Seeing the Forest for the Trees

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Abstract. Climate sensitivity is substantially higher than IPCC's best estimate (3°C for doubled CO_2), a conclusion we reach with greater than 99 percent confidence. We also show that global climate forcing by aerosols became stronger (increasingly negative) during 1970-2005, unlike IPCC's best estimate of aerosol forcing. High confidence in these conclusions is based on a broad analysis approach. IPCC's underestimates of climate sensitivity and aerosol cooling follow from their disproportionate emphasis on global climate modeling, an approach that will not yield timely, reliable, policy advice.

Our two recent papers (Global warming in the pipeline[1] and Global warming has accelerated[2]) [hereafter Paper 1 and Paper 2] were long – due to our research approach and our intent to raise numerous issues. Thus, we summarize the most important conclusions here.

Principal objectives of research in climate change are to evaluate climate sensitivity and the forcings that are driving climate change. Our analysis approach places comparable emphasis on each of three sources of information: (1) paleoclimate data, i.e., the long history of climate change, (2) modern observations of ongoing climate change, and (3) global climate modeling. Full exploitation of all three research tools allows conclusions to be reached with a higher degree of confidence than otherwise would be possible.

Jule Charney understood that the most basic climate issue is climate sensitivity: climate response to a standard climate forcing. A forcing is an imposed perturbation of Earth's energy balance. Thus, when U.S. President Carter's Science Adviser requested a report on climate implications of fossil fuel use, Charney chose to focus a study[3] by the U.S. National Academy of Sciences on a specific question: the equilibrium (eventual) global temperature response to a doubling of atmospheric carbon dioxide (CO_2).[4] Doubled CO_2 causes a climate forcing of about 4 W/m^2, due to the infrared opacity of CO_2, which reduces Earth's heat radiation to space.

The Charney study relied mainly on global climate models because data adequate for empirical evaluation of climate sensitivity were not yet available for either paleoclimate or modern climate observations. As a result, because there is uncertainty in the many known and unknown climate processes in climate models, the Charney report could only conclude that climate sensitivity was likely in the range 3°C ± 1.5°C for doubled CO_2, and in that range only with 50% confidence.

Understanding of ongoing and future climate change requires knowledge of the forcings that are driving climate change, in addition to knowledge of climate sensitivity. In close agreement with IPCC,[5] we show in our first paper[1] that the net climate forcing on decadal and longer time scales is given accurately by the sum of two forcings: greenhouse gas (GHG) and aerosol changes. There are several more human-made and natural climate forcings, but they are smaller and partly offsetting. GHG amounts are measured accurately and our calculated GHG forcing agrees with that of IPCC within about 1%, with the absolute uncertainty in both being about 10%. Aerosol forcing, in contrast, is difficult to measure because most of the aerosol forcing occurs via the effect of aerosols on clouds, not from the direct effect of aerosols on solar radiation. Because of the absence of adequate aerosol-cloud measurements there is large uncertainty in the aerosol forcing, which thus must be assessed largely in indirect ways.

1. Paleoclimate

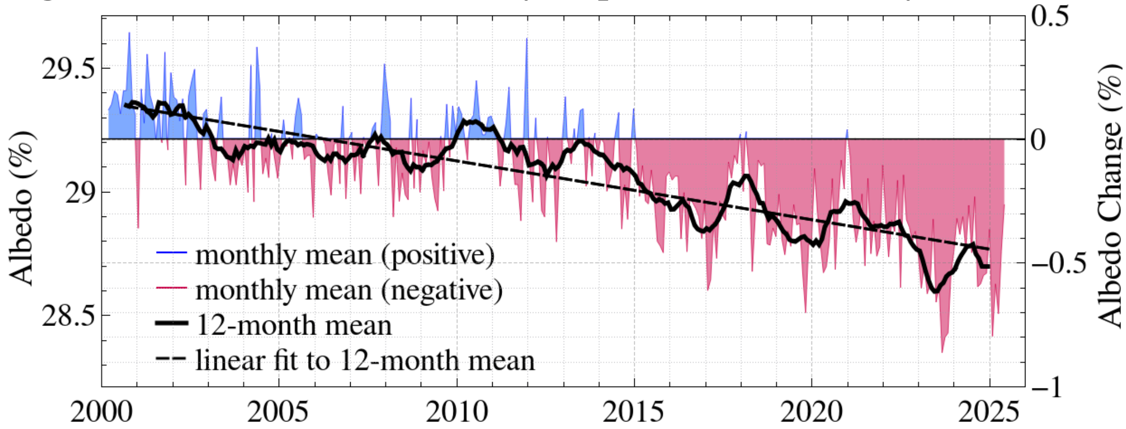
Reliable assessment of climate sensitivity can be obtained from the observed global temperature difference between two stable climate states, if the global temperature change and climate forcing change between the two states are known accurately. Real-world climate change between climate states includes all climate feedbacks (and does so correctly), which is not the case with climate models. The paleoclimate period in which GHG changes are known accurately is the past several hundred thousand years, when GHG amounts are preserved in air bubbles in the Antarctic ice sheet. The big uncertainty in using glacial-interglacial climate change to evaluate climate sensitivity has long been uncertainty in how cold the glacial periods were.

