How We Know that Global Warming is Accelerating and that the Goal of the Paris Agreement is Dead

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The drive for global temperature change is Earth's energy imbalance (EEI), the difference between the energy Earth receives from the Sun and energy Earth reflects and radiates back to space. We have good measurement of EEI today based on precise satellite data for change of reflected and emitted radiation calibrated by decadal ocean heat content change measured by deep-diving Argo floats. Interpretation of global temperature change and prediction of future temperature requires knowledge of the principal forcings that now affect EEI: human-made greenhouse gases (GHGs) and atmospheric aerosols (fine airborne particles). Aerosol climate forcing is not being measured, but information on aerosol forcing can be extracted from an ongoing "great inadvertent aerosol experiment" as a result of discrete changes in International Maritime Organization (IMO) regulations on the sulfur content of ship fuels. These limited assessment tools are threatened by the absence of firm plans to continue direct EEI observations. A shortcoming of our climate science is failure to communicate well what is known from existing data. Global warming in the pipeline and emissions in the pipeline assure that the goal of the Paris Agreement – to keep global warming well below 2°C – is already dead, if policy is constrained only to emission reductions plus uncertain and unproven CO_2 removal methods.

Delayed response of climate makes human-made climate change a grave threat, especially for young people. Governments will not make required changes to energy policies based on theoretical threats – there must be sufficient empirical evidence of harm to force action. Thus, delayed response makes it difficult to avoid near-term, growing, climate impacts, but it does not prevent achievement of policies that will lead to a hospitable climate with a bright future for young people. Time is running short, however, and effective actions at this point require a good understanding of ongoing climate change and the responsible mechanisms.

The proximate cause of ongoing global warming is Earth's energy imbalance (EEI). Earth is now absorbing more energy incoming from the Sun than the planet is sending back to space as reflected solar light and emitted thermal (heat) radiation. As long as that imbalance is positive – more energy coming in than going out – Earth will continue to get hotter. Factors that alter Earth's energy balance are called climate forcings. There are two large human-made climate forcings: changes of atmospheric greenhouse gases (GHGs) and changes of aerosols. GHGs reduce heat radiation to space; thus, an increase of GHGs causes a positive energy imbalance, more energy coming in than going out, which causes warming. Aerosols reflect sunlight to space, which is a negative contribution to EEI that causes cooling.

Greenhouse Gases. GHGs are accurately measured and their total climate forcing can be calculated with an error less than or about 10%. GHG forcing increase since 1750 is about 4.1 W/m^2; as shown in Fig. 1 of our *Pipeline* paper,[1] our calculation agrees well with that of the most recent IPCC report.[2] We can even calculate the annual change of the GHG climate forcing to high precision. In our graph of this annual change (Fig. 1), we show the five-year running mean because the large amount of "noise" in the annual mean tends to hide the trends that we wish to understand.[3] The 2022 point in the graph is a 1-year mean and the 2021 point is a 3-year mean, so these are provisional and will change as later data are added.

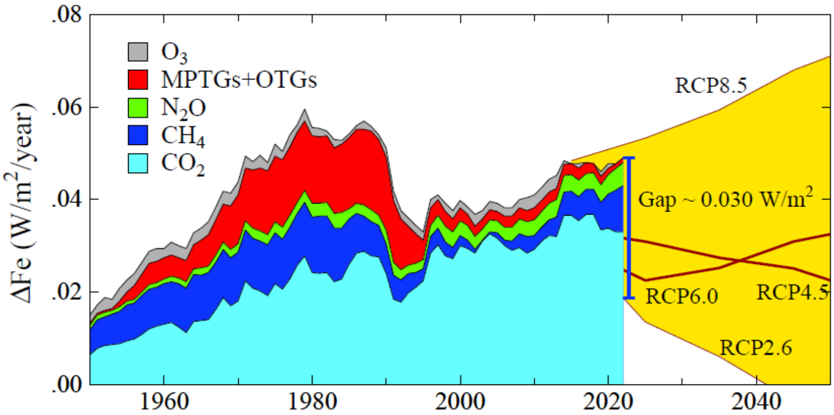

Fig. 1. Annual growth of climate forcing by GHGs[4] including the part of O_3 forcing not included in the CH_4 forcing.[1] MPTG and OTG are Montreal Protocol and Other Trace Gases.

