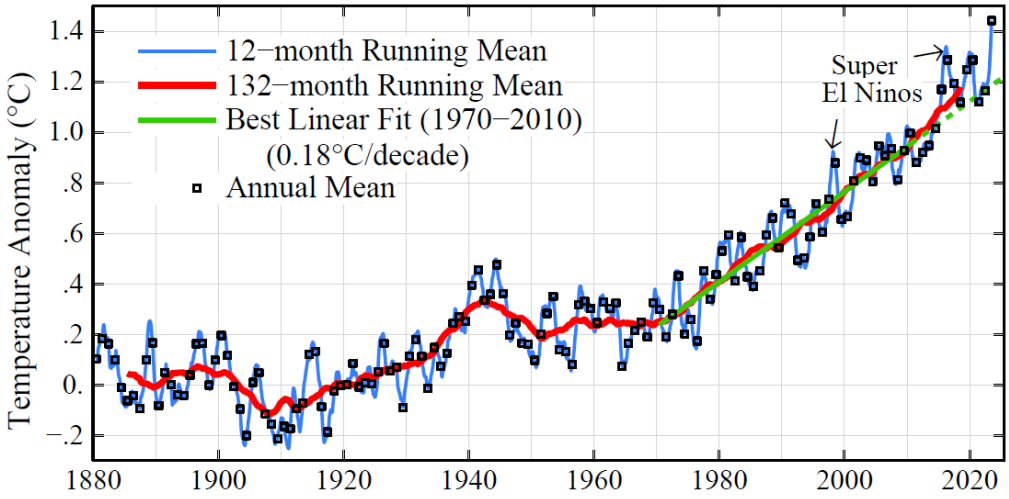

Fig. 1. Global temperature relative to 1880-1920 based on the GISS analysis.[1,2]

Global Warming Acceleration: Causes and Consequences

12 January 2024

James Hansen, Makiko Sato, Reto Ruedy

Abstract. Record global temperature in 2023 helps reveal acceleration of global warming on decadal time scales. The proximate cause of the acceleration is increase of Earth's energy imbalance, specifically a substantial darkening of the planet (decreased albedo) equivalent to a CO_2 increase of more than 100 ppm, although it is difficult to apportion the albedo change between aerosol forcing and cloud feedbacks because of limited global measurements. Large 2023 warming is consistent with key findings in *Global Warming in the Pipeline*:[3] reduced aerosol cooling and high climate sensitivity. We expect record monthly temperatures to continue into mid-2024 due to the present large planetary energy imbalance, with the 12-month running-mean global temperature reaching +1.6-1.7°C relative to 1880-1920 and falling to only +1.4 ± 0.1°C during the following La Nina. Considering the large planetary energy imbalance, it will be clear that the world is passing through the 1.5°C ceiling, and is headed much higher, unless steps are taken to affect Earth's energy imbalance.

Global temperature in the GISS analysis increased 0.28°C in 2023, from 1.16°C to 1.44°C (Fig. 1), the largest annual increase in the 144-year record. This annual rise is largely due to the ongoing tropical El Nino warming, but no prior El Nino engendered as much warming, which points to an additional drive for global warming acceleration. We have argued[3] that the imminent threat of human-made climate change is understated in IPCC[4] assessments, which are based predominately on global climate models (GCMs). We suggest that the IPCC best estimate for climate sensitivity (3°C for 2×CO_2 or 0. 75°C per W/m^2) is an underestimate, as we find real-world (paleoclimate) evidence for a sensitivity of 4.8°C ±1.2°C for 2×CO_2 (1.2°C per W/m^2). In addition, we suggest that IPCC underestimates (negative) aerosol climate forcing and global cooling by aerosols that partly counterbalances greenhouse gas (GHG) warming. These two errors compensate and allow GCMs with low sensitivity to match observed warming of the past century by using an unrealistically small aerosol effect. Compensation is not an accident; it is a result of overreliance on GCMs. With aerosol forcing unmeasured, it is natural for modelers to focus on an aerosol forcing that yields agreement with global warming of the past century. Some clarification will be possible in 2024.