CLIMAP,[6] a large NSF-funded project, evaluated climate conditions during the Last Glacial Maximum (LGM), which peaked about 20,000 years ago. Sea surface temperatures (SSTs) during the ice age were the most crucial data because the ocean covers 70% of the planet and global SST tightly fixes global surface temperature. SSTs estimated by CLIMAP implied that global temperature during the LGM was ~3.6°C cooler than preindustrial climate. In turn, this implied that climate sensitivity was ~2.4°C for doubled CO_2, because the forcing that maintained the temperature change was ~6 W/m^2 (the forcing being changed GHG amounts and changed surface albedo, i.e., surface reflectivity),[1] as discussed at the 1982 Ewing Symposium on climate sensitivity and published as an AGU Geophysical Monograph in January 1984.[7]

But how did CLIMAP obtain their SSTs? They were based on the geographical distribution of tiny biologic species in the ocean surface and an assumption that each species lived in the same temperature range as today. But what if species partly adapt to temperature change on such long timescales, so they don't need to migrate as far? In such case, CLIMAP underestimates glacial-interglacial temperature change. In addition, Dorothy Peteet, then a graduate student at New York University, noted that pollen data indicated that LGM cooling at low latitudes was twice as large as produced by CLIMAP SSTs; also LGM snowlines on low latitude mountains descended twice as far as implied by CLIMAP SSTs.[8] Thus, based also on the fact that Earth had to be in energy balance during the LGM, it was concluded only that the LGM implied a climate sensitivity of 2.5-5°C for doubled CO_2, but it was near the upper end of that range if the suspicions described here were correct.[9] This paleo evidence for high climate sensitivity was neglected by IPCC for decades, in part because of continuing uncertainty in paleo global temperature change.

Forty years later, it is known that CLIMAP underestimated ice age cooling. First, Jessica Tierney *et al.*[10] showed that there are now enough chemical proxies for LGM SSTs that the biologic species can be omitted in a global analysis; the non-biologic SST proxies yield cooling of 6.1°C for the period 23-19 kyr ago and 7.0°C ± 1.0°C (2σ) for the period of maximum cooling (21-18 kyr ago).[11] Second, Alan Seltzer *et al.*[12] used the temperature-dependent abundance of noble gases in groundwater deposited during the LGM to find cooling of 5.8°C ± 0.6°C (2σ) on land between 45°S and 35°N, which we show[1] is consistent with the global cooling found by Tierney *et al*. These paleoclimate data yield a doubled CO_2 equilibrium climate sensitivity of 4.8°C ± 1.2°C (2σ); 2σ uncertainty is the 95% confidence range. IPCC's best estimate of equilibrium climate sensitivity, 3°C for doubled CO_2, is excluded with greater than 99% confidence.[13]

Fig. 1. Earth's albedo (reflectivity, in percent), seasonality removed[14,15]



2. Modern Observations

<u>Earth's albedo (reflectivity) change</u>. The most striking modern climate observation is the change of Earth's albedo, i.e., the fraction of sunlight incident on Earth that is reflected back to space (Fig. 1). We described this darkening of Earth (as seen from space) as a BFD[16] because an albedo reduction of 0.5% is a global average increase of absorbed solar radiation of 1.7 W/m^2. The 0.5% albedo decrease is the average in the last few years relative to the first 10 years of satellite data. That is a conservative estimate, because the albedo was decreasing during the first decade of measurements. A linear fit to the data (Fig. 1) yields an albedo decrease of 0.58%, which is a 1.97 W/m^2 increase of absorbed solar radiation. Such a large increase of absorbed energy – half the climate forcing caused by doubled CO_2 – is sure to cause global warming; however, to quantify the implications, we must know how much of this extra incoming energy is climate forcing and how much is climate feedback. Feedback-related darkening of Earth is expected, in part because the planetary surface becomes darker as the area covered by ice decreases. Also, most climate models predict an amplifying cloud feedback, i.e., cloud albedo will decrease as Earth warms, mainly as a result of decreased cloud cover on a hotter planet.

Most of the increase of absorbed solar energy must be due to cloud feedback, based on the small magnitude of other potential contributions. Surface darkening is mainly due to reduced sea ice cover, which is easily identified in satellite measurements of Earth's radiation balance; sea ice change in the past 25 years contributes about 0.15 W/m^2 to the global increase of absorbed solar energy.[2] Darkening is also caused by increasing GHGs, mainly by the water vapor feedback (increase of atmospheric water vapor as global temperature increases) because water vapor has relatively strong absorption bands at red and near-infrared wavelengths. However, the magnitude of the water vapor feedback in the last 25 years is only of the order of 0.1 W/m^2.[17,15,18,19]

We conclude that most of the nearly 2 W/m^2 increase of solar radiation absorbed by Earth must be due to aerosol and cloud changes, but how much is aerosol forcing and how much is cloud feedback? Aerosol forcing occurs in two ways: (1) the direct effect of aerosol changes on Earth's albedo, and (2) an indirect effect of aerosols as they alter cloud cover and cloud brightness via the role of aerosols as condensation nuclei for cloud drops, i.e., as a mechanism for cloud formation. Satellite and in situ measurements indicate that global aerosols have decreased during the past 25 years, with decreases from Europe and the United States, and especially from China beginning in about 2005, although increases were still occurring in some places, especially India.

IPCC estimates that aerosol forcing became weaker (less negative, thus adding to warming) by a few tenths of a W/m^2, implying that the cloud feedback is ~1.5 W/m^2. We have suggested that reduction of aerosols from ships may have affected global aerosol forcing as much as 0.5 W/m^2 (Forster *et al*.[20] estimate ~0.1 W/m^2), which would make the cloud feedback closer to 1 W/m^2. More specifics of the aerosol forcing are included in our Appendix 1. The conclusion is that the cloud feedback in the last 25 years is in the range 1-1.5 W/m^2, and thus most of the observed ~2 W/m^2 increase of absorbed solar radiation in the past 25 years is cloud feedback.

