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

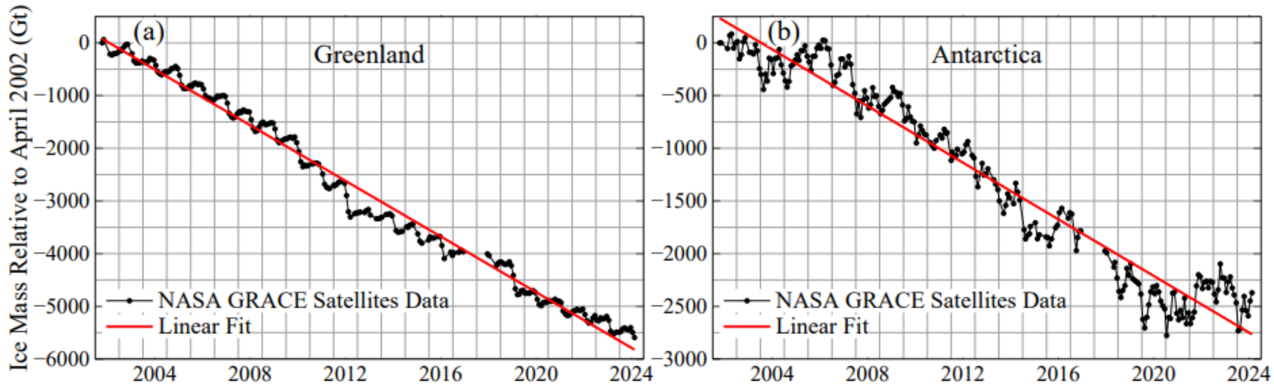
Data on ice melt deserve more attention. Forcings that drove AMOC and SMOC shutdowns in the climate model[2] were (1) growth of greenhouse gases (GHGs), and (2) growth of freshwater injection onto the North Atlantic and Southern Oceans. GHG forcing, in fact, has continued to grow at a high rate, shockingly 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]

