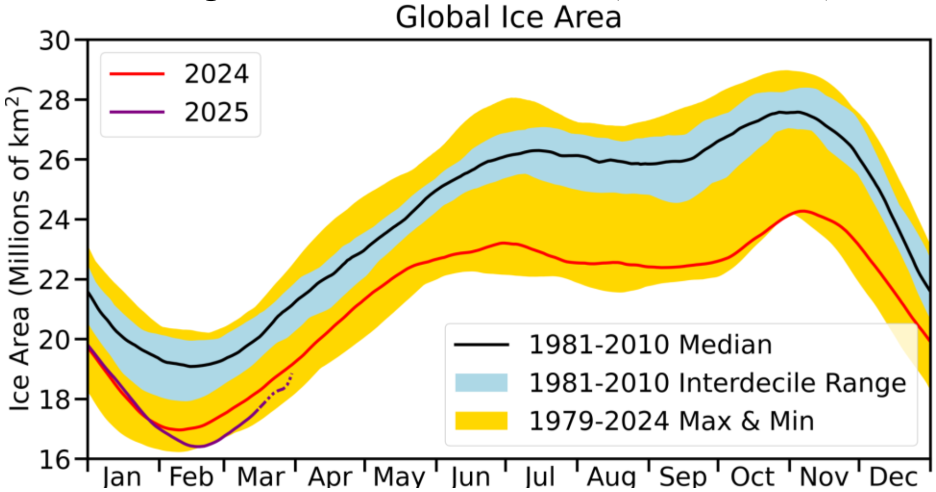
Figure 1. Global Sea Ice Extent (millions of km^2)[1]



Global Warming Acceleration: Impact on Sea Ice

James Hansen, Joe Kelly, Pushker Kharecha 02 April 2025

Abstract. Global warming has accelerated.[2] Warming melts sea ice, but it also melts ice sheets, ice shelves, ice caps and glaciers, which affects sea ice cover. Injection of cold freshwater and icebergs into the ocean tends to increase sea ice cover during a transient period until the climate forcing stabilizes and a new climate state is approached. Sea ice melt due to the warming ocean has the upper hand over freshwater injection in both hemispheres today, and thus global sea ice cover is near a historic low (Fig. 1). Arctic sea ice has been relatively stable for the past 10-20 years while Antarctic sea ice has declined, but global warming acceleration may alter both cases. In the Arctic, warm Atlantic water is intruding under the cold Arctic surface layer and warm Pacific water is spilling over the Aleutian sill into the Arctic Basin. Paleoclimate data show that warming at depth can lead to sudden loss of sea ice near Greenland, with consequences for the Greenland ice sheet. In the Antarctic, accelerated ocean warming increases melting of ice shelves and freshwater injection, which can cause temporary growth of sea ice cover. Global climate models employed by the Intergovernmental Panel on Climate Change (IPCC) have failed to account well for the freshwater effect on sea ice cover, thus contributing to IPCC's underestimate of climate sensitivity. Overall, accelerated global warming does not bode well for stability of the ice sheets, the ocean's overturning circulations, and global sea level in coming decades – despite the complexity of sea ice changes and uncertainty about the growth rate of ice sheet mass loss.

Global sea ice cover is one of the three big "fast" climate feedbacks in the classical definition of equilibrium climate sensitivity (ECS), which the Charney report[3] cemented. The Charney committee's decision to exclude the "slow" feedbacks of ice sheets and the carbon cycle in their assessment was invaluable, as it allowed focus on the crucial water vapor, cloud and ice/snow feedbacks, and their interactions, in the global climate models (GCMs) then under development. Charney realized that the excluded feedbacks may have effects on short timescales, but those could be kept in mind for later study.