The integration (sum) of the annual GHG forcing increments (Fig. 1) yields the total GHG climate forcing, which is about 4.1 W/m^2 for the interval 1750-present, as noted above. This is a huge climate forcing,[5] equivalent to that for doubled CO_2 (2×CO_2). Global warming up to 2022 is only about 1.2°C, much less than the equilibrium warming for either IPCC's best estimate for 2×CO_2 climate sensitivity (3°C) or our estimate in *Pipeline* (4.8°C ± 1.2°C). There are two reasons why the present warming is small: First, present warming is only a fraction of the equilibrium warming, because of the ocean's great thermal inertia. Even after 100 years the expected response to a forcing is only about 60 percent (Fig.2); most of the GHG forcing was added in just the past 50 years. Second, the net human-made forcing is reduced by the (negative) human-made aerosol forcing of 1-2 W/m^2 to a net of perhaps ~2.5 W/m^2. The aerosol forcing is unmeasured, but we conclude in *Pipeline* that aerosol cooling has been underestimated by IPCC and updates of IPCC.[6]

The ocean's thermal inertia, in one sense, is beneficial in damping the climate response to human-made forcings, but it is a practical problem because it allows large potential future climate change to build up before the public notices much climate change. In the paper *Young People's Burden*,[7] we argued that it was just conceivable to avoid irreversible consequences (e.g., large sea level rise) via rapid phasedown of fossil fuel emissions, improved forestry and agricultural practices, and reduction of methane (CH_4) and other trace gases. That situation has changed because of the world's continued failure to act. Fig. 1 summarizes the situation, but below we will provide more damning evidence via measured EEI and, in the final section, via examination of IPCC assumptions.

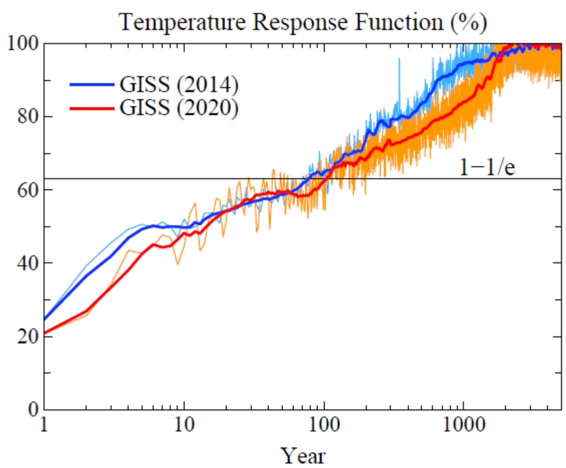

Fig. 2. Percent of equilibrium global surface temperature response to instant CO_2 doubling.[8]

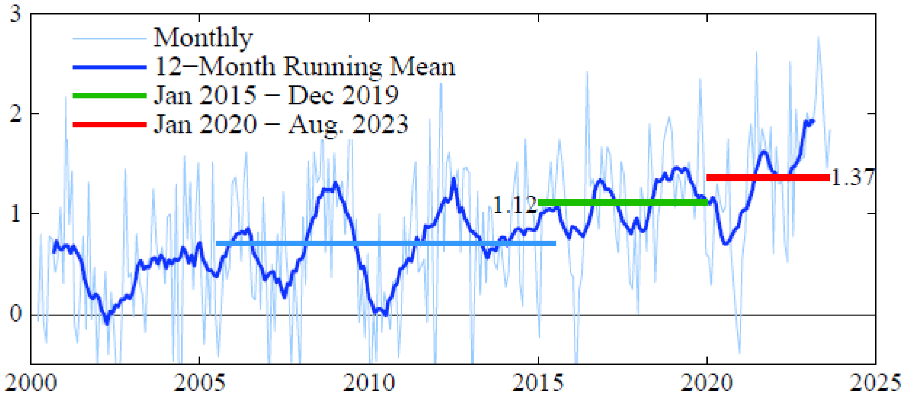

Fig. 3. 12-month running-mean of Earth's energy imbalance (EEI) from CERES satellite data[9] normalized to 0.71 W/m^2 mean for July 2005 – June 2015 (blue bar) from in situ data.[10]