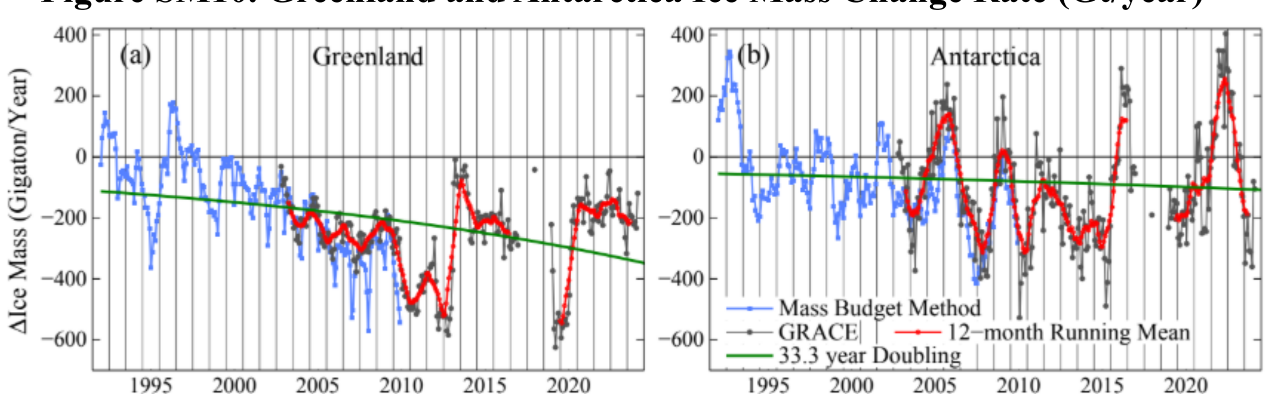
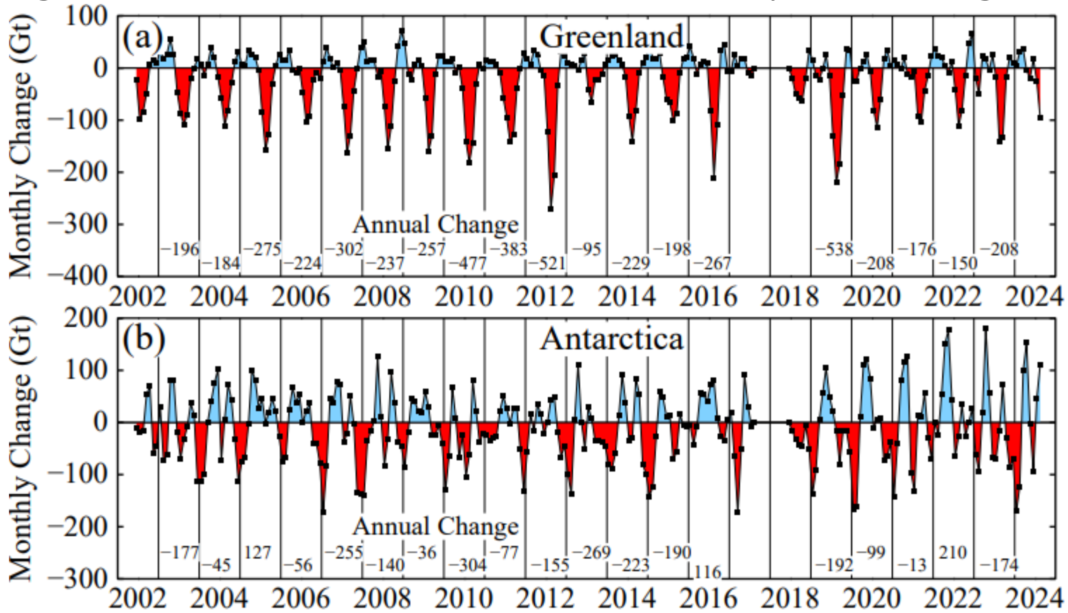
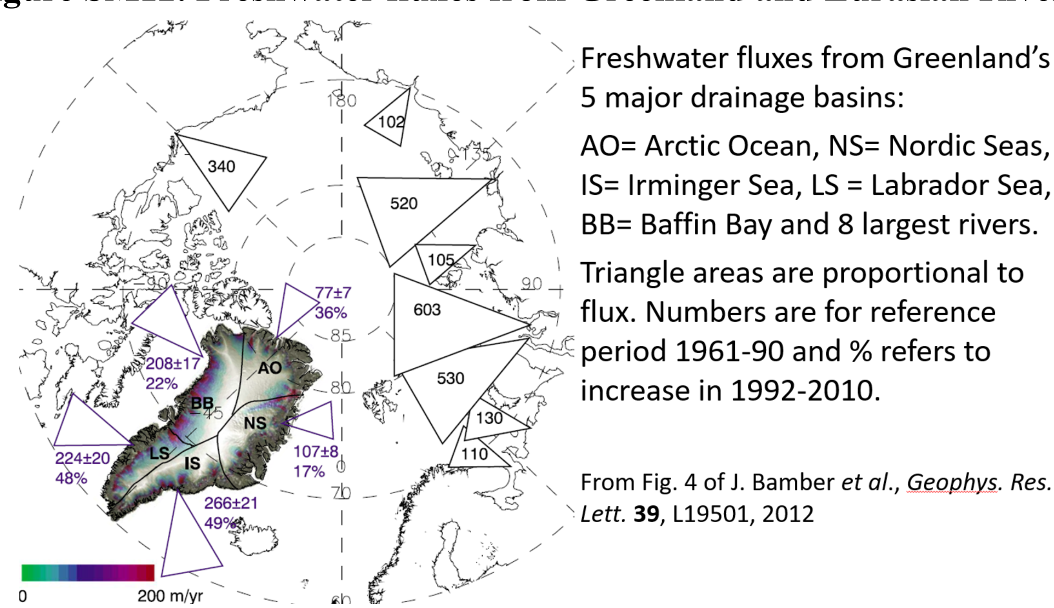


Figure SM11. Greenland and Antarctica Monthly Mass Changes[13,14]



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.

