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Global Warming Has Accelerated:

Are the United Nations and the Public Well-Informed?

by James E. Hansen, Pushker Kharecha, Makiko Sato, George Tselioudis, Joseph Kelly, Susanne E. Bauer, Reto Ruedy, Eunbi Jeong, Qinjian Jin, Eric Rignot, Isabella Velicogna, Mark R. Schoeberl, Karina von Schuckmann, Joshua Amponsem, Junji Cao, Anton Keskinen, Jing Li, and Anni Pokela

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Global warming has accelerated since 2010 by more than 50% over the 1970-2010 warming rate of 0.18 °C per decade[1] (Figure 1).[2] Earth is now warmer than at any time in the *Holocene*, the past 11,700 years of relatively stable climate in which civilization developed, and it is at least as warm as during the extreme warm *Eemian interglacial* period 120,000 years ago. Global temperature increased 0.4 °C during the recent moderate *El Niño* (a period when east-to-west equatorial trade winds weaken, allowing warm waters of the West Pacific to move toward South America), a warming much greater than during even the strongest prior El Niños. This rapid warming has baffled leading Earth scientists, who, for example, conclude that no combination of known mechanisms for warming "has been able to reconcile our theories with what has happened."[3] We conclude, on the contrary, that the known drives for climate change, principally human-made *greenhouse gases* and *aerosols*, account for observed global temperature, including a jump in sea surface temperature that amplified warming during the El Niño and has caused the widely discussed 1.5 °C temperature threshold to be breached, for all practical purposes.

Climate change burst into public attention with climate anomalies in 1988 so extreme that Time Magazine declared Earth to be "person of the year." Rising public interest in climate change, especially the role of humanity in causing change, led to the 1992 United Nations Framework Convention on Climate Change[4] and a large increase in funding for climate observations and research. The Framework Convention aimed to prevent dangerous human-caused climate change. The largest funding increase was for a NASA program initially titled Mission to Planet Earth expected to make global observations needed to understand ongoing global change.

By 1992 it was understood that two things caused large human effects on climate: *greenhouse gases* (*GHGs*) and *aerosols* (tiny, generally microscopic, particles suspended in the air). GHGs cause global warming by holding in Earth's heat radiation, acting like a blanket. The physics of this greenhouse effect is well understood and tested, for example, by comparison of Mars, Earth and Venus, with their differing amounts of atmospheric GHGs. Carbon dioxide (CO_2), produced mainly by burning of fossil fuels (coal, oil and gas) but also by deforestation, causes more than half of the human-made greenhouse warming. Human-made increases of CO_2 and the other main GHGs (Sidebar 2) have long lifetimes in the atmosphere from decades to millennia. Thus, these gases are well-mixed in the atmosphere and it is easy to measure their changing global amounts.

Human-made aerosols with greatest effect on climate are products of fossil fuel burning and biofuels (like firewood). Most aerosols increase reflection of incoming sunlight back to space and thus have a global cooling effect. Charlson and colleagues[5] concluded in 1992 that the climate forcing by aerosols – the cooling drive for climate change, see below – was similar in magnitude to the GHG forcing, but opposite in sign, thus tending to offset GHG warming. Aerosol offset of GHG warming is a Faustian bargain (Figure 2),[6] that is, a bargain providing present benefit without regard to future consequences. The aerosols providing a cooling benefit are also inherently dangerous particulate air pollution responsible today for several million annual deaths by respiratory, cardiovascular, and even neurological diseases worldwide;[7] thus, as global pollution control has improved and clean energies are introduced the cooling effect of aerosols is lost: with the change of ship regulations, our first Faustian payment came due.[1,8]

Climate sensitivity is a measure of the effect of rising levels of greenhouse gases on Earth's temperature. It is usually defined as the eventual increase of global average temperature after a doubling of CO_2 concentration in the atmosphere compared to pre-industrial levels.

In this paper, we conclude that the estimate of aerosol climate forcing (Figure 3) by the United Nation's scientific advisory body (the Intergovernmental Panel on Climate Change, IPCC) is an underestimate, and thus the Faustian bargain is worse than expected. We also show that IPCC's emphasis on global climate models led to a marriage of aerosol forcing and climate sensitivity, such that underestimate of aerosol forcing led to underestimate of climate sensitivity. The result is a double whammy that helps explain global warming acceleration and alters projections of future climate, magnifying the danger of

Sidebar 1. Global surface temperature relative to 1880-1920 in Figure 1 is the GISS (Goddard Institute for Space Studies) analysis through October 2024.[2] The 1970-2010 warming rate of 0.18 °C/decade almost doubled in 2010-2023, but this higher rate is not a prediction of the future. A downturn in greenhouse gas emissions could alter projections on decadal time scales.

Figure 1. Global surface temperature change (see Sidebar 1).

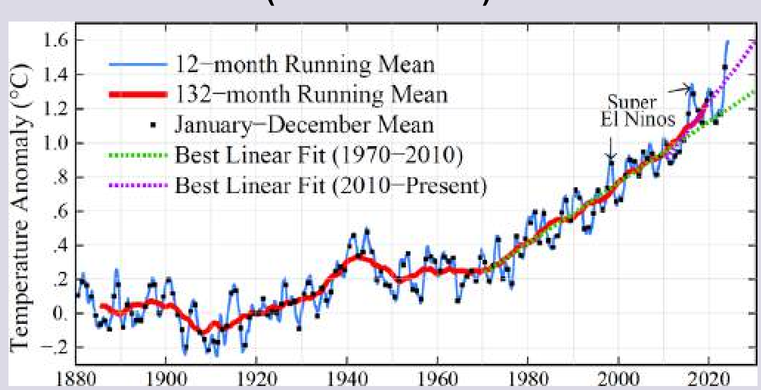


Figure 2. Faustus contemplates bargain with Mephistopheles, who offers him his present desire at the cost of future detriment, much like the cooling benefit of aerosols, which extract a cost in rapidly increased global warming once society no longer tolerates unhealthy air pollution.[8]

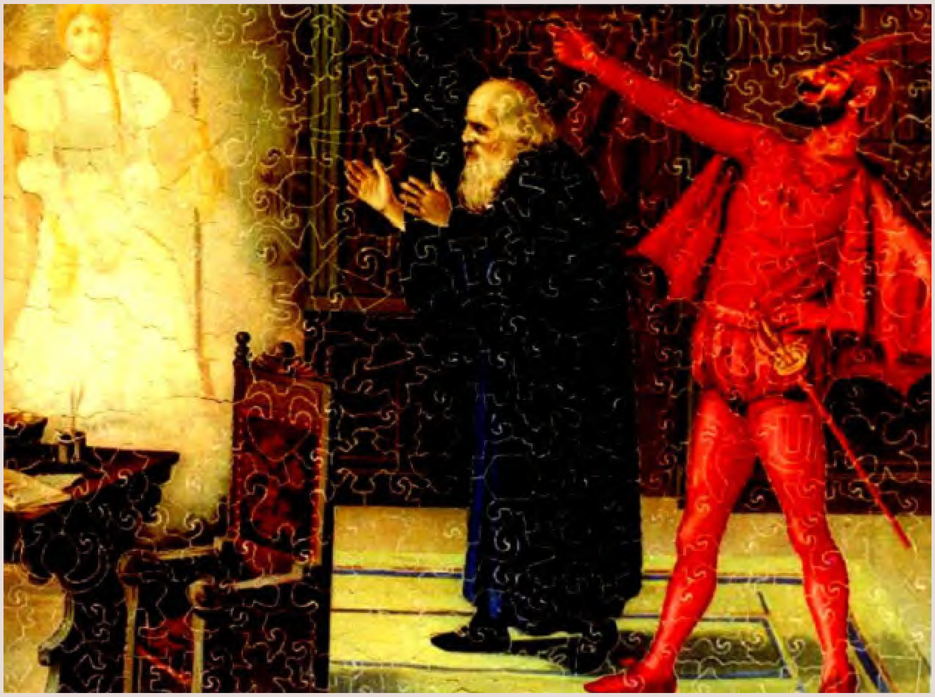
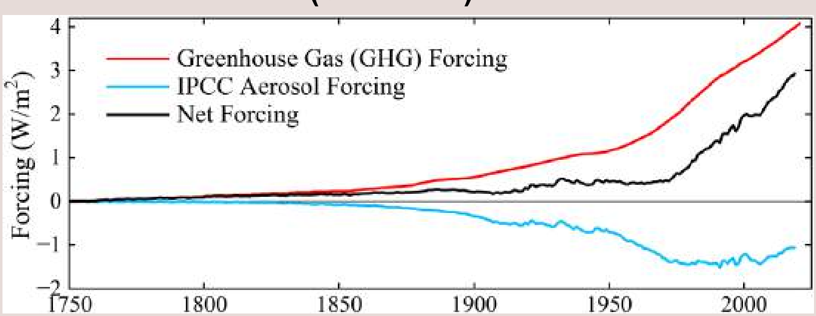


Figure 3. Greenhouse gas and IPCC aerosol forcings (Sidebar 2).**



intergenerational injustice. The delayed response of climate still allows a potential bright future for today's young people, but that happy result requires understanding of the factors driving climate change. These issues can be readily understood via the most basic concepts, beginning with climate forcings.

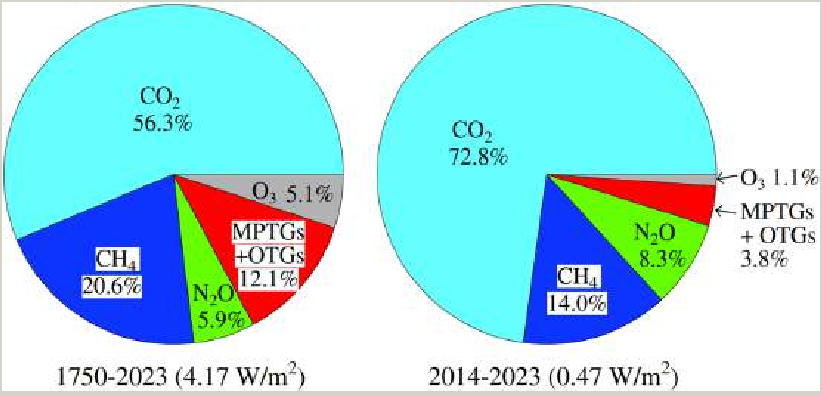
Climate Forcings

Climate forcings are imposed changes of Earth's energy balance. If the Sun suddenly became 1% brighter, for example, that would be a forcing of +2.4 W/m^2 (W/m^2 is watts, a measure of energy transfer over time, per square meter) because Earth normally absorbs 240 W/m^2 of solar energy averaged over Earth's surface. Solar variability is one of the two natural climate forcings that are important on time scales of years to centuries, the other being large volcanic eruptions that inject gases and aerosols into Earth's stratosphere (at about 15-50 kilometers, 10-30 miles). It is helpful to compare these well-understood natural forcings with human-made climate forcings.

Our Sun is a rather quiescent star, in the family of all stars, yet the variability of dark areas (sunspots) on the solar surface has long caused suspicion that the Sun may drive climate change on Earth. Fortunately, NASA has done a good job of monitoring the solar energy received at Earth since the late 1970s. Variations of the Sun's brightness during the solar sunspot cycle are about 0.1% (Figure 4), a forcing change of about 0.25 W/m^2 between solar minimum and solar maximum outputs. This solar forcing, we will show, is much smaller than human-made forcings, but large enough to be a partial cause of present climate extremes.

Volcanic eruptions produce occasional large climate forcings. When Mount Pinatubo erupted in the Philippines in 1991, producing the greatest climate forcing of the 20th century, NASA had satellites in orbit that provided a precise test of aerosol forcing. SAGE (stratospheric aerosol and gas experiment) measurements

Figure S2. Contribution to greenhouse gas climate forcing (%).**



Sidebar 2. Contributions of different greenhouse gases (GHGs) to the increase of GHG climate forcing since 1750 and in the 10 years 2014-2023. CH_4 forcing includes the effect of increasing stratospheric water vapor and the portion of O_3 change caused by CH_4 change.[1] MPTGs are Montreal Protocol Trace Gases and OTGs are Other Trace Gases. N_2O is nitrous oxide, which is increasing from applying nitrogen fertilizers and from animal waste. Forcings are calculated from published formulae[1] and other graphs of the forcings are available.[9]

yielded the average aerosol size and the dispersion of aerosol sizes.

ERBE (Earth radiation budget experiment) measured the change of Earth's energy balance, which peaked at -3 W/m^2 cooling several months after the eruption, the delay due to the time for conversion of the volcanic SO_2 gas into atmospheric sulfuric acid aerosols and the time for stratospheric winds to disperse the aerosols around much of the world. Observed global cooling after the Pinatubo eruption peaked at about 0.3 °C, consistent with expectations given the ocean's thermal inertia and the brevity of forcing (stratospheric circulation carries aerosols to polar latitudes where they descend and are washed from the atmosphere).

A huge submarine volcanic eruption on 15 January 2022 – Hunga in the Pacific Ocean, east of Australia, near the dateline – blasted about 150 million tons of water vapor and 1 million tons of SO_2 into Earth's stratosphere. It was much less SO_2 than for Pinatubo, and any cooling effect was partly offset by warming from the added stratospheric water vapor (a GHG).[16] Nevertheless, we need to estimate the possible effect of Hunga on global temperature in 2022-2023 to see if it had a significant effect on the unprecedented warming that followed. Although it is difficult to disentangle Hunga effect on Earth's measured energy balance from natural variability (due mainly to cloud variability), analysis shows that aerosol cooling dominated over water vapor warming[16] and the net volcanic forcing declined to a small fraction of its peak value by two years after the eruption. We approximate the Hunga forcing based on the Pinatubo forcing (Figure 5), but with

Figure 4. Solar irradiance (top) and sunspot numbers.[10]

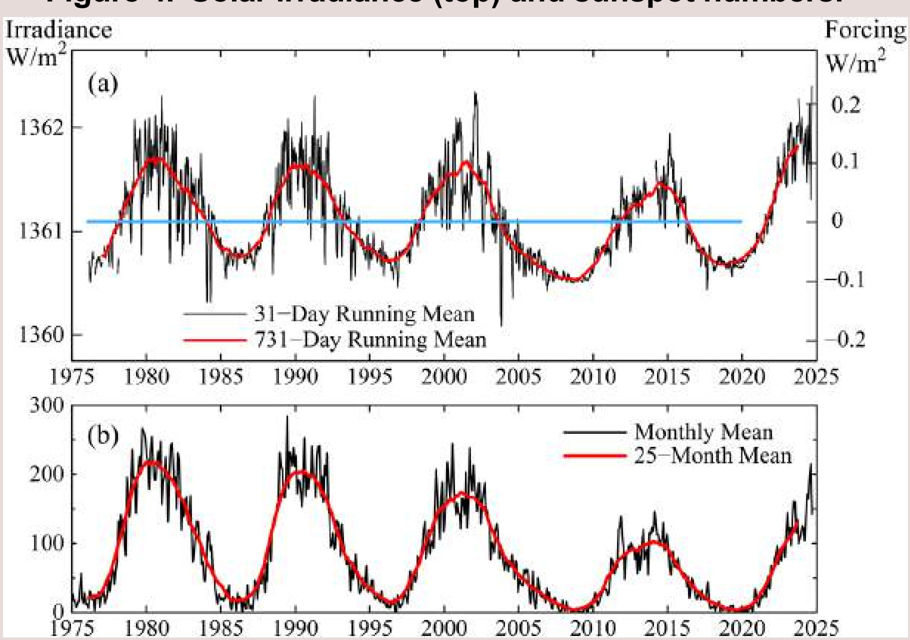


Figure 5. Observed and simulated forcing by Pinatubo aerosols (see also Sidebar 3).**

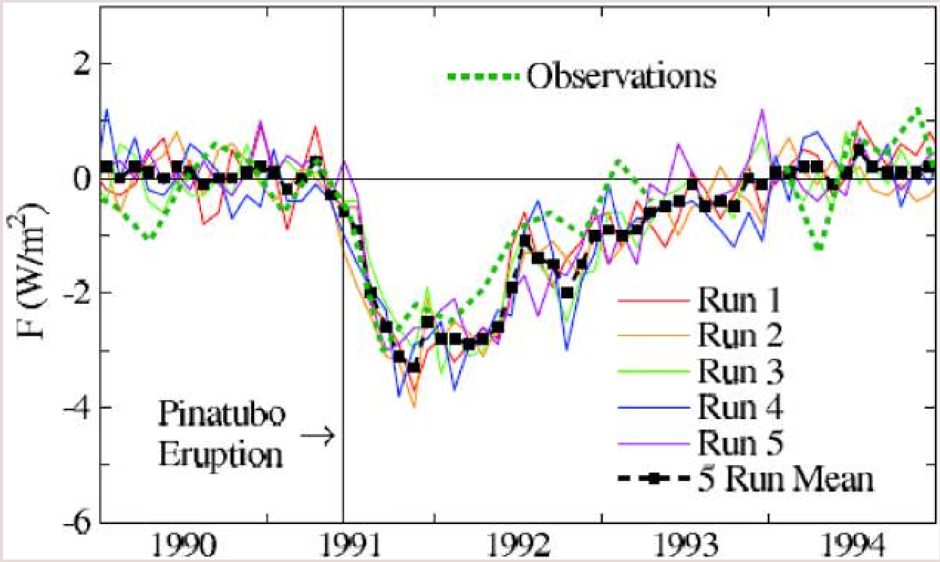
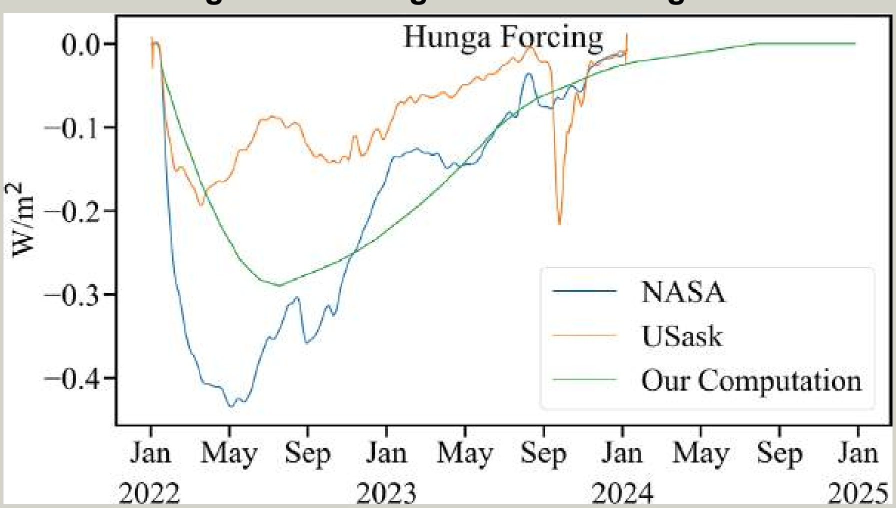


Figure S3. Hunga aerosol forcing.**



Sidebar 3. SO_2 injected into the stratosphere by volcanoes forms sulfuric acid aerosols over time that are carried toward the poles and downward by atmospheric circulation and gravity, largely removed in 1-2 years. The large 1991 Pinatubo eruption allows the aerosol forcing to be defined and provide a test of climate impact. Prediction[11] of global cooling by Pinatubo aerosols was made soon after the eruption based on initial estimates of aerosol amount, with peak aerosol forcing −4.5 W/m² and predicted global cooling 0.5 °C. Later multispectral aerosol opacity data of the SAGE satellite instrument[12] allowed precise evaluation of opacity of the Pinatubo aerosol layer and the dispersion of aerosol sizes,[13] which revealed peak forcing as actually −3 W/m². Multiple runs of a GCM (global climate model) with this aerosol forcing produced maximum global cooling after the volcano of 0.3 °C and a maximum decrease of Earth's energy balance of 3 W/m² (Figure 5) consistent with ERBE satellite observations.[14] SO_2 injected into the stratosphere by Hunga is estimated as 1 ± 0.5 megatons,[15] an order of magnitude less than Pinatubo's 20 megatons. We reduced Pinatubo forcing accordingly and smoothed the Pinatubo forcing curve[14] with a 3-month running-mean to obtain our estimate of the Hunga forcing. Later estimates (NASA and USask)[16,17] based on satellite data bracket the estimate based on Pinatubo but have earlier peak opacity, likely due to the higher latitude of the Hunga eruption, which placed the aerosols closer to where they descend from the stratosphere.

peak forcing −0.3 W/m^2. Like the solar forcing, the Hunga forcing is small.

Given that we know precisely the natural climate forcings – volcanic aerosols and solar irradiance – as well as the human-made and natural greenhouse gas forcings, it is obvious that human-made aerosol forcing is the elephant in the climate forcing story that receives too little attention. Aerosol forcing occurs in part from the direct effect of human-made aerosols as they reflect and absorb incoming sunlight, but also from the indirect aerosol effect as the added aerosols modify cloud properties as discussed below. IPCC estimates the indirect aerosol forcing based largely on mathematical models.[18] We suggest that this modeling fails to fully capture the fact that human-made aerosols have a larger impact on clouds when the aerosols are injected into relatively pristine air in places that are susceptible to cloud changes. Later in this paper, we use spatial and temporal changes of climate and Earth's energy balance to explore this indirect aerosol forcing. First, however, we discuss aerosol and cloud particle microphysics.

Aerosol and Cloud Particle Microphysics

Climate forcing by aerosols depends on aerosol and cloud processes on minute scales. Aerosol composition matters, both for the direct effect of aerosols on radiation and the indirect effect on clouds. Indirect aerosol forcing arises because aerosols are condensation nuclei (tiny sites of water vapor condensation or "cloud seeds") for cloud drops. More nuclei yield more cloud particles and brighter clouds that reflect more sunlight and cause cooling.[19] More aerosols also increase cloud cover, as shown by cloud trails behind ships ("ship tracks").[20] Observations to quantify these effects are challenging because human-made aerosols must be distinguished from changes of natural aerosols. Thus, there is large uncertainty in the overall net aerosol forcing.[21,22]

Simultaneous with human-caused aerosol and cloud changes, clouds also change as a climate feedback. [Climate feedbacks – response of the climate system (such as change of clouds or sea ice) to climate change – can be either amplifying or diminishing. Amplifying feedbacks increase climate change, tending to produce instability, while diminishing feedbacks decrease climate change, promoting stability.] Cloud feedback is the main cause of uncertainty in climate sensitivity, the holy grail of climate research.[23] Climate sensitivity is defined as global temperature response to a standard forcing. Observations reveal that the sizes and locations of zones with different characteristic clouds are changing – the intertropical convergence zone (encircling the Earth near the thermal equator) is shrinking, the subtropics are expanding, and the midlatitude storm zone (not near the poles or the equator) is shifting poleward[24] – with associated changes of Earth's energy balance that constitute potentially powerful, but still inadequately understood, climate feedbacks. Some of the difficulties in climate modeling include cloud microphysics, such as the need to realistically simulate mixed phase (both ice and water) clouds.[25] As cloud modeling has become more complex and realistic, several global climate models have found higher climate sensitivity correlated with more realistic cloud distributions (Sidebar 4).

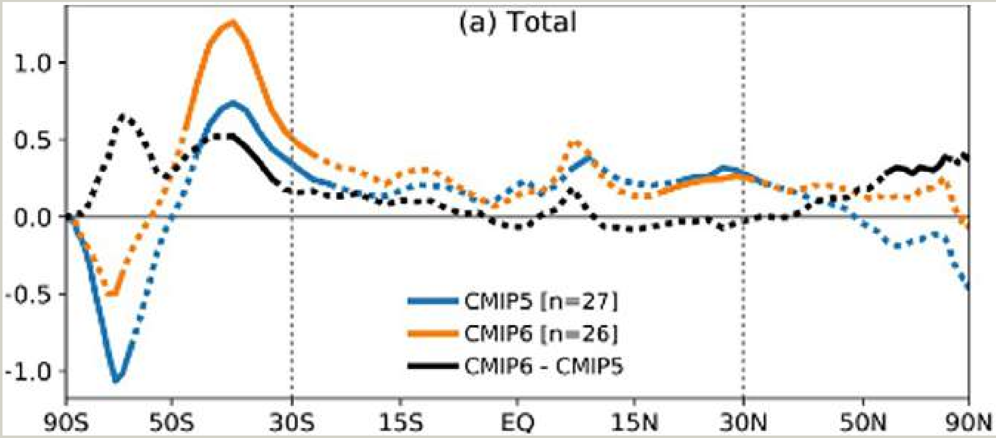
Given the importance of aerosol climate forcing and climate sensitivity,[28] there is a crying need for global monitoring of aerosol and cloud particle microphysics and cloud macrophysics[29] to help sort out climate forcings and feedbacks.[30] Global monitoring of aerosol/cloud microphysical properties and cloud macrophysics from a dedicated small satellite mission has been proposed, but not implemented.[31] The need for such data will only increase in coming decades as the world recognizes growing consequences of climate change and tries to chart a course to restore Holocene-level global climate. NASA's 2024 PACE satellite mission[32] includes polarimeters capable of measuring aerosol and cloud microphysics including aerosol and cloud droplet number concentrations, which could be a step toward a dedicated, long-term aerosol mission to monitor global aerosol and cloud properties as required to calculate climate forcings and feedbacks[33] (analogous to greenhouse gas monitoring that permits calculation of greenhouse gas forcing). In the absence of that data, we now explore less direct evidence of aerosol climate forcing.

Evidence of Aerosol Climate Forcing

Paleoclimate data suggest the important role of aerosols in global climate. In the past 6,000 years, known as the late Holocene, atmospheric CO_2 and CH_4 increased markedly, likely as a result of deforestation and methane from rice agriculture,[34] causing greenhouse gas (GHG) climate forcing to increase more than 0.5 W/m^2,[1] yet global temperature during the late Holocene held steady[35] or decreased slightly.[36] This divergence of GHG forcing and global temperature is a strong anomaly; CO_2 is a tight control knob on global temperature at other times in the ancient paleo record (see Figure 2 in Note 1 at end), as anticipated on theoretical grounds.[37] Aerosols, the other large human-made climate forcing, is a suggested solution[38] for this "Holocene conundrum." Aerosols increased in recent millennia as burning of wood and other biofuels provided fuel for a growing global population. Moving to recent, preindustrial, times, the required magnitude of the implied (negative) aerosol forcing from biofuel burning reached at least 0.5 W/m^2. Biofuel aerosol forcing has likely increased since then, as the biofuel energy source is widespread in developing countries and continues in developed countries.[1]

Recent restrictions on ship emissions provide a great opportunity to investigate aerosol forcing. The International Maritime Organization (IMO) introduced limits on the sulfur content of ship fuels in stages, with the greatest global restriction effective January 2020 (Sidebar 5). Change of global aerosol forcing from this limit on ship emissions, based on IPCC's formulation of aerosol forcing,[18] is calculated[39] as 0.079 W/m^2. Forster et al.,[40] updating IPCC's aerosol forcing, estimate the ship aerosol forcing change as +0.09 W/m^2; they also note

Figure S4a. Shortwave low cloud feedbacks (W/m² per °C).**

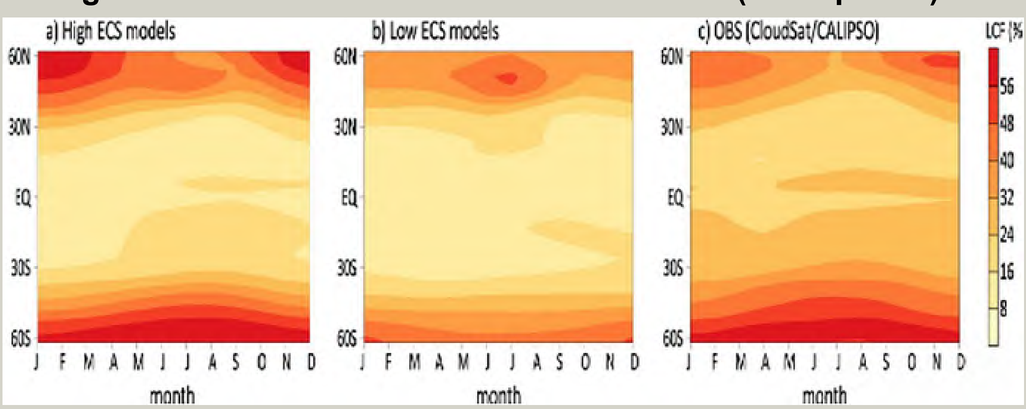


Sidebar 4. CMIP (Climate Model Intercomparison Project) studies are carried out prior to and in conjunction with IPCC reports, with corresponding numbering. Zelinka et al. (2021)[50] show that increased equilibrium climate sensitivity (ECS) of CMIP6 models is primarily due to differences in simulated shortwave (shortwave refers to solar radiation, as opposed to longwave terrestrial heat radiation) low-cloud feedbacks at middle and high latitudes in the Southern Hemisphere (Figure S4a). CMIP6 models have a stronger positive low-cloud feedback at midlatitudes in the Southern Hemisphere and a weaker negative low-cloud feedback at high latitudes; both features contribute to higher ECS in many CMIP6 models and in the average of all CMIP6 models.

Jiang et al. (2023)[26] show that CMIP6 models with higher ECS produce a realistic seasonal cycle of extratropical low clouds with peaks in the austral (southern hemisphere) and boreal (northern hemisphere) winter seasons, while models with lower ECS produce low-cloud seasonal cycles with unrealistic peaks in summer (Figure S4b). The greater skill of high ECS models in simulating cloud variability and cloud feedbacks, especially in the Southern Ocean region, suggests greater confidence in the higher ECS models. Cloud changes are the cause of higher sensitivity in high-ECS models, and thus the observed cloud seasonality provides significant support for high ECS.

Finally, Williams et al. (2020)[27] tested two alternative cloud configurations in the UK Met Office Unified Model used for weather predictions, finding that the more recent cloud parameterization scheme increases simulated ECS by 2.2 °C, improves the short-range weather forecast, and reduces the error growth over the first few hours of the forecast, indicative of more realistic modeling of local physical processes. These several works indicate that high ECS models are more skillful in simulating cloud feedbacks, a crucial factor in determining real-world ECS.

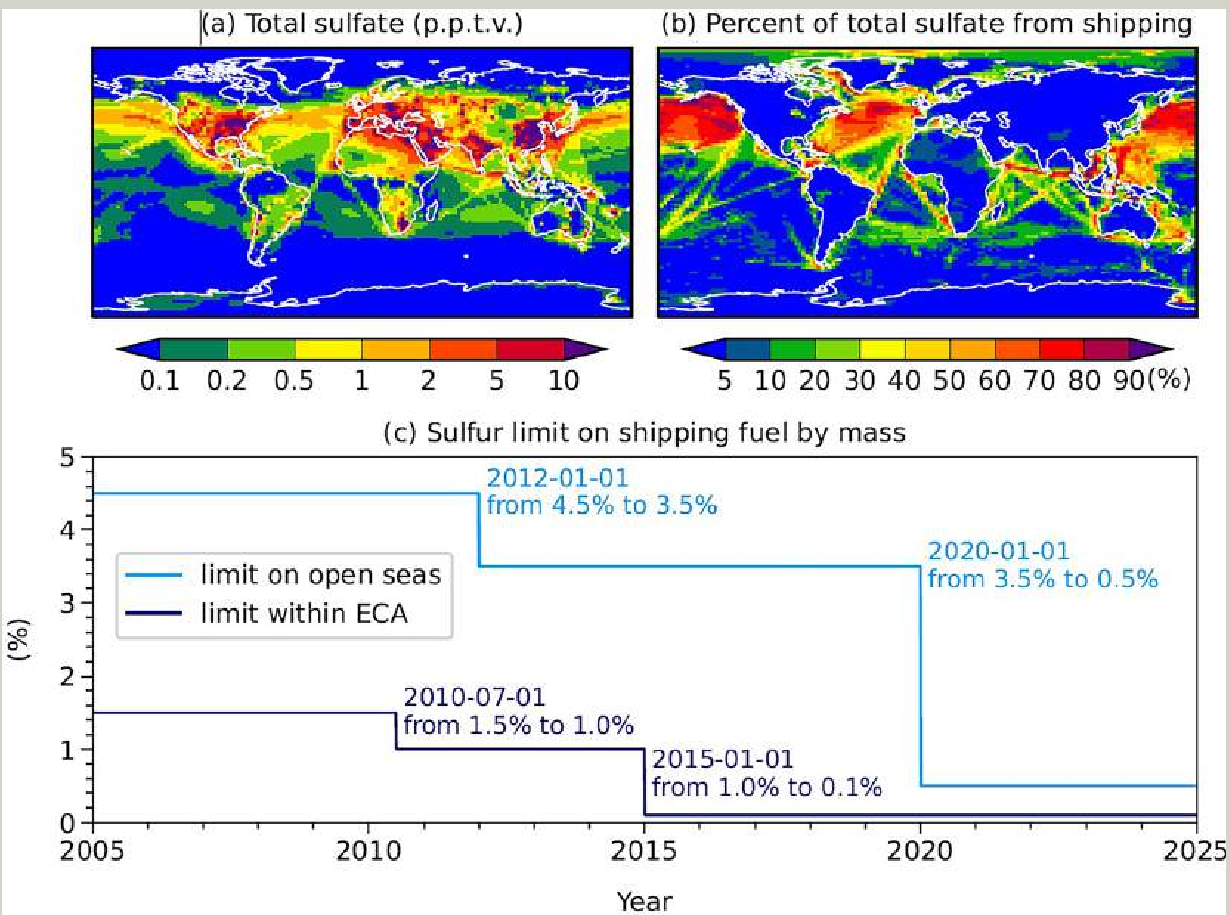
Figure S4b. Shortwave low cloud feedbacks (W/m² per °C).**



that this ship aerosol forcing would be offset by negative aerosol forcing from increased forest fires and other biomass burning. A review[41] of five ship aerosol modeling studies finds a range 0.07 to 0.15 W/m^2, with mean 0.12 ± 0.03 W/m^2. A recent model result[42] of 0.2 W/m^2 refers to ocean area and is thus a global forcing of 0.14 W/m^2. None of these modeled Ship Aerosol Forcings would have much effect on global temperature because GHG forcing currently is increasing 0.4-0.5 W/m^2 per decade.

