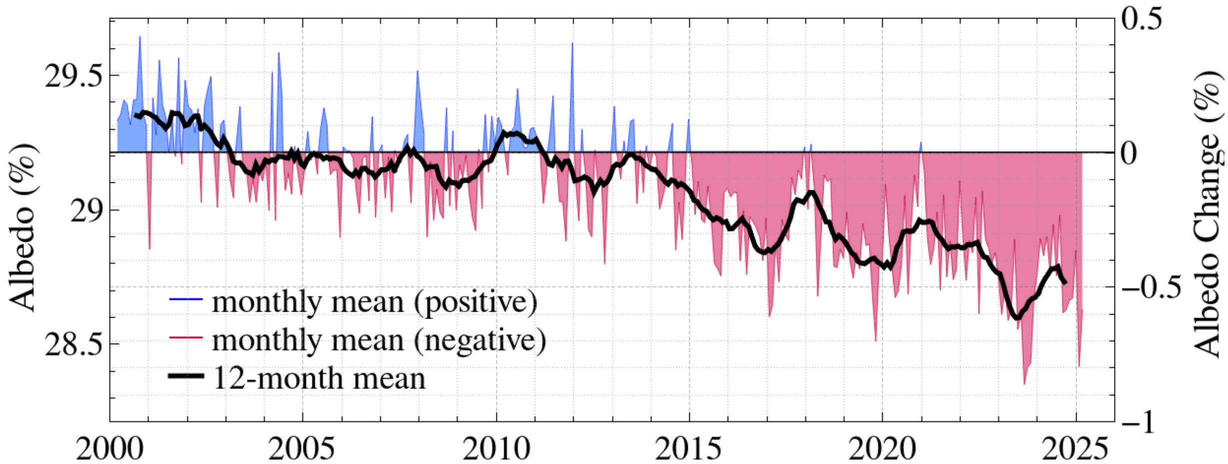

Fig. 1. Earth's albedo (reflectivity, in percent), seasonality removed[1,2,3,4]

Large Cloud Feedback Confirms High Climate Sensitivity

James Hansen and Pushker Kharecha 13 May 2025

Abstract. Earth's albedo (reflectivity) declined over the 25 years of precise satellite data, with the decline so large that this change must be mainly reduced reflection of sunlight by clouds. Part of the cloud change is caused by reduction of human-made atmospheric aerosols, which act as condensation nuclei for cloud formation, but most of the cloud change is cloud feedback that occurs with global warming. The observed albedo change proves that clouds provide a large, amplifying, climate feedback. This large cloud feedback confirms high climate sensitivity, consistent with paleoclimate data and with the rate of global warming in the past century.

A strange phenomenon occurred in response to our recent paper, "Global warming has accelerated: are the public and the United Nations well informed?"[5] A few reports appeared in the media the next day, but, almost uniformly, these reports dismissed our conclusions as a fringe opinion, out of step with the larger scientific community, and thus there was no continuing discussion of the issues raised in our paper. How did the media arrive at that conclusion, and is that conclusion truly representative of the wider scientific community? Are there important repercussions for the public of the media's approach for assessing a climate research paper, especially for today's young people, indeed, for the future of all people? The answer to the latter question, we conclude, is "yes."

Given this last conclusion, we must make special effort to clarify the situation. Perhaps the best way is to summarize our analysis, aiming for a wider community, beyond the handful of climate scientists that the media have come to rely on. Our analysis puts equal emphasis on information on climate change extracted from (1) observations of ongoing climate change, (2) global climate models (GCMs), and (3) Earth's long-term climate history (paleoclimate data). We used all three of these methods in our paper to arrive at three independent analyses of climate sensitivity, with each method concluding that climate sensitivity is high, much higher than the best estimate (3°C for doubled atmospheric CO_2) of IPCC (Intergovernmental Panel on Climate Change).

This communication concerns one of the ongoing climate observations: Earth's darkening (declining reflectivity) as seen from space. We then discuss the difficulty of communicating with the public.