Recently, we concluded that climate sensitivity is high, ECS = 4.5 ± 0.5°C (1σ) for doubled atmospheric CO_2, based on three independent analyses (glacial-interglacial climate change, 1850-2024 global warming, and Earth's darkening during 2000-2024).[2] High ECS changes everything: it fundamentally

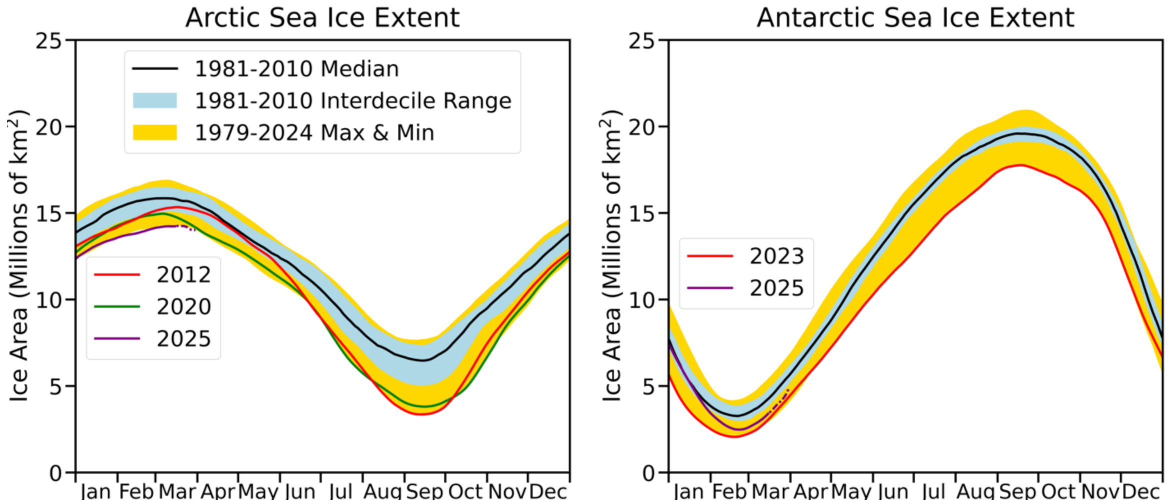


Fig. 2. Arctic and Antarctic sea ice area (31-day running-mean of daily data) from National Snow and Ice Data Center daily sea ice extent data.[1] The most recent 15 days (shown be a dotted line) are 29-day, 27-day… 3-day, 1-day means, and are thus estimates that will be replaced as data are updated.

alters expectations for continued climate change. Why? Because "fast" feedbacks are not really fast: they come into play in proportion to temperature change, not in direct response to climate forcing. Thus, climate response time is approximately proportional to climate sensitivity squared.[4] One consequence is that the "fast" feedback response to ship aerosol reduction[2] is still growing significantly after five years, which is the reason we expect 2025 global temperature to be about as high as in 2024, despite the El Nino having faded to the ENSO-neutral state. A second result is that we must simultaneously consider "fast" and "slow" feedback effects because their timescales overlap. Let's start with sea ice.

Sea ice cover is now near its minimum during the era of global satellite data (i.e., since 1979) in both hemispheres (Figs. 2 and 3). The warm-season minimum of Arctic sea ice decreased sharply in 2007 and even further in 2012. The 2007 decrease was associated with sustained wind anomalies that drove ice