However, if the aerosol effect is highly nonlinear (i.e., if aerosols emitted into polluted air have much less effect on clouds than aerosols emitted into a pristine atmosphere), decreased ship emissions may have a large effect on Earth's albedo (reflectivity). The largest effect should be in the North Pacific and North Atlantic, where ship emissions dominate over natural sulfate aerosols (Sidebar 5). Fortunately, Earth's albedo has been monitored for almost a quarter of a century by the CERES (Clouds and the Earth's Radiant Energy System) satellite instrument,[44] which reveals a stunning darkening of Earth (Figure 6).[45] Earth's albedo decreased about 0.5% (of 340 W/m^2), which is 1.7 W/m^2 additional heating of Earth since 2010! Such albedo change is equivalent to an increase of CO_2 by 138 ppm, from the 419 ppm actually measured at the beginning of 2024 to 557 ppm. However, the 1.7 W/m^2 increase in energy absorbed by Earth is not all climate forcing; it is partly climate feedback – cloud changes and reduced ice and snow cover caused by global warming. *Our task is to apportion the 1.7 W/m^2 between aerosol forcing and climate feedbacks, accomplishing this in the absence of adequate aerosol and cloud measurements.*

Figure S5. Sulfate aerosols and sulfur limit on emissions, p.p.t.v. = parts per trillion by volume.**



Sidebar 5. (a) total (natural plus human-made) sulfate aerosols in 2010 as calculated by an interactive aerosol model in an Earth system model.[43] (b) percent of sulfate from shipping in 2010. (c) limits imposed by the International Maritime Organization on sulfur content of ship fuels (% by mass) for ships on open ocean and in Emission Control Area (ECA, near coasts in Northern Europe, North America, the U.S. Caribbean region and Hawaii).

Ship-Induced Aerosol Climate Forcing

Earth's declining albedo (darkening) is "noisy" in time and space because of the large natural variability of clouds. Earth's albedo change (Figure 6) may not seem to correlate well with the 2020 change of ship emissions. However, a sharp 2020 change is clear after we consider the largest source of natural variability – the Pacific Decadal Oscillation (PDO)[46] – and additional data. The PDO is an observed natural cycle of sea surface temperature and cloud changes in the Pacific, as a large-scale manifestation of tropical El Niño/La Niña variability.[47] Absorbed Solar Radiation in the North Pacific is well correlated with the PDO from 2000 (when CERES data begins) until 2020 (Figure 7), whereupon Absorbed Solar Radiation rapidly increases, when PDO cloud changes should have spurred a *decrease* of Absorbed Solar Radiation.

Let's use the observed change of Absorbed Solar Radiation to estimate aerosol forcing change that occurred in 2020. The Absorbed Solar Radiation anomaly in 2020-2023 (Figure 8) relative to the base period (March 2000 through February 2010) reveals expected large tropical anomalies, but also increased absorption throughout the North Pacific and North Atlantic with the exception of the "global warming hole," the region southeast of Greenland that is cooling relative to the rest of the world.[48] The increase of Absorbed Solar Radiation in the North Pacific and North Atlantic since 2020 can itself account for a global climate forcing of almost 0.5 W/m^2 (see Sidebar 6).

Increased Absorbed Solar Radiation is partly climate feedback: decreased snow and ice albedo and decreased cloud cover. However, snow/ice albedo change, apparent in Figure 8 near Antarctica and in the Arctic, has little role in the North Pacific and North Atlantic. Cloud feedback, including shifting climate zones,[24] may contribute to Absorbed Solar Radiation increase in the North Pacific and North Atlantic, but the largest cloud feedback is expected to be in the Southern Hemisphere south of 30°S.[50] An illuminating picture of where and when the global darkening (of Figure 6) exists is provided by zonal-mean (i.e., average around the world at each latitude)

Figure 6. Earth's albedo (reflectivity, in percent), seasonality removed.**

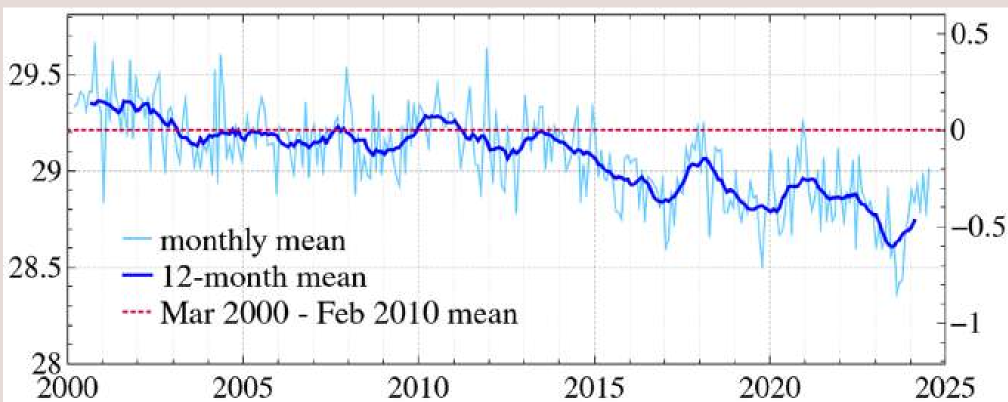


Figure 7. Absorbed Solar Radiation (ASR) and Pacific Decadal Oscillation (PDO).**

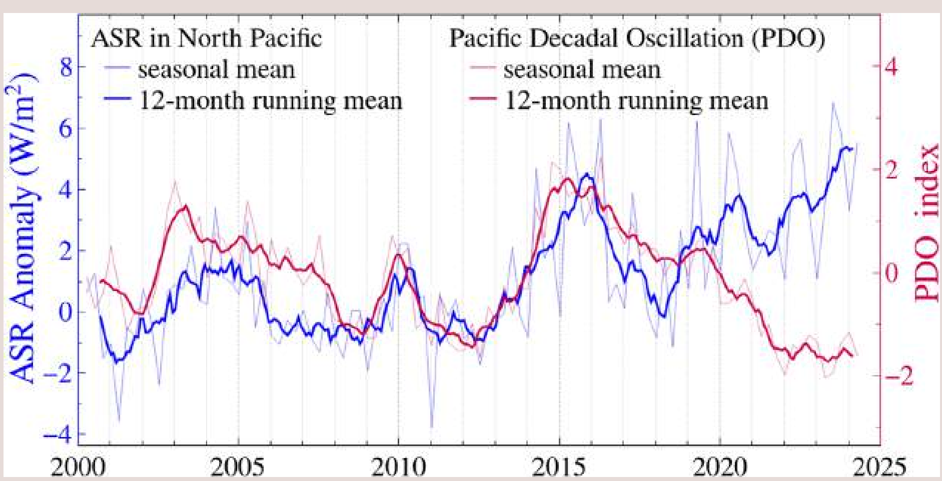
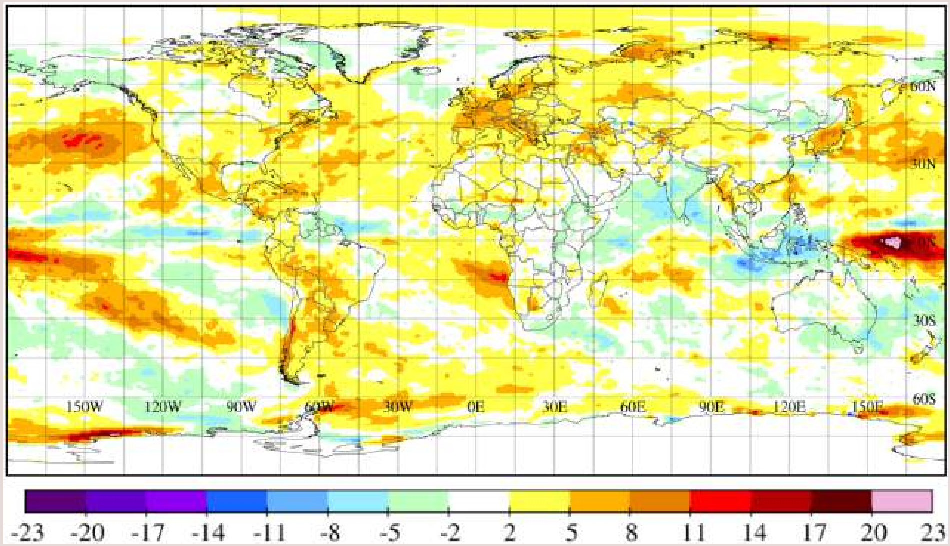


Figure 8. Absorbed Solar Radiation anomaly (W/m²) in 2020-23.**



Sidebar 6. The 2020-23 anomaly of Absorbed Solar Radiation is +3.2 W/m² in the North Pacific (15-60°N, 120-240°W) and +2.8 W/m² in the North Atlantic (15-60°N, 5-80°W). These regions are 10.1% and 6.3% of global area, so, if increased Absorbed Solar Radiation in these regions were entirely an effect of decreased aerosols, it would contribute a global forcing of $3.2 \times 0.101 + 2.8 \times 0.063 = 0.5$ W/m². Removing land areas from these two boxes reduces the Absorbed Solar Radiation anomaly to 0.42 W/m². This amount would be larger, if it were not for cooling and increased cloud cover in the "global warming hole" region southeast of Greenland. The relative cooling there is due to slowdown of North Atlantic's overturning ocean circulation,[48] which is a northward flow of warm water in upper ocean layers with a deep southward return flow of cold water. Cooling of the "warming hole' region induces increased cloud cover there (see Figures 6a and 8b in the paper "Ice Melt"[49]) that exceeds and hides the effect of decreased ship aerosols.

Absorbed Solar Radiation (Figure 9). Latitudes are compressed toward the poles in Figure 9 so that an increment of latitude in the graph is a true measure of area on the globe. *Northern Hemisphere midlatitudes are the dominant region of increased Absorbed Solar Radiation, with a large increase beginning in 2020.* Some increase of Absorbed Solar Radiation also began in early 2015, at the time a severe restriction on fuel sulfur was imposed in coastal regions around northern Europe, North America and Hawaii (Sidebar 5). If ships only used low-sulfur fuel while in port and switched to high-sulfur fuel on the open sea, then the coastal restrictions would have little effect,[51] but it is possible that some ship operators switched to low-sulfur fuel more generally.

*So, how much of the 1.7 W/m² darkening of the Earth (*Figure 6*) is from feedbacks and how much is likely aerosol forcing?* The high latitude snow/ice feedback can be estimated from the data in Figure 9: the latitude ranges 60-90°N and 60-90°S contribute +0.07 W/m² and +0.08 W/m² to the 2020-23 global Absorbed Solar Radiation anomaly, respectively. In contrast, the latitude range 30-60°N contributes +0.53 W/m² in 2020-23 and +0.67 W/m² in 2023. Part of this increase of Absorbed Solar Radiation may be cloud feedback, but that should tend to be offset by reduced ship aerosol forcing in ocean areas other than the North Pacific and North Atlantic. Half of the world is covered by these other ocean areas, where ship aerosols have an effect on cloud albedo even in regions without visible ship tracks.[52] *We conclude only that the aerosol forcing induced by International Maritime Organization restrictions on ships could be of the order of 0.5 W/m², thus much larger than the aerosol forcing (0.079 W/m²) estimated in the IPCC formulation* (see above).

Sea Surface Temperature

Sea surface temperature is indicative of heat stored in the ocean's upper "mixed layer," which is characterized by a single temperature because of continual turbulent stirring by wind and waves. Thus, sea surface temperature change is a good diagnostic to assess the effect of climate forcings over the ocean. The zonal-mean

Figure 9. Zonal-mean Absorbed Solar Radiation anomaly (W/m²).**

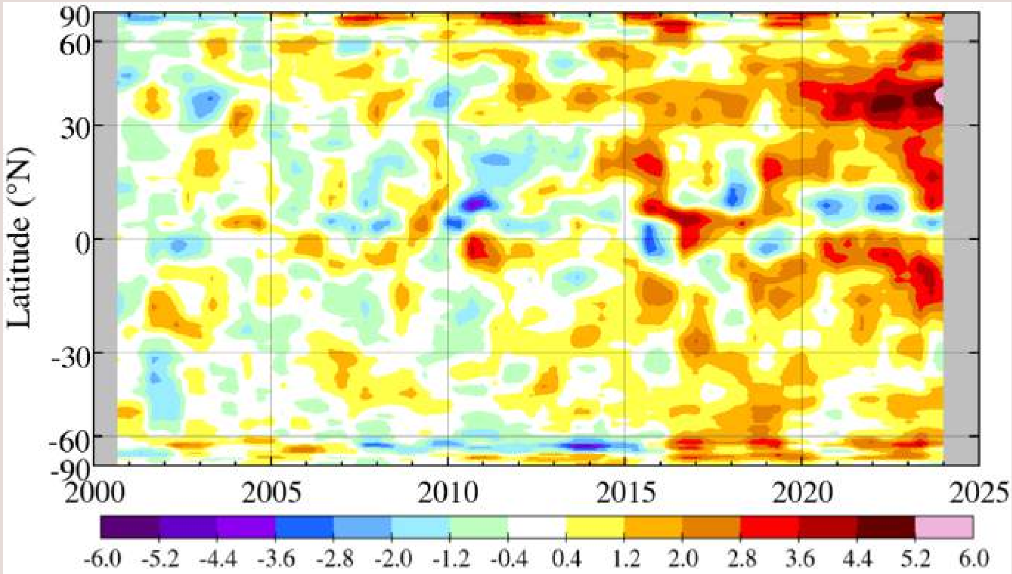
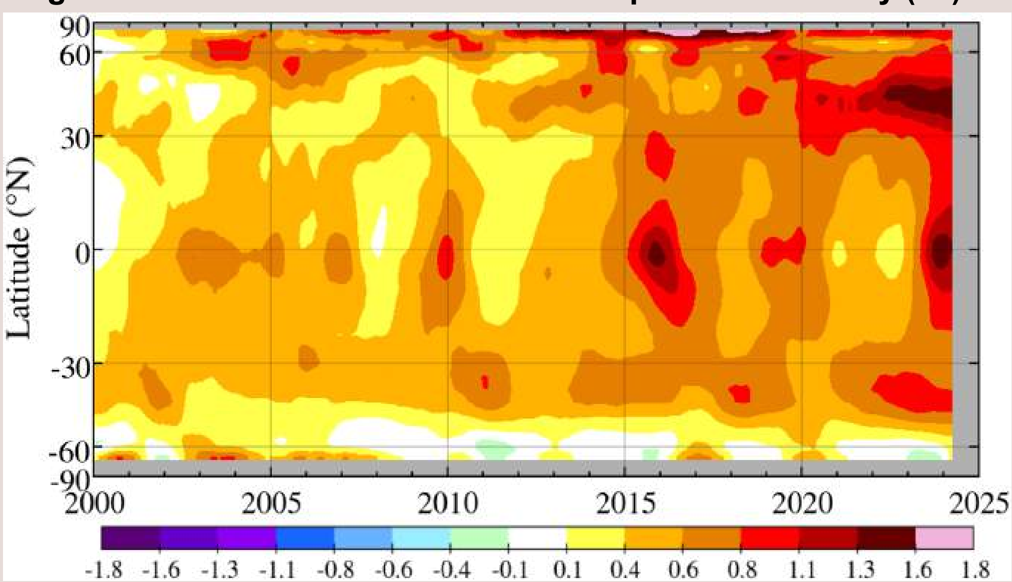


Figure 10. Zonal-mean Sea Surface Temperature anomaly (°C).**



(i.e., average around the world at each latitude) Sea Surface Temperature anomaly relative to 1951-1980 climatology (Figure 10)[53] contains a strong imprint of the Absorbed Solar Radiation anomaly at 30-60°N and reveals a clear global picture. The large global warming in 2023 is a combination of a moderate[54] tropical El Niño and additional warming that is largest at middle latitudes in the Northern Hemisphere. *We interpret the additional warming as mainly the effect of reduced human-made aerosols, especially aerosols produced by ships. The ship aerosol effect is greatest in the North Pacific and North Atlantic because that is where ship-produced sulfate aerosols exceeded natural aerosols* (Sidebar 5), but ship aerosols have some effect over most of the world ocean. We show below that natural climate forcings in 2022-2023 also made a contribution to the appearance of an unprecedented spike in global warming.

Sea surface temperatures will decline as the tropics moves into its La Niña phase, but we expect cooling to be limited, as it was after the 2015-16 El Niño (Figure 11). Temperature will not decline to pre-El Niño levels because Earth is far out of energy balance,[55] with more energy coming in than going out and with the vast majority of the excess energy being

Figure 11. Global and 30-60°N Sea Surface Temperature anomalies.**

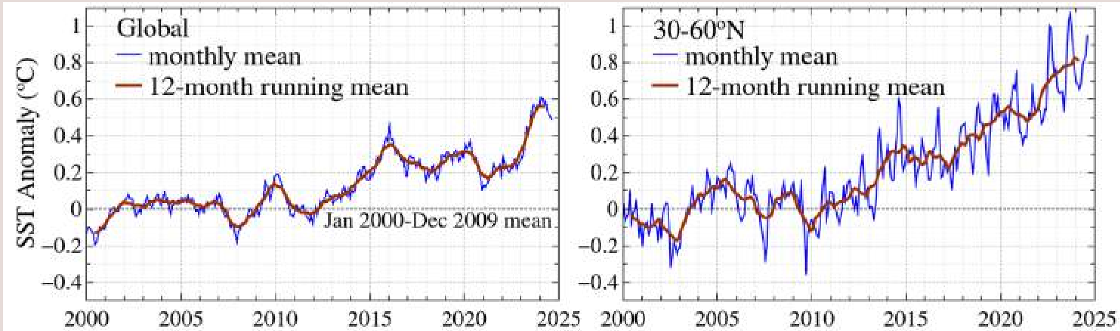
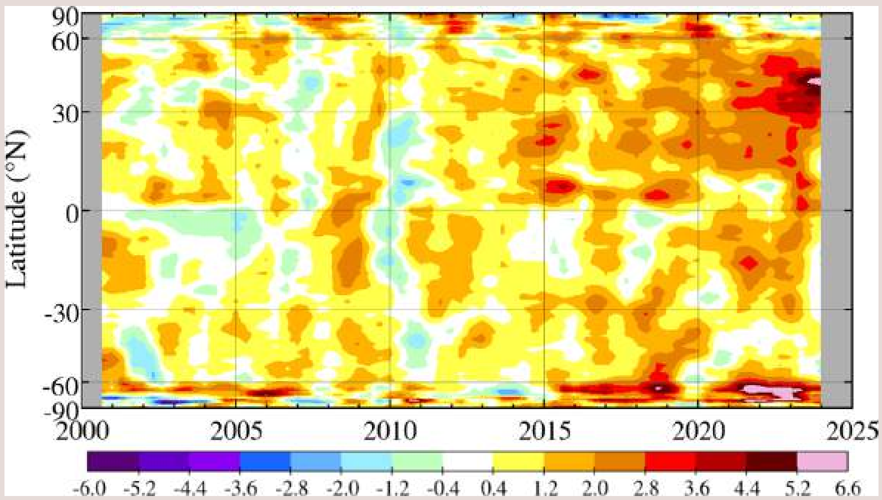


Figure 12. Zonal-mean Earth energy balance over ocean (W/m^2).**



stored as heat in the ocean. Earth's energy imbalance is measured by the combination of CERES satellite instruments[44] (which measure change of the imbalance) and 4,000 deep-diving Argo floats[55] distributed around the ocean (which calibrate the satellite data by measuring change of ocean heat content over a decade). A revealing picture is provided by the zonal-mean energy balance at the top of the atmosphere over the ocean (Figure 12). Most of the increased energy uptake occurs in the extra-tropics of the Northern Hemisphere. *Earth's global energy imbalance was 0.6, 1.11, and 1.36 W/m^2 in 2001-2014, 2015-2019, and 2020-2023, respectively. The imbalance over 30-60°N ocean was 0.67, 1.41, and 2.56 W/m^2 in the same periods.*

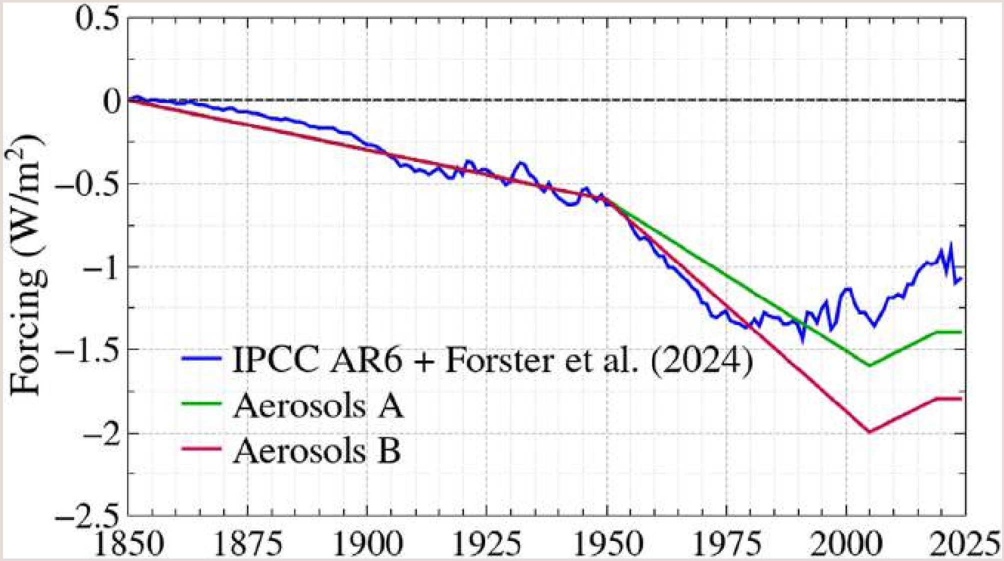
The location and timing of changes in Earth' energy balance and sea surface temperature support our interpretation that decreasing ship emissions are a major cause of the recent increase of Earth's energy imbalance and accelerated global warming. Our interpretation is at odds with that of the United Nations Intergovernmental Panel on Climate Change (IPCC). This issue must be illuminated because of implications for climate sensitivity, climate forcings, and policies that will be needed to maintain a climate similar to that in which civilization developed and thrives.

Marriage of Aerosol Forcing and Climate Sensitivity

IPCC's[56] estimate of aerosol forcing (Figure 3) is updated through 2023 by Forster et al.[57] (Figure 13). *Aerosol precursor emissions increased rapidly after World War II, as fossil fuel use grew. Global sulfur emissions reached 120 megatons of SO_2 by 1970 and stayed near that level until 2005 (Sidebar 8). Sulfur emissions in the United States began to decline in the 1970s due to the Clean Air Act*[58] *based on concern about acid rain, but decreasing aerosols in developed countries were largely compensated by growing emissions around the world until early in the 21st century. We expect, contrary to the IPCC, that aerosol forcing is more nonlinear, i.e., small emissions in relatively pristine air have an outsized effect.* This expectation is supported by our conclusion that the moderate emission reduction (about 10 megatons of SO_2) due to ship fuel regulations (Sidebar 8) altered aerosol forcing by as much as 0.5 W/m^2.

As a contrast to IPCC's aerosol forcing scenario, we consider aerosol scenarios, A and B (Figure 13), which approximate the Matrix and OMA aerosol models of

Figure 13. Aerosol forcing scenarios (AR6 = Sixth Assessment Report, Aerosols A simulates aerosol microphysical processes, Aerosols B is based simply on aerosol mass. See Notes 57 and 62 at end).



Sidebar 7. IPCC's formulation for aerosol forcing[18] is close to linear in global precursor emissions, i.e., proportionate to global emissions (Figure SM1 in Supplementary Material). Thus, IPCC's aerosol forcing is near its maximum value of about −1.3 W/m^2 by 1970 and stays near that value until 2005 (Figure 13).

Bauer et al.[62] Matrix (Aerosols A) explicitly models aerosol microphysical processes, so we might hope that it is more realistic than OMA (Aerosols B), which is simply based on aerosol mass. The Bauer aerosol models use the same CEDS (Community Emissions Data Systems)[59] emission data employed by IPCC, but we believe the Bauer models more realistically capture the nonlinearity of the aerosol effect on clouds, i.e., the fact that aerosols emitted into a pristine environment have a greater effect on clouds than aerosols emitted into air that is already heavily polluted.[63] The models agree that IPCC understates aerosol forcing: aerosol forcing increases until 2005, when a "turning point"[64] is reached mainly due to emission reductions in China during 2006-2014.[65] The continued increase of aerosol forcing in 1970-2005 has major ramifications for understanding of climate sensitivity.

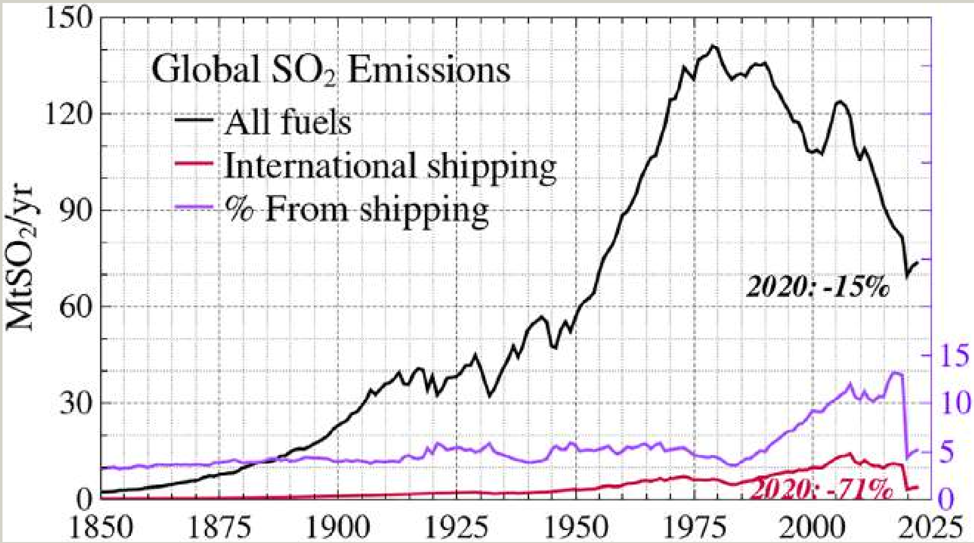
Aerosol forcing and climate sensitivity are each important and should be independent issues, but, due to the absence of global aerosol and cloud measurements needed to calculate the aerosol forcing accurately, *aerosol forcing and climate sensitivity were wedded in an inappropriate shotgun marriage. We now seek to disentangle and expose their relationship with simple computations understandable to a broad audience.* That goal requires that we first take a fresh look at the classic climate problem: how much will Earth warm if atmospheric CO_2 is doubled?

Global Temperature Response to Doubled CO_2

Global climate models (GCMs) are complex, requiring supercomputers for climate simulations. Modeling activity is well organized – Climate Model Intercomparison Projects (CMIPs) are conducted prior to the IPCC reports – but young researchers note that heavy emphasis on GCMs tends to crowd out a well-balanced focus on underpinning science issues, critical thinking, theoretical comprehension, and communication.[67] In addition, the complexity of GCMs places lead climate modelers in a position of expert gatekeepers to knowledge about climate, and their focus on complex models limits the public's understanding of climate change.

As a partial antidote, we suggest a simple calculation that is more amenable to understanding. It involves two steps. First, we need the Global Temperature Response to an instant doubling of atmospheric CO_2 for a range of plausible climate sensitivities. Second, we use these response curves for simple calculation of global temperature change due to known climate forcings of the past century. Results provide insights about climate sensitivity, aerosol forcing, and causes of the unusual global warming in 2023-2024.

Figure S8. SO_2 Emissions in current CEDS (Community Emissions Data Systems) data.**



Sidebar 8. Use of aerosol precursor emissions and aerosol modeling to define aerosol forcing is fraught because emissions are poorly known and aerosol-cloud modeling is primitive. There is consensus that CEDS (Community Emissions Data Systems)[59] emission data are more realistic than EDGAR (Emissions Database for Global Atmospheric Research)[60], but CEDS data used for CMIP6 and AR6 (IPCC Sixth Assessment Report) were inaccurate for Asia.[61] Revised CEDS data reduce organic carbon, black carbon, and SO_2 emissions from China about 50% in 2014 decreasing global emissions 5-10%. Restrictions on ship fuels in 2020 reduced ship emissions an estimated 71%, which is 15% of CEDS 2019 emissions or 7% of the peak emissions in the 1970s.

Sidebar 9. The issue we raise – that IPCC understates aerosol forcing – exposes an unadvertised feature of global climate model (GCM) simulations: unmeasured aerosol forcing is a variable parameter that lets GCMs match observed global warming for a wide range of climate sensitivities.[66] For example, if IPCC were correct that aerosol forcing was nearly constant from 1970 to 2005, the climate sensitivity required to match the observed rate of global warming is near 3 °C for doubled atmospheric CO_2. However, if global aerosol forcing continued to increase after 1970, observed global warming implies a higher climate sensitivity, as quantified below.

It is easy to see how the climate modeling community was led initially to low estimates of climate sensitivity and aerosol forcing. First, the sensitivity of early GCMs averaged near 3 °C for doubled CO_2 because cloud microphysics was absent in the models and the resulting cloud feedback was moderate. Second, aerosol forcing used in GCMs was small, largely via direct aerosol scattering of sunlight, for which the forcing is linear in aerosol amount. The concept that aerosols modify clouds existed, but realistic modeling of aerosol-cloud interactions in GCMs was beyond the state of the art. Climate sensitivity near 3 °C for doubled CO_2 and small aerosol forcing that increased little after 1970 produced global warming in the past century consistent with observed warming.

Global Temperature Response to doubled CO_2 was chosen by Prof. Jule Charney, chair of a pioneering study of climate sensitivity,[23] as a tool to study climate change.[68] It was an astute choice, allowing primitive global models – that were just budding half a century ago – to be used for computations that helped illuminate issues in climate physics. The doubled CO_2 studies were conducted for an idealized case in which the world's ice sheets were imagined to be unchanging. The effect of climate change on ice sheets is a crucial issue, but the complications of ice sheet change needed to wait until there was a better understanding of the atmosphere and ocean.

Climate response to doubled CO_2 forcing is now routinely calculated for GCMs to calibrate a model's sensitivity – and the results reveal important climate physics. The doubled CO_2 Global Temperature Response of the most recent fully-documented GCM[69,70] of the Goddard Institute for Space Studies, dubbed GISS (2020), has sensitivity ~3.4 °C, as shown in Figure 14 (in blue) along with an earlier model of sensitivity 2.6 °C (in green), and a response estimated for 4.5 °C sensitivity (in orange). The long timescale of the temperature responses – representative of today's climate models and presumably of the real world – are a consequence of the ocean's great thermal inertia.

About 40% of the eventual (equilibrium) warming is achieved in 10 years, 60% in 100 years, and 90 percent in 1,000 years.[71] The early response is largest over continents, where the response is not held down tightly by the ocean's great thermal inertia.

The long delay of climate in achieving its equilibrium response is both a curse and a blessing. The problem is that the public responds to threats that it sees and feels today, not to future threats perceived by scientists; thus, a great amount of future warming may be built up before actions required to stem climate change are undertaken. On the other hand, delayed response provides humanity time to alter climate forcing so that the equilibrium warming – or even the 100-year warming – and the most consequential consequences may never occur. The delayed climate response, actions to address it, and the effect of these actions are a prodigious topic that we can only introduce in our discussion below.

Climate Forcing Scenarios

To calculate global temperature, we must first specify the forcing scenario. On the century time scale, greenhouse gases (GHGs) and aerosols are dominant forcings, as other forcings are either negligible in magnitude or oscillatory with little long-term effect. The growth rate of GHG forcing (Figure 15) reached 0.4 W/m^2 per decade by 1970 and neared 0.6 W/m^2 per decade by 1980, when the growth rate of methane slowed and the Montreal Protocol began to reduce the growth of trace gases that threatened the stratospheric ozone layer.[73] IPCC projections of future GHG growth rates (yellow region in Figure 15) are discussed below under Policy Implications. RCP = Representative Concentration Pathway, these are IPCC scenarios; RCP2.6 requires CO_2 emissions start declining by 2020 and go to zero by 2100; RCP 4.5 is a "moderate" scenario in which emissions peak around 2040 and then decline; RCP 8.5 is a worst-case scenario in which emissions continue to rise throughout the twenty-first century.