Fig. 1 includes a scenario for growth of GHG climate forcing, RCP2.6, which was defined in relation to the 2015 Paris Agreement goal to keep global warming "well below 2°C."[11] In RCP2.6, the GHG climate forcing growth rate is defined to provide a >66% chance that global warming will remain <2°C.[12] However, an enormous gap has opened between the real world and RCP2.6. Annual increase of the GHG forcing is now ~ 0.05 W/m^2 per year (half a watt per decade), while RCP2.6 is at 0.02 W/m^2 per year today, decreasing to zero in less than 20 years. This incredible scenario was supposed to be achieved largely via a vast array of biomass-burning powerplants that capture and sequester CO_2, an implausible scheme that would be nature-ravaging and food-security-threatening.[13] There are other issues with the Integrated Assessment Models (IAMs) that IPCC uses to define future GHG amounts and future climate, which we will address. However, we first illustrate hard physical constraints that Earth's energy imbalance provides for interpretation of the current climate situation.

Earth's energy imbalance (EEI). A decade ago, we estimated that EEI during the first decade of this century was +0.6 W/m^2 averaged over the planet, which is about 16 times greater than humanity's total energy use[14] and equal to the energy of 400,000 Hiroshima atomic bombs per day.[15] About 90 percent of this excess energy is going into the ocean,[10] where it slowly warms the ocean and melts ice. That was the magnitude of energy imbalance that was addressed in *Young People's Burden*, when it still seemed conceivable that emissions could decline and realistic drawdown of atmospheric CO_2 could help restore energy balance and stabilize climate. However, since then, fossil fuel emissions have not declined; instead, they have grown, and Earth's energy imbalance has approximately doubled (Fig. 3).

Cumulative ocean heat content presents only limited indication of accelerating ocean heat uptake. Fig. 4, from Li *et al.*,[16] is representative of literature on ocean heat content change on decadal time scales.[17,6,18,19] It shows an increasing rate of ocean heat uptake, but with large uncertainty bars because of sampling limitations, changing observing systems, and calibration issues. Since 2006 there has been a good distribution of several thousand Argo floats that sample well the upper 2000 m of the world ocean, at least for latitudes 60N to 60S. Even in this "golden" era of Argo data, ocean heat data must be averaged over at least a decade to approach the accuracy desired to interpret global climate change (0.1-0.2 W/m^2 for Earth's energy imbalance). Fortunately, the era of Argo data overlaps with satellite data for Earth's emitted thermal and reflected solar radiation.[20] Decadal-mean ocean-heat-content-change calibrates satellite-observed radiation change, and the satellite data then provide finer spatial and temporal resolution of Earth's energy balance. Crucially, the satellites measure emitted thermal radiation and reflected solar radiation individually. As we will show, this specific knowledge opens a window into understanding of the current climate situation.