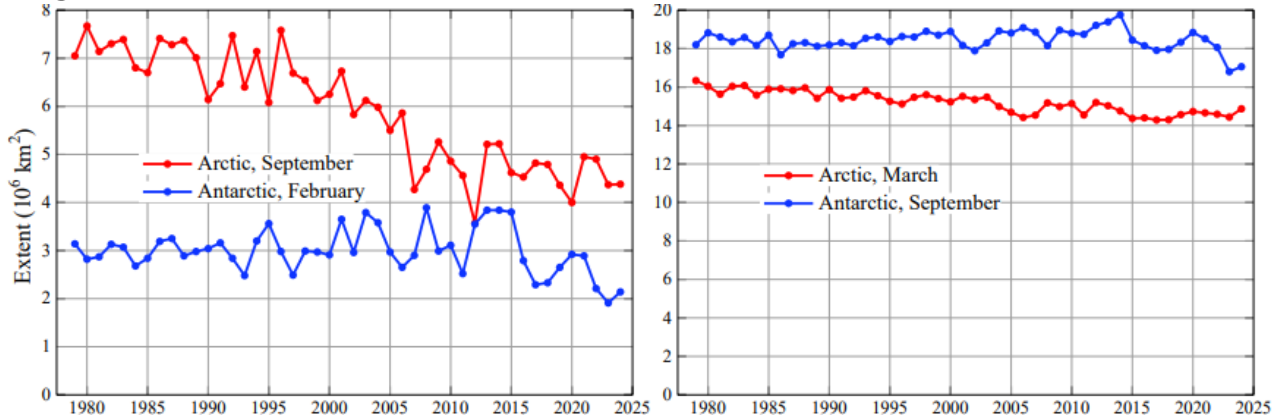
A minimum estimate of freshwater source (2), glaciers and ice caps outside Greenland, is provided by GRACE data. Averaged over 2002-2019, the gravity data yield an annual mass loss from Arctic glaciers and ice caps of 164 ± 24 Gt/yr, with larger values in recent years.[20] About half of this is from 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.

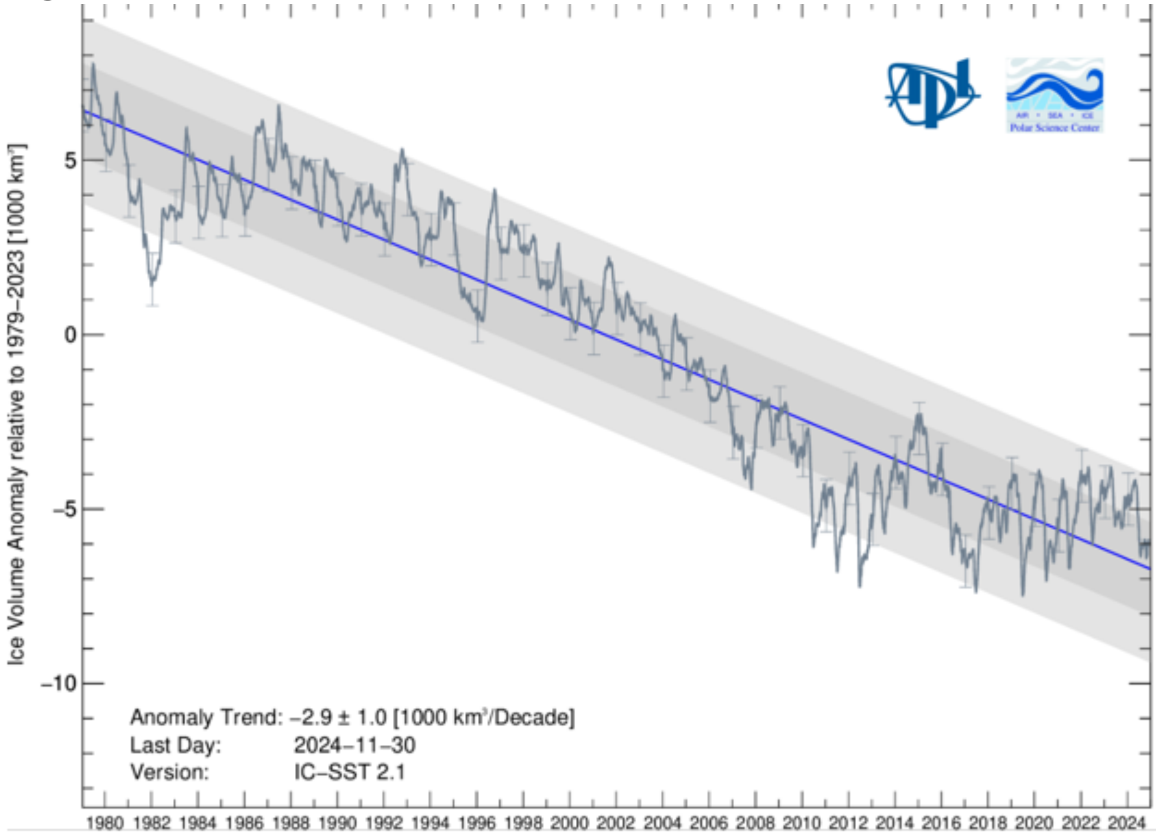
An Alternative Modeling Approach

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 21st Century storms

If GHGs continue to increase rapidly and ice melt grows, our simulations yield shutdown or major slowdown of the AMOC in the 21st 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.