Global surface temperature is well measured since about 1950,[5] but there are large interannual fluctuations of temperature that make it difficult to confirm a change in the rate of global warming until the change is large. Given that the El Nino/La Nina cycle is the main cause of interannual

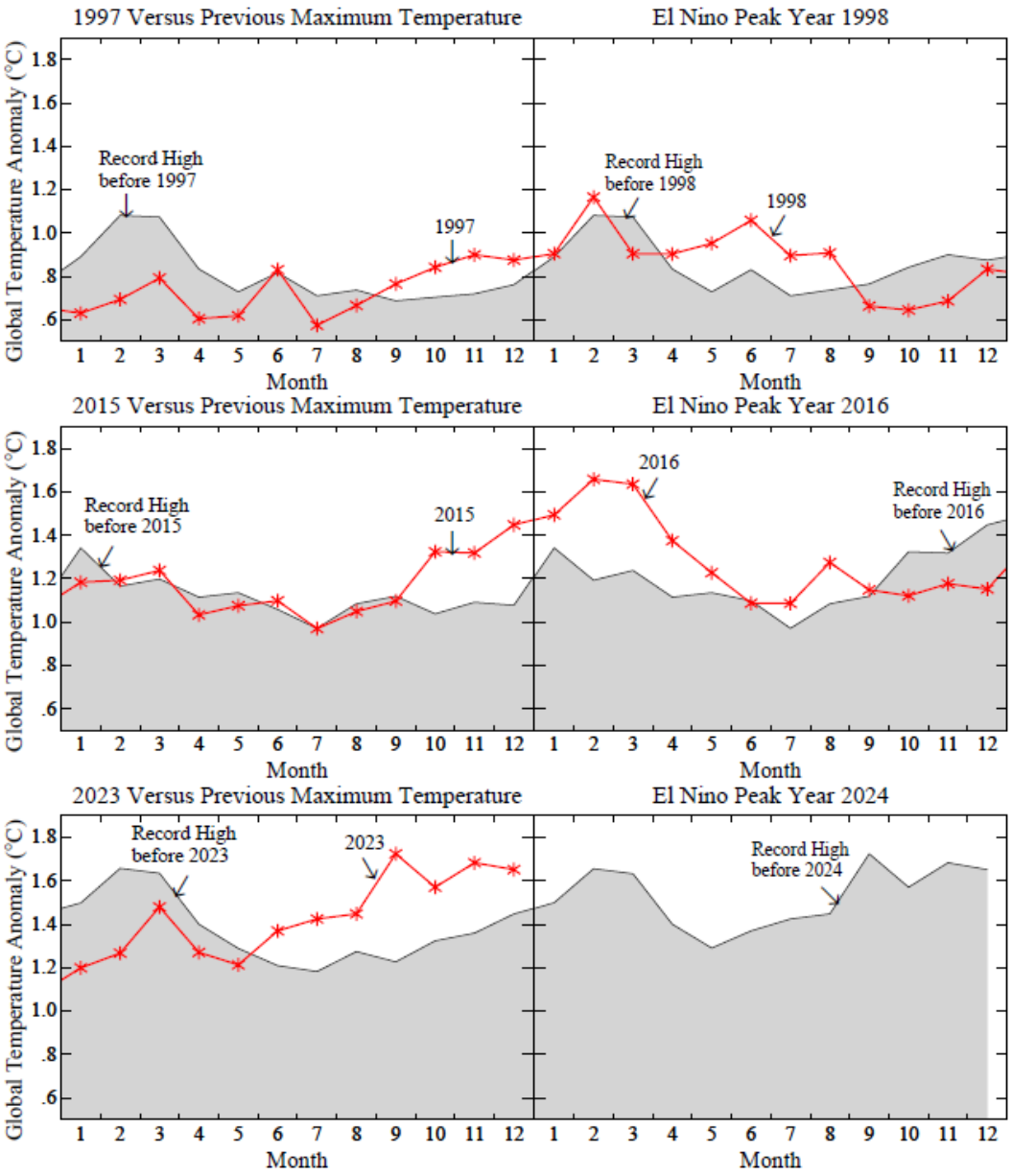

Fig. 2. Global temperature during El Nino origin years (left side) and El Nino peak years, compared with monthly record high temperatures prior to the last three strong El Ninos.

variability, comparison of global temperatures at the well-defined peaks of strong El Ninos may provide potential for early detection of global warming acceleration.[6] The three most recent strong El Ninos are 1997-98, 2015-16, and 2023-24. The first of these was prior to reduction of human-made aerosols. The second occurred just after the January 2015 imposition of restrictions on sulfur content of ship fuels by the International Maritime Organization (IMO), and the third occurred after strengthening of the restrictions in January 2020. Fig. 2 compares global temperatures during these years (red lines) with the prior record monthly temperatures (gray area).