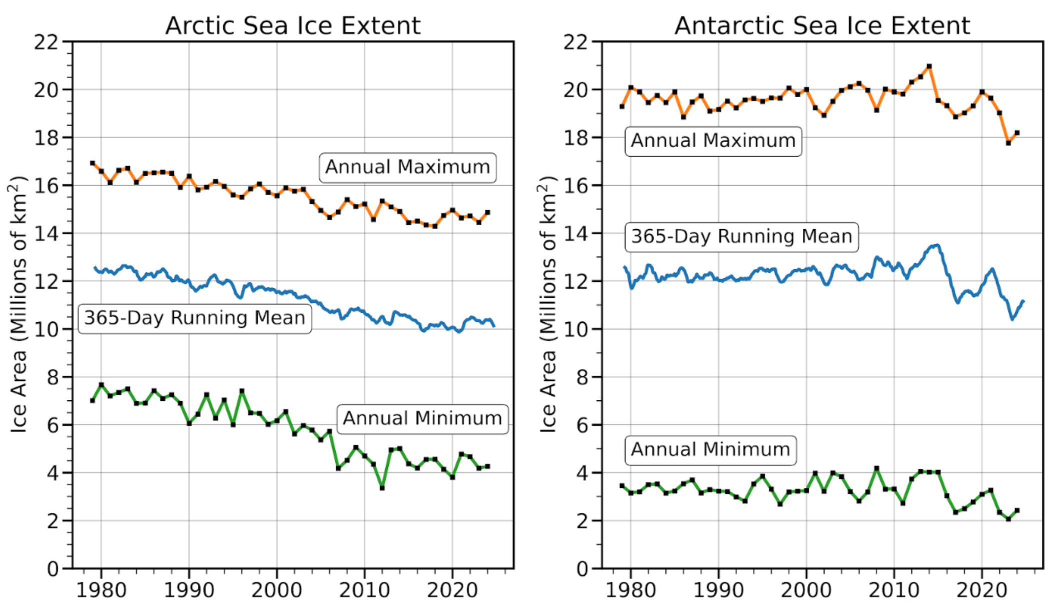


Fig. 3. Arctic and Antarctic sea ice area, with the solid curves being the 365-day running-mean of National Snow and Ice Data Center daily sea ice extent data[1] and the squares being annual results.

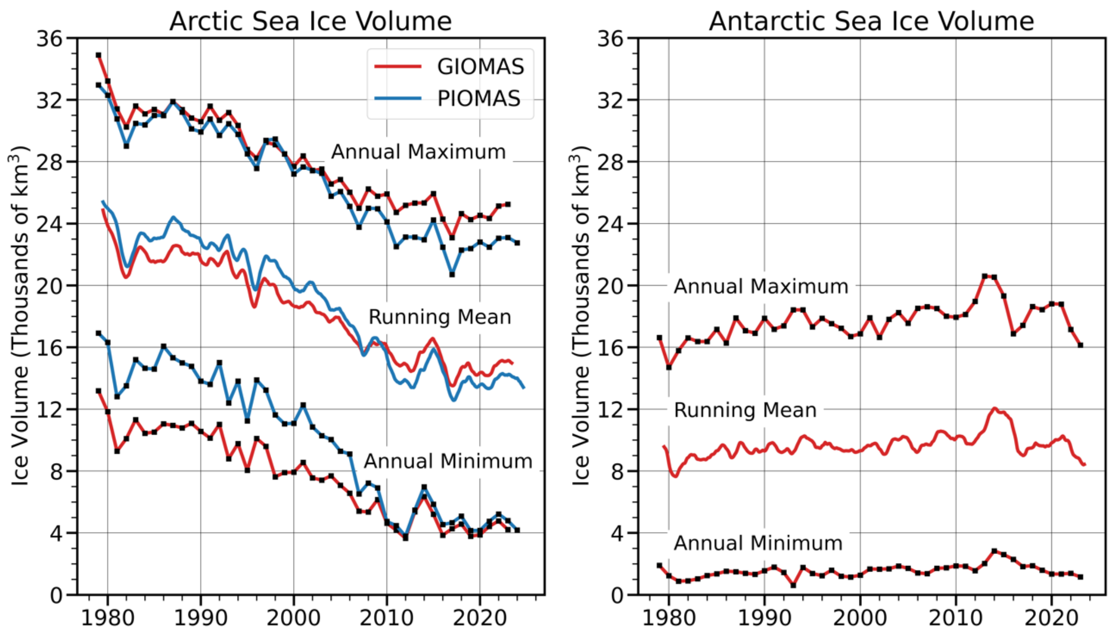


Fig. 4. Sea ice volume: solid curves are 12-month running-mean of PIOMAS and 365-day running-mean of GIOMAS data, both from the Polar Science Center of the University of Washington.[5]

from the Arctic toward warmer water and the Fram Strait.[6,7] The 2012 melt was enhanced by an intense cyclonic storm that mixed heat upward in a normally well-stratified summer ocean, thus melting sea ice from below.[8] As the thickness of sea ice declines, such weather anomalies melt ice more effectively.