<u>Implications for climate sensitivity</u>. Large cloud feedback implies that climate sensitivity is high, near the upper end of the range that Charney estimated. That conclusion and physical insight can be obtained from the feedback "gain" concept,[9] where the gain for any given feedback is the portion of the equilibrium global temperature change provided by that feedback. Although the gain concept has not caught on in the broad climate research community, it is consistent with other approaches and it is valuable in the present case because it illuminates the physics when there are multiple simultaneous feedbacks.

Gain analysis is summarized in the Appendix. Here we boil it down to a single equation for the equilibrium global warming for doubled atmospheric CO_2:

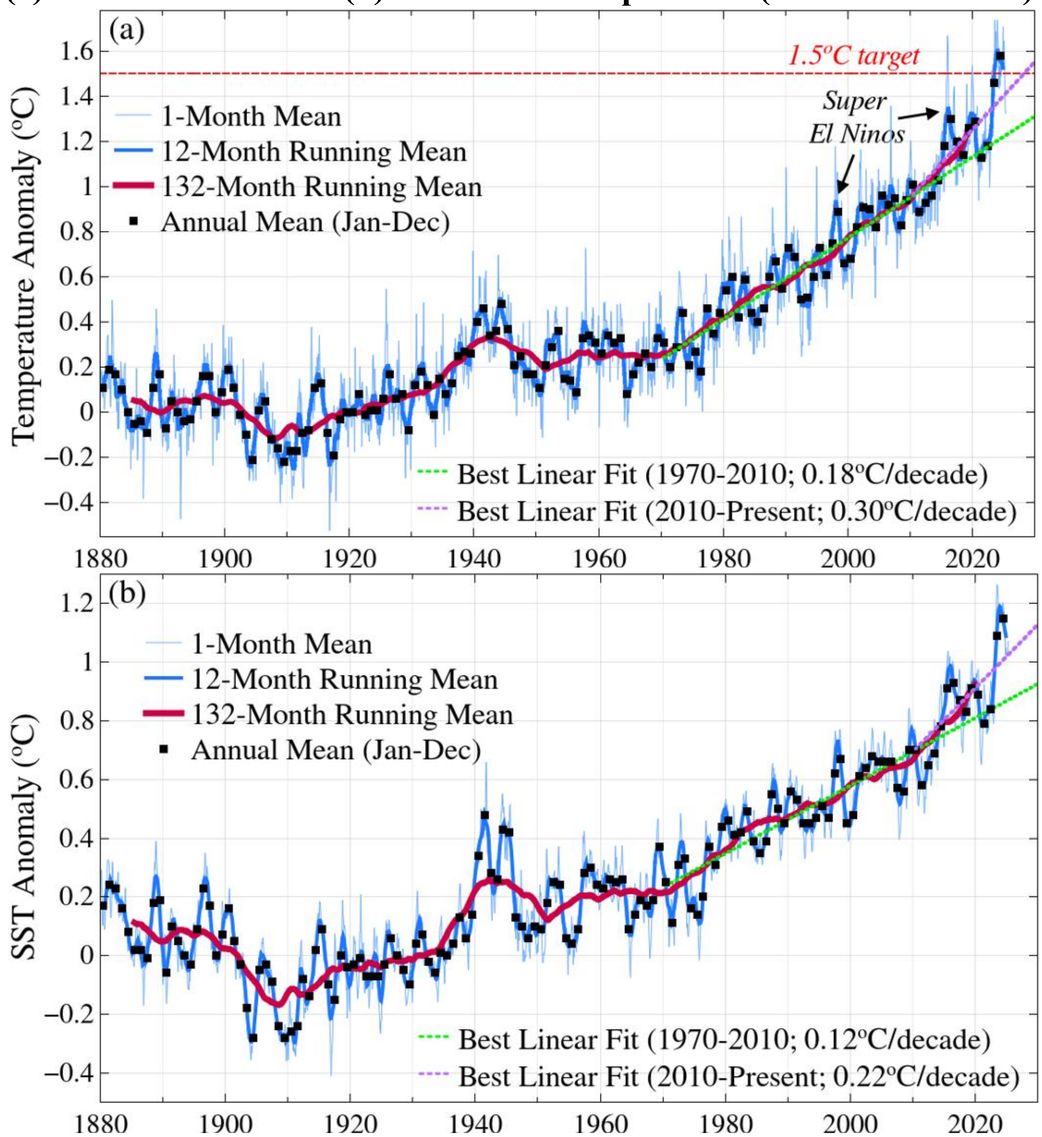
$$\Delta T_{eq} = 1.2°C/(1 - g) \qquad (1)$$

If there are no feedbacks, the gain (g) is zero and the direct CO_2 forcing of 4 W/m^2 for doubled CO_2 yields 1.2°C global warming. However, the real world has a powerful amplifying feedback (increasing water vapor as the planet warms) and a moderate amplifying feedback (decreasing surface albedo as the planet warms). Together these two feedbacks have a gain g ~0.5, and thus ΔT_{eq} = 2.4°C. As the only feedbacks, they provide an equivalent forcing of ~4 W/m^2, matching the CO_2 forcing and doubling the response from 1.2°C to 2.4°C.[21]

Now let's consider the case of strong cloud feedback (g_{cl} = 0.25), which yields total g = 0.75 (water vapor + sea ice + clouds) and equilibrium climate sensitivity ΔT_{eq} = 4.8°C (equation 1). The increase of sensitivity from 2.4°C to 4.8°C does not mean that clouds are causing half of the total warming. Multiple amplifying feedbacks boost each other, e.g., cloud feedback causes the water vapor feedback to increase. The equivalent forcing of each feedback is in proportion to its gain. Thus, for doubled CO_2, the direct CO_2 forcing is 4 W/m^2, the water vapor + sea ice equivalent forcing is 8 W/m^2, and the cloud equivalent forcing is 4 W/m^2. The 16 W/m^2 total forcing yields 4.8°C equilibrium warming. Cloud feedback is thus providing one-quarter of the total forcing, equal to the direct CO_2 forcing, and one-quarter of the warming.