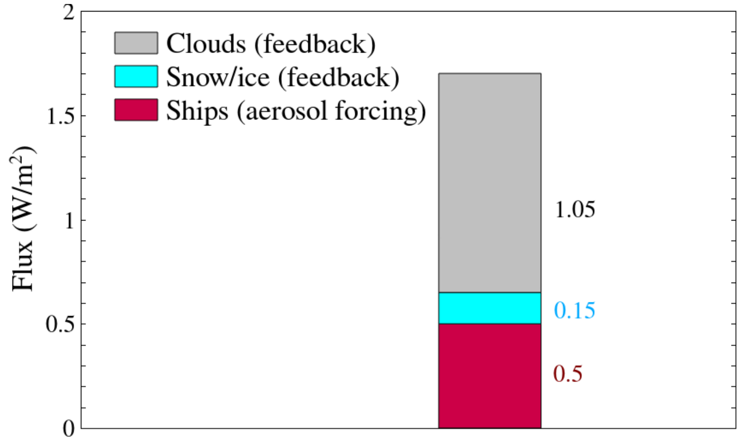
Earth's energy imbalance is a measure of how much we must do to halt global warming. As long as more energy is coming in than going out, the ocean will keep warming and ice will keep melting. Presently, we are acquiring accurate measurements of Earth's energy balance, thanks to the combination of multiple 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.

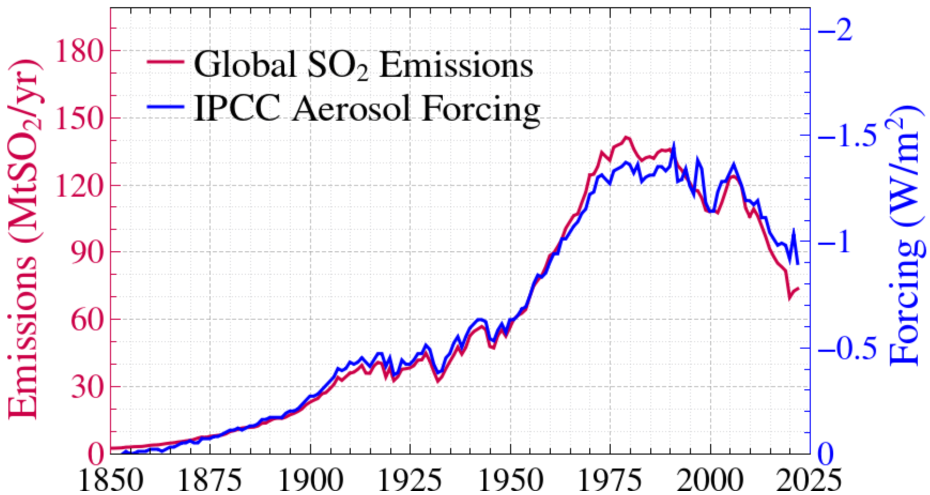
A fourth reaction, made in the New York Times and elsewhere, is that the current rapid warming falls within the range of all CMIP/IPCC climate simulations, so there is no good reason to believe that something is occurring outside of IPCC assumptions. This claim draws more attention to the big model range 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.