IPCC data has GHGs as the sole cause of rapid global warming during 1970-2005, with aerosol forcing nearly constant over that period. Climate forcing with IPCC aerosols thus grew during 1970-2005 about 0.5 W/m^2 per decade (Figure 16a) based on GHG growth (Figure 15). In contrast, with the Aerosol A and B scenarios (Figure 13) the GHG + Aerosol forcing grows only 0.2-0.3 W/m^2 per decade during 1970-2005 and then accelerates (Figure 16b). The 1970-2005 period with contrasting forcings thus allows us to examine the issue of climate sensitivity.

In addition, although solar and volcanic forcings have little effect on long-term trends, we want to know if they play a role in the unusual 2023-24 global warming. Thus, we include recent change of these natural forcings (lower right corners of Figure 16) based on satellite data. Effects of the January 2022 Hunga volcanic eruption were too small to stand out above other sources of variability, but a comprehensive analysis[16] concluded that cooling by Hunga aerosols exceeded

Figure 14. Global Temperature Response to 2 × CO_2.**

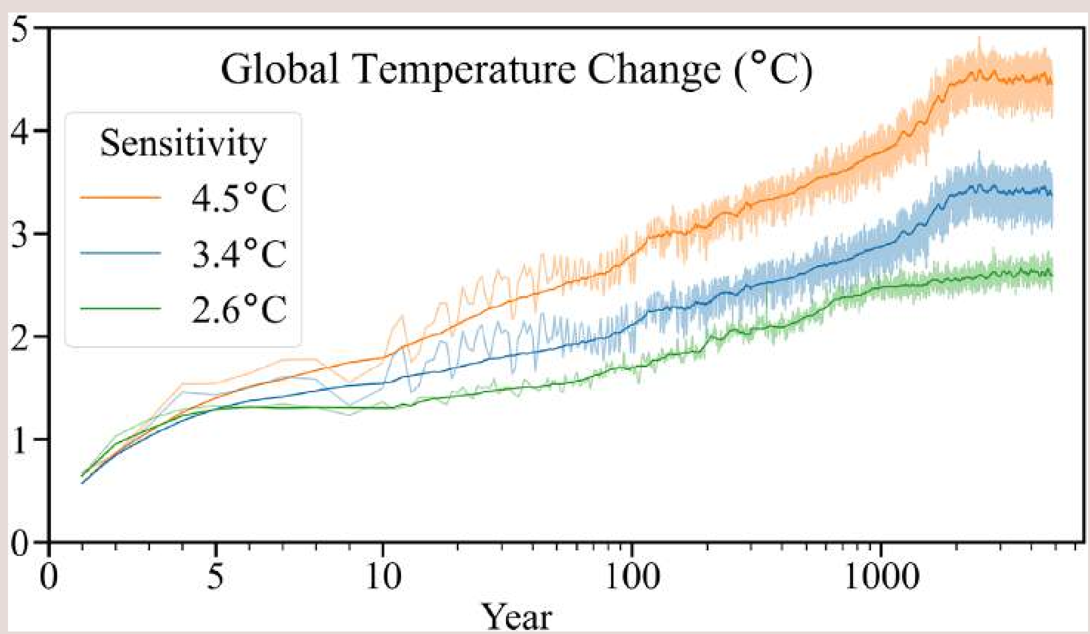


Figure 15. Annual growth of greenhouse gas forcing and various IPCC climate forcing scenarios.[72]

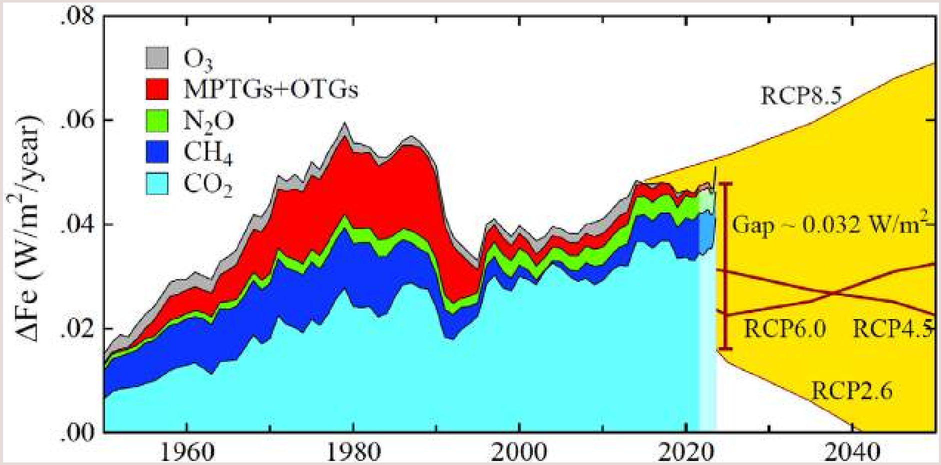
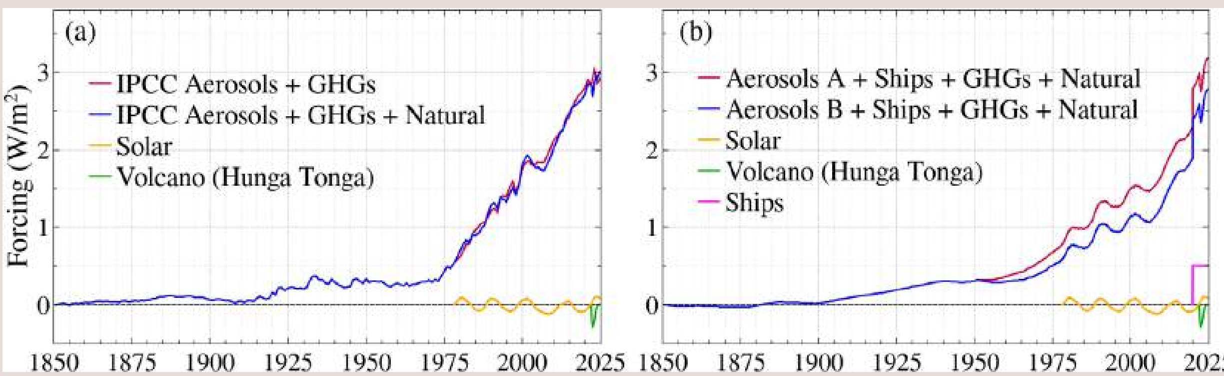


Figure 16. Climate forcing scenarios.**



warming by water vapor injected into the stratosphere by the volcano as well as induced ozone changes. We use the well-observed 1991 Pinatubo eruption to define the time scale for aerosol formation and removal from the stratosphere (Sidebar 3), with the forcing for Hunga an order of magnitude smaller, based on SO_2 injection amounts.

We approximate Ship Aerosol Forcing – for clarity and due to lack of information – as an instant +0.5 W/m^2 forcing added on 1 January 2020. Part of the forcing may have been added in January 2015 by emission limits in coastal North America and Northern Europe, if those led to changes of fuel use on the open ocean. Limits imposed in July 2010 and January 2012 may have had a small effect (Sidebar 5), but the main Ship Aerosol Forcing change occurred in January 2020.

Global Temperature Scenarios

Global temperature change can be calculated in seconds because climate responds mainly to the planetary energy imbalance, with less dependence on forcing mechanisms. Thus, knowledge of the forcing magnitude and the doubled CO_2 temperature response suffices for the calculation. Further, dependence of the response on a specific forcing can be accounted for via an "efficacy" factor.[74] Temperature change is obtained with a single equation – the most elementary in Isaac Newton's calculus – in an intuitive calculation that requires no advanced mathematics training to understand (see Note [75] at end). Validity of this temperature calculation rests on the assumption that the ocean general circulation is not altered by the climate forcing. Fixed ocean circulation should be accurate enough for the past century, but there are signs that overturning circulations (see Notes 48, 95, 96 at end) in the North Atlantic and Southern Oceans are now both on the verge of major disruptions that, if allowed to proceed, will dramatically alter future climate, as discussed below under "The Point of No Return."

Climate forcings of Figure 16 and the calculation (see Note 75 at end) yield global temperature change. GHGs and global temperature have been accurately measured since the 1950s, making post-1950 temperature relative to 1951-1980 (Figure 17) best-suited[76] for testing the ability of alternative aerosol histories to capture the 1970-2005 global warming rate. The conclusion is that all three aerosol forcing scenarios of Figure 13 can fit observed 1970-2005 warming and produce at least moderate warming acceleration, but they require successively higher doubled CO_2 sensitivities: about 3- 3.5 °C, 4.5 °C and 6 °C, for the IPCC, Aerosols A, and Aerosols B scenarios, respectively.[77] Aerosol scenarios could be tweaked in each case to obtain arbitrarily close fit to observed temperature, but there is no point to do that. *The main conclusion is that modern temperature change does not provide a tight constraint on climate sensitivity because aerosol forcing is not measured; however, if aerosol forcing is nonlinear (as in Aerosols A and B), IPCC (and thus most of the scientific community) has underestimated climate sensitivity.*

Another test is the magnitude of global warming since preindustrial time, including the unique 2023 warming. Calculated temperatures for 1850-2024 are provided in Figure SM4 (in Supplementary Material), but for clarity Figure 18 expands 21st century temperature. All three aerosol scenarios can reach 1.6 °C warming in 2023, but IPCC aerosols require a high sensitivity that then could not match warming of the past 50 years.[78] *The IPCC aerosol scenario and IPCC best estimate of climate sensitivity 3 °C do not produce warming to +1.6 °C in 2023; most decidedly, they cannot produce +0.4 °C warming in 2023, even with the help of the modest, observed, El Niño that can only add a temporary +0.2 °C. This difficulty has led to consternation that "something is wrong."* In contrast, Aerosols A and B scenarios, with their associated climate sensitivities (~4.5 and 6 °C for 2 × CO_2), the ship aerosol forcing, and a +0.2 °C El Niño, readily reach +1.6 °C current warming.

The warming detail needing explanation is the +0.4 °C leap in 2023. *We interpret temperature change in the 2020s as being affected by the strong decline of the Pacific Decadal Oscillation (PDO) in 2020-22, which temporarily hid the ship aerosol effect on global temperature.* The PDO is a natural cycle of sea surface temperature patterns in the Pacific with associated cloud changes. Positive PDO has cloud cover that yields increased absorption of solar radiation by the ocean surface (Figure 7). The PDO moved rapidly into negative values in 2020, which normally results in a negative anomaly of absorbed solar radiation, but the opposite occurred. In contradiction to the PDO, absorbed solar radiation reached +6 W/m^2 averaged over the North Pacific (Figure 7), this being, we suggest, at least in part the expected result of reduced ship aerosols. Ocean surface mixed layer and sea surface temperature in the North Pacific and North Atlantic rose steadily during the four years 2020-23 (Figures 8 and 9) in the regions of maximum aerosol effect (Sidebar 5). By 2023, PDO had reached bottom (Figure 7) and no longer added to global cooling, so the effect of decreased aerosols began to show up in global temperature.

Conclusions from the global temperature calculations are substantial. IPCC's calculated aerosol forcing and best estimate for climate sensitivity are not consistent with observed warming. Aerosols A and climate sensitivity 4.5 °C for doubled CO_2 are consistent with observed warming, which is encouraging because aerosols A is based on the newer Bauer model that simulates aerosol microphysics and 4.5 °C sensitivity agrees well with glacial-interglacial climate oscillation in the past 800,000 years,[1] the only paleoclimate case with accurate knowledge of climate forcings in equilibrium climates, as required for empirical assessment of equilibrium climate sensitivity.[79]

Now we must look in more detail at global temperature change in the 2020s, specifically asking whether the

Figure 17. Global temperature change (°C) relative to 1951-1980.**

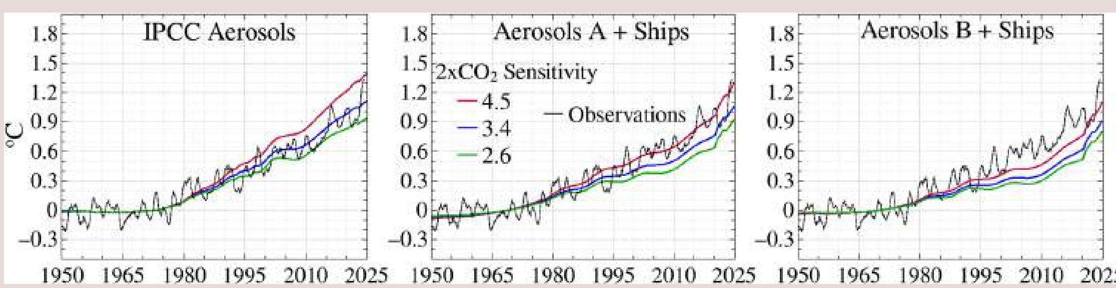
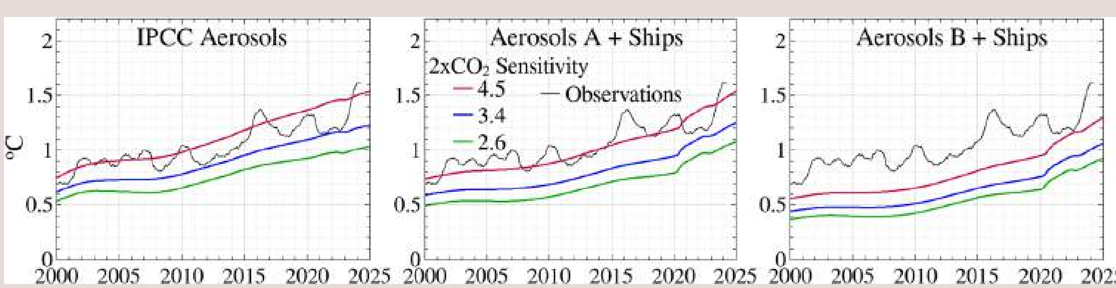


Figure 18. Global temperature change (°C) relative to 1880-1920.**



unprecedented global warming of 2023 contains information that can help confirm or refute the large ship aerosol forcing that we inferred from Absorbed Solar Radiation. The 2023 global warming was nominally the result of an El Niño, but can the El Niño alone explain the magnitude of the warming?

Fingerprinting the Climate Acceleration Mechanisms

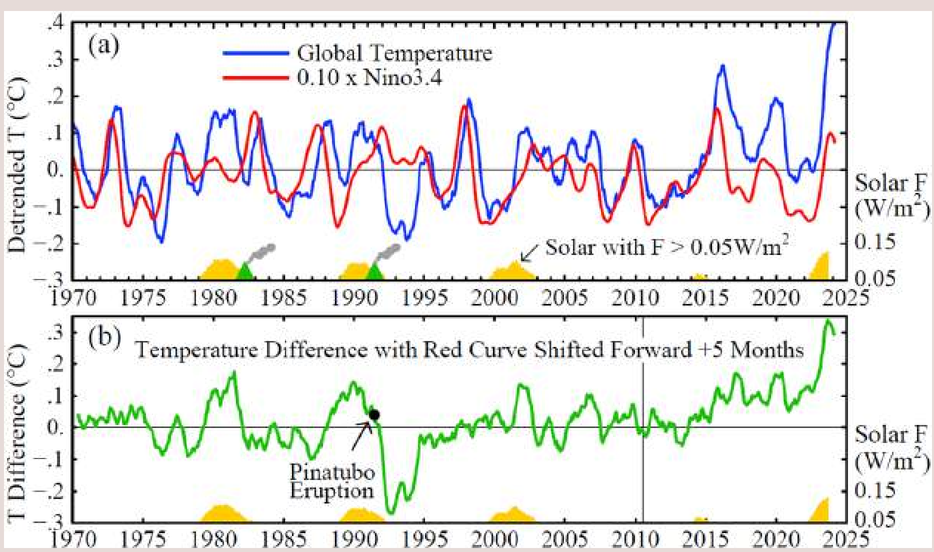
Interpretations of the 2023 warming are bookended by Raghuraman et al.[80] and Schmidt.[3] Raghuraman et al. conclude that the 2023 warming is explained by the El Niño, while Schmidt concludes that the extreme warming cannot be explained by even the full array of mechanisms in global models. Raghuraman et al. note that the 2023 El Niño rose from a deep La Niña, so, despite the El Niño being modest, the Niño3.4 (equatorial Pacific temperature used to characterize El Niño status) change from 2022 to 2023 was about as large as the Niño3.4 changes that drove the Super El Niños of 1997-1998 and 2015-2016. They suggest that the change of annual mean global temperature between 2022 and 2023 (0.28 °C, Figure 1) can be accounted for by El Niño warming. However, change of annual mean temperature (black squares in Figure 1) does not capture the magnitude of the 2023 warming, which is exposed by the 12-month running mean temperature (which includes the annual mean every December). The La Niña held down global temperature in 2020-2022, but the modest following El Niño cannot account for the remarkable 0.4 °C global warming. We conclude that Schmidt is partially right: something else important is occurring.

Here, like a detective who dusts a doorknob and lifts a fingerprint with clear adhesive tape, we extract fingerprints of the mechanisms that caused the acceleration of global warming in two simple steps. The first step is to remove the long-term trend of global temperature (0.18 °C per decade) by subtracting it from the global temperature record since 1970. (The long-term trend is caused by the net greenhouse gas plus aerosol forcing.) What remains is the blue curve in Figure 19a, which is global temperature change due to other forcings and natural variability. The main source of natural variability is the tropical El Niño cycle, shown by the temperature anomaly in the tropical Niño3.4 region (red curve). Thus, as a second step, we subtract the El Niño variability from the blue curve,[81] obtaining the green curve in Figure 19b.

Fingerprints in the green curve are apparent. Most obvious is the 0.3 °C global cooling caused by the Pinatubo volcanic eruption, but even the maxima of solar irradiance (a forcing of only ± 0.12 W/m^2, Figure 4) cause detectable warmings consistent with prior analyses.[82] The portion of the fingerprint of present interest is the decade-long anomaly that began in 2015 (Figure 19b) and grew to an astounding +0.3 °C in 2023, which we will associate mainly with ship aerosol forcing. This anomaly does not coincide with reduction of aerosol emissions in China, which began in the first decade of the century but left a still highly polluted atmosphere in China.

How much global warming is expected today from a ship aerosol forcing added five years ago (January 2020), for our estimate of a 0.5 W/m^2 forcing? A 0.5 W/m^2 CO_2 forcing yields 0.2 °C warming (Figure 14).[84] But what is the efficacy of an ocean-only forcing relative to global CO_2 forcing? To evaluate that, we ran GCM climate simulations with uniform forcing over the ocean (Figure SM3, Supplementary Material), finding an efficacy 77% the first year, 93% the second year, and 100% by the third year.[85] Thus, global warming for 0.5 W/m^2 ship forcing today is 0.2 °C. Raghuraman et al. are correct that the 2023 El Niño rise from a deep La Niña makes the 2023 El Niño effect similar to the 1997 and 2015 El Niños (Figure 19a), but that leaves an enormous 0.3 °C global warming to explain. The Sun is now near maximum irradiance, a min-to-max forcing of

Figure 19. Detrended global and Niño3.4 temperatures (°C) and difference.[83]



0.24 W/m^2 (Figure 4). Doubled CO_2 forcing of 4 W/m^2 yields warming of 1-1.5 °C in five years (Figure 14), which we must reduce by the ratio of solar and CO_2 forcings (0.24/4), yielding a solar cycle warming of 0.06-0.09 °C and leaving just over +0.2 °C warming to explain. Our estimated 0.5 W/m^2 ship aerosol forcing yields +0.2 °C warming in 2024. *Thus, the global warming anomaly in 2023-2024 is accounted for well and supports our estimated ship aerosol forcing.*

Reconciling Our Analysis and Aerosol Models

How can we reconcile our estimate of 0.5 W/m^2 for ship aerosol forcing with the six aerosol modeling studies mentioned above,[41,42] which are in mutual agreement that the global ship aerosol forcing is small, in the range 0.07-0.15 W/m^2? Let's first summarize our alternative analysis of the aerosol forcing and then suggest an approach to resolve the large difference.

Our initial estimate of the ship aerosol forcing was based on the precise CERES satellite data, calibrated absolutely with Argo float data.[44,55] The CERES data show that Earth's albedo (reflectivity) decreased 0.5% since 2010, corresponding to a 1.7 W/m^2 global average increase of Absorbed Solar Radiation. Based on the spatial and temporal coincidence of the increased absorption with regions where the effect of ship aerosols should be largest – the North Pacific and North Atlantic – we infer a Ship Aerosol Forcing of ~0.5 W/m^2, an order of magnitude larger than follows from the IPCC aerosol formulation. We also show that the albedo feedbacks due to reduced high latitude snow and ice constitute no more than 0.15 W/m^2, so there is plenty of room in the 1.7 W/m^2 to also accommodate the cloud feedback implied in the shifting of climate zones identified by Tselioudis et al.[24,86] Sea surface temperatures (SSTs) support our interpretation. SSTs are rising fastest where the aerosol forcing is largest, in the North Pacific and North Atlantic, and they are rising at low latitudes where aerosol forcing is widespread, even though smaller.

How can we explain the small aerosol forcing produced by aerosol-cloud models? Aerosol-cloud modeling involves complex microphysical interactions and is still at a primitive stage. Perhaps there is pressure to get "the right answer:"[66] ship aerosol emissions are a small fraction of total human-made emissions, so the ship aerosol forcing must be small to avoid contradicting the authoritative IPCC assessment (see Sidebar 5). Scientific reticence[87,1] may also come into play, a preference to move cautiously toward an answer that differs from that of recognized authority.

Priority in physics is given to observations, which here is global monitoring of aerosol and cloud particle microphysics and cloud macrophysics. As noted above (in Aerosol and Cloud Particle Microphysics), a relevant instrument is being tested on a current NASA mission, but adequate monitoring requires long-term observations of specific data by several instruments.[31] Aerosol and cloud changes are needed to evaluate climate forcings and climate sensitivity, which thus warrants a dedicated satellite mission, so that needed information will be available in the future as climate change rises toward the pinnacle of public interest. Radiation balance (CERES) observations must be continued with a new satellite and Argo data need to be expanded, especially around Antarctica and Greenland (see below).

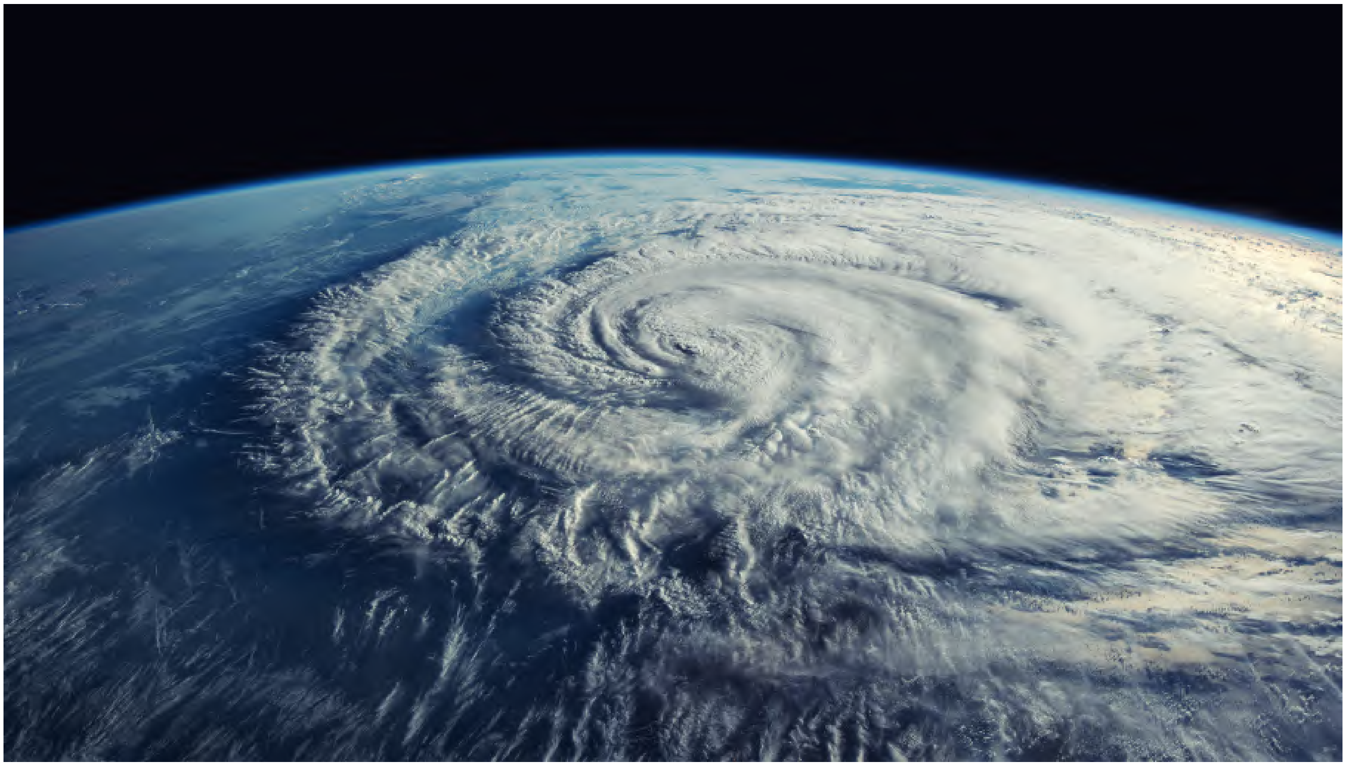
There is a danger of "being too late" with policy-relevant information. Thus, we also make an effort to define a near-term ship aerosol footprint that will help verify, or disprove, our inference of a large ship aerosol forcing as soon as possible.

Ship Aerosol Footprint: Near-Term Climate Prediction

Ship aerosol forcing should have an indelible footprint that will be obvious soon: SSTs (sea surface temperature) and global temperature will remain abnormally high. The ship aerosol effect is largest in the North Pacific and North Atlantic where human-made sulfate aerosols dominate over natural aerosols, but ship emissions are substantial at low latitudes in both hemispheres. Global SSTs, and thus global surface temperature, should remain high even during the next La Niña. Global warming of 0.2 °C from ship aerosol reduction will grow slowly beyond year 5 of forcing initiation (Figure 14), but it will prevent global temperature from falling much below +1.5 °C relative to preindustrial (late 19th century) time. Thus, our prediction is that global temperature averaged over the El Niño/La Niña cycle has already reached the +1.5 °C threshold.

These high SSTs constitute a heavy footprint for people. Increased SSTs are indicative of rising heat content of the ocean's wind-mixed surface layer, which provides energy for stronger storms with more extreme rainfall amounts. The rote explanation that "warming of 1 °C allows the air to hold 7% more water vapor" is not a full explanation of storm intensification and climate impact. Water vapor's fueling of storms – thunderstorms, tornadoes, and tropical storms – is a main factor causing more extreme storms and floods.[88] A paper[89] attached to the first author's congressional testimony in 1989, describing research by a team of eight scientists, concluded that global warming increases "moist static energy"[90] near Earth's surface and causes a larger portion of rainfall to be in more powerful thunderstorms that rise to greater heights, as opposed to gentler rainfall from stratiform clouds. Also, increased heat content in the ocean's surface layer provides energy for rapid tropical storm intensification and drives stronger, wetter, storms.

Our main conclusions – that climate sensitivity is higher and aerosol forcing is greater than in IPCC's best estimates – add to the climate threat. Nevertheless, the climate system's slow response allows the possibility to avoid the "point of no return," the point when disastrous climate change would run out of humanity's control. A happy ending – with restoration of a propitious climate – requires an understanding of this greatest climate threat.



iStock/Trifonov_Evgeniy/Elements furnished by NASA

Super typhoon.

The Point of No Return

Tipping points are a big concern in popular and scientific discussion of climate change. The most dire belief is that today's accelerated warming is a sign of runaway feedbacks that are pushing climate beyond multiple tipping points, thus causing global warming acceleration that threatens eventual collapse of civilization. Our analysis does not support such beliefs. Instead, we find that observed acceleration of global warming is caused by a human-made climate forcing: reduction of atmospheric aerosols, especially aerosols produced by commercial shipping.

Climate feedbacks are real; paleoclimate evidence shows that "fast" feedbacks (water vapor, clouds, and sea ice) amplify climate sensitivity from 1.2 °C[91] for doubled CO_2 with no feedbacks to as much as 4-5 °C, i.e., these well-known feedbacks more than triple the equilibrium climate response. However, equilibrium climate response is slowed by the ocean's thermal inertia. For example, warming from the 2020 reduction of ship aerosols is one-third complete after five years; the next third requires a century and the final third requires millennia. The mechanism that causes continued slow warming is Earth's energy imbalance – thus the additional warming will never occur, if we reduce net climate forcing to restore Earth's energy balance.

Tipping points[92] are also real. Some feedbacks can pass a point such that the process accelerates and causes amplifying climate feedback. For example, global warming may melt Arctic permafrost, releasing large amounts of greenhouse gases to the atmosphere. Or heating and drying of the Amazon rainforest may reach a point that the rainforest is not self-sustaining, with fires releasing much of the carbon stored in the forest. Many tipping point processes are reversible if Earth cools, but the recovery time varies and may be long for some feedbacks.

The most threatening tipping point – the Point of No Return – will be passed when it becomes impossible to avoid catastrophic loss of the West Antarctic ice sheet with sea level rise of several meters. Large areas in China, the United States, Bangladesh, the Netherlands, island nations, and at least half of the world's largest cities would be substantially submerged, an irreversible result on any time scale that people care about. Rising seas would be accompanied by increasing climate extremes that are already emerging at global temperature of only +1-1.5 °C.[93] Emigration from populous coastal areas and other vulnerable/disaster-prone regions would add to emigration from increasingly inhospitable low latitudes. Sea level would not stabilize after West Antarctica collapses: there is at least 15-25 m (50-80 feet) of sea level in Antarctic and Greenland ice in direct contact with the ocean. The last time Earth was at +2 °C relative to preindustrial time – in the early Pliocene – sea level was 15-25 m (50-80 feet) higher than today. Sea level change takes time, so coastlines would be continually retreating.

Clearly, we must avoid passing the Point of No Return. Learning how we can do that requires understanding how the ice sheets, ocean, and atmosphere work together.

Ice Sheet, Ocean, Atmosphere Interactions

The IPCC reports dismiss shutdown of the overturning ocean circulation and large sea level rise on the century time scale as low probability, even for high emission scenarios. How did they reach that conclusion? Models with a specific modeling approach. Climate models are an essential tool because there is no natural precedent for rapid human-made climate forcing. A complete global climate model includes the ice sheets, ocean, and atmosphere. Dynamic ice sheets are the most recent of these components to be modeled in detail and are the most challenging due to the wide range of spatial scales: from small-scale action of freeze-thaw cycles in breaking up ice to large-scale movement of ice sheets over land surface and sea floor terrain. Global climate models are supposed to allow realistic interactions among the ice sheets, ocean and atmosphere, but if one of these components is not simulated well, it affects the others.

Twenty years ago, the first author (JEH) had discussions with field glaciologists[94] who were frustrated with IPCC reports and models that they believed portrayed ice sheets as unrealistically lethargic.[95] Their concerns were based mainly on observed effects of water – on, within, under, and at the edges of the ice sheets – that could speed the movement and disintegration of the ice. Concern that ice sheet models were too "stiff" led to an alternative perspective on ice sheet stability[95] based on Earth's energy balance and feedbacks among the ocean, ice, and atmosphere; this perspective suggested that ice sheets are more mobile in the real world than in ice sheet models. Support for this perspective was provided by paleoclimate data, which revealed oscillations of ice sheet size that could not be produced by existing ice sheet models.[49]

Integrated modeling – with ice sheets, ocean, and atmosphere all included in one model – is one approach that should be, and is, being pursued. But if it is the only approach, there is a danger that it will be slow to achieve real-world dynamic realism. A complementary approach is to use well-tested atmosphere-ocean climate models with testable assumptions for ice sheet behavior. The objective is to compare the model results with reality in hopes of learning things about ice sheet behavior and future climate impacts. This latter modeling approach was pursued with the Goddard Institute for Space Studies climate model, but first it was necessary to address fundamental issues about ocean models, which have their own uncertainties.

Stefan Rahmstorf, the world-leading expert on the ocean's overturning circulations,[96] *described a tendency of ocean model development to produce models that are unrealistically stable.*[97] A related concern about ocean models was their widespread tendency to produce excessive small-scale mixing of ocean properties. As we have already discussed, the excessive mixing of surface heat anomalies caused global models to underestimate (negative) aerosol forcing.[98] Another effect of excessive mixing is to increase stability of the ocean model against possible shutdown of the overturning circulation. When freshwater from melting ice sheets is injected into the ocean surface layer it reduces the density of the salty surface mixed layer. The density reduction tends to decrease the amount of cold, salty, dense water that sinks toward the ocean floor in polar regions in winter; if the density reduction is sufficient, it can even shut down the overturning circulation. Ocean models with excessive, unrealistic, mixing tend to homogenize the water and prevent shutdown. Special effort was made to eliminate unphysical mixing in the Goddard Institute for Space Studies atmosphere-ocean climate model.[99] This model was used for climate simulations for the 20th and 21st centuries, and a paper was submitted for publication in 2015.