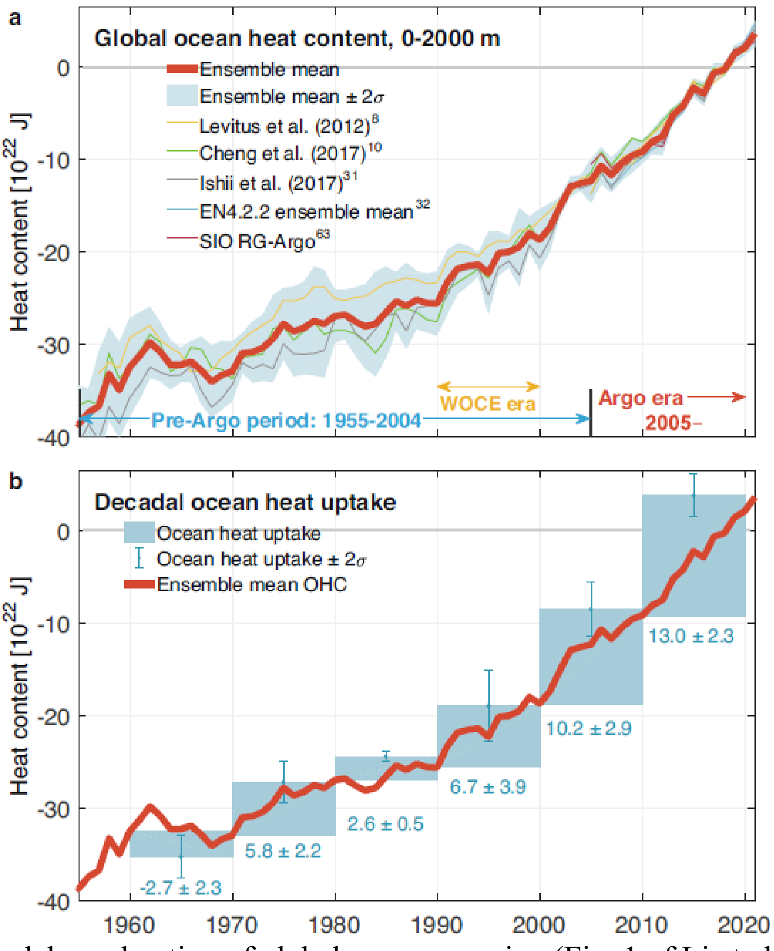

Fig. 4. Multi-decadal acceleration of global ocean warming (Fig. 1 of Li et al., 2023). The error bars in part b are two standard deviations.

Fig. 5 shows that an increase of absorbed solar energy caused the increase of EEI in the past decade, with the increase of absorbed solar energy beginning in about 2015. This information has implications for the mechanisms of accelerated global warming. An increase of GHGs – either human-made or water vapor from the Hunga Tonga volcanic eruption in early 2022 – would operate by decreasing outgoing thermal radiation. Instead, there is a large increase of absorbed solar radiation (Fig. 5) and a moderate increase of outgoing thermal radiation (Fig. 6). The known mechanisms that could produce a change of this nature are (1) change of solar irradiance, and/or (2) change of atmospheric aerosols/clouds.

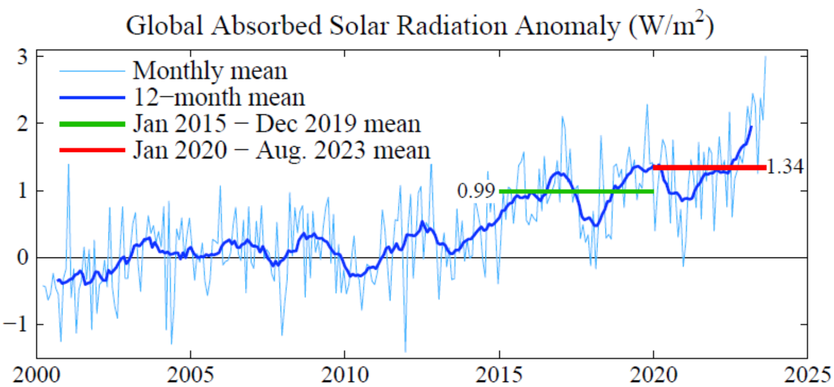

Fig. 5. Global absorbed solar radiation (W/m^2) relative to mean of the first 120 months of CERES data. CERES data are available at https://ceres.larc.nasa.gov/data/

