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Scientific Evidence on Climate Sensitivity

A technical appendix to accompany Parasol Lost

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Pathways to Sustainability

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Technical Appendix: Scientific Evidence on Climate Sensitivity

Equilibrium climate sensitivity (ECS) – defined as the long-term global temperature response to a doubling of atmospheric CO_2 – is a measure of how much the climate warms in response to CO_2eq emissions and remains one of the most important yet uncertain parameters in climate science. The IPCC's Sixth Assessment Report provides a best estimate of 3°C with a likely range of 2.5-4°C. Recent observational studies have provided new constraints on this range, though interpreting these constraints is complicated by uncertainties in aerosol forcing and the time-varying nature of climate feedbacks. This appendix reviews major lines of evidence bearing on climate sensitivity, including satellite observations of Earth's energy imbalance, temperature trend analyses, cloud feedback constraints, paleoclimate reconstructions, and historical temperature constraints on aerosol forcing.

Key findings Constraints from Earth’s Energy Imbalance

Satellite observations from the Clouds and the Earth's Radiant Energy System (CERES) provide direct measurements of Earth's energy imbalance - the difference between incoming solar radiation and outgoing thermal radiation. Recent analyses have examined whether climate models with different sensitivities can reproduce observed trends in this imbalance and its components. Myhre and colleagues (2025) analysed CERES data spanning 2001-2023 and found that models with equilibrium climate sensitivity below 2.5 cannot replicate the observed patterns in longwave and shortwave contributions to the energy imbalance. At the 99.999% confidence level, models with ECS of 2.93 or below fell outside the range of observations.

The physical basis relates to how different components of the climate system respond to warming. The longwave contribution to Earth's energy imbalance becomes more negative with surface temperature increases, while the shortwave contribution tends to remain positive and is amplified by greater warming. Models with lower climate sensitivity produce weaker trends in both components than observed. The authors note that trends in these individual components provide stronger physical constraints than net energy imbalance alone, though the relatively short CERES observation period (2001-2023) may not fully represent long-term climate sensitivity due to evolving aerosol patterns, volcanic impacts, and internal variability.

Independently, Mauritsen and colleagues (2024) and Allan and Merchant (2025) documented that Earth's energy imbalance has accelerated significantly beyond model predictions. The imbalance more than doubled from 2001 to 2024, reaching 1.8 W/ m2 in 2023 - approximately twice what state-of-the-art climate models predicted. Allan and Merchant confirmed an increase from 0.6 ± 0.2 W/ m2 in 2001-2014 to 1.2 ± 0.2 W/ m2 in 2015-2023, primarily driven by increases in absorbed sunlight related to cloud-radiative effects over the oceans. This acceleration appears dominated by a decrease in Earth's solar reflectivity, though the root causes remain incompletely understood. Models can barely reproduce the observed rate of change through 2020 within observational uncertainty, and the continued rise since then suggests the real-world signal may have departed from the envelope of model internal variability. However, the studies acknowledge that attributing this acceleration directly to higher climate sensitivity requires careful separation from other factors including evolving aerosol emissions, land-use changes, cloud cover, and decadal ocean variability.

Analysis of Recent Temperature Trends

Rahmstorf and Foster (2025) applied statistical methods to remove the effects of El Niño events, volcanic eruptions, and solar variations from multiple global temperature datasets to isolate the anthropogenic warming signal. Their analysis of the adjusted data shows that after 2015, global temperature has risen faster than in any previous 10-year period since 1945, with the most recent decade warming at approximately 0.4°C per decade compared to 0.15-0.2°C per decade since the 1970s. This acceleration persists even after removing the exceptional El Niño of 2023-2024, suggesting it may represent a genuine shift in the warming rate rather than short-term variability.

The geographic pattern of this acceleration is particularly evident in Northern Hemisphere mid-latitudes (30-60°N), where warming trends peaked during 2010-2023. This spatial signature is consistent with declining aerosol masking in heavily industrialized regions where sulphur dioxide emissions have decreased sharply, though definitively attributing the acceleration to either reduced aerosol cooling or higher underlying climate sensitivity requires further analysis. If current acceleration rates were to continue, the authors project that the 1.5°C warming threshold could be breached by late 2026 according to most datasets, though they note uncertainty about whether such rates will persist.

Paleoclimate Evidence and Cloud Feedbacks

Paleoclimate reconstructions provide important constraints on climate sensitivity by examining Earth's response to past changes in radiative forcing. However, paleoclimate studies typically estimate Earth System Sensitivity (ESS) rather than the Equilibrium Climate Sensitivity (ECS) that dominates century-scale projections. ESS includes slow feedbacks - ice sheet changes, vegetation shifts, and long-term carbon cycle responses - that operate over millennia, while ECS captures only fast feedbacks (water vapor, clouds, sea ice, lapse rate) operating over decades to centuries. he PALAEOSENS Project (2012) established a framework for distinguishing these measures. Hansen et al. (2008) estimated that ESS is approximately twice ECS based on paleoclimate data spanning glacial to ice-free conditions, suggesting ~6°C ESS versus ~3°C fast-feedback sensitivity for doubled CO_2 meaning that long-term committed warming substantially exceeds the warming realized within policy-relevant timescales.