Now let's consider the past 25 years. The GHG forcing increased ~1 W/m^2 in that period (Fig. 15 of Paper 2), but total human-made climate forcing is probably larger because of decreasing aerosols. The equivalent "forcing" from cloud feedback is of the order of +1 W/m^2 in the past 25 years based on Earth's darkening (Fig. 1), as discussed above, although quantitative analysis must also account for effects of the cloud changes on thermal emission to space, as discussed in Appendix A2. This large cloud feedback is similar in magnitude to the GHG forcing, implying that climate sensitivity is closer to 4.8°C (g_{cl} = 0.25) than to 2.4°C (g_{cl} = 0) or 3°C (g_{cl} = 0.1).

Fig. 2. (a) Global surface and (b) sea surface temperature (base = 1880-1920)[22,23,24,25]

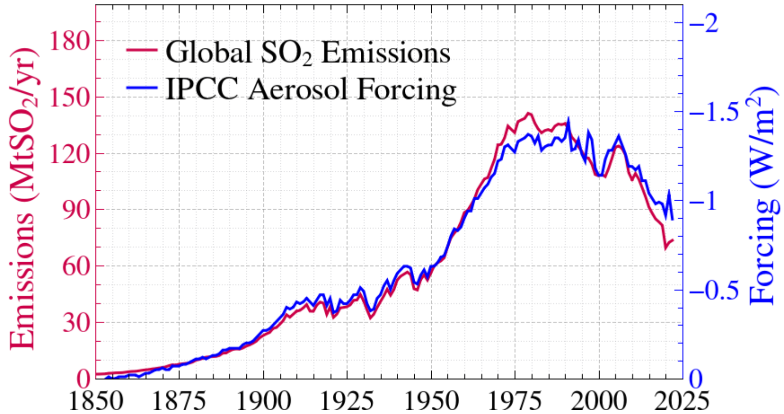


3. Global Climate Models (GCMs)

GCMs are essential for interpretation of ongoing climate change and projection of future climate. There is no known case in Earth's history when the GHG climate forcing increased at a rate approaching the speed of the present human-made change. Even the CO_2 increase during the iconic PETM (Paleocene Eocene Thermal Maximum)[26] event was an order of magnitude slower than the human-made change. Future human-made climate change is uncharted territory.

GCM modeling can be a consuming activity. Our small planetary research group at the NASA Goddard Institute for Space Studies, e.g., had to almost abandon planetary research in the late 1970s for the sake of focusing on development of a global climate model of our own planet, as described in chapters 14 and 17 of *Sophie's Planet*, which are included in 10 draft chapters. Such exclusive focus on GCM modeling can lead to mistakes, as one of us (JEH) showed by jumping to the conclusion that an instability in our then-GCM at large values of CO_2 was the beginning of "runaway" global warming.[27] In fact, a broader perspective shows that a (Venus-like) runaway greenhouse effect cannot occur on Earth – because of Earth's huge global ocean – in less than billions of years (see Chapter 10 in the 10 draft chapters of Sophie's Planet).

Figure 3. Global SO_2 Emissions and IPCC/Forster *et al*. Aerosol Forcing[28]



GCM modeling focuses on the past century for reason: the goal of interpreting ongoing climate change and projecting future change. Observed global surface temperature change (Fig. 2a) and sea surface temperature change (Fig. 2b) warrant comment. High temperature in 1940-45 is in part an artifact of inhomogeneous ocean data during World War II (see appendix, Young People's Burden),[29] although there was an El Nino then and the Arctic was unusually warm. Also, no Antarctic weather station existed until late in the 1950s. Thus, data since the middle of the 20th century are more reliable than earlier data. Temperature change in 1850-1970 has understandable relation to the major climate forcings, GHGs and aerosols, as discussed in Appendix A3, but we focus here on the major issue of climate sensitivity and its relation to aerosol climate forcing.

A crucial period begins in 1970, when temperature began rising rapidly at ~0.18°C per decade. GHG forcing after 1970 was high, averaging ~0.45 W/m^2 per decade (Fig. 15 of Paper 2).[2] The temperature inflection point at 1970 is easy to understand because GHG forcing had reached a high level and aerosol forcing stopped increasing (Fig. 3), or at least its growth slowed markedly.

IPCC's best estimate for aerosol forcing (Fig. 3) is flat (unchanging) in 1970-2005, as a moderate decline of SO_2 emissions is compensated by increase of other aerosols. However, this constant aerosol forcing in 1970-2005 is unrealistic. Global aerosol emissions may have been flat, but emissions spread out more over the globe into developing countries and over the ocean. Indirect aerosol forcing is nonlinear, as aerosols emitted into heavily polluted air have little effect on clouds. Global modeling of aerosol forcing supports our suspicion that aerosol forcing actually increased during 1970-2005. For example, the two alternative models of Bauer *et al*.[30] (the more recent one including aerosol microphysics and gas phase chemistry) yield aerosol forcing that becomes stronger by 0.5-1 W/m^2 during the period 1970-2005 (Fig. 13, Paper 2).[2]

We explore implications of alternative aerosol forcings with a transparent, readily duplicated, approach. We use a "response function," the global temperature change for a standard forcing, to achieve a simple calculation of global temperature response to any climate forcing scenario.[2] Results closely match those of GCMs, but without unforced variability generated by atmosphere/ocean dynamics. The response function allows calculation of global temperature change for alternative climate forcing scenarios and alternative climate sensitivities.