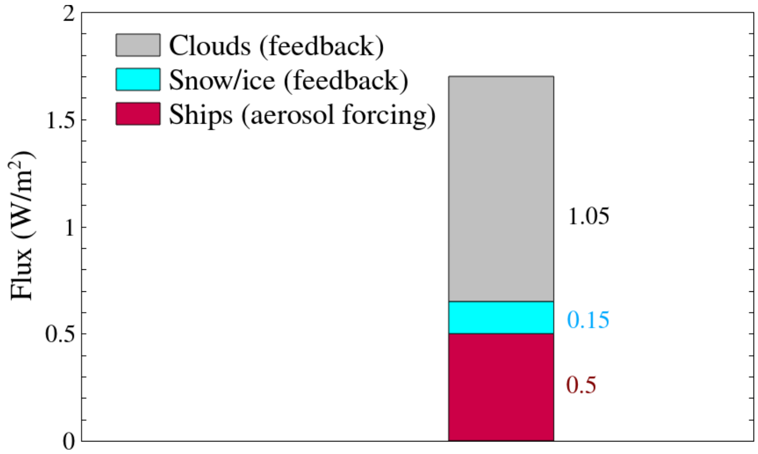

Fig. 2. Inferred contributions to reduced Earth albedo[5]

Earth's albedo (or reflectivity) is the portion (percent) of incoming solar radiation that is reflected back to space. As shown in Fig. 1, in the period of precise satellite data (since early 2000), Earth's albedo has decreased about 0.5%. We described this change as a BFD[6,7] because it has staggering implications. Solar radiation reaching Earth is about 340 W/m^2, averaged over Earth's surface, so the 0.5% albedo decrease is a 1.7 W/m increase of absorbed solar energy, much larger than the estimated potential drift[2] (<0.085 W/m^2 per decade) of the satellite data.

A 1.7 W/m^2 increase of absorbed solar energy is huge. If it were a climate forcing, it would be equivalent to a CO_2 increase of 138 ppm,[5] but most of this albedo change must be climate feedback. Of the two substantial long-term climate forcings – human-made greenhouse gases (GHGs) and aerosols – the effect of GHGs on Earth's albedo is negligible, as GHG absorption in the solar spectrum is weak. "Direct" aerosol forcing – i.e., change of the reflection and absorption of sunlight by aerosol change *per se* – is also small, at most ~0.1 W/m^2. The only substantial climate forcing affecting Earth's albedo is the "indirect" aerosol forcing that occurs via the effect of aerosols on cloud formation and cloud brightness. IPCC estimates this indirect aerosol forcing change in the past 25 years as only about +0.1 W/m^2, while we – based on the geographical and temporal change of absorbed solar radiation – estimate a larger aerosol forcing, +0.5 W/m^2, due to reduced aerosol emissions from ships and thus reduced cloud cover.

The upshot is that most of the 1.7 W/m^2 increase of energy absorbed by Earth must be due to climate feedbacks. Using our estimate of aerosol forcing, ~1.2 W/m^2 of increased absorption is climate feedback (Fig. 2), while, if IPCC's estimate of the aerosol forcing were correct, feedbacks would be >1.5 W/m^2. In either case, the huge increase of absorbed energy must be provided by some combination of the two climate feedbacks that significantly alter Earth's albedo: (1) change of the surface albedo, which is due mainly to change of sea ice area, and (2) change of clouds. The sea ice change is readily identified in satellite data and the resulting regional change of Earth's albedo is accurately measured, amounting to[5] 0.15 W/m^2 in the period 2000-2024, averaged over Earth's surface. Thus, the one remaining feedback that affects Earth's albedo – the cloud feedback – is very large. Rounding off, if our estimate of the aerosol forcing is right, the cloud feedback is increasing the flux of energy into the Earth system by an amount that has increased ~1 W/m^2 in the past 25 years. If IPCC's estimate of the aerosol forcing were right, the cloud feedback has increased the flux of energy into the system by ~1.5 W/m^2. In either case, the cloud feedback is so large that it rules out a climate sensitivity so low as IPCC's best estimate of 3°C for doubled CO_2, as we show below. The simplest way to understand this is to use Charney's approach: consider the equilibrium climate response to the large (4 W/m^2) doubled CO_2 climate forcing.