Sea ice volume is an important diagnostic because reduction of ice volume is a freshwater injection onto the ocean that can affect ocean circulation. Sea ice volume change is more difficult to measure than area change. Remarkably, changes of the ice "freeboard" (the height of the ice surface above sea level) can be detected by satellite, but measurement accuracy is limited, especially for Antarctic sea ice, which is less thick than Arctic sea ice. Sea ice volume estimates for the entire ocean (Fig. 4) are based on ice-ocean data assimilation models constrained by available observations. The difference between results from two data assimilation models for Arctic sea (Fig. 4, left) is one measure of uncertainty in sea ice volume changes. [PIOMAS[9] (Pan-Arctic Ice-Ocean Modeling and Assimilation System) and GIOMAS (Global Ice-Ocean Modeling and Assimilation System) employ different ocean and sea ice models.[10]] The PIOMAS data set is preferred for the Arctic because it has been more extensively validated and used.[11]

The volume of Arctic sea ice declined of the order of 10,000 cubic kilometers in the 40 years 1980-2020, thus about 250 km^3/year, a freshwater injection rate comparable to the annual mass loss rate of the Greenland ice sheet. This decrease of Arctic sea ice volume over the past several decades provides a substantial term to the total freshwater injection that affects stability of the Atlantic Overturning Meridional Circulation (AMOC), as discussed in the Supplementary Material of our recent paper.[2] Total freshwater injection from all sources is now large enough to affect ocean temperature, salinity, and overturning ocean circulations, as shown, for example, in observed zonal-mean ocean temperature change (Fig. 5A)[12] and in our climate simulations.[13] However, increase of freshwater injection is absent or underestimated in models employed by the Intergovernmental Panel on Climate Change (IPCC), as shown by the absence of cooling in their climate model simulations (Fig. 5B,C) and underestimates of the freshening of polar surface waters.

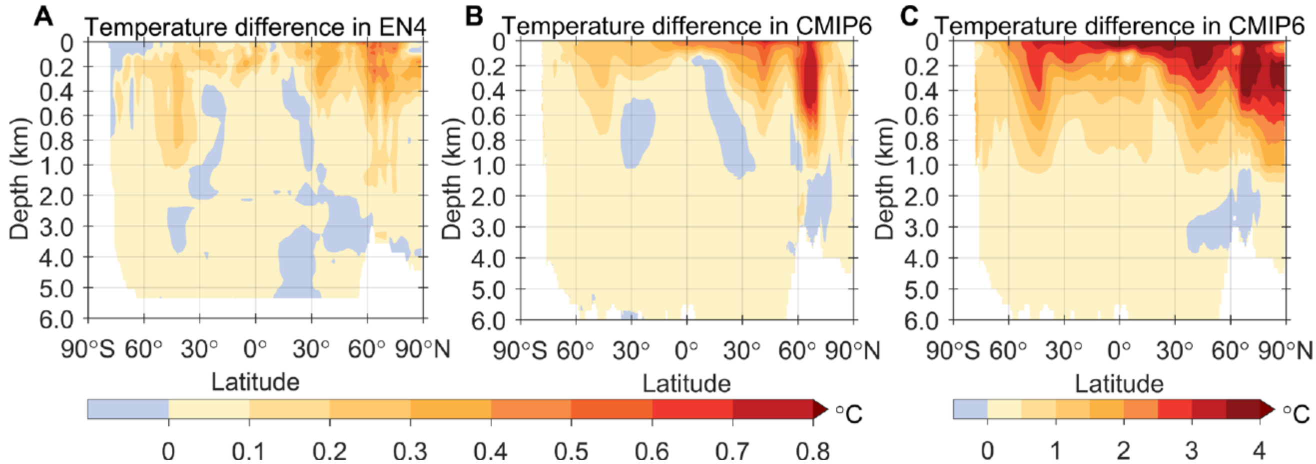


Fig. 5. (A) Observed zonal-mean 2001-2020 ocean temperature relative to 1981-2000, (B) ensemble mean of CMIP6 for that period, and (C) CMIP6 result for 2081-2100 (from Fig. 1, Shu et al., 2022).[12]