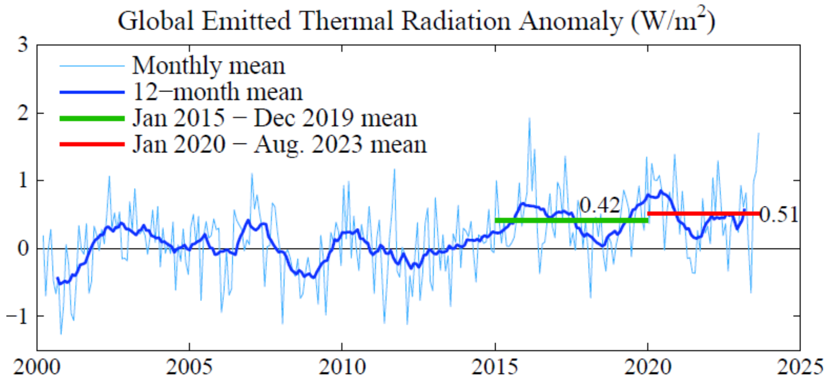

Fig. 6. Global emitted thermal radiation (W/m^2) relative to mean of the first 120 months of CERES data. CERES data are available at https://ceres.larc.nasa.gov/data/

Change of solar irradiance is ruled out because solar irradiance was in its declining phase for a few years after 2015 (Fig. 7). Also, the amplitude of solar forcing from solar minimum to maximum is only ~0.2 W/m^2, at least five times less than the observed increase of absorbed solar energy. We conclude that the likely cause of the large change in Earth's energy balance is a reduction in reflected solar radiation by aerosols and clouds. Aerosols by themselves can be only a small fraction of the change, as the entire human-made aerosol forcing is only of the order of –0.5 W/m^2,[2] so any global change would be no more than of the order of 0.1 W/m^2. On the other hand, rather small changes of clouds can have a large impact on EEI. [We conclude in *Pipeline* that cloud changes are the feedback that increases what would otherwise be a planetary sensitivity of 2.4°C for 2×CO_2 to the empirically-derived real-world sensitivity of 4.8°C for 2×CO_2. Similarly, it does not take much cloud change to produce the ~1 W/m^2 increase of absorbed solar radiation (Fig. 5).]

How can we evaluate whether decreased (less negative) aerosol-cloud forcing is the cause of the global increase of absorbed solar radiation? A great opportunity, as described in *Pipeline*, is the inadvertent experiment caused by restrictions on the sulfur content of ship fuels, which were imposed in 2015 and strengthened in 2020. Satellite data for Earth's radiation budget show that absorption of solar radiation increased about 3 W/m^2 in the regions of heavy ship traffic in the North Pacific and North Atlantic Oceans after imposition of the restrictions. This regional 3 W/m^2 forcing is greater than obtained in some aerosol-cloud modeling,[21] but the modeling is difficult and uncertainties are large.[2] Analyses of aerosol physics based on this marvelous, inadvertent, aerosol experiment, surely, are only just beginning.

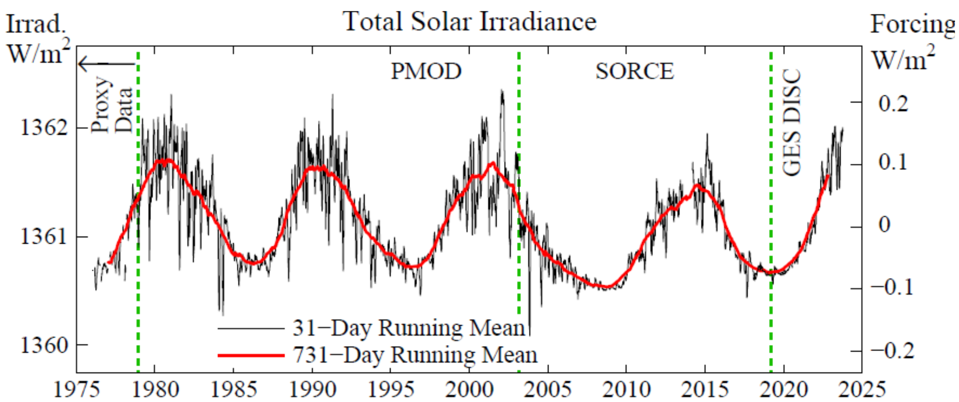

Fig. 7. Solar irradiance and climate forcing, the latter being 0.175 ×irradiance change, where 0.175 = (1 – Earth's albedo)/4, where Earth's albedo = 0.3. Data sources: Physikalisch Meteorologisches Observatorium, Davos, University of Colorado Solar Radiation and Climate Experiment and Total Irradiance Monitor on International Space Station (GES DISC)