Recent deep-time paleoclimate reconstructions have produced notably high ESS estimates. Judd and colleagues (2024) reconstructed global mean surface temperature over the past 485 million years by statistically integrating proxy data with climate model simulations. Their analysis reveals an apparent Earth System Sensitivity of approximately 8°C for CO_2 doubling, with temperatures spanning 11-36°C across the Phanerozoic Eon. This reconstruction shows a strong correlation between atmospheric CO_2 and global temperature throughout Earth's history. Witkowski and colleagues (2024) examined the mid-Miocene period (15 million years ago) using molecular fossil proxies and calculated ESS of 13.9°C and ECS of 7.2°C for CO_2 doubling. However, subsequent analysis has questioned the Witkowski estimates, suggesting they may overestimate sensitivity due to uncertainties in baseline conditions and the relationship between regional proxies and global temperature.

The high ESS values from deep-time paleoclimate studies have several important implications for understanding ECS. If ESS is 8°C as Judd suggests, and the ESS/ECS ratio lies in the typical range of 1.5-2, this would imply ECS in the range of 4-5.3°C - consistent with estimates toward the upper end of the IPCC range. The paleoclimate evidence also suggests that climate sensitivity may be state-dependent, with warmer climates potentially exhibiting higher sensitivity than cooler ones. This raises questions about whether ECS derived from modest 20th century warming or glacial-interglacial cycles fully captures the sensitivity relevant to a substantially warmer future climate.

Hansen and colleagues (2023, 2025) focused on more recent paleoclimate evidence from glacial-interglacial cycles to estimate fast-feedback equilibrium climate sensitivity at 1.2 ± 0.3°C per W/m^2, equivalent to 4.8 ± 1.2°C for doubled CO_2 (likely range 3.6-6.0°C). This estimate exceeds the IPCC's central value and remains consistent across analyses of the full Cenozoic era. The authors argue that three independent analyses - paleoclimate evidence, the magnitude of warming since preindustrial times, and recent acceleration patterns - converge on these higher values with greater than 99% confidence. Hansen's May 2025 analysis quantifies cloud feedback through observed changes in Earth's albedo, which decreased by approximately 0.5% since 2000, equivalent to 1.7 W/m^2 of additional absorbed solar energy. After accounting for sea ice albedo changes (0.15 W/ m^2), this implies that cloud feedback has increased absorbed energy by 1.0-1.5 W/ m^2 over 25 years - a magnitude the authors argue is inconsistent with climate sensitivity as low as 3°C.

Several studies have applied emergent constraint methodologies to narrow cloud feedback uncertainty from modern observations. Wu and colleagues (2025) used multi-objective optimization to reconcile constraints from tropical Atlantic and Pacific low-cloud regions, examining approximately 200,000 possible model sub-ensemble combinations. Their analysis suggests that tropical cloud feedback may be toward the higher end of current model ranges. Lutsko and colleagues (2021) found relationships between tropical cloud variability and long-term feedbacks indicating that tropical cloud feedback is likely positive (>0 W/m m^2K^{-1}). Watson-Parris and colleagues (2025) documented that marine cloud reflectivity decreased by 2.8% ± 1.2% per decade over the North Atlantic and Northeast Pacific from 2003-2022, with

69% attributable to sulfur dioxide reductions - substantially exceeding most model predictions. These observational constraints generally point toward cloud feedbacks in the positive range, though the robustness of emergent constraints across model generations remains an active area of research.

Constraints from Historical Temperature and Aerosol Forcing

An alternative approach to constraining climate sensitivity uses the historical temperature record in combination with estimates of radiative forcing. This method faces substantial challenges due to uncertainties in aerosol forcing, which is not directly measured. Morgenstern (2024) used historical temperature observations to derive scaling factors for greenhouse gas warming and aerosol cooling that optimize agreement with observed temperatures. The analysis suggests that optimal aerosol cooling consistent with observations should be approximately 47% ± 39% of what CMIP6 models simulate in their aerosol-only experiments, yielding a multi-model mean cooling of 0.24 ± 0.11 for 2000-2014 relative to 1850-1899, compared to 0.63 ± 0.28 that models simulate on average.

This analysis reveals a systematic correlation: models with higher equilibrium climate sensitivity tend to simulate stronger aerosol cooling. Wang and colleagues (2021) demonstrated that this compensation mechanism allowed CMIP6 models to reproduce observed global-mean temperature changes despite having substantially different underlying climate sensitivities. The compensation works during the historical period when both aerosols and greenhouse gases were increasing but breaks down in future scenarios where aerosol concentrations decline while greenhouse gases continue rising. This relationship complicates interpretation of historical temperature constraints, as both high sensitivity with strong aerosol cooling and moderate sensitivity with weaker aerosol cooling can produce similar historical warming.