Climate sensitivity. Failure of IPCC models to capture the cooling from freshwater injection affects IPCC's best estimate for equilibrium climate sensitivity (ECS) because IPCC relies heavily on comparison of climate simulations for 1850-present with observed global warming. Models that fail to capture the freshwater effect – which causes a delay of polar warming and reduced global warming – require unrealistically low ECS in order to avoid global warming that exceeds observations. However, this effect on estimated ECS is exceeded by the aerosol effect described next.

Aerosols are the main reason for IPCC's underestimate of climate sensitivity. IPCC's estimate of aerosol climate forcing (Fig. 3 of ref. 2) is nearly linear in global sulfur emissions (Fig. SM1 of ref. 2). With the IPCC aerosol forcing, an ECS of about 3°C for doubled CO_2 is required to yield close agreement with observed global warming over the past century. However, the impact of aerosols on clouds (which is most of the aerosol forcing) is highly nonlinear; we conclude in paper 2 that global aerosol forcing increased (became more negative) by about 0.5 W/m^2 during the period 1970-2005 as a result of human-made aerosols being spread more globally into more pristine air, including over the ocean. Aerosols thus reduced the net human-made (greenhouse gas plus aerosols) climate forcing, and as a result a higher climate sensitivity (4.5°C ± 0.5°C for doubled CO_2) is required to match observed global warming. This high climate sensitivity is also best able to simulate the strong warming in the past two years, and it is the main reason that we expect little if any cooling in the annual mean 2025 global temperature.

Two additional – independent and consistent – evaluations of climate sensitivity are provided by (1) comparison of paleoclimate equilibrium states,[14] and (2) inference of large amplifying cloud feedback based on accurate monitoring of Earth's radiation balance.[2]

Summary implications. High climate sensitivity (including the implied corollary that human-made aerosols have partly offset greenhouse gas warming) changes everything. Most important: it makes it much more difficult to avoid passing the "point-of-no-return" – shutdown of the Atlantic Meridional Overturning Circulation (AMOC) and, in turn, sea level rise of several meters.

AMOC shutdown occurs when the density of the upper ocean in the regions of deepwater formation in the North Atlantic becomes sufficiently light relative to deeper ocean layers, i.e., light enough to prevent the winter sinking of surface water that drives the global ocean conveyor. Accelerated warming has three effects that increase the likelihood of AMOC shutdown and the speed with which shutdown can occur:

(1) accelerated global warming limits mixing of the warmed surface water with deeper, colder, layers, (2) greater warming increases precipitation, adding freshwater to the surface layer; and (3) greater warming increases ice melt and thus increases freshwater injection onto the North Atlantic.

AMOC shutdown is the "point-of-no-return" because it requires centuries for the ocean circulation to recover from shutdown and, in the meantime, transport of heat from the Southern Hemisphere into the North Atlantic is greatly reduced. Resulting increase of ocean temperature in the Southern Hemisphere practically locks in demise of the West Antarctic ice sheet, with sea level rise of several meters.

Evaluation of how close the world is to AMOC shutdown is extremely difficult. IPCC's approach – relying almost entirely on global climate models – is fraught with uncertainty and errors, as suggested by a paper[15] concluding that AMOC would not shut down even with 5°C global warming and by the IPCC AR6[16] conclusion that AMOC shutdown is low probability.