Equilibrium feedback response. Charney's focus on the equilibrium climate response to doubled CO_2 aids understanding of the relative importance of different climate feedbacks, avoiding complications that arise in the transient climate response. For example, the ongoing sea ice response is a combination of melting sea ice due to ocean warming and increasing sea ice due to cold, freshwater injection from melting ice shelves. Thus, the magnitude of the sea ice feedback is complex, depending on the climate forcing scenario and the rate of ice melt. The equilibrium response allows a simpler comparison of the different major feedbacks, which can usefully precede discussion of the transient case.

Climate simulations with GCMs reveal three important, rapid, global climate feedbacks: water vapor, clouds and sea ice; we include within the water vapor feedback the effect of changes in the vertical temperature profile, which are caused mainly by the water vapor change. These three feedbacks – all amplifying – overwhelm other (amplifying and diminishing) feedbacks. *A priori*, clouds did not need to be amplifying, but there is a consensus in the models that a warmer world tends to have less cloud cover and some of the clouds tend to move to slightly higher altitude, which decreases heat radiation to space. In discussing how these feedbacks interact, we use equations from a paper prepared for the 1982 Ewing Symposium,[8] published in an AGU monograph in January 1984, but if you do not like equations, that is not a problem, as the ideas are simple and result in a single number characterizing each feedback.

If there were no climate feedbacks, global surface warming in response to doubled CO_2 would be about

$$\Delta T_O = 1.2°C, \qquad (1)$$

which is the warming needed to increase radiation to space by the amount (4 W/m^2) required to offset the reduced emission to space caused by doubled CO_2. Actual equilibrium warming, ΔT_{eq}, exceeds ΔT_O because of amplifying feedbacks. An intuitive way to characterize a feedback is with a feedback factor, f, the factor by which the feedback alters the equilibrium temperature change when it is the only feedback operating. However, in reality, multiple feedbacks operate simultaneously, affecting each other. For example, if warming reduces sea ice cover, the resulting warming increases atmospheric water vapor, adding to the water vapor increase caused directly by doubled CO_2. The algebra needed to combine feedback factors is avoided and a simple number is obtained for each feedback characterizing the feedback strength by – instead of working with feedback factors – dividing equilibrium temperature change into the portions caused directly by the forcing and the portion due to feedbacks

$$\Delta T_{eq} = \Delta T_O + \Delta T_{feedbacks} = \Delta T_O + \Delta T_{wv} + \Delta T_{si} + \Delta T_{cl} \qquad (2)$$

The climate system "gain" is defined as the ratio of the feedback portion of the temperature change to the total temperature change

$$g = \Delta T_{feedbacks}/\Delta T_{eq} = g_{wv} + g_{si} + g_{cl} \qquad (3)$$

and thus

$$\Delta T_{eq} = \Delta T_O/(1 - g) = \Delta T_O/(1 - g_{wv} - g_{si} - g_{cl}), \qquad (4)$$

the gain, g, being the sum of the water vapor, sea ice, and cloud gains, $g_{wv} + g_{si} + g_{cl}$.

GCMs and empirical data consistently indicate that the water vapor feedback, including the effect of water vapor change on the vertical temperature profile, is very large ($g_{wv} \sim 0.4$), while the sea ice feedback is modest ($g_{si} \sim 0.1$). Thus, the well-understood water vapor and sea ice feedbacks, without any cloud feedback ($g_{cl} = 0$), yield g = 0.5 and equilibrium climate sensitivity 2.4°C for doubled CO_2, i.e., the water vapor and sea ice feedbacks raise equilibrium climate sensitivity from 1.2°C to 2.4°C.

The question is: how much further is climate sensitivity altered by the cloud feedback? Let's consider three cases: (1) negligible cloud feedback, $g_{cl} \sim 0$, (2) modest cloud feedback, $g_{cl} \sim 0.1$, and large cloud feedback, $g_{cl} \sim 0.25$. These three cases yield equilibrium climate sensitivities of 2.4°C, 3°C and 4.8°C (see equation 4), respectively. The observed change of Earth's albedo during the past 25 years allows unambiguous discrimination among these three cases: the large observed decrease of Earth's albedo rules out the zero and moderate cloud feedbacks. The cloud feedback is large, implying, with a high degree of confidence, that real-world climate sensitivity is much higher than 3°C for doubled CO_2.

Change of Earth's albedo (Fig. 1) will be a great source of information about the climate system and cloud feedbacks, which include both shifting of climate zones and cloud microphysical effects. Precise data on the geographical, seasonal, and longer-term albedo changes will be crucial for understanding of ongoing climate change and projections of future climate. Thus, it is important that the high-precision Earth radiation balance data are continued without interruption, which would spoil the calibration.

