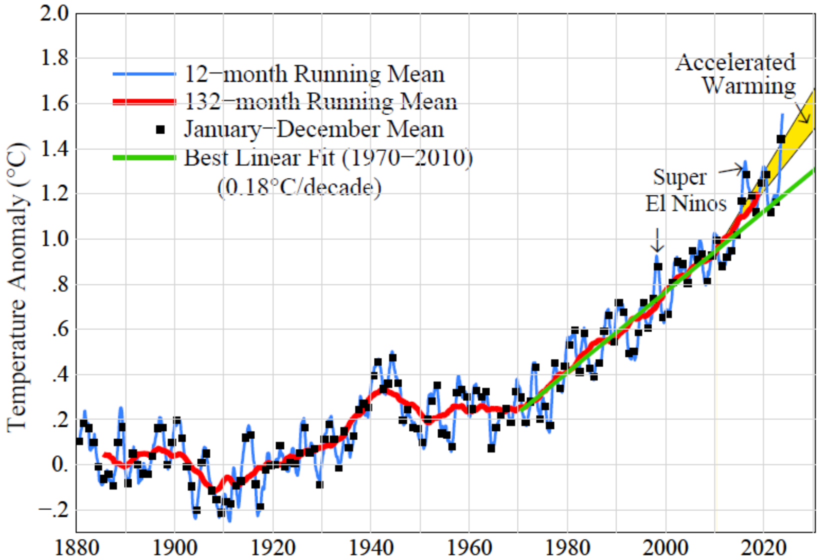

Fig. 1. Global temperature relative to 1880-1920 based on the GISS analysis.[1,2]

Comments on Global Warming Acceleration, Sulfur Emissions, Observations

16 May 2024

James Hansen, Pushker Kharecha, Makiko Sato

Global temperature (12-month mean) is still rising at 1.56°C relative to 1880-1920 in the GISS analysis through April (Fig. 1). [Robert Rohde reports that it is 1.65°C relative to 1850-1900 in the BerkeleyEarth analysis.[3]] Global temperature is likely to continue to rise a bit for at least a month, peak this summer, and then decline as the El Nino fades toward La Nina.

Acceleration of global warming is now hard to deny. The GISS 12-month temperature is now 0.36°C above the 0.18°C/decade trend line, which is 3.6 times the standard deviation (0.1°C). Confidence in global warming acceleration thus exceeds 99%, but we need to see how far temperature falls with the next La Nina before evaluating the post-2010 global warming rate.

Present extreme planetary energy imbalance will limit La Nina-driven temperature decline. Thus, El Nino/La Nina average global temperature likely is about 1.5°C, suggesting that, for all practical purposes, global temperature has already reached that milestone. Temperature is temporarily well above the 50-100 percent increase that we projected[4] (yellow region in Fig. 1) for the post-2010 warming rate. That projected increase is based on evidence that human-made aerosols and their cooling effect are in decline. In other words, we are beginning to realize the consequences of the Faustian bargain, in which humanity partly offset greenhouse gas warming with aerosol (particulate air pollution) cooling.

A recent comment in the social media that a decline of global temperature will signify that we are “back to normal” is right only if one considers accelerating global warming to be normal. However, we see no reason to believe[5] that the jump in 2023-24 global temperature indicates we are missing some fundamental climate physics – other than good aerosol physics.

The 2023-24 temperature jump is a result of strong warming trend over several years at middle latitudes combining with a switch at low latitudes in 2023 from a strong La Nina to a moderately strong El Nino, as shown by zonal-mean sea-surface temperatures (SSTs, Fig. 2). The maximum of the solar cycle in 2023-25 may add a bit to the appearance of a leap in 2023-24 temperature. When land measurements of surface air temperature are included to obtain zonal-mean global surface temperature change, the warming in the Northern Hemisphere becomes even more dramatic (Fig. 3).