Ice Melt, Sea Level Rise, and Superstorms

The full title of the submitted paper,[100] "Ice melt, sea level rise, and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global

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Exhaust from cargo ships includes aerosols.

iStock/Toa55

Amazon forest fire.

warming is highly dangerous," summarized our strategy to assess the danger of passing the Point of No Return. Insight based on combining information from paleoclimate studies, climate models, and ongoing climate change is essential to obtain early, reliable, assessment of climate change. The paper passed extensive peer review and was published in 2016.[101]

This "Ice Melt" paper paints a picture of Eemian climate (120,000 years ago) of relevance to climate change today. Eemian global temperature was about +1 °C relative to the preindustrial Holocene.[102] Mid-Eemian sea level was about the same as today and the Antarctic and Greenland ice sheets were similar to their present sizes. Late in the Eemian period,[103] sea level rose several meters within a century, the rapid rise being recorded in the rate that coral reef-building "backstepped" toward the shore in response to the rising seas.[104] It is likely that the added sea level was from collapse of the West Antarctic ice sheet because that ice sheet sits on bedrock hundreds of meters below sea level, making it vulnerable to ocean warming and rapid disintegration.

Late Eemian climate also featured shutdown of the North Atlantic overturning circulation, as revealed by ocean cores of seafloor sediments.[105] Shutdown of this ocean circulation short-circuits interhemispheric transport of heat by the global ocean conveyor,[106,107] which normally transports a huge amount of heat – 1,000 trillion watts – from the Southern Hemisphere into the Northern Hemisphere. That heat amounts to 4 W/m^2 of energy averaged over the Northern Hemisphere, but it is mostly concentrated in the North Atlantic region, which is thus warmer than expected for its latitude. When the ocean conveyor shut down, that heat stayed in the Southern Ocean, where it may have contributed to collapse of the West Antarctic ice sheet. Meanwhile, in the North Atlantic region, there was evidence of powerful storms. This picture of the Eemian, if filled out in finer detail[108] including the sequencing of events, may help us anticipate where our present climate is headed, if effective actions are not taken to halt and reverse human-made climate change, restoring relatively stable Holocene climate.

Climate simulations in "Ice Melt" were carried out with a climate model that passed crucial tests such as having deepwater formation at several locations close to the Antarctic coast, a test that many other models failed. In the climate projections, it was assumed that growth of ice sheet melt would be nonlinear, based on paleoclimate data showing that sea level on occasion rose several meters in a century. Freshwater fluxes into the ocean were estimated as 360 Gt/year (a gigaton, Gt, is one billion tons) in the Northern Hemisphere and 720 Gt/year in the Southern Hemisphere in 2011 with doubling times for these rates being either 10 years or 20 years. The largest freshwater source is melting of ice shelves, the tongues of ice that extend from the ice sheets into the ocean.[109] The range of doubling times for freshwater injection – 10 years to 20 years – was based on limited observations, but still seems to be an appropriate estimate. Observations that help improve this estimate are needed.[110]

Our climate simulations led to the staggering conclusion that continued growth of ice melt will cause shutdown of the North Atlantic and Southern Ocean overturning circulations as early as midcentury and "nonlinearly growing sea level rise, reaching several meters in 50-150 years."[111] These results contrast sharply with IPCC conclusions based on global climate models. Growing freshwater injection in the Ice Melt model[49] already limits warming in the Southern Ocean by the 2020s with cooling in that region by midcentury. In contrast, models that IPCC relies on have strong warming in the Southern Ocean. Observed sea surface temperature is consistent with results from the Ice Melt model,[49] but inconsistent with the models that IPCC relies on (Figure 20).[112]

Earth's temperature only reached the Eemian level, +1 °C, about a decade ago and is now already at +1.5 °C. It's crucial that we understand the implications of this warming for today's young people and for their children and grandchildren. We must understand it well enough, soon enough, that we can avoid handing them a planet headed irrevocably to the Point of No Return, with ice sheets headed for collapse and sea level out of humanity's control.

Long-Term Climate Change

Are the United Nations and public well-informed about the status of long-term climate change? The Secretary General of the UN in the past few years has made increasingly frantic statements about the urgency of actions to stem global warming, but in the context of unrealistic appraisal of the possibility of achieving the goal of the Framework Convention on Climate Change. Frank admission of the status of climate change and the implausibility of limiting global warming to a level below 2 °C with the present policy approach is needed. Realistic assessment is needed to help evaluate the actions that are needed to provide the best chance to attain and preserve a propitious climate and environment for today's young people and their descendants.

Global temperature leaped up in the past two years, passing the +1.5 °C level, and it will continue to rise for at least the next few decades, with natural oscillations about the human-made long-term change. The recent acceleration of the global warming rate should not last long. That acceleration is driven mainly by a unique forcing, the forcing of about 0.5 W/m^2 caused by reduction of sulfur emissions from commercial ships, not by runaway feedbacks or climate tipping points.[113] Our Faustian debt is not paid off by any means; the warming due to reduction of ship aerosols is only one-third complete, but the second and third portions will occur over a century and a millennium, which gives humanity time to take action. Potential additional reduction of aerosols, mainly of continental sources, is about 1 W/m^2 according to IPCC, but more likely in the range 1.5-2 W/m^2 for all aerosol sources, including wood and other biomass burning.[1] Although that is large forcing and large potential warming, if the world were to return to a pristine pre-human

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Costs of climate change: aftermath of Hurricane Helene near Biltmore Village in Asheville, North Carolina.

atmosphere, nothing approaching complete return is plausible with a human population of billions that is still growing. Burning of wood and other biofuels will continue for the foreseeable future and human-caused forest and grass fires are likely to grow as climate extremes increase. We need to measure aerosol changes better, but additional aerosol changes seem unlikely to be a major drive for climate change in the next few decades.

Thus, continued global warming will depend mainly on fossil fuel emissions (Figure 21b).[114,115] The resulting greenhouse gas climate forcing (Figure 15) is now increasing almost 0.5 W/m^2 per decade, an amount that dwarfs changes of other climate forcings, including aerosols. Ever since the Kyoto Protocol was achieved in 1997, it has been hoped that voluntary goals for emission reductions would slow the growth of global emissions as needed to avoid dangerous climate change. In fact, global emissions accelerated, demonstrating that short-term economic self-interest trumps concern about long-term degradation of the global commons. The gravity of the situation is shown by Figure 15, which compares reality with the greenhouse gas scenario (RCP2.6) designed by IPCC to limit global warming to less than +2 °C. Annual growth of greenhouse climate forcing is now more than double the amount in IPCC's target scenario, which was never realistic because it relied on an assumption of massive carbon capture at powerplants with permanent burial of the captured CO_2. Carbon capture at the gigaton scale does not exist; the estimated *annual* cost of CO_2 extraction is now \$2.2-4.5 trillion dollars per year,[116] and the gap between the IPCC scenario and reality is rising rapidly (Figure 15). Such hypothetical large-scale carbon capture will not happen in anything near the required timeframe.

Imaginary, implausible, scenarios are harmful. Misleading plans for "net zero" emissions by midcentury – while present policies guarantee that high fossil fuel emissions will continue – disguise failure to face reality. How is it that the United Nations advisory structure appears to be so oblivious of real-world energy needs and the time scale on which fossil fuel emissions will realistically be brought down? Contrary to hype of some environmental organizations, fossil fuels are not a narcotic pushed on the public by an evil industry; they are a convenient condensed form of energy that has helped raise the standard of living in much of the world. The realpolitik is: as long as the global commons are available as a free dumping ground for pollution, most nations with fossil fuel reserves will exploit those reserves. A radical change of global climate policy is needed, as discussed in our final section below.

Given this grim picture, what is our basis for optimism? Why do we believe that it is realistic to avoid passing the Point of No Return? Our optimism is based on the growing interest of young people in the condition of the world that they and their descendants will live in, and in their conviction that they should follow the science. The scientific approach, as we will explain, has potential to lead to a radical change of policy.

Global Justice: Policy Implications

Global emissions will remain high and climate will pass the Point of No Return, if

Figure 20. Sea Surface Temperature anomaly 15 November 2024 (°C).**

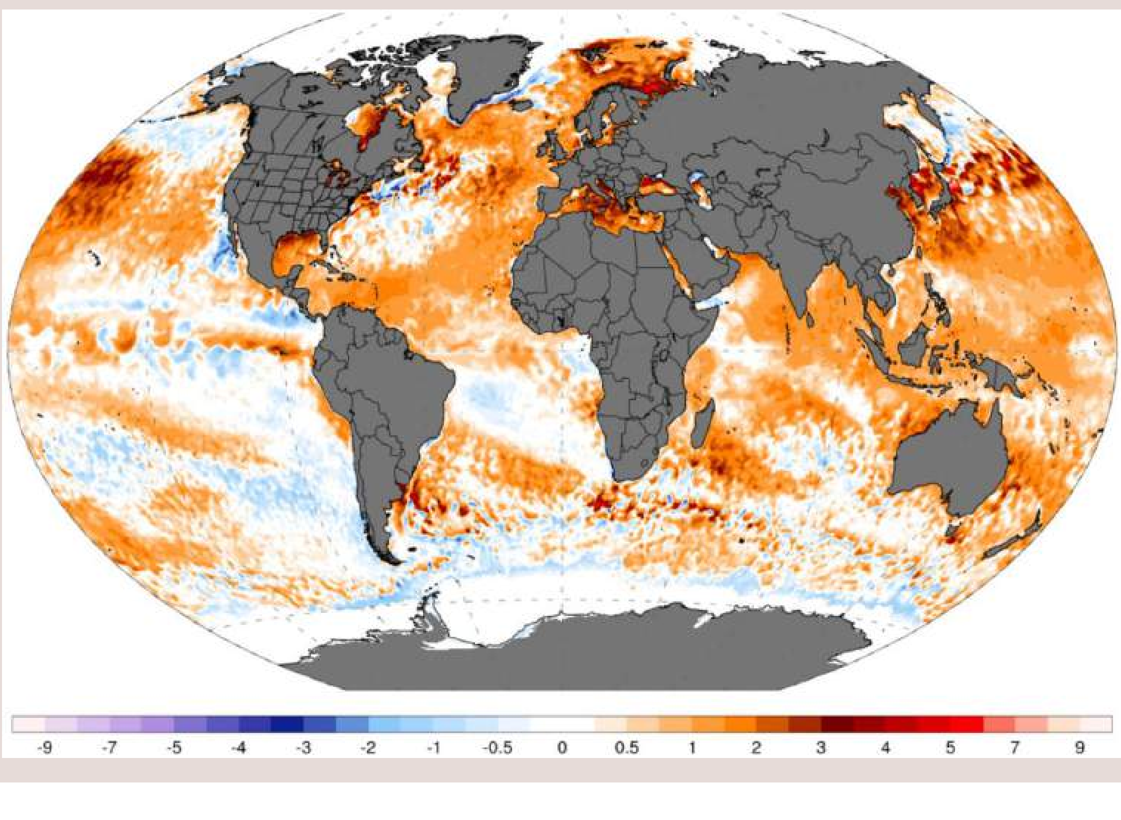
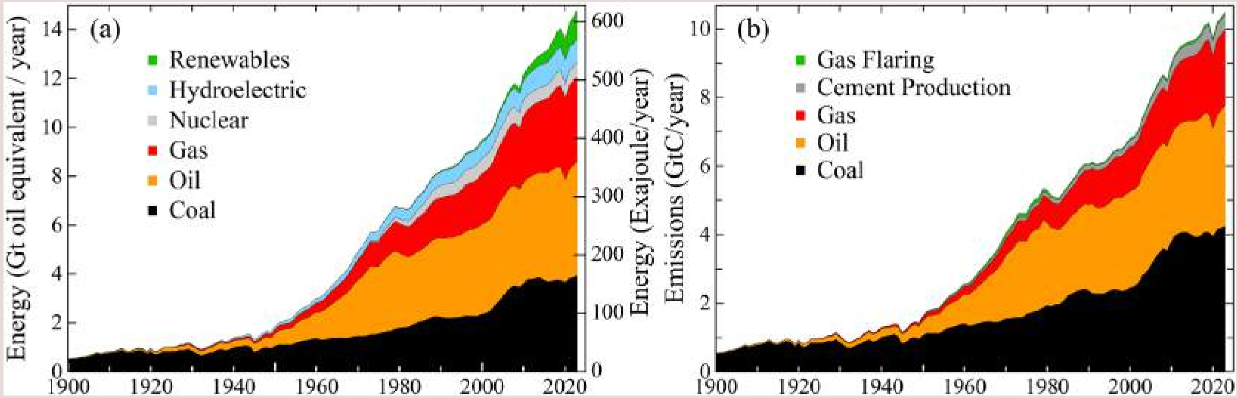


Figure 21. Global energy consumption (a) and CO_2 emissions (b).**



the atmosphere continues to be a free dumping ground for fossil fuel emissions. Current emissions are coming more and more from nations with emerging economies, such as China and India, but climate change is caused by cumulative (total historical) emissions [117,118] (Figure 22b), for which the United States and Europe are the largest contributors. This responsibility becomes even more apparent in per capita contributions to cumulative emissions (Figure 23b, based on 2020 populations). The per capita cost of removing prior emissions, as needed to restore Holocene climate, is shown on the right-hand scale of Figure 23b, based on the most optimistic (low end) cost estimate.[116] This large cost provides one measure of the scale of the climate problem.

Global injustice of the present political approach to climate change is obvious. Intergenerational injustice is clear: young people and their descendants will suffer consequences of climate change that was initiated and left unchecked by older generations. International injustice is also manifest, as many nations – especially those at low latitudes and low elevation – will be hit hardest by climate change, despite having little responsibility for climate change. The Framework Convention on Climate Change – overseen by the United Nations with annual COP (Conference of the Parties) meetings and supported by the Intergovernmental Panel on Climate Change (IPCC) – was supposed to stem climate change so as to minimize these global injustices, but it has been ineffectual. Why? We assert that this political approach has not followed the path dictated by science. There is evidence that young people are fed up with this ineffectual political approach and wish to follow the science, as we can illustrate with important examples.

The most fundamental need is for a rising price on carbon emissions, which is the essential underlying policy needed to guide the world to a prosperous clean-energy future. Economic scientists overwhelmingly agree[119] that a simple rising carbon fee (tax), collected at domestic fossil fuel mines and ports of entry, with 100% of the funds distributed[120] uniformly to the public as "dividends," is the most effective and socially just way to implement a carbon fee. Low-income and most middle-income people would gain financially, with the dividend exceeding their increased energy costs. Student body presidents at colleges and universities in all 50 states in the U.S. agreed to "follow the science" and support carbon fee and dividend.[121] Later 700 high school student leaders from all 50 states endorsed this approach.[122]

A second example of following the science is also informative. Although a rising carbon fee is the underlying requirement to phase out carbon emissions, it is not sufficient. Governments also must assure that adequate carbon-free technology is available. Yet, rather than supporting competition among alternative energies, most governments chose to support innovation and development only of "renewable" energies, a political "solution" that serves to hamstring future generations by slowing the transition away from fossil fuels.[123] Buried deep in IPCC reports is information that nuclear power has the smallest environmental footprint of major energy sources, but politics caused a failure to develop modern nuclear power (Sidebar 10). It takes time to drive down the costs of new technology – as demonstrated by solar and wind power – but there is still, if barely, time for additional

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Modern container ship.

Figure 22. CO_2 emissions in 2022 (left) and cumulative 1750-2022 (right).**

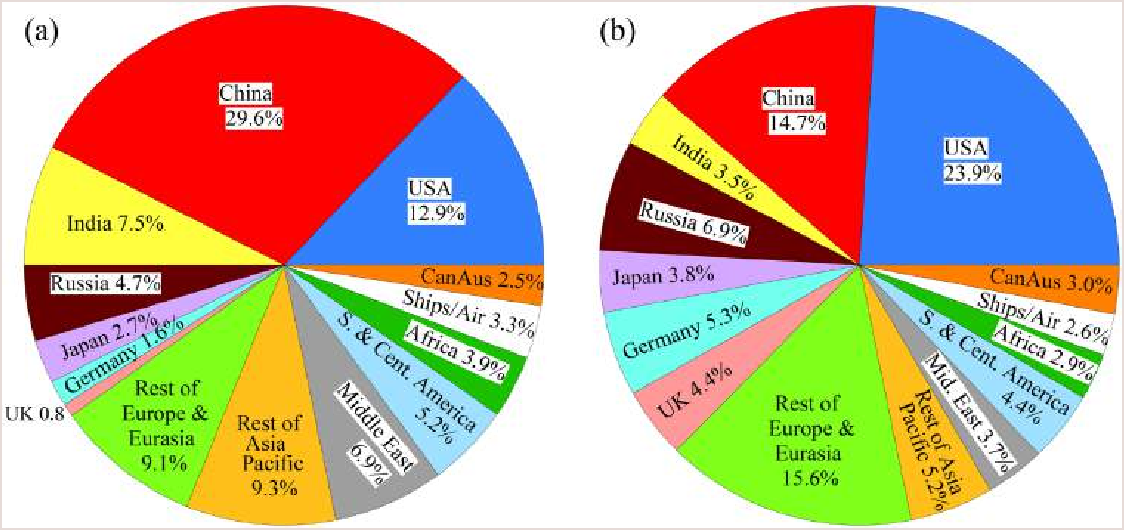
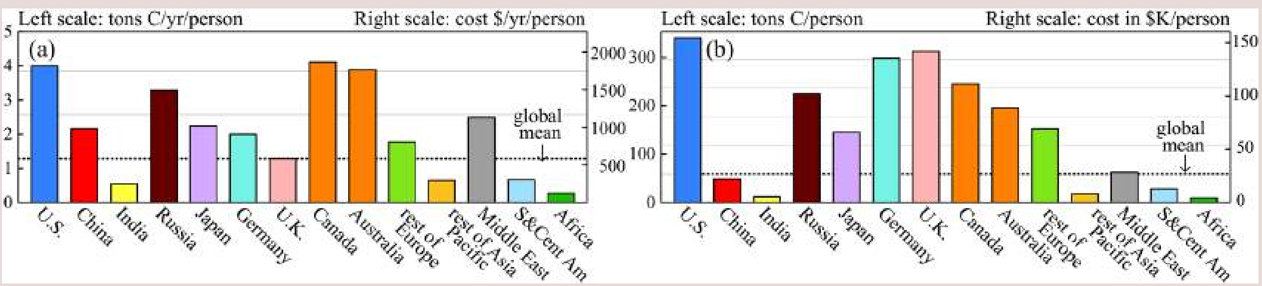


Figure 23. CO_2 emissions per capita in 2022 (left) and1750-2022 (right).**



nuclear power to be brought on-line to provide the firm (available 24/7) energy needed to complement renewables, including the ability to provide high-temperature energy required by heavy industry. It may be just in time to help us avoid passing the Point of No Return.

Nuclear power warrants a further comment because it stands as a warning about the next big issue in climate change policy, which we will discuss next. Opposition to nuclear power was "successful" in blocking development of nuclear power for several decades, thus excluding modern nuclear power from the toolbox to deal with climate change. Given the absence of low-cost, ultrasafe, modern nuclear power in the 21st century, fossil fuels were the practical option for firm electric power as the complement to intermittent renewable energy. Thus, there has been a long delay in phasedown of fossil fuel emissions in developed nations and a vast infrastructure of fossil fuel powerplants and high-carbon industry was built, especially in emerging economies. *In turn, as* Figure 15 *so vividly illustrates, global temperature in excess of +2 °C was locked in, absent purposeful actions to affect Earth's energy imbalance.*

Purposeful Global Cooling

Today's older generations – despite having adequate information – failed to stem climate change or set the planet on a course to avoid growing climate disasters. And they tied one arm of young people behind their back by supporting only renewable energies as an alternative to fossil fuels. Now, as it has become clear that climate is driving hard toward the Point of No Return, there are efforts to tie the other arm of young people behind their back. We refer to efforts to prohibit actions that may be needed to affect Earth's energy balance, temporarily, while the difficult task of reducing greenhouse gases is pursued as rapidly as practical – namely Solar Radiation Modification (SRM). Purposeful global cooling with such climate interventions is falsely described as "geoengineering," while, in fact, it is action to reduce geoengineering. Humanmade climate forcings are already geoengineering the planet at an unprecedented, dangerous, rate.

We, the authors – who range in experience from young people just beginning our careers to older scientists who have spent half a century in research aimed at better understanding of Earth's climate

– are concerned about the danger of again "being too late" in informing the public about actions that may be needed to preserve the marvelous world we inherited from our parents. We do not recommend implementing climate interventions, but we suggest that young people not be prohibited from having knowledge of the potential and limitations of purposeful global cooling in their toolbox. We do not subscribe to the opinion that such knowledge will necessarily decrease public desire to slow and reverse growth of atmospheric greenhouse gases; on the contrary, knowledge of such research may increase public pressure to reduce greenhouse gas amounts.

Given that global temperature is already +1.5 °C, given Earth's present energy imbalance of about +1 W/m^2 (see below), given the evidence that climate sensitivity is high, given the expectation of at least moderate additional reduced-aerosol warming, and given the prospect of additional greenhouse gas emissions (Figure 21), we conclude that the world is headed to temperatures of at least +2-3 °C. If such global warming occurs and persists, it will push the climate system beyond the Point of No Return, locking in sea level rise of many meters and worldwide climate change, including more powerful storms and more extreme floods, heat waves, and droughts. Given the difficulty of achieving consensus on policy actions, research is needed during the next decade to define the climate situation better and the efficacy of potential actions to minimize undesirable climate change. For that purpose, the United Nations IPCC approach, heavily emphasizing global climate modeling, is insufficient. Observations and research are needed to better understand effects of the ocean and atmosphere on ice sheets, as is a focused effort to understand rapid sea level rise during the Eemian period. Research on purposeful global cooling should be pursued, as recommended by the U.S. National Academy of Sciences.[126] Solar Radiation Modification to counter global warming was suggested by Mikhail Budyko[127] in 1974 and later by Paul Crutzen.[128] Their idea is to mimic the cooling effect of a volcano by injecting sulfates into the stratosphere. A benefit of such aerosol cooling was revealed in climate simulations[129] in which aerosols equivalent to the Pinatubo volcanic injection were added over the (1) entire globe, (2) Southern Hemisphere, (3) Southern Ocean and Antarctica, or (4) Antarctica (Figure SM5, Supplementary Material). The aerosols cool the Southern Ocean at depth (Figure 24) in mirror image of ocean warming caused by greenhouse gases. The importance of this finding is the implied effect on processes that determine ice sheet stability (Sidebar 11).

There are numerous recent modeling studies, on the effect of stratospheric aerosols, including a strong reminder[135] that a high greenhouse gas scenario such as RCP8.5 creates such great warming and melting that aerosol intervention will almost surely be fruitless in the end. Our Figure 15 is a shocking revelation that real-world greenhouse gases are increasing at nearly the RCP8.5 rate. Policy must focus on reducing actual greenhouse gas emissions to a steeply declining growth rate relative to RCP8.5 (Figure 15). Solar Radiation Modification (SRM) – whether via stratospheric aerosols or otherwise – should be considered only as a possibility to address temporary overshoot of safe global temperature while atmospheric greenhouse gases are reduced as rapidly as practical. With that caveat, numerous studies, e.g., [136,137] suggest that stratospheric aerosols have potential to reduce the risks of Antarctic ice loss and sea level rise. However, it must be borne in mind that the greatest uncertainty is in ice sheet response to changing climate. Ice sheet modeling is still so primitive that it is difficult to have confidence in these modeling studies, per se.

Modeling limitations are why we suggest comparable emphasis on paleoclimate studies, climate modeling, and modern observations of ongoing changes. In the latter category, there is the global, natural experiment of cooling by stratospheric aerosols provided by the 1991 Pinatubo volcanic eruption, which spread aerosols into both hemispheres. The maximum negative forcing was about −3 W/m^2, more than enough to offset Earth's present energy imbalance of 1-1.5 W/m^2 and cause global cooling. Such negative forcing, if maintained for years, would cause reversal of fast feedbacks, including regrowth of sea ice area. Major effects of the brief Pinatubo forcing included global cooling in the next two years that peaked at 0.3 °C and a 50% reduction[138] in the growth rate of atmospheric CO_2 that lasted about three years. Negative effects included a temporary reduction of stratospheric ozone[139] in the tropics and adverse changes of precipitation patterns.[140]

Tropospheric aerosols are a suggested alternative cooling mechanism.[141] The inadvertent global experiment arising from the sudden restriction on sulfur content of ship fuels is analogous to the

Sidebar 10. Based on construction materials (steel, concrete, etc.) for a nuclear power plant and cost of nuclear fuel, nuclear energy could be among our least expensive energies, but it is not at this time. Many governments, especially states in the U.S., required utilities to have "renewable portfolio standards" rather than "clean energy portfolio standards," thus providing an unlimited subsidy to renewable energy for decades, stunting investment in nuclear power. Disinformation played a role in opposition to nuclear power, e.g., in the emphasis of danger in "nuclear waste." Nuclear waste is contained and has caused little problem, especially in comparison to waste from other energy sources; even old technology nuclear power demonstrably saved millions of lives.[124] In addition, exaggerated danger of tiny amounts of nuclear radiation are used by nuclear power opponents to require regulations that slow nuclear construction and increase costs.[125]

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Costs of climate change: extreme drought in what was once agricultural land.

Pinatubo experiment. Based on our analysis, this ship experiment indicates the potential for a large cooling effect via tropospheric aerosols. The environmental impact of spraying salty sea water into the air with the intention of seeding clouds may generate less concern than some other cooling mechanisms, but much more scientific and engineering research is needed to explore the topic.[142]

Investigations of purposeful global cooling occasionally raise a concern of a potential threat it might pose to ambition to reduce emissions. This hypothesis is often called *moral hazard*. This concern is largely contested in research on individuals,[143,144,145] but we take it seriously. Importantly, whether moral hazard plays out should depend on how SRM is framed, e.g. as a panacea or get-out-of-jail card vs. a complementary measure. SRM must be presented as an auxiliary tool that could help reverse some of the damage already set in motion by the fossil fuel industry and irresponsible politics. The environmental movement and academia have a huge responsibility in steering public debate on SRM, which they have largely shunned to date.

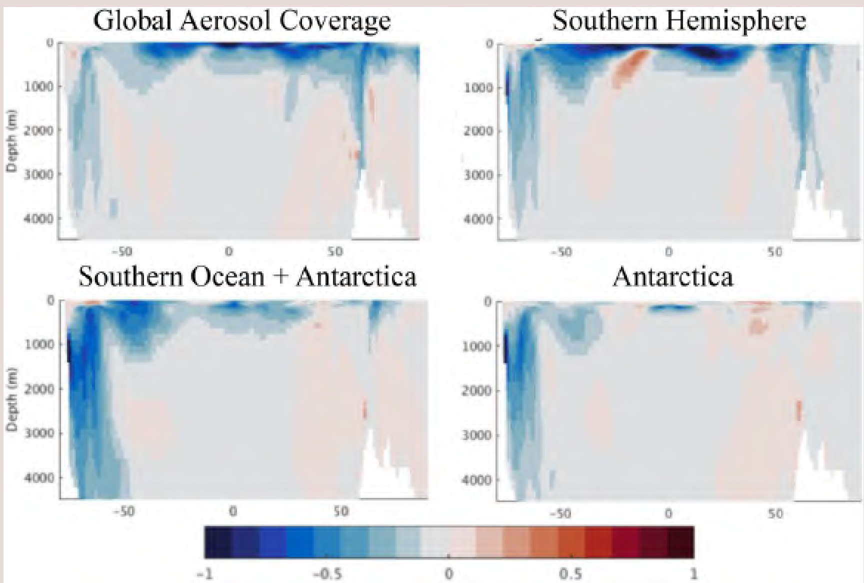
However, even in the worst case, if SRM would in some degree distract from GHG cuts, it still may be a risk worth taking, given the limited potential that greenhouse gas reductions alone now have for avoiding some catastrophic climate impacts. If, as for us, the main concern is with limiting climate disasters and subsequent human suffering, then the mere possibility of moral hazard is not *per se* a strong/valid reason for rejecting SRM research.

The main ethical issues here are (1) whether the climate impacts that are already unavoidable even with the most stringent emission scenario (not to mention with worse and more likely scenarios) are acceptable for *those who are doomed to bear them*; (2) whether SRM might help avoid some of these impacts, and how this benefit would compare to the possible side effects of the given SRM; and (3) how much SRM may distract from the main challenge of greenhouse gas reduction. There is a need for analysis that compares the risks and benefits of purposeful global cooling scenarios against scenarios with no such cooling. This comparative risk analysis is typically absent in objections to SRM research; in a similar vein, proponents of SRM research should appreciate valid concerns about the moral hazard hypothesis and deal with it in a comparative "risks vs. risks" framework. Although public perception research is nascent, it must be noted that it shows stronger support for SRM in the Global South than in the Global North, probably because of younger average age and greater exposure to climate hazards.[146,147,148]

There is no expectation of purposeful global cooling in the near-term. For now, what is needed is a strengthened resolve to transition away from fossil fuels and adequate funding to assist nations presently suffering climate disasters. Countries most responsible for climate

Sidebar 11. Ice shelves adhered to the Antarctic continent extend down the side of the continent to depths as great as 2 km in the Southern Ocean, where they provide the strongest buttressing force[130] holding the ice sheet in place. Ice shelves are the "cork" that prevents rapid expulsion of Antarctic ice into the Southern Ocean – especially the vulnerable West Antarctic ice, which rests on bedrock below sea level.[131] The rapid Eemian sea level rise likely was preceded by melting of Antarctic ice shelves. Today, ice shelves around Antarctica are again melting, with the melting accelerated by slowdown of the ocean overturning circulation. The overturning is driven by cold, salty water near the Antarctic coast that sinks to the ocean floor, compensated by rising, warmer water; this circulation is an escape valve for deep ocean heat. Global warming today is increasing ice melt around Antarctica, freshening and reducing the density of the upper ocean, thus reducing the overturning circulation[49] and escape of ocean heat to space during the cold Antarctic winter. Based on a conservative estimate[110] of observed ice melt in 2011 and a 10-year doubling time for the melt rate, a global climate model yields a 30% slowdown of the overturning circulation in 2025,[132] consistent with observational data.[133] Thus, today the ocean surface layer around Antarctica is freshening and cooling (Figure 3, Cheng et al.),[134] but the ocean below is warming. Purposeful aerosol cooling recharges this overturning Antarctic circulation, allowing deep ocean heat to escape to the atmosphere and space and cooling the ocean at depth while warming much of the thin surface layer as the upwelling deep-ocean heat melts sea ice (Figure 24).

Figure 24. Change of internal ocean temperature (°C) after 40 years.**



change will be expected to provide funding. Recognition of a growing obligation may encourage phasedown of relevant emissions. These issues are complex, but now unavoidable.

In any event, based on the discussion in this article, we believe it is likely that purposeful global cooling would be more helpful than not for limiting disastrous climate impacts. However, international agreement on such actions is undesirable until the risks and benefits of SRM are better established, and unlikely before there is better understanding of the science as well as evidence of extreme, undeniable, climate change that persuades the public of the common sense and desirability of action. That requires time, probably decades. Thus, it is important to be aware of likely near-term climate change, and to have the data needed to interpret the climate change.

The Next Decade or Two

Are the public and United Nations well-informed? Not if judged by assertions that global warming can be kept "well below 2 °C," the goal of the Paris Agreement,[149] without purposeful global cooling (in addition to phasedown of greenhouse gas emissions). Intergovernmental Panel on Climate Change (IPCC) scenarios that achieve that target, such as RCP2.6 in Figure 15, are implausible. We also conclude that IPCC underestimated cooling by human-made aerosols, and, largely as a result of that, IPCC's best estimate of climate sensitivity (3 °C for doubled CO_2) is also an underestimate. More realistic assessment of the climate situation will be needed during the next decade or two, if the world is to finally comes to grips with climate change reality.

Global Temperature

Global warming has accelerated. The warming rate of 0.18 °C per decade in 1970-2010 was less than greenhouse gases alone would have caused because aerosol cooling was growing. The warming rate increased as aerosol cooling stopped growing and warming got a big upward kick with reduction of ship aerosols. Further warming from that ship aerosol change will be slower, but if greenhouse gas forcing continues to grow (there is no evidence of a slowdown), the new global warming rate will be greater than in 1970-2010. Thus, the next year may provide a wake-up call: global temperature will remain above +1.5 °C at the end of 2024 and, at most, barely fall below +1.5 °C in 2025. Continued high temperature will support our ship aerosol forcing estimate of 0.5 W/m^2. Sea surface temperature will remain abnormally high, providing fuel for powerful storms and extreme rainfall. The 12-month running-mean global temperature[150] (Figure 1) is the single most informative temperature diagnostic, but zonal-mean sea surface temperature (Figure 10) is pregnant with more information that helps us interpret climate change. A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045.