Summary. Earth's darkening, by itself, provides strong proof that climate sensitivity is much higher than IPCC's best estimate of 3°C for doubled CO_2. In our "Pipeline"[7] and "Acceleration"[5] papers, we include two other, independent, assessments of climate sensitivity, one based on paleoclimate evidence and one based on global warming from preindustrial time to the present. Each of the three assessments concludes that the data are inconsistent with a sensitivity of 3°C. As summarized in our recent (Acceleration) paper, we conclude that climate sensitivity for doubled CO_2 is 4.5°C ± 0.5°C (1σ). In future communications, we will describe each of the other two analyses. Climate sensitivity as low as 3°C for doubled CO_2 is excluded with greater than 99 percent confidence.

A corollary to IPCC's underestimate of climate sensitivity also emerges from these studies: IPCC's best estimate of the aerosol cooling effect is a substantial underestimate, especially in the period 1970-2010. One implication of this underestimate is that there is more warming in the pipeline in reality than there is with IPCC's best estimates for climate sensitivity and aerosol forcing. These conclusions have important implications, including their impact on expectations for future warming.

Criticisms of the Acceleration paper in the media did not address the physics in our three assessments of climate sensitivity. Instead, criticisms were largely ad hoc opinions, even ad hominem attacks. How can science reporting have descended to this level? Climate science is now so complex, with many sub-disciplines, that the media must rely on opinions of climate experts. Although there are thousands of capable scientists in these disciplines, the media have come to depend on a handful of scientists, a clique of climate scientists who are willing, or even eager, to be the voice of the climate science community. But are they representative of the total community, of capable scientists who focus on climate science?

We have lamented[9] the absence of scientists with the breadth of understanding of say Jule Charney or Francis Bretherton,[10] or our beloved, sometimes crotchety, former colleague, Wally Broecker. However, the truth is that there are many scientists out there with a depth of understanding at least as great as the clique of scientists that the media rely on. Given the success of this clique in painting us as outliers, we are dependent on the larger community being willing to help educate the media about the current climate situation. For that purpose, we will discuss – one-by-one in upcoming communications – several of the matters that are raised in our papers. Thanks for your attention.

[1] Calculated based on CERES (Clouds and Earth's Radiant Energy System) https://ceres-tool.larc.nasa.gov/ord-tool/jsp/EBAFTOA421Selection.jsp. CERES satellite observations of changes in Earth's radiation balance are described in reference 2. Absolute calibration of Earth's energy balance is based on measurement of decadal changes in the ocean's heat content, primarily based on measurements by the fleet of deep-diving Argo floats as described in references 3 and 4. Albedo change is relative to the first 10 years of measurements, i.e., March 2000 through February 2010.

[2] NG Loeb et al., "Satellite and ocean data reveal marked increase in Earth's heating rate," *Geophys Res Lett* 48, e2021GL093047, 2021

[3] K von Schuckmann et al., "Heat stored in the Earth system: where does the energy go?" *Earth System Science Data* 12, 2013-41, 2020

[4] L Cheng et al., Record high temperatures in the ocean in 2024, Adv Atmos Sci https://doi.org/10.1007/s00376-025-4541-3, 2025

[5] JE Hansen, P Kharecha, M Sato et al., Global warming has accelerated: are the United Nations and the public well-informed? *Environment: Science and Policy for Sustainable Development*, 67(1), 6–44, 2025, https://doi.org/10.1080/00139157.2025.2434494

[6] A big fxcking deal, as discussed in a webinar on the "Pipeline" paper, reference 7.

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

[8] J Hansen, A Lacis, D. Rind et al. Climate sensitivity: analysis of feedback mechanisms. In: Hansen JE, Takahashi T (eds). *AGU Geophysical Monograph 29 Climate Processes and Climate Sensitivity*. Washington: American Geophysical Union, 130-63, 1984

[9] J Hansen, P Kharecha, Global warming has accelerated. Why? What are the consequences. 12 February 2025

[10] J Hansen, Battlestar Galactica, Chapter 31 in *Sophie's Planet*. New York: Bloomsbury, 2026