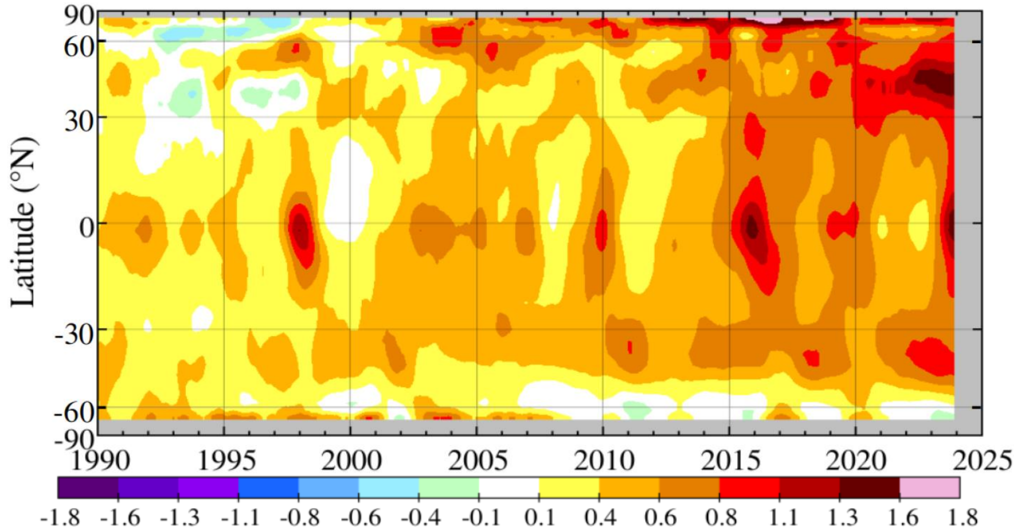

Fig. 2. Zonal-mean SST (12-month running-mean) relative to 1951-1980 base period.

We interpret acceleration of warming since 2010 to be a consequence of decreasing aerosols, with a significant contribution from reduction of ship aerosols due to the strict 2020 emission limit imposed by the IMO (International Maritime Organization). Another recent social media comment is that reduction of ship emissions is negligible compared to emission reductions by China. That comment misses the point. It is well known that ship emissions are a tiny part of total anthropogenic emissions and of emission changes, but ships emit into relatively pristine ocean air and the aerosol effect is nonlinear. The inadvertent experiment provided by the IMO emission limit is a great opportunity to improve understanding of aerosol and cloud physics.

An important issue concerns how much additional global warming lurks in our Faustian aerosol bargain. That depends on interpretation of ongoing change. Our preliminary analysis[6] suggests a ship aerosol forcing an order of magnitude (factor of ~10) greater than what follows from IPCC estimates. The 2021 IPCC report (AR6) pegs total aerosol forcing as 1.06 W/m^2 in 2019, with 0.22 direct aerosol forcing and 0.84 the indirect effect on clouds. A 2021 update[7] reduces the aerosol forcing to 0.98 W/m^2 (0.21 direct, 0.77 indirect). Based on this small aerosol forcing, Hausfather and Forster[8] obtain a forcing of 0.079 W/m^2 for 100% implementation of 2020 IMO[9] ship emission limits. Our estimate of a minimum of 0.5 W/m^2 for the aerosol forcing from shipping refers to the present (~80%) reduction of sulfates from ships. The difference with the Hausfather and Forster value is so large that it must be possible to resolve this issue within the next few years.