Greenhouse Gas Climate Forcing

The projected warming rate could slow if the growth rate of greenhouse gases slowed, but there is no evidence of that. The overwhelming drive for continuing climate change is the growth of greenhouse gases, mainly CO_2, but also CH_4 (methane) and N_2O (nitrous oxide), as shown in Figure 25. The climate forcing caused by the added gases, Figure 15, is the crucial diagnostic, showing that there has been no progress in bringing down the growth rate of greenhouse gas forcing. The gap between reality and the growth rate required to keep global warming less than +2 °C is so great (see Figure 15) that it is now implausible to keep warming under that target without purposeful cooling actions, in addition to reducing greenhouse gas amounts. This is the diagnostic most indicative of progress, or lack of progress, in efforts to slow global warming. The gases must decline in amount to yield negative growth of the greenhouse forcing in Figure 15, if we are to keep global warming close to or below 2 °C. Methane briefly reached negative growth in the first decade of the 21st century (Figure 25b) as its natural sink (chemical destruction in the atmosphere) exceeded its sources (wetlands, fossil fuel mining, agriculture, and waste disposal). The reversal is probably in part from increased leakage in mining, but also increased emissions from wetlands as a result of warming, i.e., a climate feedback.

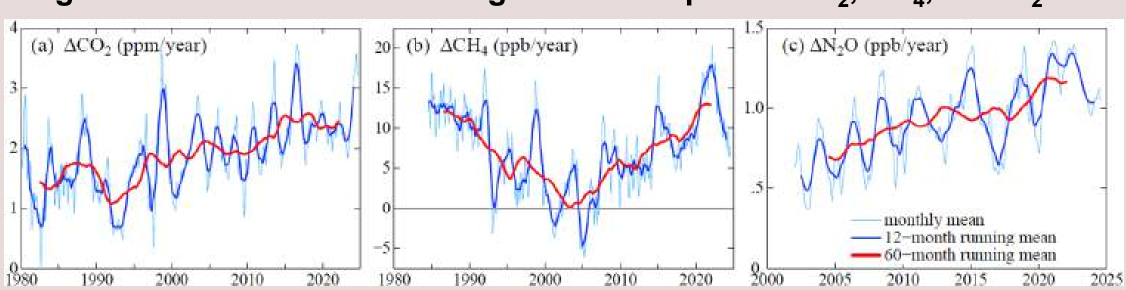
Earth's Energy Balance

The ultimate arbiter of where climate is headed is Earth's energy imbalance – as long as more energy is coming in than going out, Earth will continue to get warmer. Accurate energy balance data (Figure 26) require both precise satellite measurement[44] of radiation change and absolute calibration of this change via accurate measurement of ocean heat content change.[55] The principal satellite instruments (CERES: Clouds and the Earth's Radiant Energy System) measuring Earth's radiation balance has had remarkable longevity, but it is now near the end of its lifetime as the two NASA satellites carrying CERES are expected to reach the end of their lifetimes in 2026. The importance of these data for understanding climate change implies that replacement satellite instruments deserve high priority. There needs to be an overlap of measurements by the newer and older instruments for the sake of calibration and a continuous record. Although there are plans for new instruments, it is unclear whether they will be in time for data continuity. If data overlap with CERES is not achieved, a new calibration with Argo will be required, which will require at least a decade of measurements.

The Point of No Return

The greatest climate threat is probably the danger of the West Antarctic ice sheet collapsing catastrophically, raising sea level by several meters and leaving the global coastline in continual retreat for centuries. The West Antarctic ice sheet is vulnerable to collapse because it is a marine ice sheet sitting on bedrock hundreds of meters below sea level. There is evidence that it collapsed during the Eemian period – the last interglacial period that was warmer than the interglacial period that we live in – and now, with the rapid warming of the past 50 years, Earth is as warm as it was during the Eemian. The process of ice sheet collapse is believed to be initiated by a warming ocean melting the ice shelves

Figure 25. Annual increase of global atmospheric CO_2, CH_4, and N_2O.**

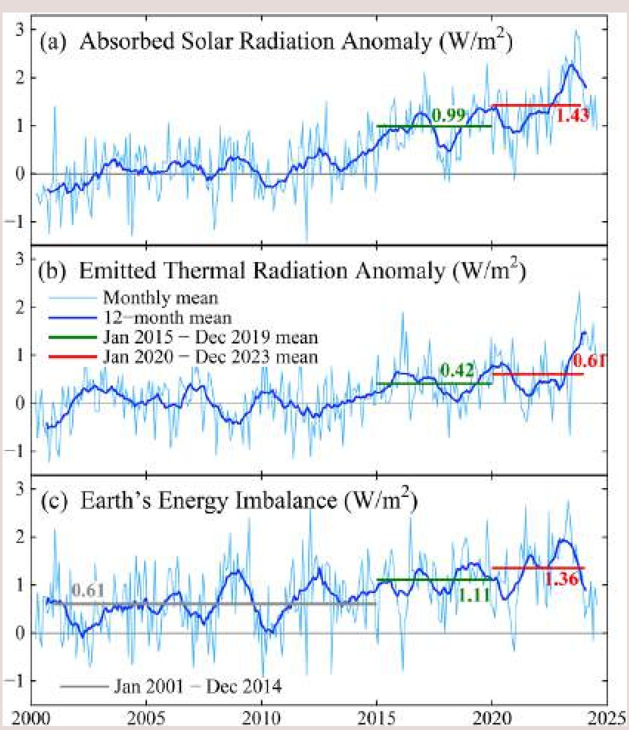


that extend from the ice sheet into the ocean, providing a buttress for the ice sheet. Those ice shelves are now melting because the ocean is warming. We do not know how far the ice shelf melting must reach before ice sheet collapse becomes inevitable. IPCC analysis of this matter has focused on global climate models that incorporate ice sheets, but the ice sheet models are primitive and unable to realistically model climate and ice sheet collapse that occurred in the Eemian.

The problem of West Antarctic ice sheet collapse is complicated because it may be related to – spurred by – shutdown of the North Atlantic overturning circulation, which is part of a global ocean conveyor that normally transports heat from the Southern Ocean into the Northern Hemisphere. When the North Atlantic Overturning circulation shuts down, that heat stays in the Southern Hemisphere where it can contribute to Antarctic ice melt. Some climate simulations for the 20th and 21st centuries that include growing ice melt from Greenland, small surrounding island ice caps, and decreasing sea ice find shutdown of the overturning North Atlantic circulation as early as the middle of the 21st century.[49] Recent statistical analysis of ongoing changes in the North Atlantic concur that shutdown of the overturning circulation could occur around mid-century, under current greenhouse gas emission scenarios.[151] Ice sheet mass balance studies including satellite-measured gravity data indicate that the rate of mass loss from the Greenland and Antarctic ice sheets has not increased during the past 20 years, as we quantify and discuss in the Supplementary Material. Ice sheet mass and ice shelf mass are distinct and, at least for a time, their changes may even be in opposite directions because increasing snowfall over the ice sheets with global warming increases ice sheet mass but does not alter the changing rate at which ice shelves are melting and providing freshwater to the polar oceans, as we have noted and discuss more in the Supplementary Material. It remains to be seen how the recent rapid increase of global warming from just over +1 °C to +1.5 °C will affect both the ice sheets and the ice shelves.

Point of No Return research deserves greater attention than it has received. There is evidence that global climate models IPCC has relied on do not realistically represent the possibility of shutdown of the North Atlantic Overturning Circulation,[1,96] nor do they simulate the rapid sea level changes that occur in the paleoclimate record.[49] A more powerful research approach would give emphasis to paleoclimate analysis and to observations of ongoing climate changes at least comparable to global climate modeling, although all three of these need to be integrated into comprehensive analysis. What was the sequence of events during the Eemian? We must try to date the events in both hemispheres on a common timescale. How exactly are the ice shelves changing today? We need to be making observations that provide knowledge of ice shelf conditions versus time, comparable to the information that we have for quantities observed from space.

Figure 26. Earth's radiation balance.**



Epilogue

Young people feel anxiety about climate change and their future. A survey[152] of 10,000 16-to-25-year-olds in ten nations found that 60% were "very worried" or "extremely worried." Two-thirds of them felt that governments are failing them, and, specifically, that governments are not acting according to science. Are they on to something? How could they get that impression? They see shootings in their schools. They see growing wars in the world. They see climate changing. In all cases, they see innocent people suffering with ineffectual government response. Yet they have faith in science. They ask: what is the truth? They do not want a sugar-coated answer: "Oh, don't worry, you will all be wealthy soon, so you can take care of the problems." They see that their parents are struggling, not becoming wealthy. Instead, governments borrow money from young people, leaving them with the obligation to pay off the debt. Yet young people want to work for a bright future and they ask of science: what is the big picture, the long story?

Failure to be realistic in climate assessment and failure to call out the fecklessness of current policies to stem global warming is not helpful to young people. The life of the first author (JEH) covers the period in which policy constraints developed. With the permission of the coauthors, the rest of this epilogue describes his perception of why policies do not serve the best interests of the public. The developments refer to the United States, but they are relevant to many nations.

The United States was ill-prepared for war when it entered World War II in 1941, but before the war was over the country had built a powerful, successful, military. The nation used its influence to help establish the United Nations and rules-based international bodies that promoted free trade and raised living standards in much of the world. The U.S. maintained a strong military, given the perceived threat of the Soviet Union, but President Dwight Eisenhower, in his 1961 Farewell Address, warned of danger in "the military-industrial complex." The draft of that speech[153] – with input from his brother, Milton, then President of Johns Hopkins University – referred to the military-industrial-congressional complex, but the President deleted "congressional" before delivering his address on national television. When Milton asked about the omission, Eisenhower explained "It was more than enough to take on the military and private industry. I couldn't take on the Congress as well." The public wishes he had. The public knows that Washington is a swamp of special interests, with huge negative effect on the public's best interest.

John F. Kennedy, in campaigning for the Presidency of the U.S. in 1960, received rousing support on university campuses when he proposed a Peace Corps to promote world friendship, and he gave the Peace Corps high priority when he assumed office in 1961. Kennedy was promptly introduced to the "deep state" when he let the Central Intelligence Agency orchestrate an invasion of Cuba by Cuban exiles, which ended in fiasco at the Bay of Pigs; Kennedy was angry at the CIA, but blamed himself for accepting their plan. In 1963 President Kennedy gave a surpassing "Peace Speech"[154] that led to a nuclear test ban treaty with the Soviet Union, and, shortly before his assassination in November 1963, decided on a specific plan to withdraw from Vietnam regardless of the military situation there.[155] If Kennedy had served eight years instead of 2 years and 10 months, perhaps America would have followed a different path, but, instead, the United States now has a military presence in almost too many nations to count.[156]

The path followed by the United States after JFK's assassination was not chosen by the American people, who, in fact, have a distaste for meddling in the internal political affairs of other nations. As a NASA post-doc in 1967 and 1968, I worked in a Columbia University building a short distance from where students protested the Vietnam war and Columbia involvement in war-related research. Most Americans accept the need for a strong military, but not the continuous pursuit of global military hegemony with interference in the internal affairs of other nations. The origin and continuation of a militaristic approach with frequent, often secret, support of "regime changes" in nations deemed unfriendly to our interests – as opposed to Kennedy's greater emphasis on being "as a city upon a hill,"[157] a positive example with the eyes of all people on us – is important for understanding why effective actions to preserve climate are not being taken and how this can be changed.

Now let's summarize emergence of climate change science and the world's political response.

Charles David Keeling[158] initiated precise measurements of atmospheric CO_2 in 1958, confirming that humanity was changing our atmospheric composition. During the 1960s and 1970s concern grew about possible impacts on climate, culminating in the 1979 Charney report[23] that concluded climate sensitivity was likely in the range 1.5-4.5 °C for doubled atmospheric CO_2, thus implying large potential climate change. Paleoclimate data supported high climate sensitivity, favoring a sensitivity in the upper half of Charney's range.[159] Observed, ongoing, global warming added to concerns, leading to adoption of the UN Framework Convention on Climate Change[4] at the Rio Earth Summit in 1992 and the Kyoto Protocol[160] in 1997, with the objective of limiting changes of atmospheric composition, so as to avoid dangerous human-made interference with climate.

Subsequently, every year for three decades, the nations of the world have gathered for the annual Conference of the Parties (COP), duly noting the growing climate threat. Nations duly promise to take action to reduce their emissions, and each year (barring a pandemic or global recession) global emissions actually grow (Figure 21). Why? Fossil fuels are a marvelous, condensed energy source that raises living standards. As long as their waste can be dumped into the global commons, the atmosphere, without paying a fee for the cost to society, they will continue to be used and the climate problem will remain unsolvable. There are still plenty of fossil fuels in the ground. Individuals and nations will not readily give up the benefits that fossil fuels can bestow.

Cost of Carbon

Governments, almost universally, try to limit carbon emissions with some "cap-and-trade" scheme. For example, a cap may be placed on emissions from some activity, with allowances to emit distributed or sold accordingly. If a business or nation cannot stay within its cap, it can purchase the right to emit from someone else. Or the business or nation can "offset" its emissions via an activity such as planting trees or, supposedly, helping another business or nation reduce its emissions. The problem is that the offsets are often hokey, hard to verify, or actions that are needed anyhow, actions that should be additional, not offsets.

In 2008-2009, Peter Barnes and I, respectively, tried to persuade the U.S. Congress that "cap-and-dividend" and "fee-and-dividend, (Sidebar 12) were much superior to cap-and-trade. Barack Obama, who had warned of a "planet in peril" in his 2008 campaign, missed a golden opportunity with the financial crisis that existed when he took office. Congress had to approve legislation to deal with the crisis. Obama could have included fee-and-dividend in the legislation, but, instead, he treated climate as a separate matter. I went to Washington to testify to the Ways and Means Committee of the U.S. House of Representatives, but there seemed to be stronger voices behind the scenes pushing the Waxman-Markey bill, which grew to several thousand pages.

Senator John Kerry, who would shepherd the legislation through the Senate for President Obama, listened patiently to my explanation of the superiority of fee-and-dividend approach, which is an underlying policy that makes all other actions to reduce emissions more effective and work faster. It would be hard to reverse because 70% of the public receives more in their dividend than they pay in increased costs (wealthy people with large carbon footprints lose money, but they can afford it) and it could readily be made global via border duties on products from countries without a carbon fee, which would pressure them to have their own carbon fee. "That may be best," Senator Kerry said, but he insisted that he could not get the votes for it; each congressperson needed the opportunity to add pages to the bill (legislation). That is why every bill with substantial funding is long and requires several days to write; the congresspeople are obtaining input from special interests who provided them "campaign" money and adding them to the legislation.

The Waxman-Markey bill failed to pass, as it was opposed by the fossil fuel industry. I went to a dozen other countries to talk about climate change, including the need for fee-and-dividend, but I found that the power of special interests is not unique to the United States. Back in the U.S. at an event in San Francisco, with California Governor Jerry Brown in the front row about to give me some award, I described Brown's plans for cap-and-trade legislation as "half-assed* and half-baked" (*my mother's favorite description of a foolish plan). The high-society audience gasped, but Jerry Brown laughed good-naturedly and said that his climate plan was "pretty darned good." My double criticism was that the plan was both ineffectual and could not grow, as the resulting increased energy cost, with no dividend for the public, would eventually lead to resistance.

That is harsh criticism of government leaders, which I reached reluctantly. When I first went to Washington and capitals of other nations, my impression of legislators was positive: most elected officials are intelligent, concerned, and articulate. However, when politicians propose policies to address climate change, they commonly choose complex, expensive, ineffective policies – policies preferred by special interests, rather than policies defined by the best scientific analysis. Before discussing this fundamental problem further, let's consider one more, related, essential topic.

East-West Cooperation and Nuclear Power

Climate simulations reported by the IPCC (Intergovernmental Panel on Climate Change) in the 1990s, including those with greenhouse gas emissions consistent with Kyoto Protocol[163] goals, all yielded global warming well above 2°C. That result did not generate consternation, perhaps because early IPCC reports ignored paleoclimate data and thus did not recognize the dangers in 2°C global warming, but the large warmings led my colleagues and I to define an "alternative scenario."[164] Our idea was to rapidly reduce non-CO_2 climate forcings and slowly reduce fossil fuel CO_2 emissions over 50-100 years, thus keeping warming under 2°C. That result would require cooperation between the major CO_2 emitters – the United States, China and India – none of whom were required by the Protocol to reduce emissions; the U.S. did not ratify the Protocol and China and India were classified as developing countries, who were not required to reduce emissions yet. I obtained funding from a philanthropist[165] for workshops[166] in 2002 and 2005 at the East-West Center in Hawaii, where scientists from the U.S., Europe, China and India discussed the alternative scenario and related science. The workshop established scientist-to-scientist connections that were useful, even if governments paid little attention and did not work together.

Those connections came into play in February 2014 after I was invited by the Kissinger Institute on China and the United States to join the U.S. Ambassador to China at a symposium in Beijing with the promising title: "New Type of Major Power Relationship." The symposium covered two topics where China-U.S. cooperation is essential: climate and human health/infectious disease.[167] The Chinese experts were convened by the think tank of China's State Council. My presentation[168] was blunt: without a major direction change, the world was headed to climate disaster. As the nation most responsible for ongoing climate change and the nation with the largest current emissions, we should work together. Our Chinese hosts responded by showing their budding efforts to build huge solar panel and windmill factories. As we toured large cities my asthma succumbed to air pollution (Sleepless in Ningbo)[169] and I stayed up at night to write a summary of our collective crime against young people and nature.[170] Large city mayors told us that their CO_2 emissions were skyrocketing because coal was their only option for baseload energy (available 24/7) to complement intermittent renewable energy. They had no plans to invest in nuclear power.

China and the U.S. have shared interest in stabilizing climate and reducing pollution. Faster progress in nuclear technology is possible if we work together. A workshop was needed to explore the potential, so I initiated correspondence with nuclear experts, leading to a workshop in Hainan, China, in 2015, where a range of ideas were discussed. The main barriers to nuclear power – high cost and slow construction – could be addressed by mass construction analogous to aircraft manufacture or by shipyard construction of floating power plants. Product-type licensing could address slow regulatory approvals. Nuclear reactors can be built to operate at high temperature, allowing use for industrial processes that now rely on fossil fuels, but

Sidebar 12: Carbon Fee and Dividend. In 2008 I proposed "Carbon Tax and 100% Dividend"[161] (changing the name to "fee and dividend" in 2009) as an alternative to the "cap and dividend" approach promoted by Peter Barnes.[162] The tax (fee) would be collected at the fossil fuel source – domestic mines or ports of entry – so no carbon escapes the rising fee. The funds would be added uniformly to debit cards of all legal residents (monthly or quarterly). Economic studies show that fee and dividend drives CO_2 emissions down rapidly. It has since been endorsed by 28 Nobel Prize-winning economists, all living federal reserve chairs, 15 former Chairs of the President's Council of Economic Advisers, and more than 3500 economists in the U.S.

LNG tanker with a lot of exhaust including aerosols maneuvering in an offshore gas terminal.

needed nuclear development was dormant for decades. Our workshop paper[171] describing potential China/U.S. collaboration noted that governments and industry must balance interests in cooperation and competition, but the climate threat should help find ways to overcome the obstacles.

The world is finally beginning to realize that nuclear power is needed to address climate change. At the United Nations COP29 meeting in Baku, 31 nations,[172] including the United States, pledged to work together toward tripling nuclear power capacity by 2050. However, the United States and China are not cooperating to speed development of modern nuclear technology that would drive down carbon emissions of both nations, as a result of constraints that the United States has placed on technology transfer. How did we get to this point, where we seem to give such low priority to the future of young people and their descendants? There is one more overarching topic that I must mention, but only briefly. I will try to discuss it more clearly in the last chapters of my overdue book, *Sophie's Planet*.

Science and the Media

I am a political independent in part because, it seems to me, that provides the best chance of looking at problems without an initial preference about the answer. An answer, however, is only useful to the extent that one can communicate it accurately. That communication is difficult, if the media has a preferred answer. Let me illustrate with examples from the topics discussed in this section.

I continued to advocate fee-and-dividend not only because almost all economists agree that it is most effective underlying policy – it is also socially just. Wealthy people have a large carbon footprint, so they lose money, while 70% of the public come out ahead. Thus, fee-and-dividend helps address growing wealth disparities that exist in most countries. (All the money collected within a country stays within that country – it is just redistributed in a way that encourages all people to reduce their carbon footprint. If developing countries are compensated by the major polluting countries – as has been agreed – developing countries will come out ahead as global carbon emissions decline.) I was surprised that President Obama allowed his administration to push cap-and-trade, an approach that benefits Wall Street and special interests. I wondered if this was related to the revolving door that existed between Wall Street, Ivy League universities, and Washington. So, I wrote an article Sack Goldman Sachs Cap-and-Trade[173] in hopes it would find its way to Obama. The article pointed out that big banks with skilled trading units lobbied for cap-and-trade with the anticipation of making billions of dollars. Where would that money come from? Increased energy prices for consumers. It could not be claimed that trading helped consumers, as studies showed that cap-and-trade would be less efficient than a carbon tax or fee-and-dividend.

I was encouraged to write an op-ed to the New York Times, pleased when it was accepted, and shocked when I saw what was published. Without informing me, the Times editors changed the title of the op-ed from "Sack Goldman Sachs" to "Cap and Fade," which meant the opposite of what I was trying to convey. Incredibly, on the same day the Times published two articles by Krugman. One, an op-ed opposite mine, began "Action on climate, if it happens, will take the form of "cap and trade." Period. A news article by Krugman noted that the carbon cap would generate several hundred billion dollars, which was just the amount that Obama needed for health reform. A third article by Krugman, published on his blog simultaneously with the newspaper, was titled "Unhelpful Hansen." He claimed that I advocated a carbon tax, which the public would never accept, and he scolded me to leave the matter to economists. He did not mention the dividend or the fact that fee-and-dividend is revenue neutral, with the government not gaining one thin dime.

Krugman's blog generated hundreds of responses, many of them supporting me. One of them compared Krugman to Colonel Nicholson in the "Bridge on the River Kwai," explaining what he meant by that.[174] The experience forced me to notice just how biased the New York Times is toward leftwing policies. It was little consolation when, several year later, more than 3,500 economists came out in favor of carbon fee-and-dividend, as well as 28 Nobel Prize-winning economists, all living federal reserve chairs, and 15 former Chairs of the President's Council of Economic Advisers.[175] Nevertheless, despite this consensus among economists, when President Biden had an opportunity to include revenue-neutral fee-and-dividend in legislation that Congress would certainly pass to address the covid pandemic, he chose not to include it, even though it would have provided financial assistance to people who needed it most, without contributing to inflation. Instead, large subsidies were provided for specific infrastructure including carbon-free energies, all via deficit spending, i.e., money borrowed from young people and future generations. With a touch that would make George Orwell smile, the bill was titled "Inflation Reduction Act."

That legislation, albeit at great cost, addresses a long overdue need for investment in clean energy technology. It attempts to ensure the longevity of progress via financial investments in regions where people are most skeptical of government programs. But the impact on global emissions will be small, as U.S. emissions were already headed down, and the heavy-handed top-down approach is likely to generate backlash in an increasingly polarized society. We are having great difficulty in addressing fundamental needs that almost everyone agrees upon. More than half a century ago at the University of Kansas, Robert F. Kennedy gave a talk focused on the need to end the war in Viet Nam and eliminate childhood poverty in the United States, but he included the following poignant paragraph: "But even if we act to erase material poverty, there is another greater task, it is to confront the poverty of satisfaction - purpose and dignity - that afflicts us all. Too much and for too long, we seemed to have surrendered personal excellence and community values in the mere accumulation of material things. Our Gross National Product, now, is over $800 billion dollars a year, but that Gross National Product – if we judge the United States of America by that – that Gross National Product counts air pollution and cigarette advertising, and ambulances to clear our highways of carnage. It counts special locks for our doors and the jails for the people who break them. It counts the destruction of the redwood and the loss of our natural wonder in chaotic sprawl. It counts napalm and counts nuclear warheads and armored cars for the police to fight the riots in our cities. It counts Whitman's rifle and Speck's knife, and the television programs which glorify violence in order to sell toys to our children. Yet the gross national product does not allow for the health of our children, the quality of their education or the joy of their play. It does not include the beauty of our poetry or the strength of our marriages, the intelligence of our public debate or the integrity of our public officials. It measures neither our wit nor our courage, neither our wisdom nor our learning, neither our compassion nor our devotion to our country, it measures everything in short, except that which makes life worthwhile. And it can tell us everything about America except why we are proud that we are Americans."

Less than three months later, on 6 June 1968, Robert F. Kennedy was assassinated. Robert F. Kennedy, in working in President John F. Kennedy's administration, developed an understanding of the "deep state" and the underlying problem that Eisenhower was reluctant to describe. Special financial interests, with their influence on Congress, provide the fuel not only for the military industrial complex and endless wars, but for many other problems. The assassinations of both Kennedys were a big setback to hopes of addressing the basic problem. Today, with rising crises including global climate change, we have reached a point where we must address the problem of special interests.

Why am I optimistic that we can succeed? Young people have demonstrated an extraordinary ability to affect politics without taking any money from special interests. That was obvious in the ascendancy of Barack Obama is 2008 and the surprising strength of Bernie Sanders in 2016. Social media provide the ability to communicate at little cost. The essential requirement is an effective, knowledgeable political party that takes no money from special interests. The two major political parties in the United States have tried to wall themselves off from competition, but the obstacles they throw up can be overcome. A crucial place to start is ranked voting, which assures that no person loses their vote; they need volunteers. Even prior to formation of an effective third party, ranked voting incentivizes bi-partisan behavior and counters polarization. We should be eager at the opportunity to save not only our democratic system, but our climate and all that entails for humanity and nature. This conversation will need to be continued.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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NOTES

** See Supplementary Material for data sources for this figure.

1. J.E. Hansen et al., "Global warming in the pipeline," *Oxford Open Clim. Chan.* 3 (1) (2023): doi.org/10.1093/oxfclm/kgad008.
2. Temperature is from the Goddard Institute for Space Studies analysis described by N.J.L. Lenssen et al., "A NASA GISTEMPv4 Observational Uncertainty Ensemble," *J. Geophys. Res. Atmos.* 129, (2024) e2023JD040179, and J. Hansen et al., "Global surface temperature change," *Rev. Geophys.* 48, (2010): RG4004. Datasets available at https://data.giss.nasa.gov/gistemp/ (11 December 2024, date last accessed).
3. G. Schmidt, "Why 2023's heat anomaly is worrying scientists," *Nature* 627 (2024): 467.
4. United Nations Framework Convention on Climate Change. *What is the United Nations Framework Convention on Climate Change?* https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change) (21 July 2024, date last accessed).
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6. J.E. Hansen and A.A. Lacis, "Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change," *Nature* 346, (1990): 713-19.
7. World Health Organization, *Ambient (outdoor) air pollution*, https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (22 July 2024, date last accessed).
8. J. Hansen, *Storms of My Grandchildren*. ISBN 978-1-60819-502-2. (New York: Bloomsbury, 2009).
9. https://www.columbia.edu/~jeh1/Data/GHGs/.
10. A detailed version of Figure 4 and original data sources are available at https://www.columbia.edu/~jeh1/Data/Solar/ (energy crossing unit area perpendicular to the Sun-Earth line at Earth's mean distance from the Sun) exceeds 1360 W/m^2, but about 29% of incident solar energy is reflected back to space and Earth's surface area is four times the planet's cross-sectional area. Thus, absorbed solar energy is about 240 W/m^2 averaged over the Earth.
11. J. Hansen, A. Lacis, R. Ruedy and M. Sato, "Potential climate impact of Mount Pinatubo eruption," *Geophys. Res. Lett.* 19, no. 2 (1992): 215-18.
12. M.P. McCormick, L.W. Thomason and C.R. Trepte, "Atmospheric effects of Mt. Pinatubo eruption," *Nature* 373 (1995): 399-404.
13. A.A. Lacis, B.E. Carlson and J.E. Hansen, "Retrieval of atmospheric N_2O, O_3, aerosol optical depth, effective radius and variance information form SAGE II multispectral extinction measurements," *Appl. Math. Comput.* 116 (2000) 133-51.
14. See Figure 11 and its documentation in (J. Hansen et al., "Efficacy of climate forcings," *J. Geophys. Res.*110 (2005): D18104.
15. P. Sellitto et al., "Observing the SO2 and Sulfate Aerosol Plumes From the 2022 Hunga Eruption With the Infrared Atmospheric Sounding Interferometer (IASI)" *Geophys. Res. Lett.* 51 no. 19 (2024): e2023GL105565; S.A. Carn et al., "Out of the blue: volcanic SO_2 emissions during the 2021-2022 Hunga Tonga – Hunga Ha'apai eruptions," *Front. Earth Sci.* 13 (2022) https://doi.org/10.3389/feart.2022.976962.
16. M.R. Schoeberl et al., "Evolution of the climate forcing during the two years after the Hunga Tonga-Hunga Ha'apai eruption," *J. Geophys. Res. Atmos.* 129 (2024): c2024JD041296.
17. A.E. Bourassa et al., "Tomographic retrievals of Hunga Tonga-Hunga Ha'apai volcanic aerosol," Geophys. Res. Lett. 50 (1978): e2022GL101978, https://doi.org/10.1029/2022GL101978.
18. Chapter 7 of the latest IPCC (AR6) report discusses aerosol forcing, labeling the aerosol direct forcing as ARI (aerosol-radiation interactions) and the aerosol indirect forcing as ACI (aerosol-cloud interactions). IPCC calculates ARI and ACI with equations 7.SM.1.1 and 7.SM.1.2, provided in Supplementary Material to AR6 Chapter 7. ARI is a linear function of emissions of selected aerosols and their chemical precursors: sulfur dioxide (SO_2), black carbon (BC), organic carbon (OC), and ammonia (NH_3). IPCC takes ACI to be a logarithmic function of emissions of SO_2, BC, and OC. Coefficients in these equations are derived from climate model results. Note that the historical aerosol forcing time series from each equation is scaled to match AR6 estimates for ARI and ACI for the most recent decade of model analysis. Figure SM1 in our Supplementary Material shows that the nonlinearity in the IPCC formulation is slight, much less than we infer based on observations following changes in ship emissions.
19. S.A. Twomey, M. Piepgrass and T.E. Wolfe, "An assessment of the impact of pollution on global cloud albedo," *Tellus* 36B (1984): 356-66.
20. J.A. Coakley, R.L. Bernstein and P.A. Durkee, "Effect of ship-stack effluents on cloud reflectivity," *Science* 237, no. 4818, (1987): 1020-2.
21. G. Myhre et al., "Aerosols and their relation to global climate and climate sensitivity," Nature Education Knowledge 4 no.5 (2013): 7 pp.
22. N. Bellouin et al., "Bounding global aerosol radiative forcing of climate change," *Rev. Geophys.* 58 (2020): e2019RG000660.
23. J. Charney et al., *Carbon Dioxide and Climate: A Scientific Assessment*. (Washington: National Academy of Sciences Press, 1979).
24. G. Tselioudis et al., "Oceanic cloud trends during the satellite era and their radiative signatures," *Clim. Dyn.* (2024): doi.org/10.1007/s00382-024-07396-8.
25. A. Korolev and J. Milbrandt, "How are mixed-phase clouds mixed?" *Geophys. Res. Lett.* 49, no. 18 (2022): e2022GL099578.
26. X. Jiang et al., "Muted extratropical low cloud seasonal cycle is closely linked to underestimated climate sensitivity in models," *Nat Comm* 14, no. 1 (2023): 5586, doi:10.1038/s41467-023-41360-0.
27. K.D. Williams, A.J. Hewitt, and A. Bodas-Salcedo A, "Use of short-range forecasts to evaluate fast physics processes relevant for climate sensitivity," *J. Adv. Mod. Earth Sys.* 12 (2020): e2019MS001986.
28. Estimates for equilibrium climate sensitivity (ECS) of 3 °C or less for doubled CO_2 were common for decades not only because GCMs with simple cloud schemes yielded such sensitivities, but because the main paleoclimate study of climate sensitivity supported low sensitivity. The large CLIMAP project (CLIMAP project members, "Seasonal reconstruction of the Earth's surface at the last glacial maximum," *Geol Soc Amer, Map and Chart Series*, No. 36, 1981), which reconstructed Earth's surface conditions during the last ice age, found SSTs not much colder than today. SSTs were based on an assumption that tiny shelled marine species would migrate to stay in the temperature zone where they live today. However, if, instead, species partly adapt to changing temperature over millennia, a larger SST change would be inferred. Recent studies (M. B. Osman et al., "Globally resolved surface temperatures since the Last Glacial Maximum, *Nature* 599 (2021): 239-44) that exclude any assumption about migrating species, instead relying on chemical proxies for temperature change, yield ice age cooling of 6-7 °C, implying ECS of 4.8 °C ± 1.2 °C for doubled CO_2. Narrowing this range requires improved evaluation of the "efficacy" of ice sheet climate forcing, which requires realistic simulation of clouds in GCMs.

IPCC's AR6 climate analysis, unlike earlier IPCC reports, makes good use of paleoclimate data, especially the climate sensitivity study of S.C. Sherwood et al., "An assessment of Earth's climate sensitivity using multiple lines of evidence," *Rev Geophys* 58 (2020): e2019RG000678. That study is exceptionally comprehensive, but its estimate of ECS

(2.2-4.9 °C, 95% probability) is marred by an estimate that glacial-interglacial temperature change (the only paleo case with accurate greenhouse gas amounts) was only 5 °C and by an assumption that paleo aerosol changes are a climate forcing. Natural aerosol changes are a climate feedback, like cloud changes; indeed, aerosols and clouds form a continuum and distinction is arbitrary as humidity nears 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 biogenic dimethyl sulfide and its secondary aerosol products, all varying geographically and in response to climate change. We do not know, or need to know, paleo aerosol changes because those changes are feedbacks included in the climate response. The choice of Sherwood et al.to count estimated paleo aerosol changes as a forcing caused an underestimate of ECS.