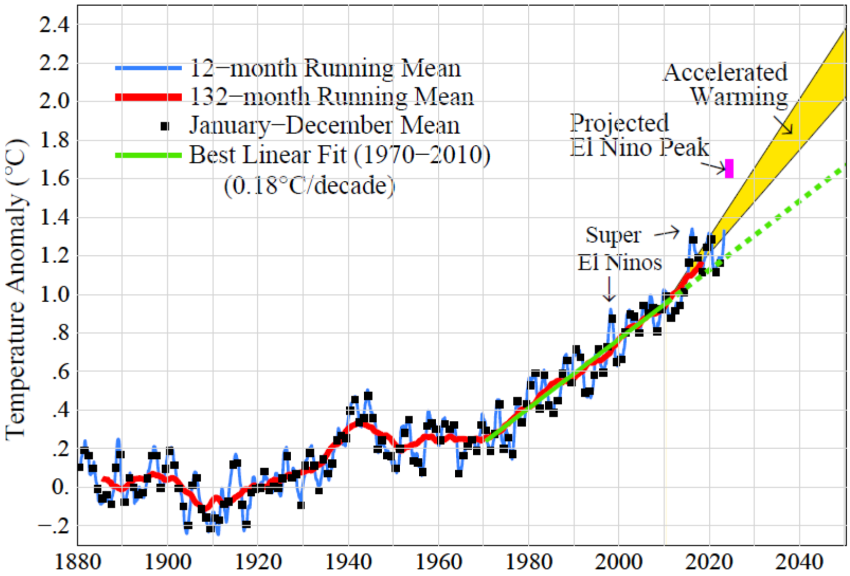

Fig. 8. Global temperature relative to 1880-1920 based on the GISS analysis.[22,23]

Is increased absorption of solar radiation (Fig. 5) a BFD? It was asserted by one of us during the webinar[24] on the *Pipeline* paper that observed increase of solar radiation absorbed by Earth is a BFD (a big deal). That assertion is based on our interpretation that the increased absorption of solar energy by Earth results from reduced aerosol pollution, i.e., it is the first payment in our Faustian bargain[25] in which we offset much of GHG warming via aerosol cooling. Implications of an increase of absorbed incoming energy of the magnitude in Fig. 5 are staggering. The increased absorption of solar energy is a climate forcing, equivalent to the forcing from increasing GHGs. Increased climate forcing of 1 W/m^2, given current global CO_2 amount of about 420 ppm, is equivalent to increasing atmospheric CO_2 to about 500 ppm. The observed increase of solar energy by 1.34 W/m^2 since 2020 (Fig. 5) is equivalent to increasing CO_2 to about 525 ppm.

Here is another illuminating impact of this increased absorption of solar radiation. As a conservative estimate let's take 1 W/m^2 as the increase of absorbed solar radiation. Also, as a round, conservative, estimate, let's take equilibrium climate sensitivity (ECS) as 4°C for 2×CO_2. How much added warming will this cause, over and above the 0.18°C per decade warming from GHGs? Fig. 2 tells us the answer. Within less than a decade, we must expect 0.4×0.25×4°C = 0.4°C additional warming.[26] Given global warming of 0.95C in 2010, the warming by 2030 will be about 0.95°C + 2×0.18°C + 0.4°C = 1.71°C. Global warming of 2°C will be reached by the late 2030s, i.e., within about 15 years. The added climate forcing – presumed to be our first Faustian payment – is, indeed, a BFD.