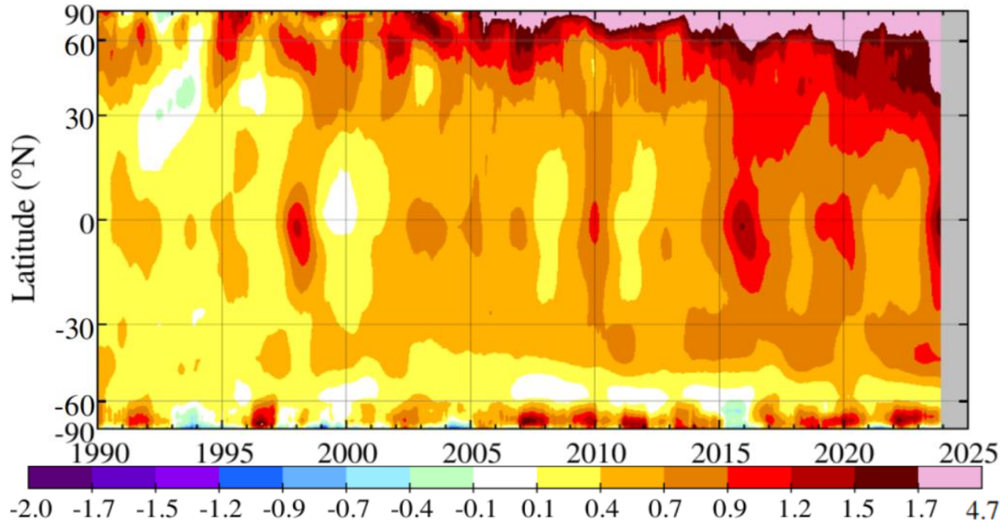

Fig. 3. Zonal-mean surface temperature (12-month running-mean) relative to 1951-1980.

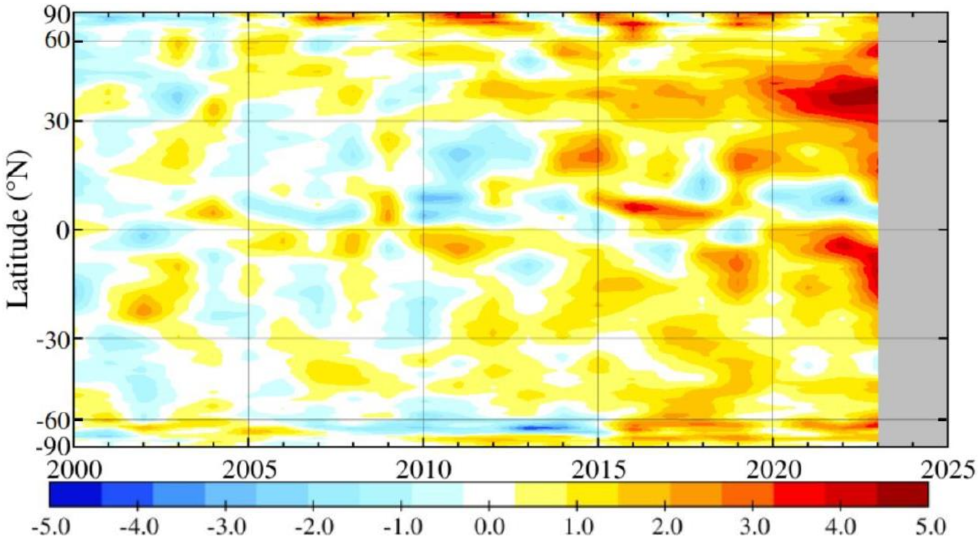

Fig. 4. Zonal-mean absorbed solar radiation (ASR) anomaly relative to mean of first 10 years.

Accurate evaluation of humanmade aerosol forcing has double importance because of implications for climate sensitivity, as we have discussed elsewhere.[4] If IPCC has underestimated aerosol forcing, they probably have also underestimated climate sensitivity.

Aerosol climate forcing is unmeasured[10] and difficult to estimate because (1) aerosol forcing operates mainly by altering clouds, (2) cloud changes also occur as a climate feedback that is poorly quantified, and (3) clouds have large natural variability. We obtain an indication of likely aerosol forcing from precise data for changes of Earth's absorbed solar radiation (ASR) and Earth's energy imbalance (EEI). Unbroken time series of ASR and EEI are available from March 2000 to the present from CERES (Clouds and Earth's Radiant Energy System) instruments[11] with calibration via precise measurement of changing ocean heat content over decades; the calibration depends on a global network of deep-diving Argo floats.[12]

With this indirect approach we use the temporal and spatial variations of measured quantities to glean information on unmeasured climate forcings. An example is the zonal-mean absorbed solar radiation (Fig. 4). The large anomaly of increased absorbed solar radiation at midlatitudes in the Northern Hemisphere is consistent with and a likely cause of the unusual warming rate there. The latitude location is consistent with the region of decreased shipping emissions. Increased ASR occurs over the North Atlantic,[4] as well as the North Pacific, the two regions where ship aerosols are dominant condensation nuclei.[13]