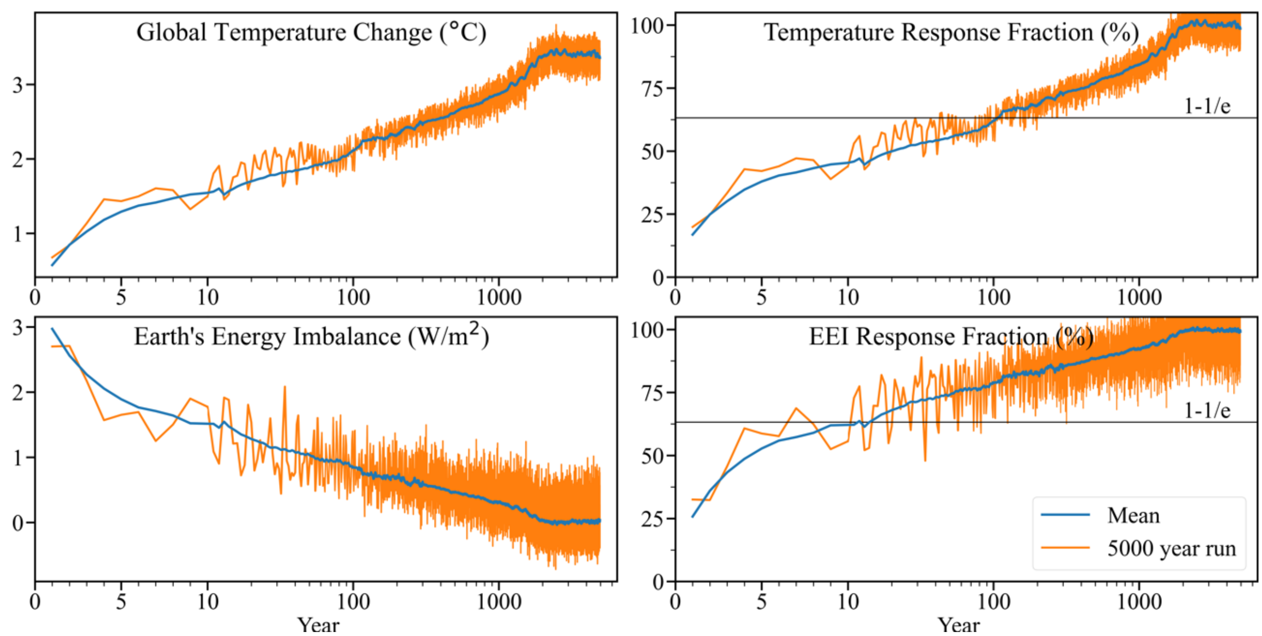
Supplementary Figures SM1-SM8

Figure SM1. Global SO_2 Emissions and IPCC Aerosol Forcing



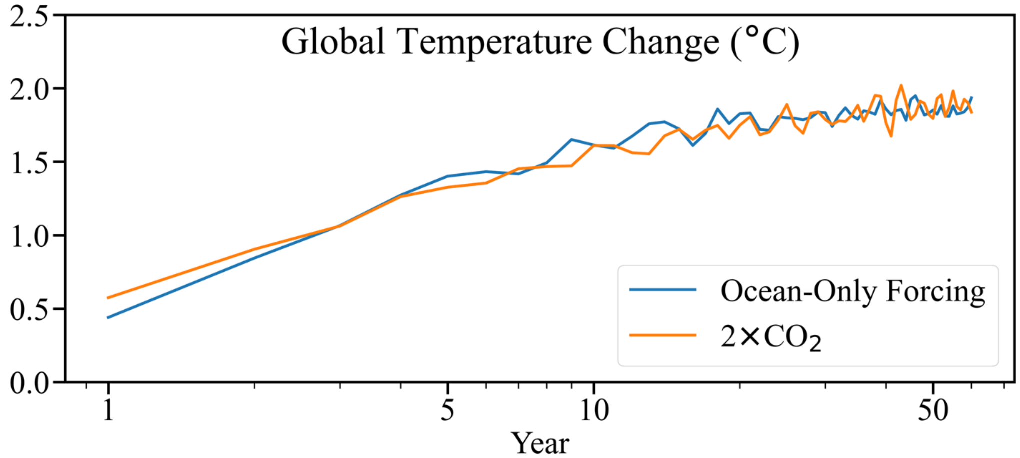
IPCC aerosol forcing and CEDS SO_2 emissions used in IPCC's calculation of aerosol forcing almost coincide, revealing the minimal nonlinearity in IPCC's aerosol forcing formulation.

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×CO_2 run described in reference 1.

Figure SM3. Global Temperature Response to Ocean and $2\times CO_2$ Forcings



The GISS (2020) model was used, for our present paper, for 5-member ensembles of runs for increased solar irradiance and $2\times CO_2$ 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 $2\times CO_2$ forcings are not identical, we normalize the response to the solar forcing by the factor 4.11/4.52, which is the ratio of $2\times CO_2$ 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 $2\times CO_2$ 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)