Note that absorbed solar radiation (Fig. 5) shows no indication of an increase in the period 2005-2015 when sulfur emissions in China are thought to have decreased rapidly. The likely explanation is that the air there was still polluted with aerosols even after sulfate reductions; also, remaining sulfates were not negligible. Aerosols in pristine marine environments are expected to have a much larger effect on clouds.

High priority observations. The scientific method dictates that we monitor GHG and aerosol climate forcings. However, given that we are not monitoring the aerosol forcing,[27] it is essential to continue satellite radiation budget and Argo float measurements. Radiation budget observations have been a priority of NASA for the past two decades, but the workhorse satellites are nearing the end of their lifetimes.[24] It is important that the measurements continue with comparable data quality. This will surely require investment in small satellite technology. Despite many competing proposals for research, development, and space deployment, this topic surely deserves high priority. The Argo measurements need to be expanded, especially into the polar regions where some of the most important climate change is occurring

Given that access to space is becoming easier, we might ask whether the private sector could support the measurements. That is a steep ask, but during the Trump Administration – when it appeared that support for climate research in the U.S. government may be severely curtailed – philanthropists picked up some of the slack. We made a proposal (Aerosols, the Ocean and Ice: Impacts on Future Climate and Sea Level) [28] including Chinese colleagues with the emphasis on satellite aerosol observations and analysis of Eemian climate change, when sea level rose several meters in less than a century while global temperature was little warmer than today. The major cost, for satellite observations, would have been covered entirely by the Chinese government. Although Schmidt Futures did not provide a debriefing when the proposal was not selected, our impression was that they had a preference for GCM studies, similar to the IPCC emphasis on GCMs as opposed to a more equal balance of paleoclimate, GCMs and analysis of ongoing Earth observations. Independent of proposals, it seems to us that scientists in the West should make a special effort to continue collaborations with colleagues in the East, as successful actions to address climate change will surely depend upon much improved East-West cooperation.

Climate sensitivity. Out of time, so will need to address this in a later communication, but we can point out a couple of nuggets of information. One is Fig. 9, which was shown by George Tselioudis in our webinar, based on figures in published papers of Zelinka *et al.*[29] and Jiang *et al.*[30] Fig. 9 compares low cloud feedbacks in CMIP5 and CMIP6 GCMs, those being the models used in support of the last two major IPCC reports. Higher sensitivity in the later models is mainly a result of stronger, amplifying, cloud feedbacks. The question is: which models are more realistic. A hint is provided by the colored diagrams on the right. The first of those shows cloud cover generated by the average of the models with high climate sensitivity (average ECS about 5°C for $2\times CO_2$), the second shows the same for low ECS models, and the third is observations. High ECS models look a lot more like observations; it is not just a matter of a numerical value. The low ECS models have the seasonal variation of cloud cover entirely wrong at high latitudes, where the cloud feedbacks are large, while the high ECS models capture the correct seasonality. This doesn't prove that the high ECS models are "correct," but it is a strong point in their favor.

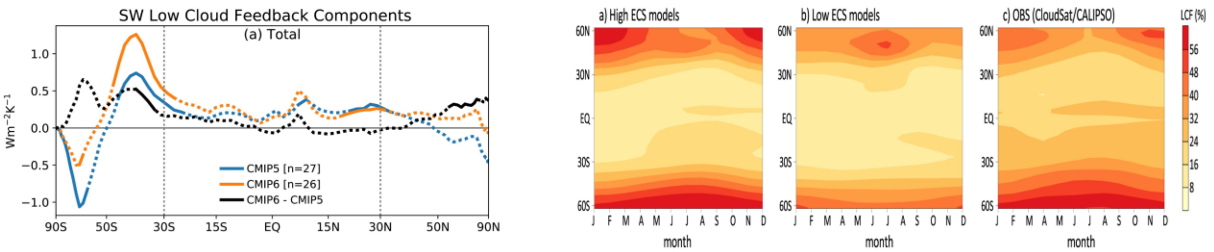

Fig. 9. See text.