The strong 1997-98 “El Nino of the century” produced 8-9 clear global temperature records, the 2015-2016 El Nino produced 10 clear record months, and the 2023-24 El Nino has already produced 7 record months about half way through the period of Nino-elevated temperature. The rate of warming between the first two El Ninos, i.e., between 1998 and 2016, was 0.23°C/decade, moderately larger than the 0.18°C/decade warming rate during 1970-2010. Another eight months of temperature data are needed to assess the warming rate between the last two El Ninos.

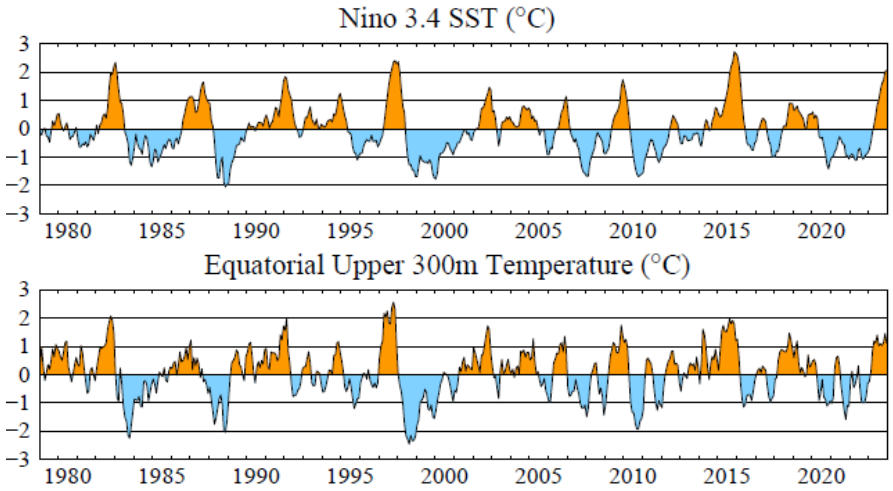

Fig. 3. Nino3.4 SST (upper panel) and temperature of ocean upper 300m in equatorial region.[7]

Use of El Ninos as a measuring stick depends on the El Ninos being comparable. The Nino3.4 temperature (Fig. 3) may be a flawed measure of El Nino strength. It implies that the 2015-16 El Nino was stronger than the "El Nino of the (20th) century" in 1997-98. A better measure is probably the heat content anomaly in the upper 300m of the equatorial Pacific (Fig. 3, bottom) because the 300m heat anomaly is a direct measure of the excess heat available for expulsion to the atmosphere. The 300m heat content shows that the three El Ninos successively decrease in magnitude, with the 2023-24 El Nino notably unimpressive. Further discussion and illustration of this matter is in a prior communication.[8] A declining strength of the El Ninos only enhances our conclusions.

How do we know global temperature will continue to grow in the next 5-8 months, carrying the 12-month running-mean to at least 1.6-1.7°C? The main reason is the large increase of global absorbed solar radiation (ASR) since 2015 (Fig. 4), which is a decrease of Earth's albedo (reflectivity) by 0.4% (1.4/340).[9] This reduced albedo is equivalent to a sudden increase of atmospheric CO_2 from 420 to 530 ppm. Increase of EEI (Fig. 5) is smaller than the increase of ASR because the warming increases thermal emission to space. The increase of ASR since 2015 is particularly important because it acts as a "fresh forcing," regardless of whether it is a forcing, a persistent feedback, or a combination thereof. Given the absence of monitoring of global aerosol forcing, ASR provides our best clue as to the changing drives for global warming. These assertions warrant discussion.