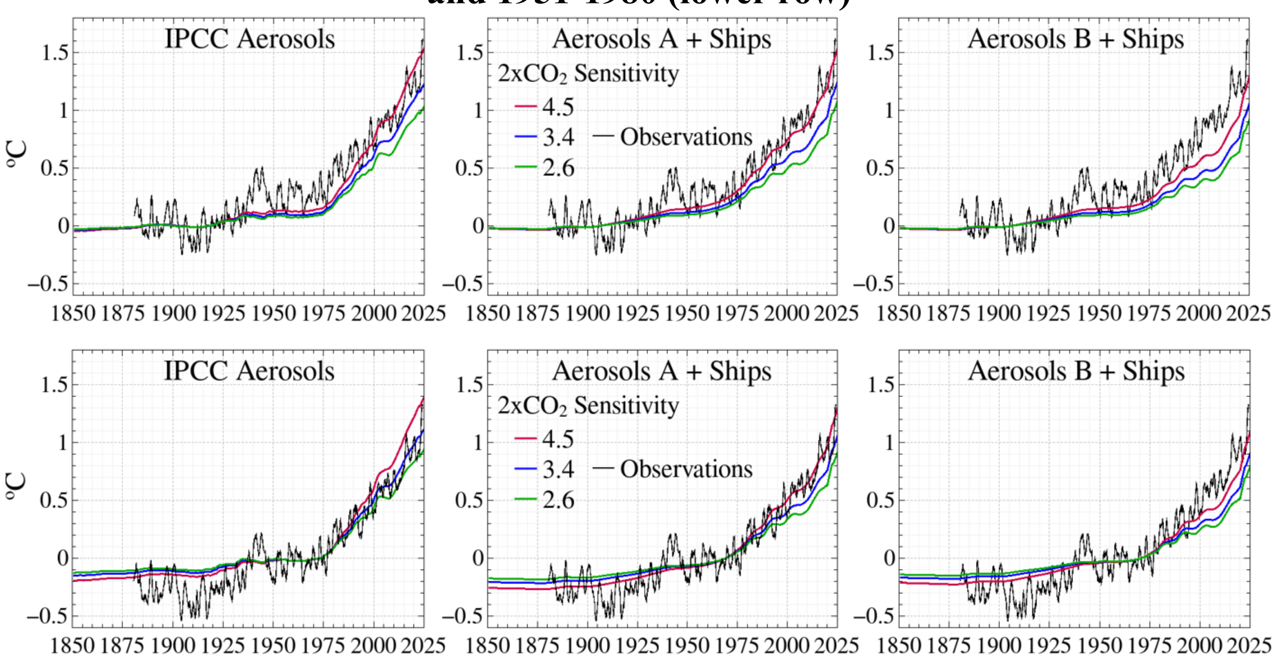


Figure SM4 provides the data for the full period of Green's function calculations (1850-2025) for which shorter periods at higher temporal resolution are shown in Figures 17 and 18.