29. Cloud fraction, liquid water path (amount of liquid water per unit area in the cloud), cloud albedo and height, e.g.

30. A.E. Luebke et al., "An assessment of macrophysical and microphysical cloud properties driving radiative forcing of shallow trade-wind clouds," *Atmos. Chem Phys*. 22, no. 4 (2022): 2727-44.

31. Aerosol and cloud particle properties can be monitored by a satellite-borne instrument measuring the polarization of sunlight reflected by Earth to accuracy ~ 0.1% in ~10 spectral bands between the ultraviolet and near-infrared; this accuracy requires measuring orthogonal intensities simultaneously for exactly the same scene. Resulting data defines aerosol opacity, mean size, dispersion (variance) of size distribution, refractive index, particle shape, and single scatter albedo – for both the fine and coarse particle modes in the usual bimodal aerosol size distribution (M.I. Mishchenko et al., "Accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission," *Bull. Amer. Meteorol. Soc.* 88 (2007): 677-91. In cloudy regions the data define cloud opacity, the mean size and variance of the cloud particle size distribution, and the proportions of water drops and ice in the cloud-top region. A small satellite including such a polarimeter with potential for ground-track and cross-track observing, an infrared spectrometer to monitor multiple climate forcings and feedbacks, and a cloud camera was proposed as part of NASA's Mission to Planet Earth (J. Hansen, W. Rossow and I. Fung, "*Long-term monitoring of global climate forcings and feedbacks*," Washington: NASA Conference Publication 3234, 1993), but not chosen, based on the rationale that other instruments on the Mission's large polar platform would measure aerosols (see J. Hansen, Battlestar Galactica, Chapter 31 in *Sophie's Planet*. New York: Bloomsbury, 2025).

32. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite mission was launched 8 February 2024.

33. Adequate aerosol and cloud monitoring needs to exploit the full information available in precise polarization of reflected solar radiation and in the spectrum of emitted thermal radiation. Long-term monitoring dictates economical, replaceable, small satellites dedicated to orbits and viewing geometries providing maximum information.

34. W.F. Ruddiman et al., "Late Holocene climate: natural or anthropogenic?" *Rev Geophys* 54 (2016): 93-118.

35. M. B. Osman et al., "Globally resolved surface temperatures since the Last Glacial Maximum, *Nature* 599 (2021): 239-44.

36. S.A. Marcott et al., "A reconstruction of regional and global temperature for the last 11,300, *Science* 339 (2013): 1198-201.

37. A.A. Lacis et al., "Atmospheric CO_2: principal control knob governing Earth's temperature," *Science* 330 (2010): 356-9.

38. J. Hansen et al., "Climate change and trace gases," *Phil Trans Roy Soc A* 365 (2007): 1925-54.

39. Z. Hausfather and P. Forster, Analysis: How low-sulphur shipping rules are affecting global warming, *Carbon Brief*, (3 July 2023).

40. P.M. Forster et al., Supplement of Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence *Earth Syst. Sci. Data* 16 (2024): 2625–58 https://doi.org/10.5194/essd-16-2625-2024-supplement.

41. A. Gettelman et al., "Has reducing ship emissions brought forward global warming?" *Geophys Res. Lett*. 51 (2024): e2024GL109077.

42. T. Yuan et al., "Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming," *Commun Earth Environ* 5 (2024): 281.

43. Q. Jin et al., "Impacts on cloud radiative effects induced by coexisting aerosols converted from international shipping and maritime DMS emissions," *Atmos. Chem. Phys.* 18 (2018): 16793-808.

44. N.G. Loeb et al., "Satellite and ocean data reveal marked increase in Earth's heating rate," *Geophys Res Lett* 48 (2021): e2021GL093047.

45. We take the first 10 years of data as the base period (defining the zero point for anomalies) as the longest that avoids intrusion into the time of IMO restrictions on ship emissions. Ten years does a reasonable job of averaging over the solar cycle.

46. https://www.ncei.noaa.gov/access/monitoring/pdo/ (last accessed 5 August 2024).

47. Y. Zhang et al., "Pacific Decadal Oscillation: Tropical Pacific Forcing versus Internal Variability," *J. Clim.* 31 (2018): 8265-79.

48. S. Rahmstorf et al., "Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation," *Nat. Clim. Change* 5 (2015): 475-80.

49. J. Hansen et al., "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 C global warming could be dangerous," *Atmos Chem Phys* 16 (2016): 3761-812.

50. M.D. Zelinka, et al., "Causes of higher climate sensitivity in CMIP6 models," *Geophys. Res. Lett.* 47 (2020): e2019GL085782.

51. Qinjian Jin, unpublished simulations.

52. P. Manshausen et al., "Invisible ship tracks show large cloud sensitivity to aerosol," *Nature* 610 (2022): 101-6.

53. Figure 10 is the 12-month running-mean temperature to minimize variability and noise, so its most recent data are the September 2023 through August 2024 average.

54. See graphs presented by J. Hansen, M. Sato and P. Kharecha, "Global warming acceleration: hope vs hopium," CSAS communication, 29 March 2024; also see NOAA data.

55. K. von Schuckmann et al., "Heat stored in the Earth system: where does the energy go?" *Earth System Science Data* 12 (2020): 2013-41.

56. P. Forster et al., The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Masson-Delmotte V (ed). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press, New York, (2021): 923-1054.

57. P.M. Forster et al., Supplement of Indicators of Global Climate Change 2023: annual update of keyindicators of the state of the climate system and human influence *Earth Syst. Sci. Data* 16 (2024): 2625–58 https://doi.org/10.5194/essd-16-2625-2024-supplement.

58. United States Clean Air Act, Wikipedia, last accessed 21 August 2024.

59. R.M. Hoesly et al., "Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS)," *Geosci. Model Dev*. 11 (2018): 369–408.

60. M. Crippa et al., "Insights into the spatial distribution of global, national, and subnational greenhouse gas emissions in the Emissions Database for Global Atmospheric Research (EDGAR v8.0)," Earth Syst. Sci. Data 16 no. 6 (2024): 2811-30.

61. Z. Wang et al., "Incorrect Asian aerosols affecting the attribution and projection of regional climate change in CMIP6 models," *NPJ Clim Atmos Sci.* 4 no. 2 (2021): https://doi.org/10.1038/s41612-020-00159-2.

62. S.E. Bauer et al., "Historical (1850-2014) aerosol evolution and role on climate forcing using the GISS ModelE2.1 contribution to CMIP6," *J Adv Model Earth Syst* 12 no. 8 (2020): e2019MS001978.

63. Aerosols A (based on Matrix) has moderate nonlinearity with the aerosol forcing reaching −1.6 W/m^2 in 2005. The aerosol forcing in Aerosols B (based on OMA) reaches −2 W/m^2 in 2005.

64. S.E. Bauer et al., "The turning point of the aerosol era," *J Adv Model Earth Syst* 12 no. 8 (2022): e2022MS003070.

65. Z. Wang et al., "Incorrect Asian aerosols affecting the atributin and projection of regional climate change in CMIP6 models," *NPJ Clim Atmos Sci.* 4 no. 2 (2021): https://doi.org/10.1038/s41612-020-00159-2.

66. One of the world's top modelers wrote to our paper's first author (JEH): "…most importantly we do not understand cloud microphysics well enough to be modeled in climate models, and respond to the changes in aerosol forcing. At this point many climate models set parameters to get the 'right' answers, aka simulate transient climate change as observed by surface temperature records, but that doesn't mean aerosol cloud interactions are done correctly." Does this same pressure affect aerosol modelers who, almost uniformly, find that the aerosol forcing caused by ship emissions is very small, consistent with IPCC requirement of total aerosol forcing ~ 1 W/m^2.

67. S. Jain et al., "Are we at risk of losing the current generation of climate researchers to data science?" *AGU Advances* 3, e2022AV000676, 2022.

68. J. Hansen, Charney's Puzzle: How Sensitive is Earth? Chapter 17 in *Sophie's Planet*. New York: Bloomsbury, 2025.

69. M. Kelley, G.A. Schmidt, L. Nzarenko, et al., "GISS-E2.1: Configurations and climatology. *J Adv Model Earth Syst* 12 no. 8 (2020): e2019MS002025.

70. R.L. Miller, G.A. Schmidt, L. Nazarenko L *et al.* CMIP6 historical simulations (1850-2014) with GISS-E2.1. *J Adv Model Earth Syst* 13 no. 1 (2021): e2019MS002034.

71. The time scale in Figure 14 is linear for the first 10 years to show the early response in detail, and then logarithmic to show the approach to equilibrium in millennia. Rapid global warming in the first few years after CO_2 doubling is mainly a direct response to the forcing and has limited dependence on climate sensitivity because the feedbacks that affect sensitivity do not come into play in response to the forcing, but rather in response to temperature change, which requires time to develop.

72. The light shaded region has less than 60 months of data and thus the result will change as additional data are added, as the graph is nominally based on 60-month running-mean data is inadequate in the most recent 30 months. We are indebted to NOAA Global Monitoring Laboratory for continually updating and making available the greenhouse gas data, e.g., Lan, X., K.W. Thoning, and E.J. Dlugokencky: Trends in globally-averaged CH4, N2O, and SF6 determined from NOAA Global Monitoring Laboratory measurements. Version 2024-11, https://doi.org/10.15138/P8XG-AA10 The forcings are calculated with formulae of Table 1 in the reference in Note 1, using data from Figure 31 of that reference and from https://gml.noaa.gov/ccgg/trends/data.html, https://gml.noaa.gov/aftp/data/hats/Total_Cl_Br/, and https://www.ipcc.ch/report/ar5/wg1/ (11 December 2024, date last accessed for each).

73. J. Hansen and M. Sato, "Greenhouse gas growth rates," *Proc Natl Acad Sci* 101 (2004): 16109-14. A list of MPTGs and OTGs used in our computations is in reference 1. The largest forcings are by chlorofluorocarbons (CFCs), used mainly as refrigerants and propellants. MPTGs and OTGs are Montreal Protocol Trace Gases and Other Trace Gases.

74. J. Hansen et al., "Efficacy of climate forcings," *J. Geophys. Res.*110 (2005): D18104.

75. Let $T_C(t)$ be global temperature change calculated by a GCM at time t after an instant CO_2 doubling, i.e., one of the curves in Figure 14. $T_C(t)$ can be used to calculate the expected temperature for any climate forcing scenario. For example, assume that climate was in equilibrium in 1850. The tempera-

ture in 1851 is the product of the forcing added in 1851 (expressed as a fraction of $2\times CO_2$ forcing) x T_C (year 1). Global temperature in 1852 is the sum of two terms, the first term being the forcing added in 1851 × T_C (year 2) and the second term being the forcing added in 1852 × T_C (year 1) – and so on for successive years. An equation for this is $\mathbf{T_G}\ \mathbf{(t)} = \int \mathbf{TC}(t - t')\times[dF_e(t')/dt']\times dt'$.

T_G is our "Green's function" estimate of global temperature and dF_e is the forcing change per unit time divided by the doubled CO_2 forcing of 4 W/m². Integration begins when Earth is in near energy balance, e.g., in preindustrial time. The 5000-year run of the GISS (2020) model used in the *Pipeline* paper[1] for was a bit of an outlier for $T_C(t)$ in the first year, e.g., Earth's energy imbalance (EEI), which was initially 4 W/m², decreased rapidly to 2.7 W/m² averaged over year 1. For our present paper, we made 5 more $2\times CO_2$ runs and used the ensemble-mean to define a smooth $T_C(t)$. This "ultrafast" response is still present in the ensemble mean, but for year 1 the ensemble average EEI is 3.0 W/m². Also, the ensemble-mean warming in years 10-50 is less than the average warming in those years in the 5000-year run, as the GISS (2020) single model runs had multi-decadal variability that is believed to be unrealistic. Our estimate for 4.5 °C Global Temperature Response to $2\times CO_2$ is obtained by multiplying the 3.4 °C Global Temperature Response by a scale factor that allows the 4.5 and 3.4 responses to begin to increase similarly at time t = 0, but diverge on a decadal time scale toward their equilibrium responses. The scale factor is $S(t) = S_f - \exp[-(t-1)/r] \times (S_f - 1)$, where $S_f = 4.5/3.4$ and r = 13 years.

76. Annual greenhouse gas amounts began to be measured in the 1950s and good coverage of global temperature in the Southern Hemisphere, including Antarctic data, began then.

77. The best fits can be altered a bit by inclusion of volcanic aerosol effects, but proper treatment of volcanoes should incorporate the effect of volcanoes prior to 1850 on internal ocean temperature, which introduces some arbitrariness.

78. The IPCC aerosol scenario has zero aerosol forcing change between 1970 and 2005, which requires low climate sensitivity (near 3 °C for $2\times CO_2$) to match observed warming.

79. The still larger aerosol forcing of Aerosols B would require a climate sensitivity of at least 6 °C, which is difficult to reconcile with paleoclimate data.

80. S.P. Raghuraman et al., "The 2023 global warming spike was driven by the El Niño-Southern Oscillation," *Atmos. Phys. Chem.* 24 (2024): 11,275-83.

81. Niño3.4 temperature (equatorial Pacific temperature used to characterize El Niño status) is multiplied by 0.1 so that its variability about the zero line averages the same as the global temperature variability (Figure 19a). Global and Niño3.4 temperatures are highly correlated (56%) with global temperature lagging Niño3.4 by almost 5 months. Global cooling following the 1991 Pinatubo volcanic eruption and solar variability prevent higher correlation.

82. K.K. Tung, J. Zhou, C.D. Camp, "Constraining model transient climate response using independent observations of solar-cycle forcing and response," *Geophys. Res. Lett*. 35 (2008): L17707, doi:10.1029/2008GL034240.

83. Global temperature is from Note 2, and Niño3.4 temperature (equatorial Pacific temperature used to characterize El Niño status) is multiplied by 0.1 so that its variability about the zero line averages the same as the global temperature variability (Figure 19a).

84. 1.5 °C × 0.5/4 = 0.2 °C, where 0.5/4 is the ratio of the assumed forcing and doubled CO_2 forcing.

85. Global CO_2 forcing drives a big, rapid, response over land because of low continental heat conductivity, while the ocean-only forcing has limited response over land; but by the third year the global patterns of warming are similar enough that global temperature responds to Earth's energy imbalance, not the location of the forcing.

86. G. Tselioudis et al., "Oceanic cloud trends during the satellite era and their radiative signatures," *Clim. Dyn.* (2024): doi.org/10.1007/s00382-024-07396-8 suggest that most of the albedo change is cloud feedback associated with shifting of climate zones, but their attribution to that mechanism doubled when they added the final six years of data to their analysis and attributed the entire change to cloud feedback. The added period coincides with the change in ship emissions, so it is likely that the cloud changes include aerosol forcing as well as cloud feedback.

87. B. Barber, "Resistance by scientists to scientific discovery," *Science* 134 (1961): 596-602.

88. J. Hansen, Dry gets drier, wet gets wetter, storms get stronger, Chapter 28 in *Sophie's Planet*, Bloomsbury, 2025.

89. Hansen J, Rind D, Del Genio A et al. Regional greenhouse climate effects, in *Preparing for Climate Change*, Climate Institute, Washington, D.C., 1989.

90. Storms are not resolved by GCMs, but the effect of warming on storm intensity can be inferred from changes in the fuel for storms, called moist static energy, which is the sum of sensible heat, latent heat, and geopotential energy. We found (prior reference) that doubled CO_2 leads to more powerful moist convection extending several hundred meters higher in the atmosphere, dumping a larger portion of total rainfall in moist convective storm cells. Kerry Emanuel inserted SSTs from our doubled CO_2 simulation into his hurricane model, finding a decrease of minimum surface pressure from 880 to 800 mb and an increase of maximum wind speed from 175 to 220 miles per hour.

91. If there were no feedbacks, doubled CO_2 is a radiation calculation. There is good agreement that the no-feedback warming would be ~1.2 °C. See reference 1.

92. T.M. Lenton et al., "Tipping elements in the Earth's climate system," *Proc. Natl. Acad. Sci.* 105 no. 6 (2008): 1786-93.

93. Temperatures preceded by the + sign, as context makes clear, usually refer to temperature change relative to preindustrial value, which is approximated by the 1880-1920 average in the GISS temperature analysis.

94. Jay Zwally, Eric Rignot, Konrad Steffen, and Roger Braithwaite.

95. J.E. Hansen, "A slippery slope: how much global warming constitutes 'dangerous anthropogenic interference?'" *Clim Change* 68 (2005): 269-79.

96. S. Rahmstorf, "Is the Atlantic overturning circulation approaching a tipping point?" Oceanography https://doi.org/10.5670/oceanog.2024.501.

97. M. Hofmann, S.Rahmstorf, "On the stability of the Atlantic meridional overturning circulation," *Proc. Natl. Acad. Sci. USA* 106, 20584-9, 2009.

98. Excessive ocean mixing moves ocean surface layer heat into the deeper ocean, so a large climate forcing is needed to match observed surface warming. The large forcing is achieved by understating the (negative) aerosol forcing.

99. Changes, documented by Kelley et al. (reference 69), include use of a high-order advection scheme (M.J. Prather, "Numerical advection by conservation of second order moments," *J Geophys Res* 191 (1986): 6671-81), a 40-layer ocean allowing high resolution near the ocean surface, and an improved mesoscale eddy parameterization.

100. J. Hansen, M. Sato, P. Hearty et al., "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2C global warming is highly dangerous," *Atmos Chem Phys* 16 (2016): 3761-812.

101. At the last moment, after the paper passed extensive peer review, the editorial board of the journal stepped in and changed "is highly dangerous" in the paper's title to "could be dangerous," thus obviating the paper's main conclusion. They also, retroactively, changed the title of the 2015 submitted paper, without informing us. This phenomenon of scientific reticence is discussed in reference 1.

102. See the review of several independent measures of Eemian temperature in J. Hansen, M. Sato, P. Kharecha et al., "Young people's burden: requirement of negative CO_2 emissions," *Earth Syst Dyn* 8 (2017): 577-616.

103. Summer insolation on the Southern Ocean was maximum in the late Eemian (Figures 26 and 27 in the Ice Melt paper, reference 49), conditions favoring Antarctic ice sheet mass loss.

104. P. Blanchon et al., "Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand," *Nature* 458 (2009): 881–4.

105. N. Irvali, U.S. Ninnemann, H.F. Kleiven et al., "Evidence for regional cooling, frontal advances, and East Greenland Ice Sheet changes during the demise of the last interglacial," *Quatern. Sci. Rev*. 150 (2016): 184-99.

106. A.L. Gordon, "Interocean exchange of thermocline water," *J. Geophys. Res.* 91(C4) (1986): 5037-46.

107. W.S. Broecker, "The biggest chill," *Natural History* 74-82, October 1987.

108. The likely collapse of the West Antarctic ice sheet in the late Eemian probably began with long preconditioning of the ice sheet as high southern latitudes were slowly warming while high northern latitudes were cooling. The present climate forcing is stronger, growing much faster, with warming in both hemispheres, yet better understanding of Eemian climate and ice sheet changes will be helpful in projecting future change. It should be possible to put Eemian changes in the North Atlantic and the Southern Ocean on a common time scale to help investigate inter-hemispheric interactions. International cooperation, beginning with a workshop focused on definition of key issues that must be understood to help avoid passing the "point of no return," would have multiple benefits, as briefly described in a proposal "Aerosols, the Ocean, and Ice: Impacts on Future Climate and Sea Level."

109. There are both floating ice shelves and "fast" ice shelves, the latter adhering to the continent and extending deep into the ocean. Some of the fast ice shelf melt occurs at great depth and rises toward the surface because of its low density, although it may not reach all the way to the ocean upper mixed layer. The contribution of ice shelves to freshwater injection in climate simulations is thus complex. For discussion of changing ice shelves see E. Rignot, S. Jacobs, J. Mouginot et al., "Ice shelf melting around Antarctica," *Science* 341 (2013): 266-70.

110. The appropriate freshwater flux for the climate simulations is the change from the freshwater flux rates that existed during the pre-industrial Holocene. For the fast ice shelves, we need the changing ice shelf mass. For floating ice shelves, which are continuously replenished with ice by the continental ice sheet, we need both the change of ice shelf mass and change in the rate of replenishment. For the continental ice sheets, the mass change measured by gravity satellites is an underestimate of the ice sheet freshwater contribution: increased snowfall on the ice sheet arising from distant airmasses should be excluded from the ice sheet mass for the purpose of quantifying the freshwater flux on the parts of the ocean relevant to the ocean's overturning circulation.

111. The 50-150 year range reflects the 10-20 year estimate for doubling time of freshwater injection into the ocean.

112. There were at least minor changes in the GISS climate model between the Ice Melt simulations and the model documentation by Kelley et al. (reference 69), so new ice melt simulations were made with the documented model, confirming an already present cooling effect on the Southern Ocean (C.D. Rye, J. Marshall, M. Kelley et al., "Antarctic Glacial Melt as a Driver of Recent Southern Ocean Climate Trends," *Geophys. Res. Lett.* 47 no. 11 (2020): doi:10.1029/2019GL086892 An example of recent SSTs is Figure 20, sea surface temperature anomalies for 15 November 2024 (from University of Maine ClimateReanalyzer.org based on NOAA's SST anomaly relative to 1971-2000) are typical of the real world, much cooler in the Southern Ocean than the models that IPCC relies on.

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Supplementary Material

Supplementary Material for "Global Warming has Accelerated" [1] (*Acceleration*) is organized as: (1) A perspective based on *Acceleration*, "Ice melt, sea level rise and superstorms"[2] (*Ice Melt*) and "Global warming in the pipeline"[3] (*Pipeline*). (2) Figures SM1-SM8, mentioned in the main text, but placed here to limit the paper size. (3) Additional data sources for figures in the main text.

An Alternative Perspective on Global Warming

Acceleration,[1] *Ice Melt*,[2] and *Pipeline*[3] each employ comparable emphasis on paleoclimate data, global climate modeling, and modern observations of ongoing climate processes. We describe this as an alternative perspective because it differs from that of IPCC, which places heavier emphasis on global climate models (GCMs), especially simulations for the recent, human-affected era and its projection into the future. Such global modeling is essential because no natural climate forcing has increased as rapidly as the human-made forcing. However, there is also merit in a perspective that adds comparable emphasis on the other major sources of information.

This alternative perspective leads to a conclusion that continued rapid growth of humanmade climate forcings will cause shutdown of the Atlantic Meridional Overturning Circulation (AMOC) likely within 20-30 years, and multimeter sea level rise in the lifetime of today's young people. AMOC shutdown and large sea level rise stand out because they are irreversible on any time scale that people care about; they differ from other "tipping points,"[4] many of which may be reversible via global cooling. AMOC shutdown and large sea level rise – if they are allowed to occur – are not reversible on a time scale less than several centuries. The question is how close we are to the "point of no return," when it becomes impossible to prevent these consequences. The urgency of better understanding is highlighted by a recent study of the Ditlevsens,[5] which finds empirical information that the North Atlantic is headed toward AMOC shutdown this century.

AMOC shutdown and sea level rise are related. AMOC shutdown short-circuits the ocean "conveyor,"[6,7] the global ocean currents that transport heat, salt, and nutrients. In its normal mode of operation,[8] the ocean conveyor transports heat from the Southern Hemisphere into the Northern Hemisphere, especially into the North Atlantic, where it helps[9] keep Europe much warmer than would be expected, given its high latitude. If the conveyor shuts down, that heat will stay in the Southern Ocean, helping to melt the West Antarctic ice sheet, the biggest threat to sea level. So, do the Ditlevsen study[5] and *Ice Melt*[2] simulations imply that AMOC shutdown and large sea level rise are now inevitable? Not so fast; the story is complicated. Shutdown of AMOC and its cousin in the Southern Ocean (Antarctic Bottom Water Formation, or SMOC, the Southern Meridional Overturning Circulation) are complicated. The drive for shutdown depends not only on the rate of meltwater (freshwater) injection on the ocean surface, increased precipitation, and warming of the ocean's upper layer, but also on increased storminess and, thus, increased ocean mixing.

Acceleration of global warming is a game changer, however, which will make it more difficult to avoid both AMOC shutdown and large sea level rise. Suddenly, +1.5°C global temperature has been reached and +2°C is on the horizon. This sudden warming is likely to have impacts in the next 5-10 years that need to be reliably interpreted. If appropriate observations are made, climate science will be in a better position to provide guidance about actions required to avoid harmful climate impacts, especially shutdown of the AMOC and large sea level rise.

Ice Melt and AMOC

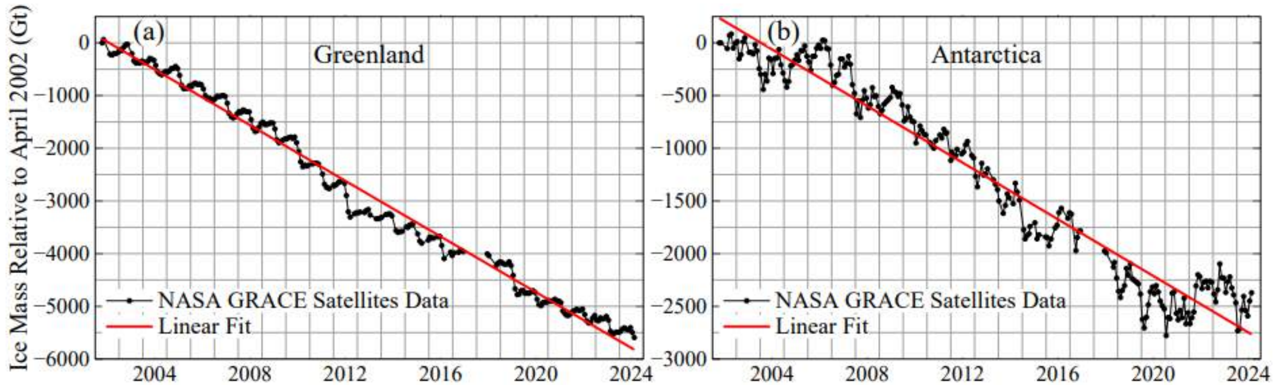
Data on ice melt deserve more attention. Forcings that drove AMOC and SMOC shutdowns in the climate model[2] were (1) growth of greenhouse gases (GHGs), and (2) growth of freshwater injection onto the North Atlantic and Southern Oceans. GHG forcing, in fact, has continued to grow at a high rate, shockingly close to the extreme IPCC scenario RCP8.5 (Figure 15). Thus, the issues requiring better data and understanding are the magnitude of freshwater injection and the ability of global climate models (GCMs) to simulate AMOC and SMOC shutdown.

Freshwater injection rates. After *Ice Melt* appeared, a paper[10] was published contradicting the conclusion that AMOC (Atlantic Meridional Overturning Circulation) could shut down this century. The 15 authors, from leading climate modeling groups, used 21 climate projections from eight "…state-of-the-science, IPCC class…" GCMs to conclude that "…the probability of an AMOC collapse is negligible. This is contrary to a recent modeling study [*Hansen et al., 2016*] that used a much larger, and in our assessment unrealistic, Northern Hemisphere freshwater forcing… According to our probabilistic assessment, the likelihood of an AMOC collapse remains very small (<1% probability) if global warming is below ~5K… ".[10] What was their "probabilistic" assessment? They took their ensemble of model results as if it were the probability distribution for the real world, an approach commonly employed by IPCC. IPCC then blackballed the *Ice Melt* paper, not mentioning it in its AR6 report. The indictment of *Ice Melt* was accepted by the wider research community; papers on AMOC or SMOC ignore *Ice Melt* or refer to it parenthetically with a statement that freshwater injection rates used in the *Ice Melt* paper were unrealistically large.

Ice Melt assumed freshwater injection in 2011 of 360 Gt/yr on the North Atlantic Ocean and 720 Gt/yr on the Southern Ocean. Injection was assumed to increase exponentially with a doubling time of 10 or 20 years (and decrease toward earlier time with "halving time" 10 or 20 years). Observed mass loss from Greenland and Antarctica grew in the decade prior to 2011 with about a 10-year doubling time (Fig. 30 in *Ice Melt*), which was one reason to assume continued growth. Another reason is that sea level in the Eemian period (about 120,000 years ago) went up at least a few meters in less than a century, as shown by the rate at which coral reef building "backstepped" toward the shoreline as sea level increased.[11] Such rapid sea level rise requires a characteristic change time much less than a century; this occurred in the Eemian, even though the forcing was weak and changed slowly; the present human-made forcing is larger and increasing much faster.

Here we show that the initial (2011) forcings that drove AMOC and SMOC shutdowns in *Ice Melt* were of a realistic magnitude; indeed, they were an underestimate. Melting did not continue to grow as fast in the decade 2015-2024, but that slowdown is likely temporary and the freshwater injection averaged over the past two decades was accurate. Future melt rates should grow, given the recent 0.5°C leap of global temperature, the doubling of Earth's energy imbalance in the past decade,[12] and ice sheet feedbacks; as the melt season lengthens and becomes warmer with more rainfall, lower parts of the ice sheet will become wetter, darker, and lower in altitude. It is important to track and understand changes of freshwater injection. Change does not occur along a smooth curve; it's a bumpy ride, as we will show in cases with available data.

Figure SM9. Greenland and Antarctica Ice Mass Changes[13,14]



The largest term usually associated with increased freshwater injection onto the North Atlantic is Greenland melt estimated from ice sheet mass loss measured by the GRACE gravity satellite. GRACE yields a freshwater injection of about 250 Gt/year (Fig. SM9). Based on GRACE data through 2014, mass loss increased with a doubling time of 10 years for both Greenland and Antarctica (Fig. 30 of *Ice Melt*).[2] However, ice sheet mass loss did not continue to grow at such a high rate after 2014; instead, Antarctica even gained mass in some years (Fig. SM10). This is not surprising – over most of the ice sheets, during most of the year, the temperature is below freezing and increased precipitation on a warming planet accumulates on ice sheets. Thus, we must take account of increased snowfall in interpretation of ice sheet mass changes measured by GRACE.[15] Most increased snowfall originates with evaporation at lower latitudes, with little effect on the ocean's salinity in the region of deepwater formation. Thus, snowfall increase above the preindustrial snowfall rate should be deleted from GRACE-measured ice sheet mass in calculating the ice sheet contribution to freshwater injection.[16] Figure SM11 provides a useful indication of enhanced snowfall. The largest mass losses in Antarctica occur in January and February, which are summer months equivalent to July and August in the Northern Hemisphere. In recent years, since the decline of Southern Ocean ice cover, summer mass loss of the Antarctic ice sheet is followed promptly by a large mass gain. Warmer air masses containing more water vapor than in the preindustrial atmosphere cause increased snowfall. Such increased snowfall occurs even in summer months when the ice sheet is losing mass; most of the ice sheet is below freezing in the summer and substantial snowfall accumulates at altitude.

