global warming in the pipeline (ΔTpl) after a CO_2 doubling is the portion of the equilibrium response (Teq) that remains to occur at time t, i.e., ΔTpl = Teq – T(t). If EEI were equivalent to a climate forcing, warming in the pipeline would be the product of EEI and climate sensitivity (°C per W/m^2), i.e., warming in the pipeline would be EEI ×ECS/4, where we have approximated the 2×CO_2 forcing as 4 W/m^2.

Fig. S4 shows the 2×CO_2 results for the GISS (2014) and GISS (2020) GCMs. EEI is not a good measure of the warming in the pipeline, especially for the newer GISS model. The warming in the pipeline for the GISS (2014) model is typically ~30% larger than implied by EEI and ~90% larger in the GISS (2020) model. If these results are realistic, they suggest that reduction of the human-made climate forcing by an amount equal to EEI will leave a planet that is still pumping heat into the ocean at a substantial rate.

Real-world climate forcing is added year-by-year with much of the GHG growth in recent years, which Fig. 4 suggests will limit the discrepancy between actual warming in the pipeline and that inferred from EEI. Thus, we also make Green's function calculations of global temperature and EEI for 1750-2019 for GHG plus IPCC aerosol forcings. Green's function calculations are useful, with a caveat noted below, for quantities for which the response is proportional to the forcing. We calculate T_G (t) using Eq. (4) and EEI_G (t) using

EEI_G (t) = ∫ [1 – R_{EEI}(t)] × [dF(t)/dt] dt,   (S1)

where R_{EEI} (Fig. 5b) is the EEI response function (% of equilibrium response) and dF is forcing change per unit time. Integrations begin in 1750, when we assume Earth was in energy balance.

The results (Fig. S5) show that the excess warming in the pipeline (excess over expectations based on EEI) is reduced to 15-20% for the GISS (2014) model, but it is still 70-80% for the GISS (2020) model. This topic thus seems to warrant further examination, but it is beyond the scope of our present paper.
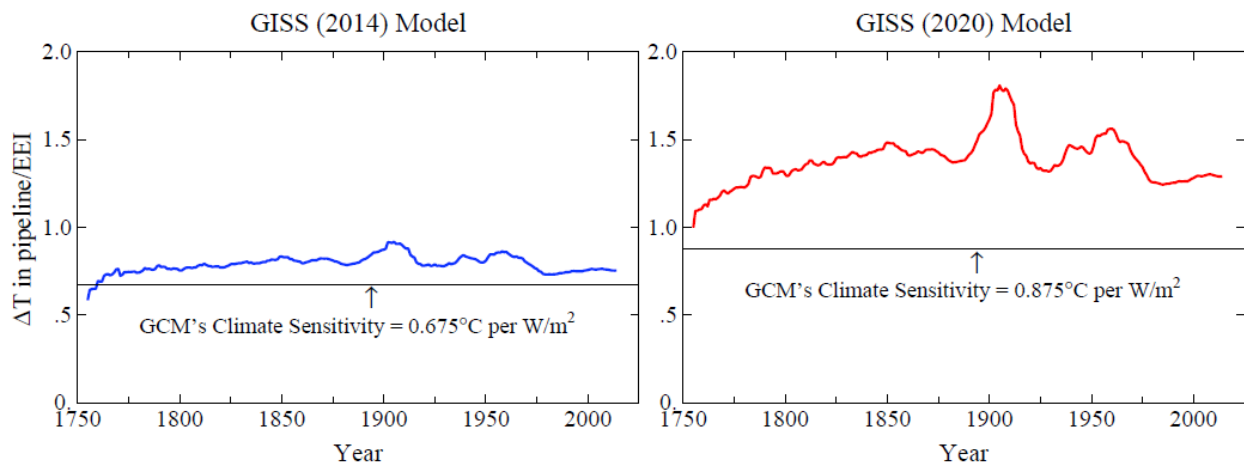
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Fig. S5. Ratio of warming in the pipeline to EEI, $(Teq - T_G)/EEI_G$, in response to GHG and IPCC aerosol forcing for the period 1750-2019 using the response functions for the GISS (2014) model (left) and (b) GISS (2020) model (right).

The first matter to investigate is the cause of the ultrafast response of EEI (Fig. 5 of the main paper), which could be done via the model diagnostics discussed in that section of our paper. If the large difference between the EEI response functions of the two GISS models is related to supercooled cloud water, Fig. 1 of the Kelley et al. paper[34] suggests that the real-world effect may fall between that of the two models. If the higher climate sensitivity of the GISS (2020) model is related to this cloud water phase problem, more realistic treatment of the latter may yield a climate sensitivity between that of the 2014 and 2020 models.

If real world climate sensitivity for $2\times CO_2$ is near 4°C or higher, as we have concluded, the total cloud feedback is likely to be even higher than that of the GISS (2020) model. We suggest that it would be useful to calculate response functions for other models, especially models with high climate sensitivity, to help analyze feedbacks and to allow inexpensive climate simulations for arbitrary forcing scenarios. One major caveat: we have used a single response function calculated for $2\times CO_2$. Especially in view of cloud feedbacks, it seems likely that the response function for aerosol forcing is different from that for CO_2 forcing, because most tropospheric aerosols exist well below the clouds. Much might be learned from calculating response functions for GHGs, tropospheric aerosols, stratospheric aerosols, and solar irradiance, for example.

The response functions for global temperature and EEI, for both the 2014 and 2020 models, smoothed and unsmoothed, are available at
http://www.columbia.edu/~mhs119/ResponseFunctionTables/

DATA AVAILABILITY

The data used to create the figures in this paper, upon publication of the paper, will be available in the Zenodo repository (URL TBD)

ACKNOWLEDGMENTS

Jessica Tierney et al.[23] and data on changing ship emissions provided by Leon Simons led to the need for new analyses and division of the paper into two parts. We thank Jessica also for pointing out the paper by Zhu et al.[83], which independently identifies cloud drop microphysics at cloud tops as key physics affecting climate sensitivity that can be constrained by paleoclimate data. JEH designed the study and carried out the research with help of Makiko Sato; Larissa Nazarenko provided data from GISS models and helped with analysis; Leon Simons provided ship emission information and aided interpretations; Norman Loeb and Karina von Schuckmann provided EEI data and insight about implications; Matthew Osman provided paleoclimate data and an insightful review of the entire paper; Qinjian Jin provided simulations of atmospheric sulfate and interpretations; all authors contributed to our prior research incorporated in the paper and reviewed and commented on the manuscript.

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