Figure SM5. Stratospheric Aerosol Coverage in Four Simulations

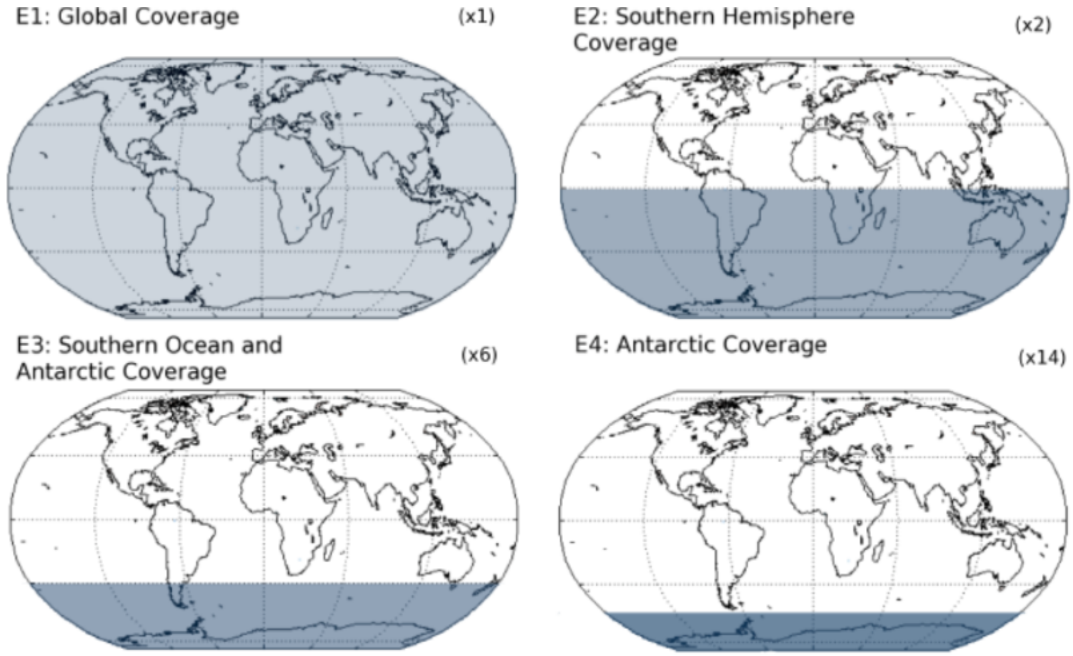
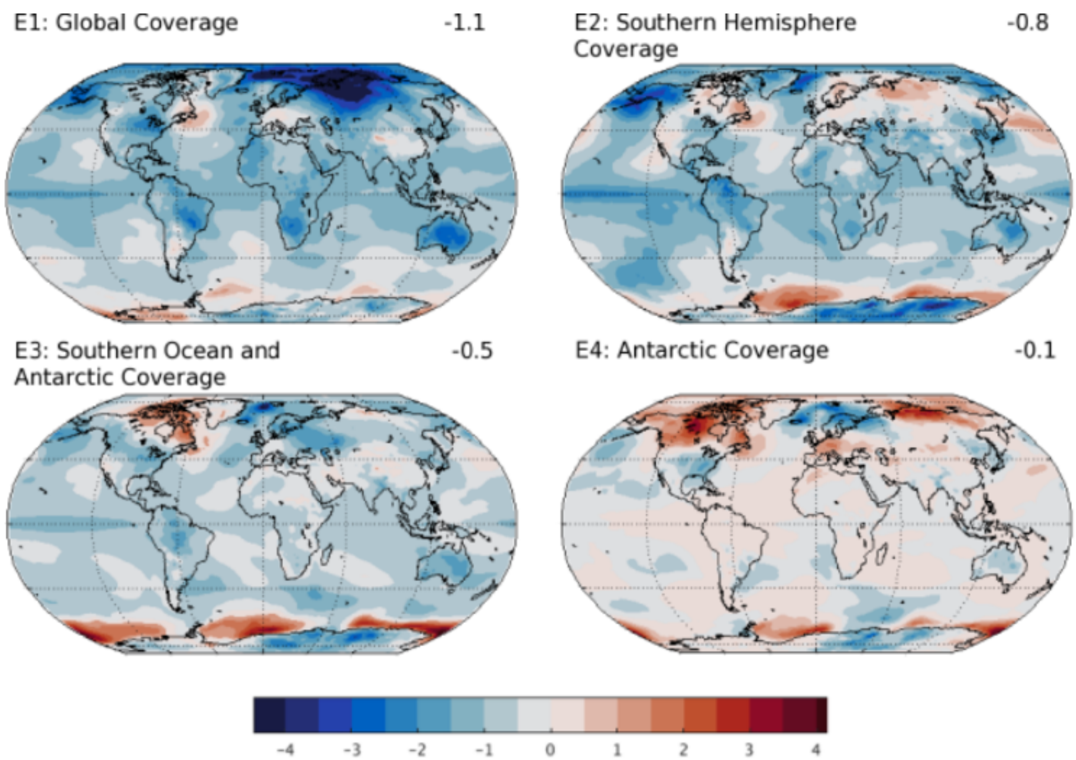