The upshot of the climate simulations is: the observed global warming rate after 1970 can be matched with the IPCC aerosol forcing and climate sensitivity near 3°C (for doubled CO_2), but if aerosol forcing actually became stronger by 0.5 W/m^2 during 1970-2005, the climate sensitivity required to match observed global temperature is about 4.5°C. This result is readily understood: aerosol forcing change by −0.5 W/m^2 in 1970-2005 reduces the net (GHG + aerosol) forcing by almost one-third. Aerosol forcing change of −1 W/m^2 would require climate sensitivity near 6°C.

The full period, 1850-2025. Ambiguity in interpretation of the 1970-2005 period occurs because there is one constraint (observed global warming) and two unknowns (climate sensitivity and aerosol forcing change). That ambiguity also exists for 1850-2025, but the longer period provides additional insight. The case with climate sensitivity 3°C for doubled CO_2 and IPCC aerosol forcing does not readily achieve the recent 1.6°C global temperature level nor produce a global temperature jump of 0.4°C in the past few years. These shortcomings led to consternation in the climate research community that "something is wrong;" Schmidt[31] concluded that no combination of known mechanisms can explain observed global warming.

We disagree. The problem that IPCC has gotten itself into results in part from their excessive dependence on GCMs. Independent information – from paleoclimate and modern climate observations – shows with greater than 99% confidence that climate sensitivity is substantially higher than IPCC's best estimate. Once that is realized, it follows that IPCC also underestimated the strength of the aerosol forcing. With realistic climate sensitivity and aerosol forcing, there is no big mystery in recent global temperature change.

It is unsurprising that, for decades, most GCMs yielded climate sensitivity near 3°C for doubled CO_2, given the simple treatment of cloud physics in early GCMs, which, e.g., did not model cloud microphysics. GCM "beauty contests" that occur with the major IPCC reports tend to force a choice of cloud and aerosol models such that the GCMs yield realistic global warming in the past century. Once the choices of cloud modeling and aerosol forcing are set, this tends to make it difficult, or at least slow, to change either of them. Further development of the GCMs is then like changing the direction of a barge in a sea of molasses.

4. Summary: seeing the forest for the trees

Climate change depends on climate sensitivity and the strength of the forcing that drives change. Of the main sources of information – paleoclimate, modern observations, and GCMs – the first two are least ambiguous, but all three are consistent with climate sensitivity 4.5°C ± 1°C (2σ, 95% confidence) for doubled CO_2, which excludes IPCC's best estimate of climate sensitivity (3°C for doubled CO_2). IPCC also underestimates the strength of the aerosol climate forcing.

In the real world, climate sensitivity and aerosol forcing are independent, but they are joined at the hip in climate assessments that focus on the ability of GCMs to reproduce observed global warming. It is reasonable that climate modelers use observed global temperature change to help constrain the GCMs. The complication is that there are two major unknowns: climate sensitivity (mainly because the cloud feedback is uncertain) and the climate forcing (because the aerosol forcing is unmeasured), while there is only one hard constraint (the observed global warming rate). As a result, if climate sensitivity turns out to be high, greater aerosol forcing (i.e., greater aerosol cooling) is required for agreement with observed global temperature.

Independent sources of information, from paleoclimate on climate sensitivity and from satellite data on the cloud feedback, show that, in reality, climate sensitivity is high. Thus, aerosol forcing (and the aerosol cooling effect) have also been underestimated by IPCC. In addition, aerosol cooling has weakened since 2005, mainly because of reduced emissions from China and ships.

Those are the principal conclusions of our two papers ("Global warming in the pipeline" and "Global warming has accelerated") that address the fundamental issues of climate sensitivity and the human-made climate forcing. These issues are a large part of the "forest" of climate science.

Within that part of the climate science forest, many uncertainties remain. For example, how does the cloud feedback work? Tselioudis *et al*.[32] suggest that it is mainly from a poleward shifting of climate zones, as opposed to an effect of global warming on cloud microphysics. It is important to understand such issues, as the correct explanation may affect continuing climate change.

Another example: we argue that reduction of ship aerosols has more effect on global temperature than reduction of aerosols from China, even if the mass reduction of Chinese emissions is larger. Ships emissions are more efficient in affecting clouds because they are injected into relatively pristine ocean air at altitudes that have greatest effect on cloud formation. Observed global distributions of albedo and temperature change are consistent with a large role for ship emissions, although alternative explanations for those distributions may be possible. Temporal changes of albedo and temperature also match better with the 2015 and 2020 changes of ship emissions, rather than with the decrease of emissions from China, which began in 2006.

The forest of climate science includes other areas – besides climate sensitivity and climate forcings – that are also important. For example, potential impacts of climate change include shutdown of the overturning ocean circulation and large sea level rise,[33] which may be the most important of all the climate issues. These climate impacts depend on the magnitude of global warming, which is a reason to first consider climate sensitivity and climate forcings.

5. Communication of the climate situation

The Secretary General of the United Nations asserts that the goal of keeping global warming under 1.5°C is still reachable if nations increase their ambitions for future emission reductions. In reality, the 1.5°C goal has long been deader than a doornail. This raises the question: are we, the scientific community, doing an adequate job of informing governments and the public?

In our present communication, we criticize IPCC's science analysis. However, despite the flaws that we note, IPCC is doing what they were asked to do. Their reports contain authoritative information painstakingly written by experts in their fields. The reports are useful references, but governments and the public need more to properly inform their decision-making.