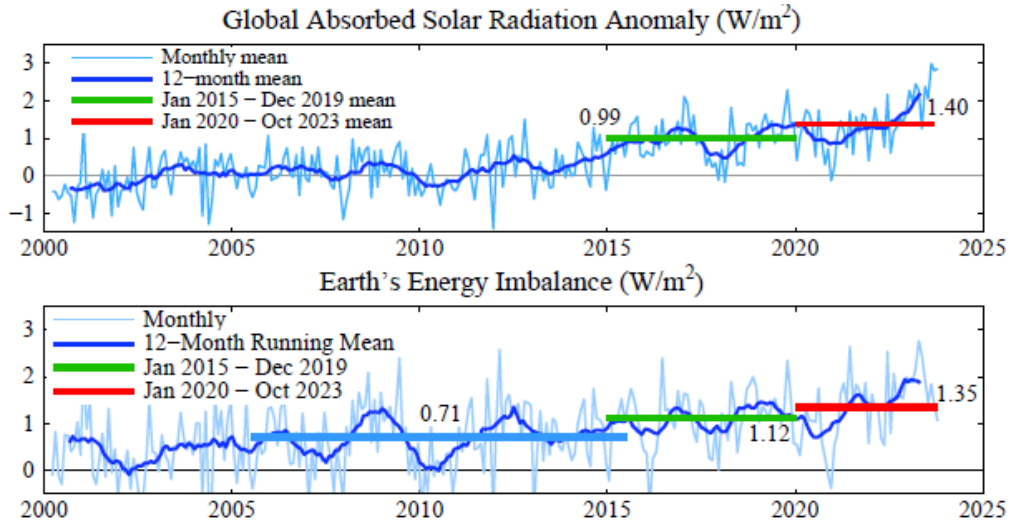

Fig. 4. Global absorbed solar radiation and Earth's energy imbalance relative to the mean of the first 120 months of CERES data. CERES data[10] **are available at http://ceres.larc.nasa.gov/**

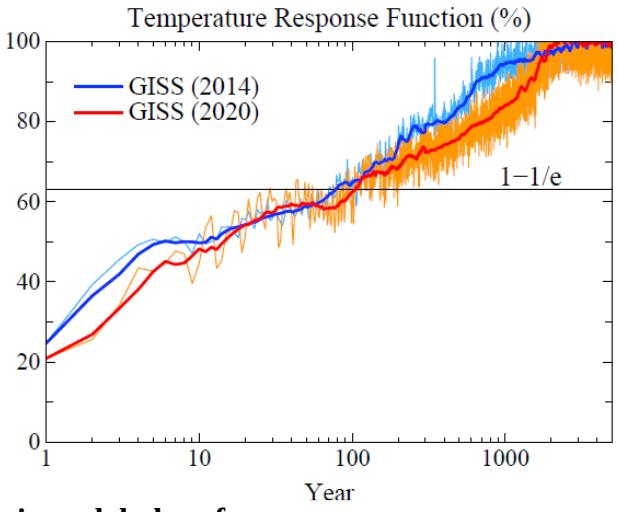

Fig. 5. Percent of equilibrium global surface temperature response to instant CO_2 doubling.[11]

Almost half of the global temperature change in response to a climate forcing occurs within the first decade after imposition of the forcing (Fig. 5), the remaining response requiring many decades and centuries.[11] Earth's energy imbalance was about 0.7 W/m^2 in the first 15 years of this century[12] and solar radiation absorbed by Earth was relatively constant (Fig. 4). The change since 2015, especially the increase of absorbed solar radiation, is a BFD (a big deal).[13] The magnitude, longevity, and growth of the phenomenon rule against some unexplained natural climate oscillation. Instead, it is likely a combination of a climate forcing(s) and feedbacks. Our interpretation[3] is that a reduction of human-made aerosols, especially the two-step (2015 and 2020) reduction of marine aerosols, causes an increase of climate forcing of at least ~0.5 W/m^2, possibly as great as 1 W/m^2. Aerosol modeling studies[14] report a global climate forcing due to the change of regulations on ship emissions only of the order of *O*(0.1 W/m^2), while we suggest a forcing *O*(1 W/m^2), i.e., at least ~0.5 W/m^2. Despite the absence of global monitoring of the aerosol climate forcing, it should be possible to resolve this issue within the next few years with the help of the great inadvertent aerosol experiment caused by the sharp imposition by the International Maritime Organization of rule changes on ship emissions.

The significant climate feedbacks that affect ASR are changes of sea ice and clouds. There is little trend of Arctic sea ice since 2015. The large loss of Antarctic sea ice in the past year may contribute to the spike in absorbed solar radiation in the last few months of data in Fig. 4, which will be testable from the geographic and seasonal variation of the observed ASR. Analysis of cloud feedbacks will be more difficult because both the aerosol forcing and cloud feedbacks operate via cloud changes, but superficial examination of the ASR data supports the idea of an aerosol forcing *O*(1 W/m^2) as well as a significant cloud feedback (Fig. 22 in *Pipeline* paper).