Skeie and colleagues (2024) used a Bayesian framework incorporating temperature and ocean heat content observations to estimate that inferred effective climate sensitivity ranges from 2.0 to 2.4 K depending on assumed aerosol forcing pathways - values toward the lower end of the IPCC range. Their analysis emphasizes that uncertainties in the time evolution of aerosol forcing remain a critical limitation. Hodnebrog and colleagues (2024) quantified that aerosol emission reductions contributed approximately 0.2 ± 0.1 W/m^2 per decade to the 2001-2019 energy imbalance trend. These studies suggest that much of the recent acceleration in warming may reflect aerosol reductions unmasking greenhouse warming, though the question remains whether this indicates moderate climate sensitivity with previously overestimated aerosol cooling, or higher climate sensitivity that is now becoming apparent as aerosol masking diminishes.

Reconciling Different Lines of Evidence

The evidence reviewed above presents apparently divergent implications for climate sensitivity. Satellite observations of energy imbalance components, recent temperature acceleration, large observed cloud feedbacks, and paleoclimate reconstructions point toward values at or above the upper half of the IPCC range, with some analyses suggesting substantially higher values. Conversely, historical temperature constraints suggest that if models overestimate aerosol cooling, observed warming may be consistent with climate sensitivity near or below the IPCC central estimate. Both perspectives acknowledge that declining aerosol emissions drive much of the recent acceleration in warming but differ on implications for underlying climate sensitivity.

Several factors complicate reconciliation of these perspectives. Recent research demonstrates that climate models face multiple potential biases in representing aerosol-cloud interactions. Chen and colleagues (2025) found that all six diverse global climate models examined fell outside the 90% confidence level for cloud cover response during the Holuhraun volcanic eruption, suggesting systematic underrepresentation of certain aerosol-cloud feedbacks. Simultaneously, Watson-Parris and colleagues (2025) showed that improved aerosol-climate modelling could reproduce the large observed decreases in cloud reflectivity when aerosol-cloud interaction physics were better represented. This suggests models may simultaneously underrepresent certain feedback mechanisms while potentially overestimating direct aerosol cooling.

The Myhre study's finding that models with ECS below 2.5°C cannot reproduce energy imbalance component trends provides a constraint less dependent on absolute aerosol forcing magnitude, as these component trends reflect fundamental physics of how the climate system's radiative response scales with warming. The convergence of multiple independent paleoclimate analyses toward higher values provides another line of evidence less affected by historical aerosol uncertainties. However, questions remain about whether paleoclimate sensitivities fully translate to the modern climate system, and whether the large observed cloud feedback identified by Hansen is primarily driven by reduced aerosol masking or indicates fundamentally higher climate sensitivity.

The most robust conclusion is that very low climate sensitivities (below 2.5°C) appear inconsistent with multiple lines of evidence, particularly the failure to reproduce energy imbalance component trends and the difficulty of reconciling observed acceleration with natural variability alone. Whether climate sensitivity lies near 3°C or substantially higher remains uncertain and depends critically on resolving aerosol forcing uncertainties and better understanding time-varying feedbacks. The compensation between high model sensitivity and strong aerosol cooling identified by Morgenstern suggests both parameters may require adjustment, though the direction and magnitude of adjustments needed remains debated. However, it is possible that ECS is at the top of or above the IPCC range.

Implications

The range of plausible climate sensitivity values has important implications for climate projections and policy. If climate sensitivity is near 3°C with aerosol cooling having been overestimated in models, then recent acceleration primarily reflects unmasking of greenhouse warming, and future warming may track mid-range model projections once aerosol effects are properly accounted for. If climate sensitivity is substantially higher (4-5°C or above), then current projections underestimate future warming, carbon budgets are overestimated, and timelines for reaching critical thresholds are shorter than anticipated. Under the highest estimates from Hansen and colleagues (ECS ~4.8°C), equilibrium warming for today's greenhouse gas forcing would be approximately 8-10°C after accounting for aerosols, with profound implications as aerosol emissions continue declining.

The rapid warming of 2023-2024, which exceeded projections from just a few years earlier, may help narrow these uncertainties as more data accumulate. However, definitively resolving climate sensitivity requires addressing several research priorities. Maintaining and enhancing satellite observations of Earth's radiation budget, aerosol properties, and cloud characteristics is essential - current CERES instruments are scheduled for decommissioning within a decade with limited follow-on missions planned. Better constraints on historical aerosol forcing through improved emissions inventories, enhanced process understanding of aerosol-cloud interactions, and targeted observations during periods of rapid emission changes would help separate aerosol effects from underlying sensitivity. Continued refinement of paleoclimate reconstructions and process-based understanding of cloud feedbacks provides important complementary evidence less dependent on historical aerosol uncertainties.

As aerosol concentrations continue declining globally due to air quality regulations, the masking effect will further diminish, potentially making climate sensitivity more apparent in coming years. Whether recent acceleration represents the beginning of this unmasking or reflects shorter-term variability superimposed on more stable long-term trends remains to be determined. Resolving these questions has fundamental implications for climate risk assessment and mitigation policy, determining whether humanity faces manageable climate change requiring aggressive but achievable mitigation, or more severe warming demanding immediate transformative action.

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