When we presented our most recent paper,[2] responses in the media by other scientists consisted of ad hominem attacks on the first author, e.g., "Hansen exaggerates," "Hansen makes lots of mistakes," "Hansen is not collegial," and comments that our analysis was "too simple" and our conclusions were "outside the mainstream." None of the comments addressed the climate science in our paper, which we have summarized here. Yet these few articles in the media, appearing on the day that our paper came out, were sufficient to shut down public discussion of our paper.

Issues raised in our paper are relevant to understanding the course of climate change. So, how is it that a small (all-male)[34] clique is able to control the climate research conversation? At least they spurred the first author to move back to Columbia University (see End of an Era),[35] where it may be possible to work more with young people, and hopefully communicate more effectively.

We are grateful to the people who continue to support CSAS. This year, our long-time friend, colleague, and senior scientist Makiko Sato retired. Her unique combination of scientific and artistic abilities is irreplaceable; her dedication as our climate data expert will be sorely missed. The consolation is that we can now support two entry-level positions at Columbia University: one specializing in climate data and one as program coordinator for CSAS, a position that has been vacant for the past several years. Gen Z is coming of age; we hope to find new graduates ready to realize their potential to help shape the future.

6. International Court of Justice

Let's end on a bright, scintillating, note: the recent ruling by the International Court of Justice in the Hague on global climate change, which deserves far more attention than it has received. It is the first time that the ICJ has taken up climate change. In a unanimous decision the Court determined that:

> ". . . customary international law sets forth obligations for States to ensure the protection of the climate system and other parts of the environment from anthropogenic greenhouse gas emissions. These obligations include the following:
>
> (a) States have a duty to prevent significant harm to the environment by acting with due diligence and to use all means at their disposal to prevent activities carried out within their jurisdiction or control from causing significant harm to the climate system and other parts of the environment, in accordance with their common but differentiated responsibilities and respective capabilities;
>
> (b) States have a duty to co-operate with each other in good faith to prevent significant harm to the climate system and other parts of the environment, which requires sustained and continuous forms of co-operation by States when taking measures to prevent such harm. . . ."

Philippe Sands, legal scholar, author, and leader in getting the case before the Court and arguing the case, was thrilled that the Court's ruling was even stronger than he had hoped. Over time, this ruling surely will be used extensively and affect courts globally, even within the United States, despite the fact that such ICJ decisions are advisory.

My long-time attorney Dan Galpern and I went to the Hague during the trial, even though we knew that I would not be able to deliver testimony before the Court that I had prepared at the request of the government of Mauritius (because that government had since been turned out of office in an election). Instead, I presented my testimony[36] in a press briefing organized with the help of Eelco Rohling, which included discussions by Rohling and his Utrecht University colleagues Appy Sluijs (Prof. of Paleo-oceanography) and Ingrid Robeyns (Prof. of Ethics of Institutions) and by Dan Galpern.

Philippe Sands notes that at least some of the judges read my testimony, it was mentioned during their proceedings, and Sands believes that it affected their ruling. I mention this because CSAS donors have been supporting our legal efforts for many years. The legal approach can be slow and often ends in disappointment, but it is an essential part of actions to preserve climate, and thus we want to emphasize the successes.

Fireflies. Lastly, I note that Lightning bugs are making a comeback this summer. We will miss the displays we saw on our farm in Bucks County, but I will see if there are any in Riverside Park. Longterm, insects[37] will depend on whether insecticides and herbicides are controlled.

Appendix

A1. Aerosol forcing. The magnitude of the direct aerosol forcing, relative to preindustrial conditions, is estimated to be only −0.22 W/m^2,[20] thus the change of the direct aerosol forcing over the past 25 years, at most, is only of the order of +0.1 W/m^2, with the aerosol forcing becoming weaker (less negative), thus adding to the warming forcing of GHGs. The indirect aerosol forcing is unmeasured, so its change is more uncertain. Recent update[20] of IPCC's estimated total (direct + indirect) aerosol forcing change during the past 25 years is +0.36 W/m^2; this includes a contribution of the order of 0.1 W/m^2 from a reduction of ship aerosols. We have suggested that the aerosol forcing change is larger, with reduction of ship aerosols providing a forcing as much as +0.5 W/m^2.[1,2]

A2. Cloud feedback: Implications for climate sensitivity. If there are no climate feedbacks, the equilibrium global temperature change in response to doubled CO_2 climate forcing (4 W/m^2) is

$$\Delta T_{eq} = 1.2°C \text{ (no feedbacks).} \qquad (A1)$$

Water vapor and sea ice feedbacks are reasonably well understood and modeled. Together they produce a feedback gain $g = g_{wv} + g_{si} = \sim 0.5$ and an equilibrium global warming

$$\Delta T_{eq} = 1.2°C/(1 - g) = 2.4°C \text{ (water vapor and sea ice feedbacks, zero cloud feedback).} \qquad (A2)$$

This doubling of the no-feedback response implies that the feedback (water vapor + sea ice) supplies an equivalent forcing of 4 W/m^2.