Our interpretation – that aerosol forcing changes constitute a substantial fraction of the change of ASR, not ~ 0.1 W/m^2 – seems to place us at odds against another community: aerosol/climate modeling. We wonder, however, whether the small values from aerosol models are not influenced by the expected results based on IPCC aerosol estimations. There is still large uncertainty in aerosol modeling. As noted above, the situation may be clarified within the next few years, which will be none too soon, as better understanding is required for policy considerations.

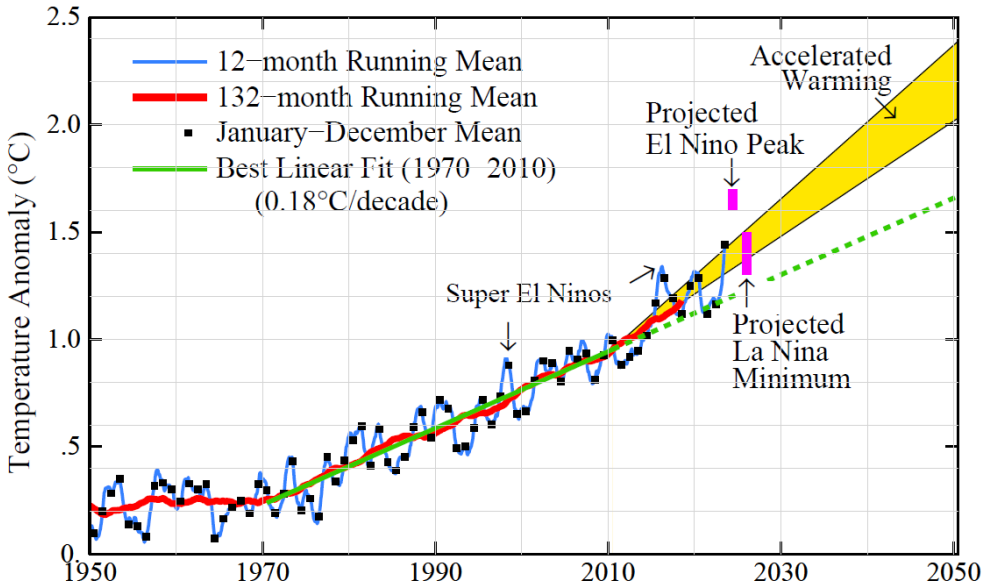

Fig. 6. Global temperature relative to 1880-1920 based on the GISS analysis.[1,2] Projected El Nino warming and La Nina cooling discusses in text and decadal acceleration in *Pipeline*.[3]

Summary.

Empirical evidence related to aerosol climate forcing will become clearer soon. If the forcing change is as large as we believe, it will push global warming to at least +1.6-1.7°C (Fig. 6), well above the level that would be expected for the moderate ongoing El Nino, and it should also limit the decline of global temperature following the El Nino.

The coupled aerosol forcing & climate sensitivity issue is not unrelated to the coupled ocean overturning & sea level issue that spurred the writing of the *Pipeline* paper. In both cases, we assert that IPCC has excessive reliance on global models with inadequate attention to analyses that pay comparable attention to paleoclimate information, global models, and evidence from ongoing observed climate changes. A case in point is the present tug-of-war occurring in the Southern Ocean. Global warming seems to be pushing the sea ice boundary south, diminishing sea ice cover. But we found in our *Ice Melt* paper[15] that freshwater injection from observed shrinking of ice shelf volume was already sufficient to begin cooling of the Southern Ocean mixed layer, pushing the sea ice area north. This topic is discussed in one of our recent communications.[16]

This story is to be continued. The climate situation needs to be clarified in the next several years, as that clarification will help clarify the actions that are needed to assure a bright future for young people and future generations. We appreciate your concerns and support. We are grateful to the people who responded to our appeal for support[16] of Climate Science, Awareness and Solutions, thus helping assure an additional perspective in the discussion of actions needed to address ongoing global climate change.

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[8] Hansen, J, Sato M, Ruedy, R. Global warming acceleration: El Nino measuring stick looks good, 14 December 2023

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[11] The graph shows results for two Goddard Institute for Space Studies GCMs 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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