Figure SM10. Greenland and Antarctica Ice Mass Change Rate (Gt/year)[17]

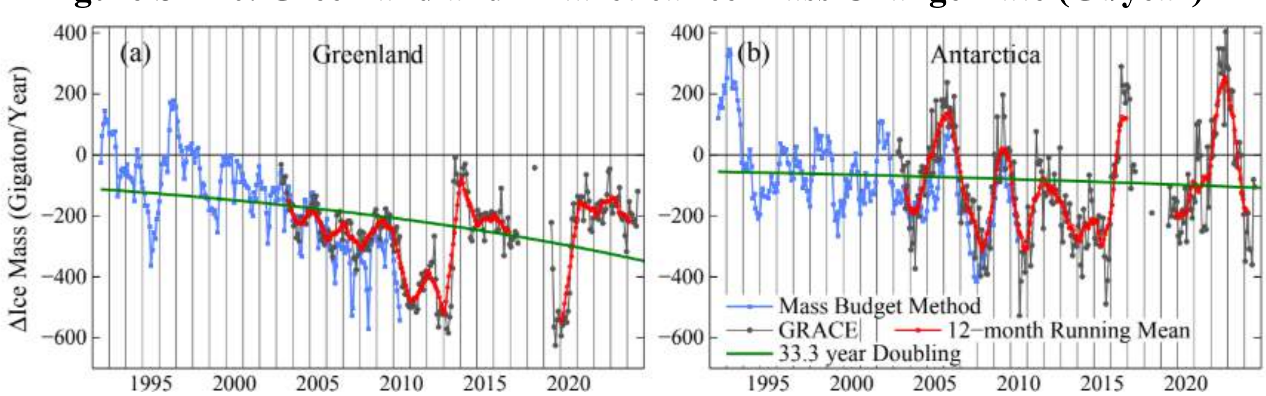
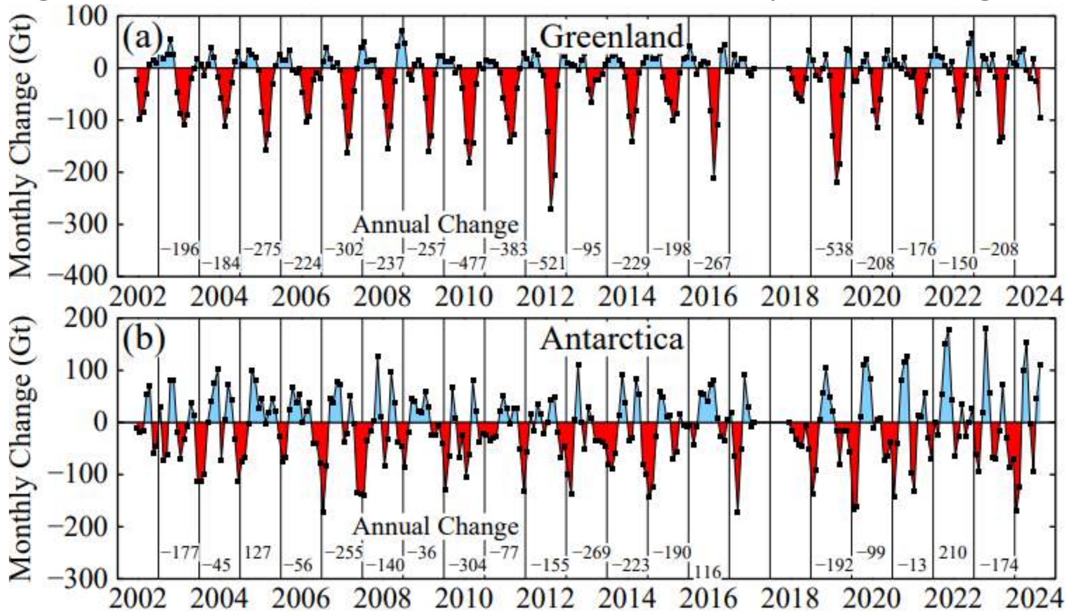
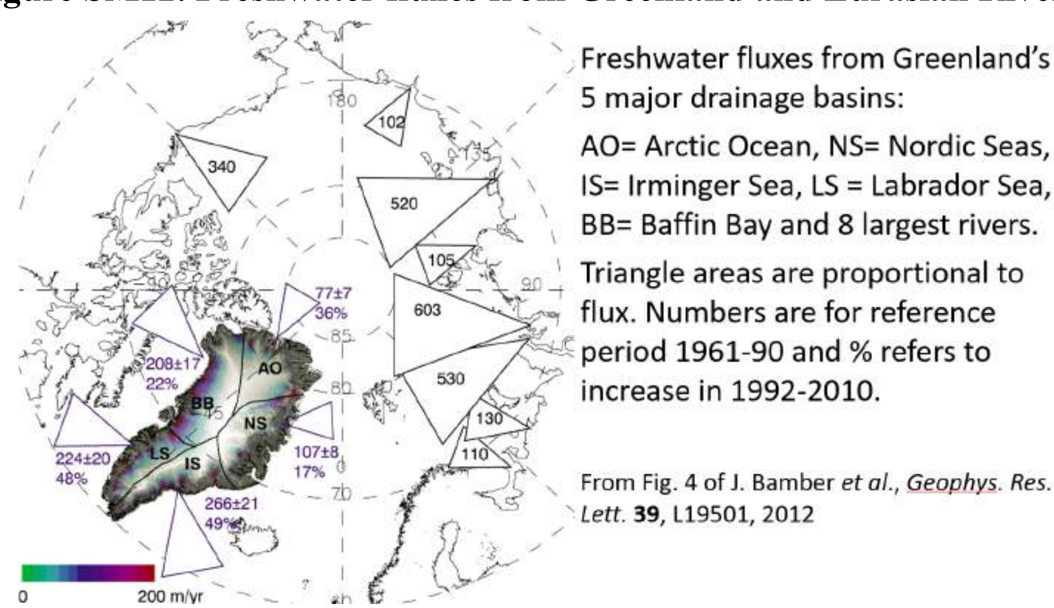


Figure SM11. Greenland and Antarctica Monthly Mass Changes[13,14]



Surface mass balance calculations are needed, for both Greenland and Antarctica, to account for changes of precipitation. For that purpose, Figure SM12, from Bamber *et al.*[18] is a helpful picture of freshwater fluxes into the Arctic and the North Atlantic from Greenland's drainage basins and Eurasian rivers. Triangle sizes are proportional to 1961-1990 reference period fluxes. Bamber *et al*. calculate Greenland runoff with a regional climate model (forced at its boundaries by reanalyses of ECMWF, European Centre for Medium-Range Weather Forecasts) and solid ice discharge (iceberg flux) from estimates of ice stream flux at 37 drainage basins, with the flux gate being the ice sheet grounding line, i.e., the place where the ice enters the ocean. In Figure SM12 these 37 drainage basins are lumped into five drainage basins that empty into the Arctic Ocean (AO), Nordic Seas (NS), Irminger Sea (IS), Labrador Sea (LS) and Baffin Bay (BB). The

Figure SM12. Freshwater fluxes from Greenland and Eurasian Rivers[18]



percentages in Figure SM12 are the increases of freshwater flux from 1961-1990 to 1992-2010. The sum of the increases for the five basins is 330 Gt/yr.[19] Thus, (1) the increased freshwater flux from Greenland alone yields approximately the flux increase assumed in the *Ice Melt* paper (360 Gt/yr in 2011). However, there are three additional, significant, contributions to growing freshwater injection: (2) in the Northern Hemisphere, melting of glaciers and ice caps outside of Greenland, (3) in both polar regions, reduction of the volume of ice shelves, and (4) especially in the Northern Hemisphere, reduction of the volume of sea ice not captured in today's GCMs.

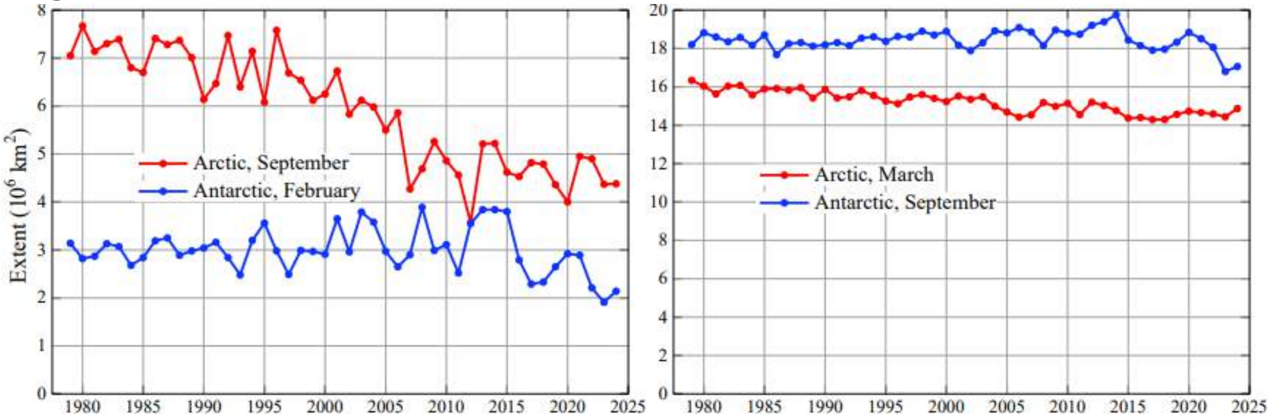
A minimum estimate of freshwater source (2), glaciers and ice caps outside Greenland, is provided by GRACE data. Averaged over 2002-2019, the gravity data yield an annual mass loss from Arctic glaciers and ice caps of 164 ± 24 Gt/yr, with larger values in recent years.[20] About half of this is from Iceland, Svalbard, and the Canadian Archipelago, which would affect the salinity of the upper layers of the North Atlantic in regions of deepwater formation within several years. This freshwater source is larger, if the glaciers or ice caps include submarine ice (whose melt is not captured by GRACE). A conservative estimate for the glacier and ice cap freshwater source in 2011 is 75 Gt/yr, with the source continuing to grow after 2011.

Freshwater source (3), the changing volume of ice shelves, provides almost the entire growth of freshwater injection for Antarctica. The estimate in *Ice Melt* of 720 Gt/yr for Antarctica was based in part on the Antarctic ice shelf mass loss rate of 2765 Gt/yr (1500 Gt/yr from basal melt and 1265 Gt/yr from calving) during 2007-2008 estimated by Rignot *et al*.[21] and similar estimates by Depoorter et al.[22] Combining these recent melt rates with an estimated preindustrial Antarctic snowfall rate of 2000 Gt/yr and the assumption of preindustrial equilibrium of continental snowfall and coastal ice discharge[16] led to the 720 Gt/yr estimate for mass loss of ice shelves in 2011. A remarkable independent check was provided by Rye *et al*.,[23] who found that coastal freshwater injection had a detectable (2 mm) effect on the slope of sea level away from the continent. They inferred an increase of 430 Gt/yr in ice shelf melt over a 20-year period, and they noted that it was a lower bound on the increase of ice shelf melt rate, which must have begun to increase prior to the satellite data, consistent with the fact that Antarctic bottom water formation and the global volume of Antarctic bottom water was already declining at least since 1980.[24]

Greenland also has declining ice shelf volume. Greene et al. (2024)[25] made a comprehensive study of Greenland glacier terminus positions for the period 1985-2022, finding that the Greenland ice sheet lost 5,091 ± 72 km^2 of its area to secular glacier terminus retreat, which corresponds to 1,034 ± 120 Gt of ice loss beyond the steady-state calving rate that would be necessary to maintain constant areal extents of the ice sheet. The ice sheet area was relatively constant until the late 1990s, followed by a loss of 42 Gt/yr since January 2000. Specific events, such as huge calvings from the Petermann Gletscher in 2010 and 2012 (which totaled 380 km^2 of ice shelf and reduced the ice shelf length from 81 to 46 km), can affect even decadal mass balance trends, but Greene et al. conclude that overall the ice shelf mass loss has continued "without any marked slowdown."

This Greene et al. estimate is a lower limit on the ice shelf mass loss rate, for two reasons. First, it does not include thinning of remaining ice shelves. Second, it does not include mass loss from submerged ice adhered to Greenland below sea level, a loss that must be occurring, given the warming oceans around Greenland. Nevertheless, the Greene et al. data indicate the freshwater source from shrinking ice shelves did not continue to grow exponentially in the past decade.

Figure SM13. Sea Ice Extent at Months of Minimum & Maximum Ice Cover[26]



Instead, ice shelf mass loss continued at a high rate. Before we compare total real-world freshwater injection with the amount assumed in the *Ice Melt* simulations, we must estimate freshwater source (4), reduction of sea ice volume not captured in global climate models (GCMs).

Figure SM13 shows sea ice area. Freshwater injection from declining sea ice, in principle, is computed by GCMs, but, in practice, most GCMs – including the GISS model used in *Ice Melt* – do not get a realistic, large, sea ice volume reduction. Arctic sea ice volume in the real world[27] decreased more than 6000 km^3 in the decade leading up to 2011,[28] yielding a freshwater injection of the order of 500 Gt/yr. Some of this sea ice loss occurred directly in the North Atlantic, and most Arctic sea ice reduction contributes to freshening of the North Atlantic, as the principal gateway for Arctic surface circulation into the North Atlantic is via the Fram Strait (between Greenland and Spitsbergen), which feeds into the East Greenland Current and East Icelandic Current (e.g., Fig. 1 of Clotten et al.[29]). Sea ice loss in the Arctic Basin reduces the salinity of water transported into the North Atlantic, which is likely one reason that the salinity of the North Atlantic is at its lowest level in modern records.

Our estimates for the four North Atlantic freshwater sources from ice melt are 330, 75, 50, and 50-250 Gt/yr, a total 505-705 Gt/yr in 2011 (50 is a conservative estimate for ice shelves, given the two terms that are not included in Greene's evaluation. 50-250 is a conservative estimate for sea ice loss, with the wide range due to uncertainty in how much sea ice loss in the Arctic basin contributes to reduced salinity in the North Atlantic. In GCM studies, excess real-world sea ice loss can be added in locations of observed sea ice diminution.). We conclude that freshwater sources in the North Atlantic in 2011 were *underestimated* by 50-100 percent in *Ice Melt*. This high freshwater injection rate is an appropriate estimate for the decade 2005-2014. In the next decade, 2015-2024, real-world freshwater injection did not increase exponentially; at most, the loss rate remained comparable to the prior decade, but, for the past two decades overall, the North Atlantic freshwater source employed in *Ice Melt* was realistic.

The question is: will freshwater forcing now grow, as assumed in *Ice Melt*? We suggest below that the climate system is now poised for accelerated freshwater injection. However, discussion of the prospects for AMOC and SMOC shutdowns and large sea level rise requires that we also consider whether climate models are able to realistically simulate freshwater effects on AMOC and SMOC, even when the freshwater injection rate is known accurately.

Ability of GCMs to simulate AMOC and SMOC shutdown. There are at least two model issues that are likely to cause most GCMs to be less sensitive than the real world to freshwater injection; in other words, AMOC and SMOC may not shut down as easily in the models as in the real world. The first issue has long been articulated by Stefan Rahmstorf, initially in a paper by Hofmann and Rahmstorf (2009).[30] The basic concern is with the many model parameters that must be set in the development of an ocean model, and specifically with modelers' preference for a stable model, which may bias parameter selection. It is difficult, if not impossible, to quantify such an effect. The best approach is probably continual improvement of the models, including comparisons with as many relevant observations as possible.

The second model issue is concern about excessive, unrealistic, mixing in ocean models. This excessive ocean mixing issue – unrealistic diffusion of ocean properties – was raised as early as 2008,[31] when the concern was the effect on inferred climate sensitivity and aerosol climate forcing. Mixing is also a crucial issue for AMOC and SMOC shutdown because excessive mixing makes it more difficult for freshwater injection to reduce the density of the ocean's upper layer to the point required to halt the sinking of water from the upper layer ocean. Some excessive (i.e., unrealistic) mixing is almost inherent in ocean models because solution of the ocean dynamical equations via numerical finite differencing causes spatial diffusion of properties. Diffusion of "tracer" quantities, such as salinity, can be limited by use of high order differencing schemes, e.g., Prather's second order moments method,[32] but small-scale mixing assumptions (eddy diffusivity and mesoscale eddy parameterizations) are another source of uncertain mixing. Nevertheless, the mixing problem is one that can be addressed with current knowledge and computing power.

The mixing issue was of special concern for *Ice Melt* simulations because of the model's coarse resolution. The final simulation for the *Ice Melt* paper, with 2011 freshwater fluxes of 360 Gt/yr in the North Atlantic and 720 Gt/yr in the Southern Ocean, included improvements in the sub-grid-scale calculations introduced by Max Kelley, which lead to realistic ocean stratification. It was shown (Fig. 19 in *Ice Melt*) that the model formed Antarctic Bottom Water along the Antarctic coastline in observed locations (especially in the Ross and Weddell Seas, but also off Adelie Land and Cape Darnley), despite the model's coarse resolution and unlike most contemporary models, which produced deep water in the open Southern Ocean (Heuze et al.).[33] The climate simulations with this model – assuming a 10-year doubling time for freshwater injection – caused shutdown of AMOC and SMOC by midcentury.[2] However, there were indications that the real world was beginning to show effects of the freshwater injection – such as the absence of warming, or even slight cooling, in the Southern Ocean and southeast of Greenland – earlier than in the model. We suspected that the model was less sensitive than the real world because of the model's coarse resolution (4°×5° in both atmosphere and ocean, with a 13-layer ocean).

Thus, Craig Rye, as a post-doc at Columbia University and the Goddard Institute for Space Studies (GISS), carried out simulations with the then newest version of the GISS model (with ocean resolution 1°×1.25° and 40 layers). The experiments were limited to the simplest problem: an instantaneous 200 Gt/year (step-function) increase of freshwater injection on the Southern Ocean. This amount was smaller than the then current estimate of 300-800 Gt/yr for real-world freshwater injection, but it was large enough to provide a clear signal by averaging over a 20-member ensemble of runs. The result was qualitatively consistent with the simulations in *Ice Melt*, but with a higher sensitivity. Injection of 200 Gt/year of freshwater was enough to constrain warming of the Southern Ocean sea surface temperature and yield slight cooling just north of the winter sea ice region, consistent with empirical data (Fig. 20 of our present main paper). Increased sensitivity to freshwater injection with higher resolution is not surprising, as 4°×5° resolution is as large or larger than many polynyas, the regions of convective deepwater formation. Although a coarse resolution model adjusts to vertical instability with considerable realism, it is not surprising that the sensitivity is higher with a model resolving polynyas. Increased vertical resolution of the modeled ocean also contributes to higher sensitivity.

The higher sensitivity to freshwater is relevant to deepwater formation in the North Atlantic, thus to AMOC. Based on only the above information, we might estimate that instead of the three doubling (factor of 8) increase of freshwater source in Ice Melt, two or even one doubling is likely enough to shut down AMOC. With the slower growth of ice melt suggested by observations, the net effect is that midcentury is still a good estimate for the time of AMOC shutdown, assuming that the only radiative climate forcing is continued high GHG emissions. However, there is no good reason why estimated future climate should be based on only the above information – it is possible to do much more realistic climate simulations now.

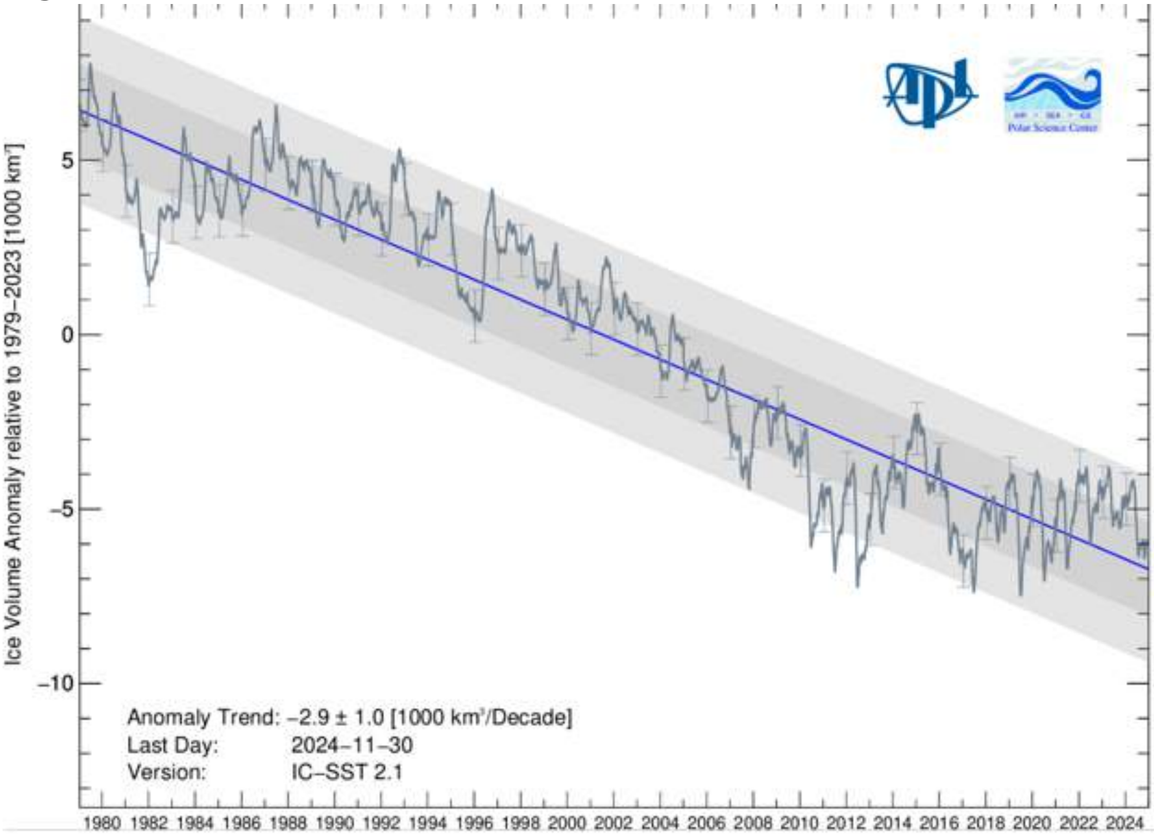
An Alternative Modeling Approach

Yogi Berra, it is claimed, was once asked directions for how to get to a distant place, and, after pondering for a while, he concluded: "you can't get there from here." The wisdom often hidden in remarks of the Yankee legend may be apropos. If we restrict our modeling to a standard approach, we may not reach needed answers in time to usefully advise humanity.

A common modeling approach is to include as many relevant processes as practical in a comprehensive model, which has the merit of allowing various components of the climate system to interact. However, our knowledge and modeling ability for some parts of the climate system are limited, and a poorly simulated component can gum up the works, making model predictions unrealistic. Ice sheets are a case in point. It is argued[34] that many sea level projections based on global climate models are implausible; some models even had sea level falling with increased warming. GCMs can realistically model increasing snowfall as a result of a warming atmosphere and ocean (with the increased snow causing the interior, high altitude, portion of an ice sheet to grow), but it is hard to model processes, including the ocean-atmosphere interactions, that cause the lower reaches of ice sheets to begin to disintegrate and release freshwater in a warmer world. Even sea ice modeling is difficult. There is a tremendous range in the projections of Arctic sea ice in different climate models.[35] Sea ice modeling has been pursued since the 1960s, with realistic modeling always "just around the corner."

Sea ice modeling is hard. We know from data for the early Pliocene – when global temperature at most approached +2°C[3] – that seasonal sea ice still occurred in the Arctic, but some regions near Greenland were as much as 5°C warmer than today.[29] Unless the humanmade climate forcing is reduced, the Arctic is headed toward a much warmer state. Warm Pacific water is flooding over the Aleutian sill into the Arctic surface mixed layer and warm Atlantic water is increasing the temperature of the Arctic ocean beneath the surface mixed layer (see Fig. 17 of Polyakov et al.).[36] Climate modeling needs to include the freshwater injection from ice shelves and ice sheets. The CMIP6 models that inform IPCC AR6 cannot produce realistic temperatures in the Southern Ocean or the Arctic because they lack this freshwater source (Fig. 1 of Shu et al.;[37] see also Fig. 5

Figure SM14. Arctic Sea Ice Volume, 1979-2024 (Polar Science Center)[28]



of the Cheng et al.[38] 2025 paper). We suggest that the seeming stability since 2010 of Arctic sea ice area (Fig. SM13) and volume (Fig. SM14 of the Polar Science Center)[28] is in part a result of ice melt freshwater sources, including Arctic glaciers, ice caps, and ice shelves. From Greenland, Petermann Glacier had large calving events in 2010 and 2012 (Munchow et al.;[39] Ciraci et al.[40]) and northern Greenland ice shelves are an increasing freshwater source (Khan et al.,[41] Millan et al.,[42] Narkevic et al.,[43] and Zeising et al.[44]).

Certainly, ice sheet and sea ice modeling coupled to GCMs should continue to be pursued with high priority, but as a complement to this approach it would be informative to also pursue modeling in which freshwater injection is based on observational data up to the present and projected forward with a small number of alternative assumptions (scenarios). The rationale for this approach is that the physics of deepwater formation is reasonably simple, but it depends on having the correct forcing, specifically accurate freshwater perturbation. It is also important to assure that the model does not have unrealistic mixing. There is no need to remove model components (such as sea ice and/or ice sheet modeling), just correct their calculated freshwater injection to match observations in the past and to yield desired future scenarios.

We plan to pursue this approach, but if we are the only ones, our results may be ignored again. It would be more effective if a few modeling groups pursue such a modeling strategy. Also, it would be better if freshwater inputs for the past are defined by people with expertise in observations. If the past forcings are specified accurately and the future scenarios are well defined, comparisons of simulated climate with future observations – especially climate changes that occur in the near future – should yield helpful insights about the prospects for AMOC shutdown.

AMOC shutdown deserves special attention, because it likely constitutes the point of no return. The expected cold, stormy weather in the North Atlantic and northern Europe would be largely regional, but there also will be global effects. Large sea level rise is probably unavoidable, if AMOC shuts down. The global ocean conveyor circulation presently carries across the equator an amount of energy equal to 4 W/m^2 averaged over the Northern Hemisphere, depositing most of the energy in the North Atlantic region. If that energy is instead left in the Southern Hemisphere as a result of AMOC shutdown, it will speed melting of Antarctic ice. Principal issues are thus the time scale over which effects will occur and what can be done to avoid AMOC shutdown.

Storms and Ocean Stratification

Storms and ocean stratification are affected by global warming, with practical implications. Higher sea surface temperatures (SSTs) and increased atmospheric water vapor create potential for more powerful tropical storms,[45] tornadoes, and thunderstorms.[1] The power dissipation of a wind storm increases as the cube of wind speed[46] as does the monetary damage of storms.[47,48] Precipitation and floods that accompany storms often have still greater practical impact. The relationship of these effects to climate forcings and to global temperature is not defined as well as it must be. Effects of +1.6C global temperature in the past year, with record SSTs, arguably were noticeable in 2024, but the period was too short for statistical confirmation. Given our interpretation of the recent leap in SSTs and global surface temperature, we expect temperature to hover about +1.5°C for several years – pushed down by La Nina and declining solar radiation, but upward by rising GHGs and the continuing effect of reduced aerosols – and then continue on its course toward 2°C. We are now living in the +1.5C world and we need to define the climate impacts better.

Increased ocean stratification is a matter of concern. Increased stratification is expected[49] with rising surface layer temperature, as the warmer surface water is less dense and thus less prone to mix with colder, deeper water. That is not a good thing, as the deeper water contains nutrients that must be mixed upward to support a healthy marine ecosystem. Upwelling of nutrient rich water does not occur uniformly over the ocean, but instead mainly at fronts[50] – boundaries separating water masses with different properties. Movement toward the surface of cooler, nutrient-rich, water is thus facilitated at many locations, but increased stratification makes such upwelling less likely. GCM climate simulations driven by increasing GHGs (but without freshwater injection from melting ice) yield a long-term decline in ocean productivity, including, e.g., a 60% decline in North Atlantic fishery yields.[51]

Sallee et al.[52] find that the drive for ocean change must be more complex than simply increasing GHGs. They show that stratification is increasing over most low and middle latitude ocean areas, but so too is the ocean's mixed-layer depth, the latter opposite of what is expected for GHG forcing alone. A likely explanation is higher wind speeds and thus increased turbulence in the ocean's wind-stirred surface mixed-layer. Young and Ribal[53] use satellite observations from 1985 to 2018 to investigate trends in wind speed and wave height over the ocean; their Fig. 2 reveals a trend in wave height of about 1 cm/year over the entire Southern and North Atlantic Oceans, i.e., a 33-year increase of 33 cm (13 inches) in wave height. These are just the regions where freshwater injection increased the eddy kinetic energy of the atmosphere in the *Ice Melt* GCM climate simulations. The model had been shown to do a good job of simulating atmospheric dynamics, so it may be worth repeating the brief relevant section of the *Ice Melt* paper:

3.9.2 21^{st} Century storms

If GHGs continue to increase rapidly and ice melt grows, our simulations yield shutdown or major slowdown of the AMOC in the 21^{st} century, implying an increase of severe weather. This is shown by zonal mean temperature and eddy kinetic energy changes in simulations of Sec. 3.3-3.6 with and without ice melt (Fig. 21). Without ice melt, surface warming is largest in the Arctic (Fig. 21, left), resulting in a decrease of lower tropospheric eddy energy. However, the surface cooling from ice melt increases surface and lower tropospheric temperature gradients, and in stark contrast to the case without ice melt, there is a large increase of mid-latitude eddy energy throughout the midlatitude troposphere. The increase of zonal-mean midlatitude baroclinicity (Fig. 21) is in agreement with the localized, North Atlantic-centered increases in baroclinicity found in the higher resolution simulations of Jackson et al. (2015)[54] and Brayshaw et al. (2009).[55]

Increased baroclinicity produced by a stronger temperature gradient provides energy for more severe weather events. Many of the most memorable and devastating storms in eastern North America and western Europe, popularly known as superstorms, have been winter cyclonic storms, though sometimes occurring in late fall or early spring, that generate near-hurricane force winds and often large amounts of snowfall (Chapter 11, Hansen, 2009).[56] Continued warming of low latitude oceans in coming decades will provide a larger water vapor repository that can strengthen such storms. If this tropical warming is combined with a cooler North Atlantic Ocean from AMOC slowdown and an increase in midlatitude eddy energy (Fig. 21), we can anticipate more severe baroclinic storms. Increased high pressure due to cooler high latitude ocean (Fig. 20) can make blocking situations more extreme, with a steeper pressure gradient between the storm's low-pressure center and the blocking high, thus driving stronger North Atlantic storms.

Freshwater injection on the North Atlantic and Southern Oceans increases sea level pressure at middle latitudes and decreases it at polar latitudes (Figs. 20, S22), but the impact is different in the North Atlantic than in the Southern Ocean. In the Southern Ocean the increased meridional temperature gradient increases the strength of westerlies in all seasons at all longitudes. In the North Atlantic Ocean, sea level pressure increase in winter slows the westerlies (Fig. 20). Thus, instead of a strong zonal wind that keeps cold polar air locked in the Arctic, there is a tendency for a less zonal flow and thus more cold air outbreaks to middle latitudes.

These effects are already beginning today and will increase as long as the low latitudes continue to warm, the Antarctic and Greenland ice sheets shed increasing amounts of cooling freshwater, and the North Atlantic proceeds toward AMOC shutdown. Caesar[57] presents evidence that AMOC has been in decline and is at its weakest point in a millennium. Storms are getting stronger in the North Atlantic and the Southern Ocean, if we take wave height as a measure.[53] Greater storminess at high latitudes increases ocean mixing and brings nutrients to the surface layer, overwhelming the stratification tendency that was projected[51] based on GHG warming as the only forcing. This picture is consistent with the data of Yang et al.[50] in which most equatorial hotspots are experiencing a decline in frontal upwelling and chlorophyll concentration, while most high-latitude hotspots have increased frontal upwelling and chlorophyll concentration.

Crucial Observations

Earth is presently far out of energy balance – more energy coming in than going out – so global warming will continue and its effects will become more obvious. When the world is finally ready to take effective action to address climate change, it is important that we understand climate change to help define actions with the best chance of achieving effective results. That means that we must obtain observations essential for understanding of ongoing change. We limit discussion here to observations closely related to the main topics in our present paper, but, in fact, these are essential data for defining the big picture. Given what is at stake, it would be shocking if we do not continue crucial observations needed to understand ongoing climate change, the prospects for further change, and progress in restoring Earth's energy balance.

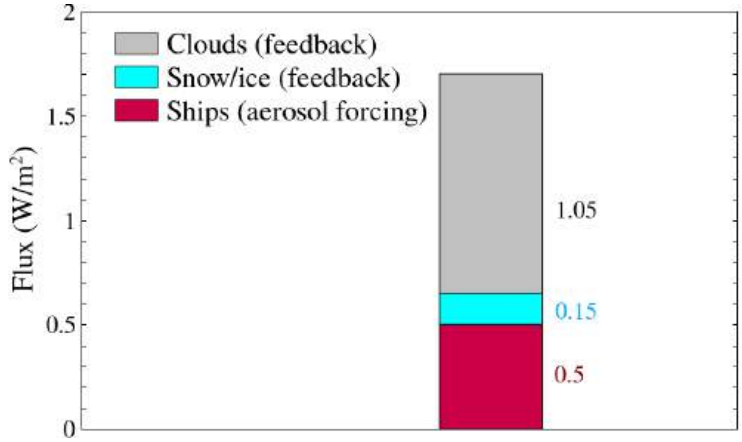
Earth’s energy imbalance is a measure of how much we must do to halt global warming. As long as more energy is coming in than going out, the ocean will keep warming and ice will keep melting. Presently, we are acquiring accurate measurements of Earth’s energy balance, thanks to the combination of multiple CERES (Clouds and Earth’s Radiant Energy System) instruments in space and several thousand deep-diving Argo floats dispersed around the global ocean, with Argo heat content measurement providing absolute calibration for the CERES data. CERES data are being used for more than measuring Earth’s energy balance. In the absence of long-term monitoring of aerosol climate forcing – a very difficult task, requiring precise long-term monitoring of aerosol and cloud microphysics – CERES data have provided the best proxy for aerosol climate forcing, despite ambiguities in their use for that purpose.

NASA’s CERES instruments have been remarkably long-lived, the initial launch being in 1999, but the satellites and instruments are well past their prime mission lifetime. A follow-on to CERES, Libera, is planned for launch in 2027, but there are no plans after that. There is danger of a discontinuity in the data. If there is no overlap of successive instruments, the calibration is lost, and stitching together a long-term becomes problematic. There is no persuasive evidence that adequate replacement instruments will be in space in time for data continuity. Given the importance of the data, it would make sense for others – e.g., the U.S., European Union, Japan and China – to work collaboratively to ensure continuity of data. Indeed, it would be useful in any case for more than one of these countries to obtain data, as a cross-check.

The Argo deep-diving floats provide much more than an absolute measure of change in Earth’s energy balance (thus calibration of satellite data), their precise measurements of temperature and salinity are the backbone of global ocean observations. However, few measurements are being obtained in the regions essential to understand the ocean’s effect on the ice sheets: data on the continental shelves, in Greenland fjords, and inside ice shelf cavities. The technical capability to extend Argo measurements under ice and inside ice cavities now exists and needs to be deployed at scale in order to develop understanding and predictive capability for ice shelf melt rates and their impact on glacier evolution and sea level rise. The existing Argo program monitors most of the global ocean in an international cooperation involving many nations. The need is to expand the program to include data from the deeper ocean, and especially greater focus on the polar oceans, which will determine the future of both the ocean’s overturning circulations and sea level.