More reliable analysis, we argue, requires comparable emphasis on information obtained from (1) paleoclimate, (2) global climate models, and (3) ongoing observations of climate change and climate processes. That is the approach that we will follow at Climate Science, Awareness and Solutions (CSAS) and we appreciate support that allows us to continue to pursue that research. We plan to make available and continually update a broad array of the most essential data, e.g., the sea ice graphs are here.[17] However, timely results in support of policy needs are dependent on continuation and enhancement of crucial observations. We draw attention especially to:

(1) the global ARGO float program[18] of several thousand deep-diving autonomous floats, which needs to be continued and expanded with more capable floats in the polar regions that can assess changes near vulnerable ice shelves and in the sub-sea-ice ocean. The United States National Oceanic and Atmospheric Administration (NOAA) has provided a large fraction of these floats, but it is unclear whether they can be counted on to continue and to enhance the observations. It is important for more nations to step up their contributions to the program.

(2) the global Earth radiation budget measurements presently obtained by CERES[19] instruments nearing their end-of-life. It is not clear that NASA has adequate plans for continuation of the measurements. In any case, it would be very useful if the European Union and/or China carried out measurements with a quality comparable to the high-precision NASA data and made the data freely available.

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[1] Sea ice extent is defined by NSIDC (National Snow and Ice Data Center) as the ocean area with sea ice concentration exceeding 15%. NSIDC Artic Sea Ice News and Analysis and daily updates of sea ice extent for the Arctic and Antarctic are available from NSIDC.
[2] 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
[3] J Charney et al., *Carbon Dioxide and Climate: A Scientific Assessment*. (Washington: National Academy of Sciences Press, 1979)
[4] J Hansen, G Russell, A Lacis *et al.* Climate response times: dependence on climate sensitivity and ocean mixing. *Science* 229, 857-9, 1985
[5] Polar Science Center. *Data*. Applied Physics Laboratory, University of Washington. (last accessed 31 March 2025), https://psc.apl.uw.edu/data/
[6] J Zhang, RW Lindsay, A Schweiger, I. Rigor, What drove the dramatic retreat of Arctic sea ice during summer 2007?, *Geophys Res Lett*, 35, doi:10.1029/2008GL034005
[7] RW Lindsay, J Zhang, A. Schweiger et al, Arctic sea ice retreat in 2007 following thinning trend, *J Clim* 22, 165-76, 2009
[8] J Zhang, R Lindsay, A. Schweiger, M Steele, The impact of an intense cyclone on 2012 Arctic sea ice retreat, *Geophys Res Lett* 40, 720-6, 2013

[9] J Zhang, DA Rothrock, Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates, *Mon. Wea. Rev*., 131(5), 681-97, 2003
[10] S Liao, H Luo, J Wang et al., An evaluation of Antarctic sea-ice thickness from the Global Ice-Ocean Modeling and Assimilation System based on in situ and satellite observations, *The Cryosphere*, 16, 1807-19, 2022
[11] J Zhang, private communication, 27 March 2025
[12] Q Shu, Q Wang, M Arthum et al., "Arctic Ocean amplification in a warming climate in CMIP6 models," *Sci. Adv*. 8, eabn9755, 2022
[13] J Hansen, M Sato, P Hearty et al., "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 C global warming is highly dangerous," *Atmos Chem Phys* 16, 3761-812, 2015. See also the Supplementary Material of reference 2
[14] JE Hansen, M Sato, L Simons et al., "Global warming in the pipeline," *Oxford Open Clim. Chan.* 3 (1) (2023): doi.org/10.1093/oxfclm/kgad008
[15] P Bakker, A Schmittner, JTM Lenaerts et al., Fate of the Atlantic Meridional Overturning Circulation: strong decline under continued warming and Greenland melting. *Geophy Res Lett*; 43, 12252-60, 2016
[16] 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
[17] Various data sets are being revised and updated, to be made available at https://www.columbia.edu/~jeh1/Data/
[18] K. von Schuckmann, L Cheng, ND Palmer et al., "Heat stored in the Earth system: where does the energy go?" *Earth System Science Data* 12, 2013-41, 2020
[19] NG Loeb, GC Johnson, TJ Thorsen et al., "Satellite and ocean data reveal marked increase in Earth's heating rate," *Geophys Res Lett* 48, 2021: e2021GL093047