Part of the increased absorption of solar radiation could be related to reduced aerosols from China, as has been proposed by Hai Wang *et al*.[14] However, neither the temporal nor spatial distribution of aerosol changes from China are a good match with the changes of absorbed solar radiation. For example, according to Zhili Wang *et al*.[15] the reduction of sulfate aerosols from China was mainly in the period 2006-2014. Changes during that period cannot be the cause of the strong observed changes of absorbed solar radiation and zonal temperature in the period 2020-2024.[16] Thus, if the GCMs employed by IPCC are obtaining an acceleration of global warming, as noted in social media, they may be getting the right answer for the wrong reason. In other words, a GCM can obtain accelerated warming via a large reduction of aerosols from China, but it needs to be shown that the temporal and geographical response of absorbed solar radiation and temperature look like observations.

The same challenge applies to ship aerosols, even though qualitatively the observed changes of absorbed solar radiation and temperature seem to be consistent with expectations for ship emissions. Simulating the highly nonlinear effects of aerosols on clouds is challenging. Aerosol-cloud modeling is still developing, with the impact of ship aerosols varying among different models by an order of magnitude. That's why the IMO inadvertent experiment is so useful; it provides a chance to test and improve the models. Global measurements of aerosol and cloud properties also are needed and are being pursued, but these, too, are challenging and will not, by themselves, define the effect of aerosols on climate. It is crucial to also assure continuation of the CERES or CERES-like monitoring of Earth's radiation balance.

---

[1] Lenssen NJL, Schmidt GA, Hansen JE *et al.* Improvements in the GISTEMP uncertainty model, *J Geophys Res Atmos* **124(12)**, 6307-26, 2019

[2] Hansen J, Ruedy R, Sato M *et al.* Global surface temperature change. *Rev Geophys* **48**:RG4004, 2010

[3] Rohde R, tweet on 15 May 2024

[4] Hansen J, Sato M, Simons L *et al*. Global warming in the pipeline. *Oxford Open Clim Chan* **3(1)**, doi.org/10.1093/oxfclm/kgad008, 2023

[5] Dance S, Scientists fear shift as record ocean heat enter second year. Washington Post, 20 March 2024.

[6] Hansen, J, Kharecha P, Sato, M. Global warming acceleration, research and publication priorities, 14 Feb 2024

[7] Forster PM, Smith CJ, Walsh T *et al*. Indicators of global climate change 2022: annual update of large-scale indicators of the state of the climate system and human influence, *Earth Syst. Sci. Data* **15**, 2295-327, 2023

[8] Hausfather Z, Forster P. Analysis: How low-sulphur shipping rules are affecting global warming, *Carbon Brief*, 3 July 2023

[9] International Maritime Organization. IMO 2020 – cutting sulphur oxide emissions, lowers sulfur limit from 3.5% to 0.5%. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx 5/12/2022 last access

[10] Hansen J, Sato M, Ruedy R, Simons L. Global warming is accelerating. Why? Will we fly blind? 14 September 2023

[11] Loeb NG, Johnson GC, Thorsen, TJ *et al.* Satellite and ocean data reveal marked increase in Earth's heating rate. *Geophys Res Lett* 2021;**48**:e2021GL093047

[12] 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

[13] Jin Q, Grandey BS, Rothenberg D *et al.* Impacts on cloud radiative effects induced by coexisting aerosols converted from international shipping and maritime DMS emissions. *Atmos Chem Phys* **18**, 16793-808, 2018

[14] Wang H, Zheng XT, Cai W *et al.* Atmosphere teleconnections from abatement of China aerosol emissions exacerbate Northeast Pacific warm blob events. *Proc Natl Acad Sci*, doi.org/10.1073/pnas.2313797121, 2024

[15] Wang Z, Wang C, Yang S *et al.* Evaluation of surface solar radiation trends over China since the 1960s in the CMIP6 models and potential impact of aerosol emissions. *Atmos Res* **268**, 105991, 2022

[16] See the discussion of the climate response function in our Pipeline paper (reference 3 above).