Now consider a strong cloud feedback ($g_{cl} = 0.25$): the gain is $g = g_{wv} + g_{si} + g_{cl} = 0.75$ and the equilibrium global warming is

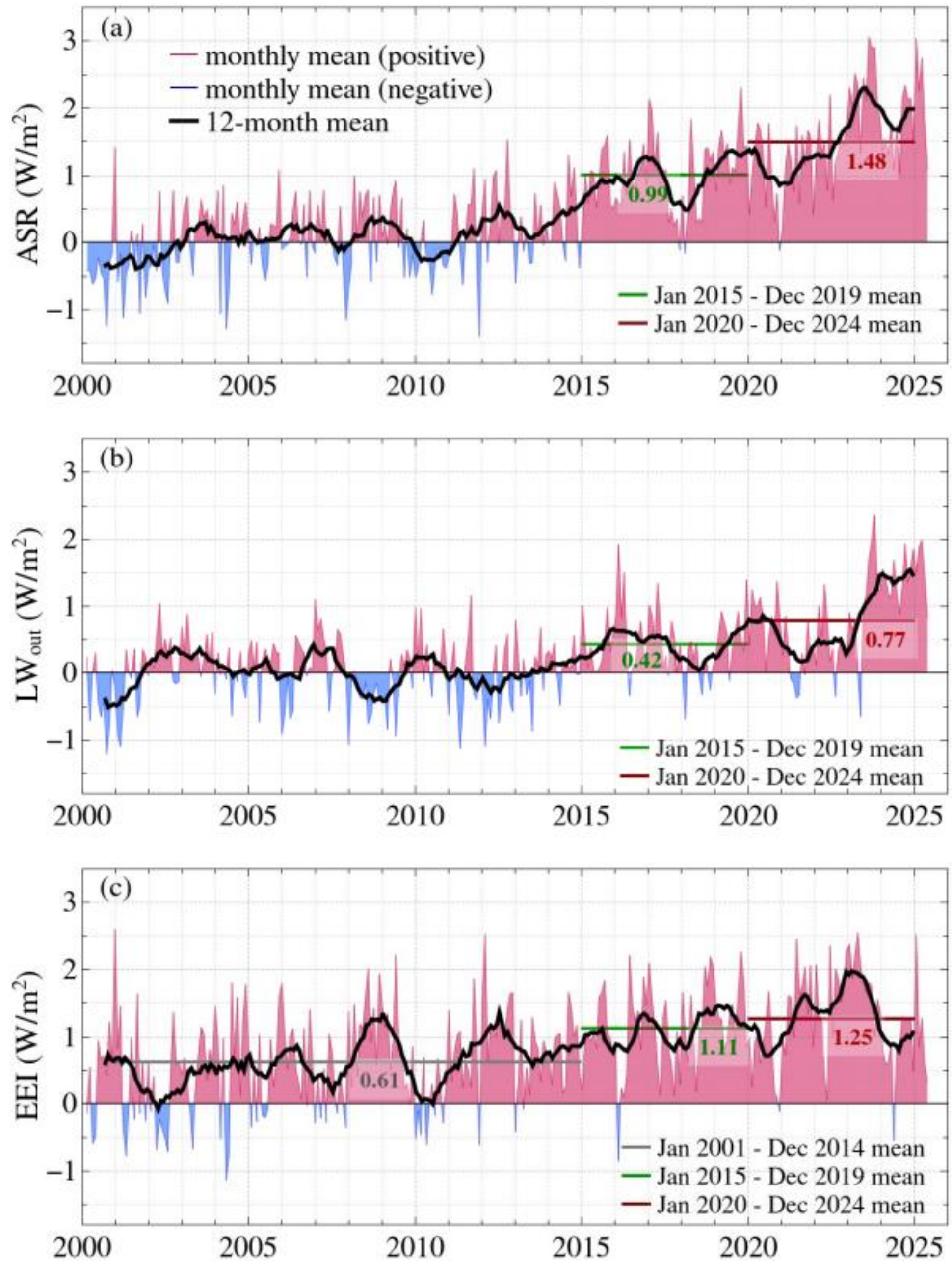
$$\Delta T_{eq} = 1.2°C/(1 - g) = 4.8°C \text{ (water vapor, sea ice, + strong cloud feedback).} \qquad (A3)$$

In comparing zero cloud feedback and strong cloud feedback, the increase of warming from 2.4°C to 4.8°C does not mean cloud feedback is responsible for half of the 4.8°C equilibrium warming. The cloud feedback increases global warming, which causes the water vapor and sea ice feedbacks to also increase. The 4.8°C equilibrium warming consists of 1.2°C direct warming from doubled CO_2 and 3.6°C from feedbacks. Individual feedback warmings are in proportion to their gains, thus 1.2°C is from cloud feedback and 2.4°C from water vapor + sea ice feedback.[38]

Now we can appreciate implication of the increase of absorbed solar energy due to cloud change. GHG climate forcing increased ~1 W/m^2 in the past 25 years (see Fig. 15 of reference 2). At the same time, the "equivalent forcing"[39] of the cloud feedback increased 1-1.5 W/m^2, which would imply climate sensitivity in the range from 4.8°C to higher values. However, there are two reasons that this comparison exaggerates the implied climate sensitivity. First, the climate forcing increase in the last 25 years exceeds +1 W/m^2 due to decreasing aerosols. Second, "equivalent forcing" of the cloud change includes the immediate effect of cloud changes on Earth's thermal emission to space, in addition to the effect of the cloud changes on Earth's albedo.

Let's search for the cloud-caused increase of thermal emission to space (LW_{OUT}). The global data for LW_{OUT} (Fig. A1, middle panel) shows no clear evidence of an increase associated with the reduction of aerosols from China (which began ~2006); there is an increase of LW_{OUT} after 2015, but it is not notably larger than the global increase that must occur due to observed acceleration