Jim Zachos, despite his modesty, is probably the world's leading authority on long-term climate change and especially on knowledge obtained from ocean sediment cores, so we were glad to receive the recent note from him:

"FYI...there are some new studies using independent proxies to quantify deepsea T over the Cenozoic, for example, based on clumped isotopes (or Mg/Ca), all suggesting warmer T than previous reconstructions based solely on benthic d18O. The discrepancies involve multiple factors most notably a pH effect. This is not surprising...something I've always suspected. Nevertheless, these studies conclude that the 1:1 scaling of deepsea d18O with GMST is still valid in part because of an increasing seasonal bias in deep water formation as GMST increases, which balances polar amplification. The bottom line is that these higher T estimates will yield a higher ECS for the early Eocene, in the range of 5°C."

The Cenozoic climate analysis is probably the best part of the *Pipeline* paper, but the discussions of the paper have largely ignored it. We will summarize that part of the paper in a later communication. Further discussion of the difficulties with the Integrated Assessment Models (IAMs) that IPCC relies on will also have to wait for a later communication.

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[1] Hansen J, Sato M, Simons L *et al*. Global warming in the pipeline. *Oxford Open Clim Chan* 2023;3(1):kgad008, doi.org/10.1093/oxfclm/kgad008
[2] IPCC. *Climate Change 2021: The Physical Science Basis [Masson-Delmotte V, Zhai P, Pirani A et al. (eds)].* Cambridge and New York: Cambridge University Press, 2021
[3] The noise is due mainly to fluctuations in the annual growth of atmospheric CO_2. Fossil fuel emissions of CO_2 change only slowly, a few percent per year, but growth of CO_2 in the air is erratic. Averaged over several years the growth of CO_2 in the air averages only about 55% of the fossil fuel emissions, because CO_2 "sinks" – the ocean, soil and biosphere – take up a large portion of the CO_2 emissions. These sinks fluctuate from year-to-year mainly because of climate variability, e.g., droughts can turn a CO_2 sink into a temporary source.
[4] Hansen J, Sato M. Greenhouse gas growth rates. *Proc Natl Acad Sci 2004;* **101**:16109-14
[5] A small part of this 4.1 W/m^2 is "slow feedback," i.e., it is engendered by climate change. The convention is to use the precisely observed GHG amounts in calculating climate change. Separate studies including the carbon and nitrogen cycles are needed to estimate the portions of CO_2, CH_4, and N_2O change from feedbacks. Most of the observed increases are traced to human-made sources.
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[8] The graph shows results for two specific climate models of the Goddard Institute for Space Studies defined in the Pipeline paper, but the approximate 100-year e-folding time for surface temperature response is common to most global climate models.
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[13] Creutzig F, Erb KH, Haberl H *et al.* Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *GCB Bioemergy* 2021;**13**:510-5
[14] In 2022 global energy use was 600 EJ (Energy Institute). This converts to 0.0373 W/m^2 in 2022, so a planetary energy imbalance of 1 W/m^2 is about 27 times greater than world energy use.
[15] Hansen, J. TED talk in 2012
[16] Li Z, England MH, Groeskamp S. Recent acceleration in global ocean heat accumulation by mode and intermediate waters, *Nature Comm* 2023;**14**,https://doi.org/10.1038/s41467-023-42468-z
[17] von Schuckmann K, Cheng L, Palmer MD *et al.* Heat stored in the Earth system: where does the energy go?, *Earth System Science Data* 2020;**12**:2013-41

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[26] We estimate from Fig. 2 that the fraction of equilibrium response in a decade is about 0.4. Note that for short time scales the fractional response is proportional to the inverse of equilibrium climate sensitivity. Therefore, our estimated effect of the forcing implied by the sudden increase of absorbed solar radiation is nearly independent of climate sensitivity. The simple explanation is that the feedbacks causing high sensitivity do not come into play in response to the forcing, but rather in response to the induced warming, which is still small in the first decade after the forcing is introduced. See Hansen J, Russell G, Lacis A *et al.* Climate response times: dependence on climate sensitivity and ocean mixing. *Science* 1985;**229**:857-9
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