In the past 10 years there were specific, limited, programs for Greenland (NASA’s Ocean Melting Greenland, OMG program) observations and an international cooperation to investigate the most vulnerable Antarctic ice – the Thwaites glacier – but these were limited programs that have ended. As global climate change is accelerating, it is important to follow up those studies, which can be done most comprehensively as an international cooperation. That cooperation should pay off as it helps us develop mutual understanding of where climate is headed and what needs to be done to achieve a bright future for today’s population and generations to come.

Figure SM15. Inferred Contributions to Reduced Earth Albedo



Summary

Danger of being too late. The great thermal inertia of the climate system – due to the massive global ocean – creates the danger of being too late because the public sees only limited climate change, so far, and thus does not prioritize the climate issue. The *Pipeline* paper (*Global Warming in the Pipeline*)[3] revealed – with the help of paleoclimate data – that the eventual (equilibrium) climate response to today's atmospheric greenhouse gases (GHGs) would be a nearly ice-free planet with coastlines very different than today. Achieving that equilibrium would require millennia, enough time for humanity and natural processes to draw down excessive greenhouse gases (GHGs) in the air, avoiding such an extreme fate. However, in fact, GHGs are continuing to increase at a rate about 10 times faster than any known case in Earth's history. Humanity is hammering our planet with a force for change that Earth has never felt before. The great inertia of the climate system has limited the climate response so far, but as change accelerates, some critical responses of the planet may begin to run so fast that they become difficult, if not impossible, to control. That is the danger of "being too late."

Global warming acceleration. The *Pipeline* paper, based on paleoclimate data, concluded that equilibrium climate sensitivity is 4.8°C ± 1.2°C for doubled CO_2, higher than the best estimate (3°C for doubled CO_2) of IPCC (Intergovernmental Panel on Climate Change). Paleoclimate, because it actually achieves equilibrium climate changes, provides a reliable measure of climate sensitivity. *Pipeline* also concluded that restrictions imposed in 2015 and 2020 on aerosol precursor emissions from ships was likely a main cause of global warming acceleration.

Our present *Acceleration* paper[1] investigates these issues with more data. We confirm acceleration of global warming and conclude that the +1.5°C global temperature threshold (averaged over El Nino and coming La Ninas) has been breached. The GISS (Goddard Institute for Space Studies) analysis of 12-month running-mean global temperature reached +1.6°C relative to the 1880-1920 mean in August 2024, and then began a slow decline to +1.56 at the end of 2024. If our estimated ship aerosol forcing of 0.5 W/m^2 (several times larger than estimated by IPCC and aerosol modelers) is accurate, global temperature in the next few years will decline at most to ~1.4°C, but it may not even reach that. Earth's large energy imbalance assures that warming will continue on a path to +2°C and beyond, unless extraordinary actions are taken to affect that imbalance. There is no need to wait a decade to confirm that the +1.5°C threshold has been reached.

A stunning observation that we focus on is decrease of Earth's albedo (reflectivity) by about 0.5% in the 21st century, with most of the change occurring since 2010 (Fig. 6 in the main text). Sunlight incident on Earth averages 340 W/m^2, so 0.5% is an increase of 1.7 W/m^2 in the downward radiative flux at the top of the atmosphere. This increased downward flux is some combination of climate forcings and climate feedbacks. We use the geographical and temporal distribution of the change in Earth's reflected sunlight to estimate a ship aerosol forcing of 0.5 W/m^2 and an upper limit on ice/snow albedo feedback of 0.15 W/m^2. That leaves (Fig. SM15) about 1 W/m^2 for cloud feedback (which would be even larger if our estimate of ship aerosol forcing is too large). This large cloud feedback is consistent with the high climate sensitivity, 4-5°C for doubled CO_2, that we find is necessary to match observed global warming of the past century. The high climate sensitivity inferred from global temperature change in the past century is consistent with climate sensitivity inferred from paleoclimate data in *Pipeline*.

Leap of global temperature in 2023-2024. The unprecedented leap of global temperature in the past two years is fully accounted for, about equally, by the modest El Nino and the ship aerosol forcing, with a smaller contribution from the present solar maximum, as shown in Fig. 19. The suddenness of the warming spike is explained by the zonal-mean sea surface temperature in Fig. 10: the North Atlantic and North Pacific Oceans warmed steadily beginning in 2020 while the 3-year La Nina cooled the tropical Pacific. When the tropics turned from a strong La Nina to a modest El Nino in 2023, the full effect of both aerosol forcing and the tropical change appeared.

Our estimated aerosol forcing is larger than calculated by aerosol-cloud models, but the modeling is primitive. Our estimate of the aerosol forcing is based on interpretation of changes in satellite-measured radiation in the regions where ship aerosols dominate. A check on our interpretation will be provided by temperature change in the next few years as the tropics descend into their La Nina phase and solar irradiance declines. If our estimated aerosol forcing is accurate, we expect global temperature to hover about 1.5°C for a few years before resuming ascent to +2.0C within 20 years.

The leap of global temperature to +1.5°C affects people and nature. Perhaps the most noticeable and consequential effects are on the frequency and severity of extreme events. The qualitative effect of global warming has been recognized at least since 1989: generally, wet gets wetter and dry gets drier, which is true both for the geographical distribution of changes and the temporal changes at a given location.[58] Implications include: more extreme floods, stronger storms driven by greater absolute humidity and warmer sea surface temperatures, and more extreme heat waves and droughts – even regions with plentiful annual rainfall may experience "flash droughts" due to extreme temperatures. The effect for the ocean is salty gets saltier and fresher gets still fresher. Oceans are affected now by increased heating from both greenhouse gases and reduced aerosol and cloud shielding, so high average SSTs and ocean hotspots will continue.

All this is not to blame the recent Los Angeles fires on global warming, although warming is one contributing factor. The amplitude of wet-dry climate oscillations is a relevant factor and shifting of climate zones[59] is another. The tragedy can be blamed more on unwise development and poor governance, but even those, it is suggested,[60] are not the principal, root cause of the problem, which is the role of special (financial) interests in creating poor governance. Nevertheless, the problem would be substantially mitigated if the world went back to a lower temperature, which, in fact, is essential if we wish to maintain shorelines close to their present locations, the existence of today's coastal cities, and polar climates essential for many species.

Reactions to these papers. Given that our papers disagree with IPCC conclusions, it is not surprising that they generate reactions on social media. We generally have not responded, as it is very time consuming to respond and debate when we are outnumbered – it seems a better use of time to work on the next paper and include responses in it, if warranted, as we do here.

The first reaction was that there was no significant acceleration of global warming. This is an issue where it seems best to let others and the real world provide the response.

A second reaction was that, if there is acceleration, it is captured in the GCM simulations that IPCC employed, therefore accelerated global warming does not support of our assertion that IPCC underestimated ship aerosol forcing. That reaction exposes the problem with lumping CMIP/IPCC model results into a model fog, and then treating that fog as if it is a probability distribution for the real world or even a sharp tool useful for climate analysis. The problem in this case is that many of the models in the fog did not use the IPCC aerosol forcing. For example, the fog includes GISS model runs that used Susanne Bauer's aerosol modeling, with both her Matrix and OMA aerosol models;[61] the latter model has an even greater aerosol forcing change than the aerosol scenario that we employed. A subset of the model runs consisting of only those that use the IPCC aerosol forcing (not precursor emissions) would likely produce only a slight acceleration (due to growth of the annual GHG forcing in the past several years, which exceeds that in the prior two decades; see Fig. 15), much smaller than the observed acceleration of global warming.

A third reaction was that our estimate of high climate sensitivity is an outlier. However, many recent climate sensitivity studies include a key role for an "emergent constraint." What is an emergent constraint, you may ask? The emergent constraint on climate sensitivity emerges from a desire to keep global warming similar to observations. Our present paper shows that there is a one-to-one relation between the trend of late 20th century aerosol forcing and the climate sensitivity required to match observed warming. Specifically, for the IPCC aerosol scenario, the climate sensitivity required to match observed warming is near 3°C for doubled CO_2. If one accepts the IPCC aerosol scenario, the emergent constraint is that climate sensitivity cannot be far from 3°C for doubled CO_2. Thus, given the one-to-one relation, the emergent constraint amounts to "if we assume that climate sensitivity is near 3°C for doubled CO_2, we find that climate sensitivity is near 3°C for doubled CO_2." Not many people question the IPCC aerosol scenario, leading to a seeming consensus that sensitivity is near 3°C for doubled CO_2. However, as we show in the paper, there are reasons to believe that the real-world aerosol forcing change exceeds IPCC's estimate.

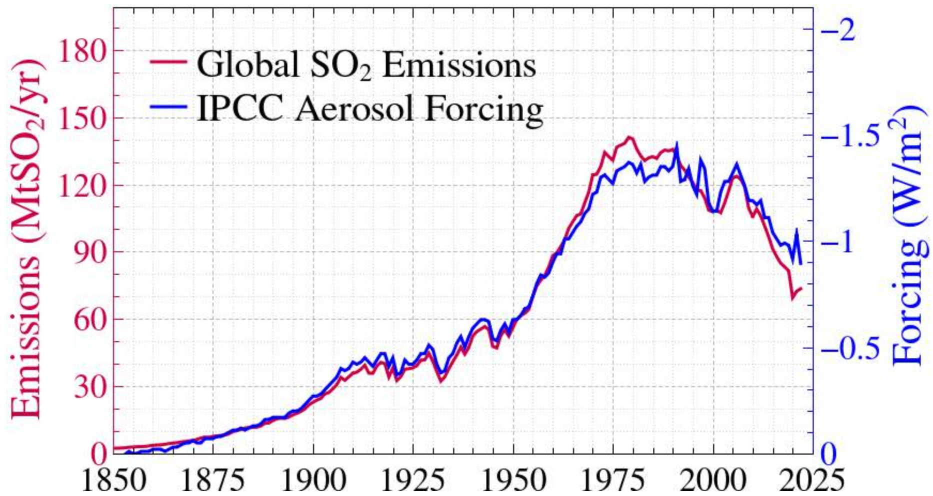
A fourth reaction, made in the New York Times and elsewhere, is that the current rapid warming falls within the range of all CMIP/IPCC climate simulations, so there is no good reason to believe that something is occurring outside of IPCC assumptions. This claim draws more attention to the big model range produced by CMIP/IPCC simulations and the assumption that it is a probability function for the real world. The problem is that the range is a combination of apples and oranges, as shown by the example above, but also of bananas and figs, because of a range of assumptions or treatments of different physical processes in the models – and, to be brutally honest, some pretty awful models. A scientist who wishes to help science writers understand the situation should do more than note that some model produces a response even more extreme than the real world; it would be more useful if the scientist looked at that model to see what caused the extreme response and assessed its plausibility.

Responsibility and opportunity. As scientists with at least qualitative understanding of the delayed response of climate to humanity's heavy footprint, we recognize the danger of "being too late" and potentially leaving young people with "no way to get there from here." And we feel the need to communicate this situation to the public more clearly. But we also know that more data are needed for better understanding of climate change and definition of actions that will be most effective in helping to find a path to a healthy planet and attractive world for future generations.

We are where we are. The near future has become the critical time to develop and communicate understanding of ongoing climate change. We should take the inadvertent ship aerosol experiment as an opportunity to test our understanding. If our interpretation is correct, global temperature, and global sea surface temperatures in particular, will remain exceptionally high even as the world moves into the cool La Nina climate phase. Emerging climate impacts will be a chance to help the public understand what is happening. Despite growing disinformation wars, most of the public appreciates and places trust in objective science – that provides our opportunity to help young people.

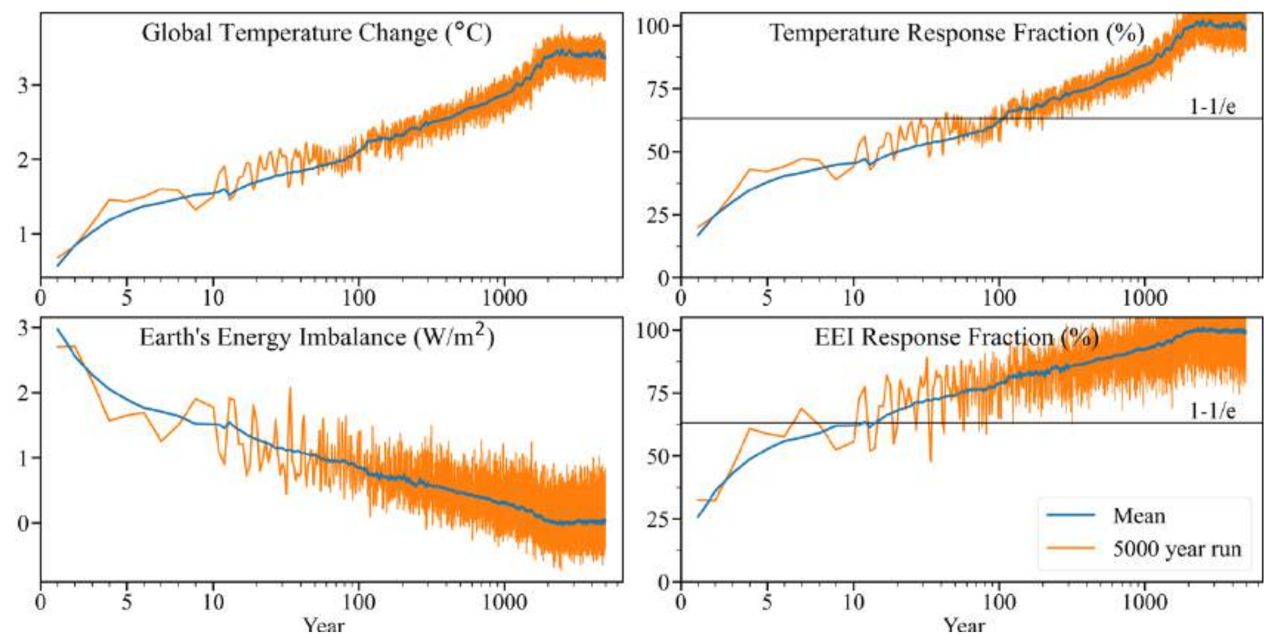
Supplementary Figures SM1-SM8

Figure SM1. Global SO_2 Emissions and IPCC Aerosol Forcing



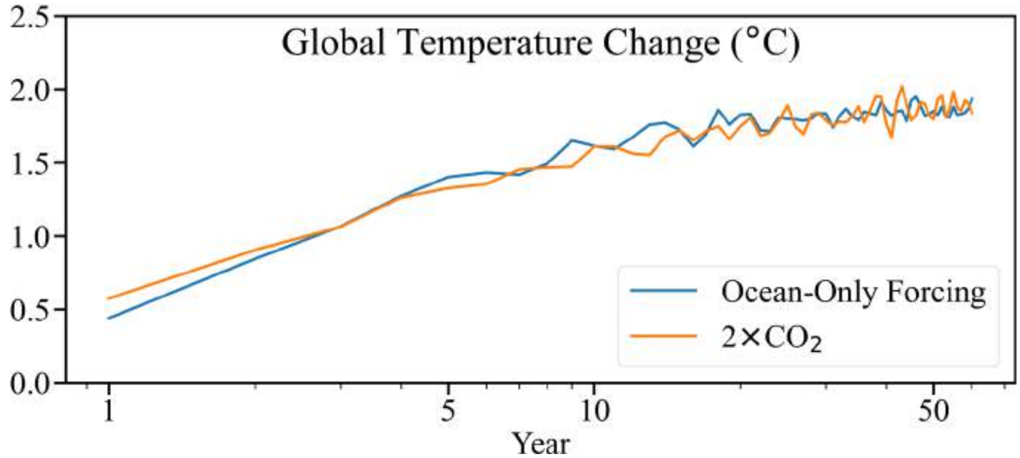
IPCC aerosol forcing and CEDS SO_2 emissions used in IPCC's calculation of aerosol forcing almost coincide, revealing the minimal nonlinearity in IPCC's aerosol forcing formulation.

Figure SM2. Global Temperature Response and Earths Energy Imbalance



The gold curves in Figure SM2 are the response of the GISS (2020) model to doubled CO_2 forcing (see the paper "Global warming in the pipeline").[3] The blue curve for temperature is $T_C(t)$ used for Green's function calculations. The first 60 years of the blue curve is the mean of five runs of the GISS(2020) GCM; the rest of the blue curve is a smoothing of the single 5000 year $2\times CO_2$ run described in reference 1.

Figure SM3. Global Temperature Response to Ocean and 2×CO_2 Forcings



The GISS (2020) model was used, for our present paper, for 5-member ensembles of runs for increased solar irradiance and 2×CO_2 forcings. Solar irradiance was increased only over the ocean by the equivalent of a 2% global increase of solar irradiance, i.e., the solar irradiance over the ocean was increased by the factor 0.02/0.7. In addition, because 2% solar and 2×CO_2 forcings are not identical, we normalize the response to the solar forcing by the factor 4.11/4.52, which is the ratio of 2×CO_2 and 2% solar forcings as evaluated from climate simulations with fixed SST [Tables 1 and 3 of J. Hansen et al., "Efficacy of climate forcings," *J. Geophys. Res.*110 (2005): D18104]. The global warming for the ocean-only forcing is only 76% of the warming for 2×CO_2 in year 1 of the simulations (Figure SM3), but by year 3 the response with ocean-only forcing catches up to the response for CO_2 forcing.

Figure SM4. Global Temperature Change for Base Periods 1880-1920 (top row) and 1951-1980 (lower row)

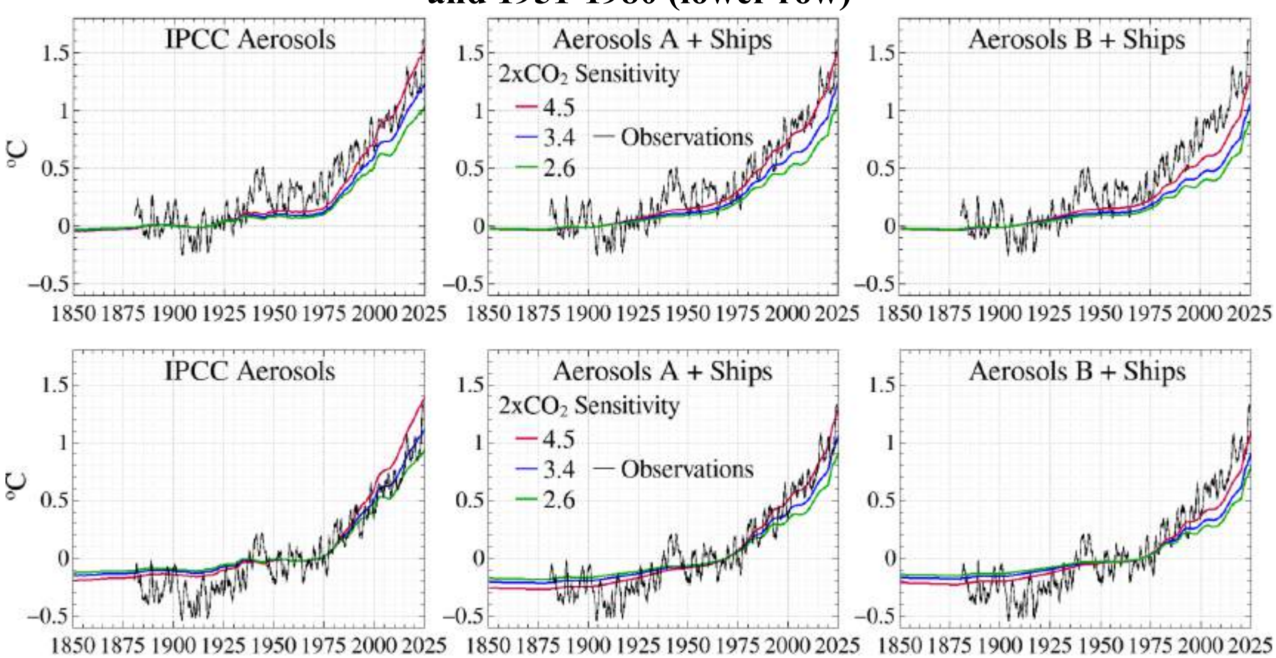


Figure SM4 provides the data for the full period of Green's function calculations (1850-2025) for which shorter periods at higher temporal resolution are shown in Figures 17 and 18.

Figure SM5. Stratospheric Aerosol Coverage in Four Simulations

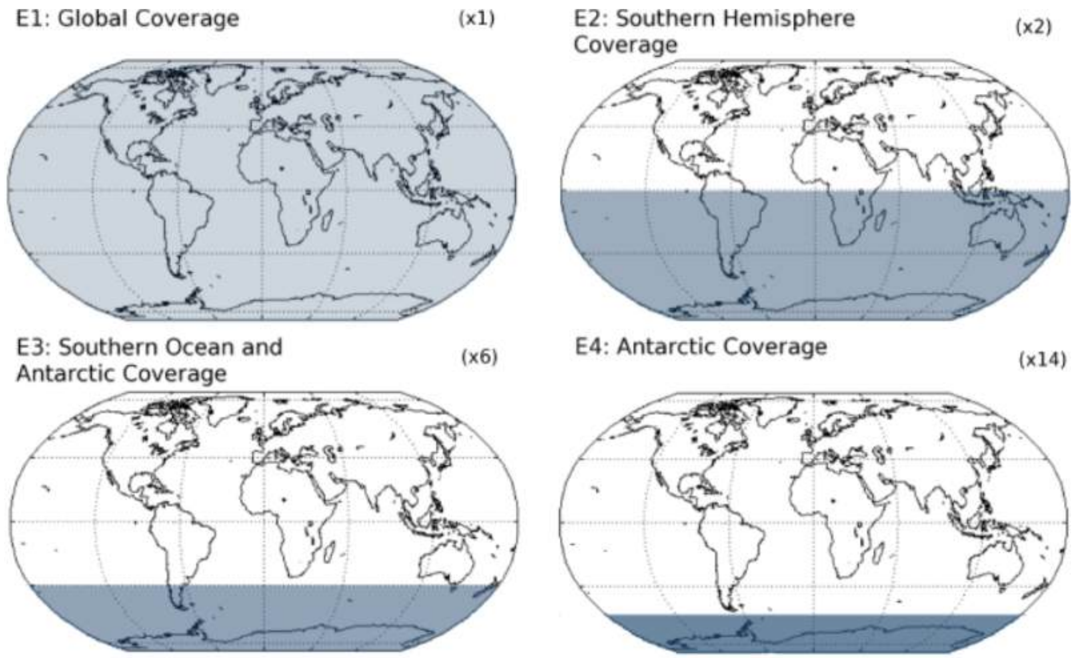
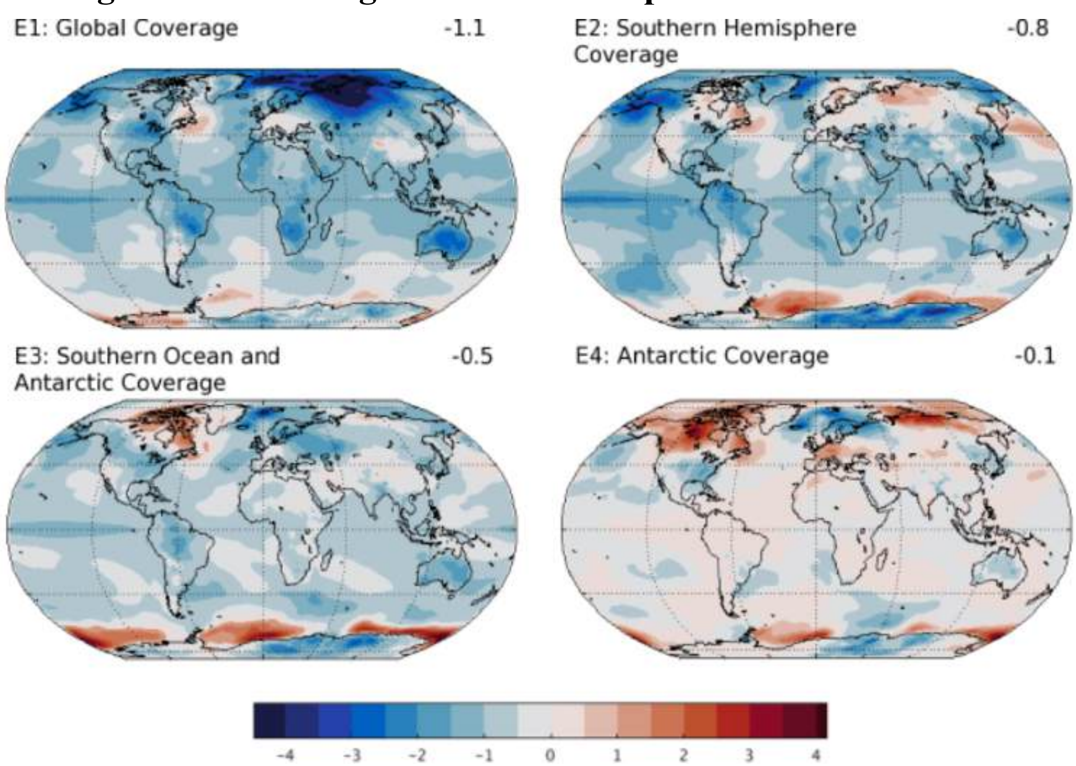


Figure SM6. Change of Surface Temperature After 40 Years



The grey areas in Figure SM5 are the regions with stratospheric aerosols in four climate simulations. The global average aerosol amount is the same in all four cases as for the real-world Pinatubo volcanic eruption in 1991, which requires multiplying the aerosol opacity by 2, 6 and 14 for experiments E2, E3, and E4. Note the surface warming around Antarctica, as the resurgence of the SMOC (Southern Meridional Overturning Circulation) melts sea ice around Antarctica.

Figure SM7. Clear-Sky Absorbed Solar Radiation, 2020-2023 vs 2000-2010

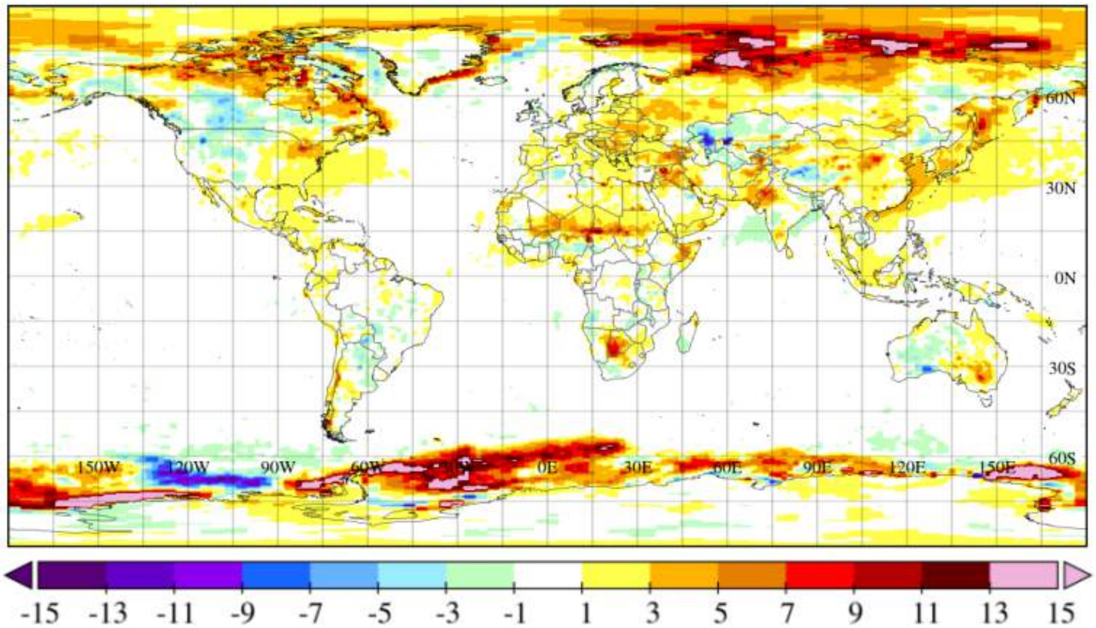
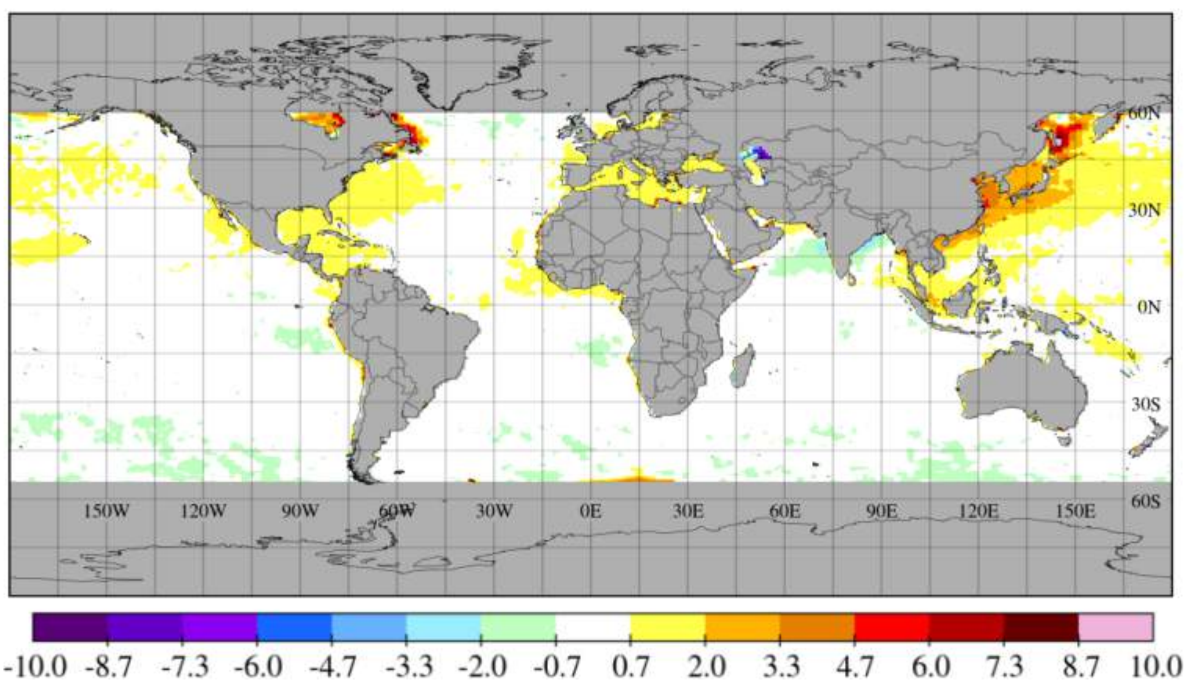


Figure SM8. Clear-Sky Absorbed Solar Radiation, 2020-2023 vs 2000-2010



Change of clear-sky Absorbed Solar Radiation in 2020-2023 relative to the first 10 years of CERES data (March 2000 – February 2010) for the entire globe (Figure SM7) and limited to the ocean and latitudes that largely exclude contributions from sea ice change (Figure SM8), but some change due to loss of sea ice exists near northeast Canada and Kamchatka. The effect of reduced aerosols east of China and increased aerosols near India is apparent. The global-mean contribution of these clear-sky changes, which is a measure of the direct aerosol forcing change, is +0.1 W/m^2.

Additional Data Sources for Figures in Main Text

Figure 3. Adapted from Figure 17(a) in the reference in main text Note 1 (*Pipeline* paper).

Figure 5. Copy of Figure 11b in main text Note 14 reference.

Figures 6, 8, 9, 12, and 26. Authors' calculations based on CERES_EBAF-TOA_Edition4.2 database: https://ceres-tool.larc.nasa.gov/ord-tool/jsp/EBAFTOA42Selection.jsp

Figure 7. Authors' calculations based on CERES_EBAF-TOA_Edition4.2 database above (for ASR) + https://www.ncei.noaa.gov/access/monitoring/pdo/

Figures 10 and 11. Authors' calculations based on NASA GISS sea surface temperature analysis (using NOAA ERSSTv5 data): https://data.giss.nasa.gov/gistemp/zonal_means/

Figures 14, 16-18. Authors' calculations for this paper using the methods described in the associated main text.

Figure 20. Authors' download from University of Maine Climate Reanalyzer: https://climatereanalyzer.org/clim/sst_daily/

Figures 21-23. Authors' calculations based on main text Notes 114, 115 references.

Figure 24. Authors' calculations using the GISS climate model.

Figures 25 and S2. Authors' calculations based on *Pipeline* paper + https://gml.noaa.gov/ccgg/trends/data.html and https://gml.noaa.gov/aftp/data/hats/Total_Cl_Br/

Figure S3. Authors' calculations + main text notes 16 and 17 references.

Figure S4a. Copy of Figure 2a in main text Note 50 reference.

Figure S4b. Copy of Figure 3 in main text Note 26 reference.

Figure S5. Authors' calculations based on main text Note 43 reference.

Figure S8. Authors' calculations based on CEDS v_2024_07_08 Release Emission Data: https://zenodo.org/records/12803197

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