Figure SM6. Change of Surface Temperature After 40 Years



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

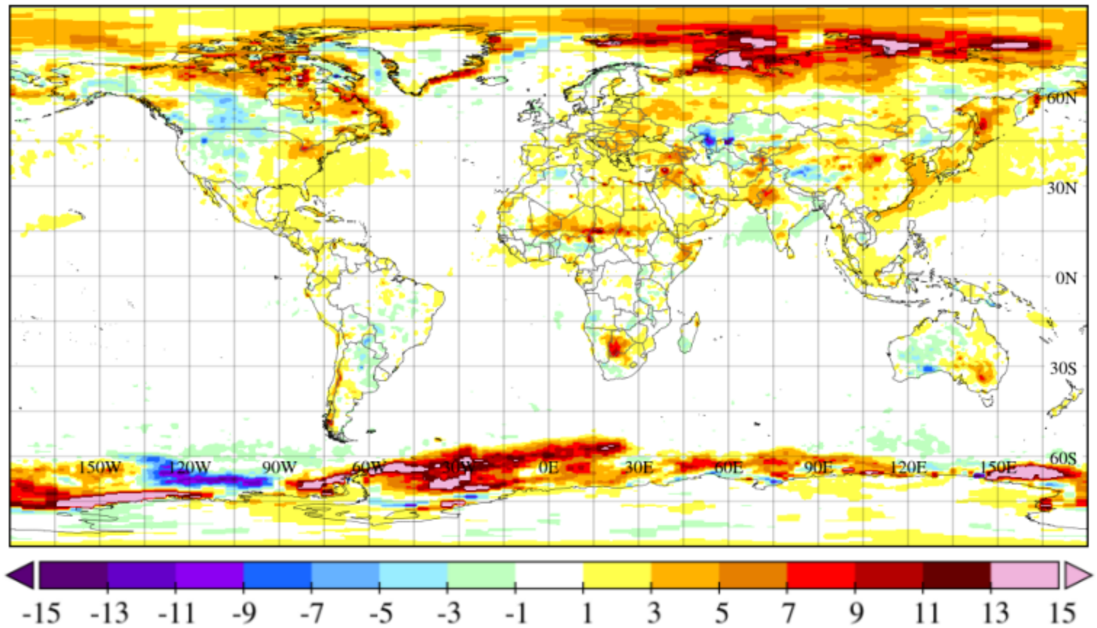
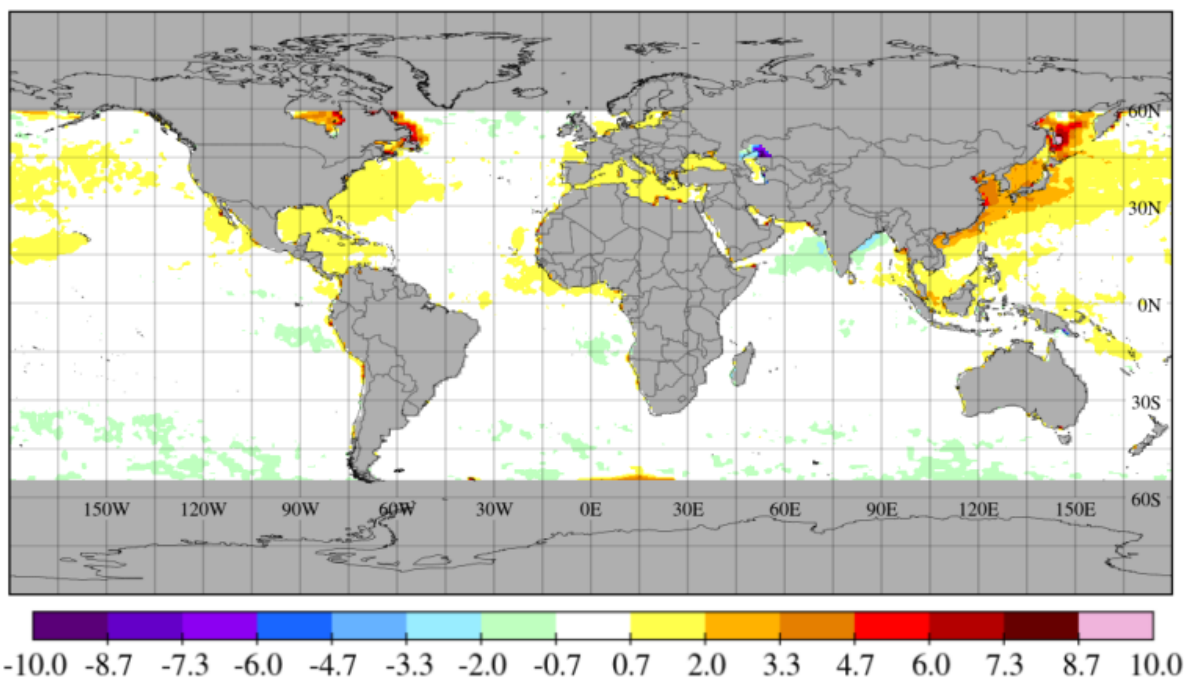


Figure SM8. Clear-Sky Absorbed Solar Radiation, 2020-2023 vs 2000-2010



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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[1] J.E. Hansen, P. Kharecha, M. Sato et al., "Global warming has accelerated: are the United Nations and the public well-informed?" *Environment* 66:1 (2025) **This should include a link to the PDF; also in first sentence on page 1**

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[16] In the preindustrial state, the sizes of the ice sheets are assumed to be stable, with snowfall on the ice sheets balanced by discharge to the ocean, mainly in the form of icebergs. Thus, in the GISS climate model, snowfall on the ice sheet in the preindustrial control run is used to define the rate of discharge of freshwater to the ocean. The freshwater is distributed in the region of iceberg transport in the climate simulations for the modern era, and additional freshwater is added based on measured or estimated reduction of ice mass in the real world.
[17] The blue data are from the mass balance calculations of E.Rignot, I. Velicogna,, M.R. van den Broeke et al., "Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise," *Geophys. Res. Lett*. 38 (2011): L05503, while the black and red data are based on analyses of GRACE gravity data (reference 5). The green line in part (a) is for the best fit doubling time, which is 20 years.
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