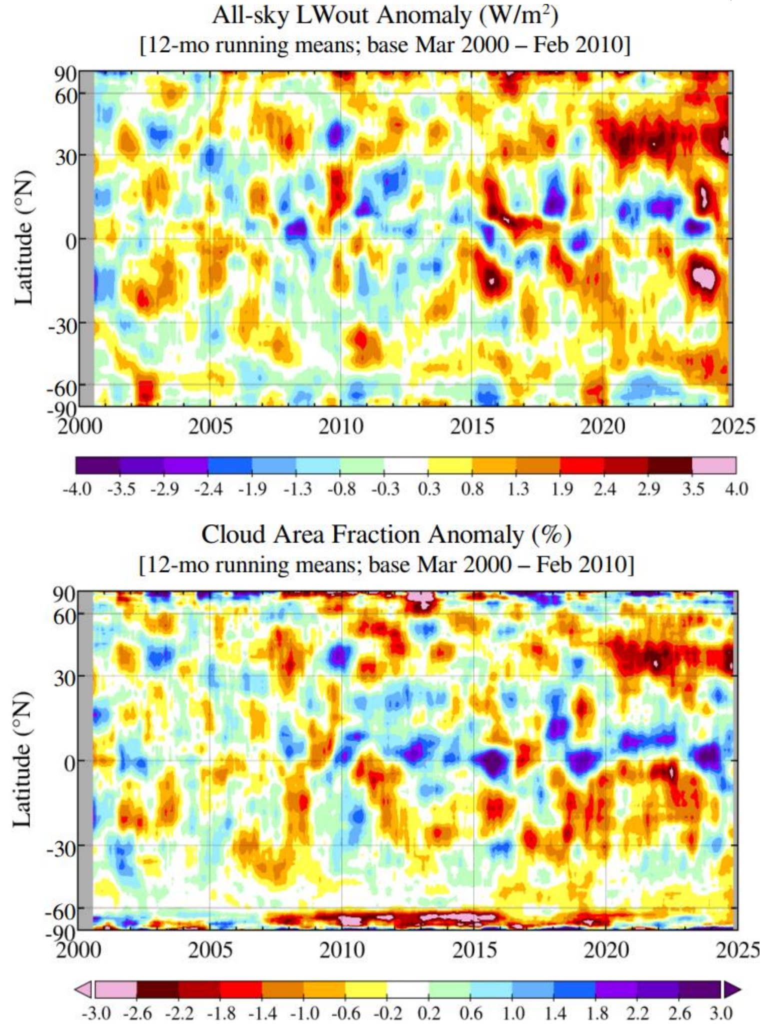
Fig. A1. Earth's radiation balance



of global warming in that period. Additional insight is provided by changes of LW_{OUT} in the 30-50°N region where the 2020 ship aerosol reduction is expected to have its largest effect. Fig. A2 reveals sudden changes in that region in 2020, with cloud cover decreasing and LW_{OUT} increasing. These data support our interpretation that ship aerosols have substantial effect and suggest that the immediate cloud reduction contributes to the global increase of LW_{OUT}, but the contribution of cloud change to global increased LW_{OUT} is at most a few tenths of 1 W/m^2.

The upshot is that changes of Earth's radiation balance in the past 25 years, including changing albedo and changing LW_{OUT}, are inconsistent with zero or small cloud feedback (g_{cl} = 0-0.1), instead favoring large cloud feedback (g_{cl} = 0.2-0.25), which corresponds to climate sensitivity 4.0-4.8°C for doubled CO_2. Based on this, and on the estimates from paleoclimate and temperature change since 1850, we infer climate sensitivity 4.5°C ± 1.0°C (2σ).[2,40]

Fig. A2. Zonal-mean LWOUT and cloud area anomalies (CERES data)



A3. Global temperature prior to 1970. GHG forcing has likely increased monotonically because of the long lifetimes of the major GHGs, but the balance between aerosols and GHGs has oscillated. Our best indicator of aerosol forcing is global emission of SO_2 (Fig. 3), which is known from knowledge of the sulfur content of fossil fuels (SO_2 gas resulting from fossil fuel burning is a precursor of the dominant human-made aerosols, sulfates). Fossil fuel use increased exponentially during the industrial revolution until 1910, so even though GHGs were beginning to accumulate in the air, cooling by aerosols likely exceeded warming by GHGs. During 1910-45, due to world wars and weak economies, the growth of fossil fuel use slowed. Because aerosol forcing depends on current emissions, while the GHG forcing grows as the long-lived gases accumulate, the GHG warming tended to win out during 1910-45, as aerosol emissions were almost stagnant. During 1945-1970, exponential growth of emissions resumed, which probably accounts for a near balance of GHG warming and aerosol cooling during 1945-70.

GCM research groups work hard to improve their models between each successive IPCC report, submitting model runs to the accompanying Climate Model Intercomparison Projects (CMIPs). CMIPs are often described as beauty contests, as each group hopes that their model compares well with the real world. A principal model test is whether it can simulate the rate of global warming during the period of rapid climate change, i.e., since 1970. For decades, most climate models had simple cloud models or just "parameterizations" of cloud effects, such that clouds had only a small effect on simulated climate sensitivity. The common climate model sensitivity was in or near the range 2.5-3.5°C for doubled CO_2 (see, e.g., the most recent IPCC report).[5] A GCM with such climate sensitivity can match observed global warming since 1970 with little or no contribution from changing aerosol forcing. Although cloud modeling in GCMs remained primitive for decades, recent research[41,42,43] provides insights consistent with clouds contributing substantially to high climate sensitivity, as described in Sidebar 4 of Paper 2.[2]

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[4] Charney's climate sensitivity refers to an idealistic case in which the large ice sheets remain fixed and other "slow" feedbacks such as permafrost melt are also neglected.

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[14] Calculated based on CERES (Clouds and Earth's Radiant Energy System) https://ceres-tool.larc.nasa.gov/ord-tool/jsp/EBAFTOA421Selection.jsp through May 2025. CERES observations of Earth's radiation balance are described in reference 2 and the next reference below. Absolute calibration of Earth's energy balance is based on measurement of decadal changes in the ocean's heat content, primarily based on data from the fleet of deep-diving Argo floats. Albedo change is relative to the first 10 years of measurements, March 2000 through February 2010.

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