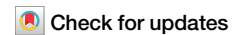




Arctic climate tipping points under delayed CO₂ emissions mitigation



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The Arctic is warming more than three times faster than the global average – driven by increasing CO₂ emissions – yet its response to the cessation of these emissions remains uncertain. We analyze 6-member ensembles of an Earth system model in which CO₂ emissions are set instantaneously to zero at cumulative emission totals ranging from 800 to 2000 PgC. While global mean temperature stabilizes after CO₂ emissions cessation, we find that the Arctic exhibits nonlinear and bifurcating behavior: either continued warming and sea-ice loss (below 1700 PgC), or abrupt cooling and sea-ice expansion (above 1700 PgC). The cooling results from a near-collapse of the Atlantic Meridional Overturning Circulation, causing reduced poleward ocean heat transport and amplifying lapse-rate and surface-albedo feedbacks. This collapse occurs when CO₂ emission mitigation is delayed and global-mean temperature exceeds the 2°C Paris Agreement target. Our results suggest stochastic tipping behavior modulated by the increased greenhouse gas forcing, triggering an abrupt transition to an alternative Arctic climate state.

The Arctic climate is one of the most sensitive components of the Earth system^{1–3}. The region is warming at a rate more than three times the global average, a fact known as Arctic amplification^{4–6}. This rapid Arctic warming associated with considerable sea-ice decline, with significant impact on ecosystems, economies, and geopolitics^{7–9}. It is well established that these climate changes are primarily driven by increasing greenhouse gas concentrations in the atmosphere^{10–12}, particularly carbon dioxide (CO₂)^{13,14}, which is the largest contributor to present-day climate forcing^{3,15}. While numerous future scenarios of CO₂ emissions have been explored in the context of Representative Concentration Pathways (RCPs)¹⁶ and Shared Socioeconomic Pathways (SSPs)¹⁷, among others, most studies have focused on the climate response to monotonically increasing emissions. At this time CO₂ emissions mitigation scenarios remain underexplored, especially in terms of how the Arctic system will respond anthropogenic cease.

CO₂ mitigation frameworks, including the Paris Agreement¹⁸, aim to limit global mean temperature rise to below 2°C above preindustrial levels, requiring CO₂ emissions to reach net zero around mid-21st century. Because CO₂ is the dominant driver of long-term warming, the global warming response to emission cessation is often characterized by the Zero Emissions Commitment (ZEC)—the amount of additional warming that occurs after CO₂ emissions stop^{19–21}. Unlike the RCP or SSP scenarios, which generally prescribe long-term forcing (i.e., concentration) for many GHGs, ZEC experiments focus solely the transient climate response to CO₂ emissions,

allowing greater insight into the physical and biogeochemical mechanisms that govern post-emission CO₂ climate evolution. The Zero Emissions Commitment Model Intercomparison Project (ZECMIP)^{22,23} provides a coordinated framework to evaluate these processes across Earth system models. Recent studies show that while global mean ZEC in most climate models is close to zero^{24,25}, regional responses such as in the North Atlantic are more uncertain due to intermodel differences in ocean heat uptake and carbon-cycle feedbacks^{26,27}.

Despite the assumption that the global mean ZEC is close to zero, there exist pathway dependence and regional uncertainty in its estimates^{23,28,29}. With the sign and magnitude of post-cessation climate responses depending on both the peak CO₂ concentration and the timing of emission cessation, which together influence large-scale climate dynamics such as the Atlantic Meridional Overturning Circulation (AMOC)^{30,31}, thereby shaping regional climate responses, especially in the Arctic. One might expect that the Arctic ZEC would exhibit particularly strong pathway dependence, given the inherently large variability and forcing sensitivity of the region. Hence, in this study, we focus specifically on the ZEC in the Arctic, extending the original ZECMIP framework by including a wider range of cumulative emissions (800–2000 PgC) to better capture potential nonlinear Arctic climate responses and tipping points.

In this study, we utilize extensions to the original ZECMIP protocol, which include a wider range of cumulative emissions and ask: (1) What

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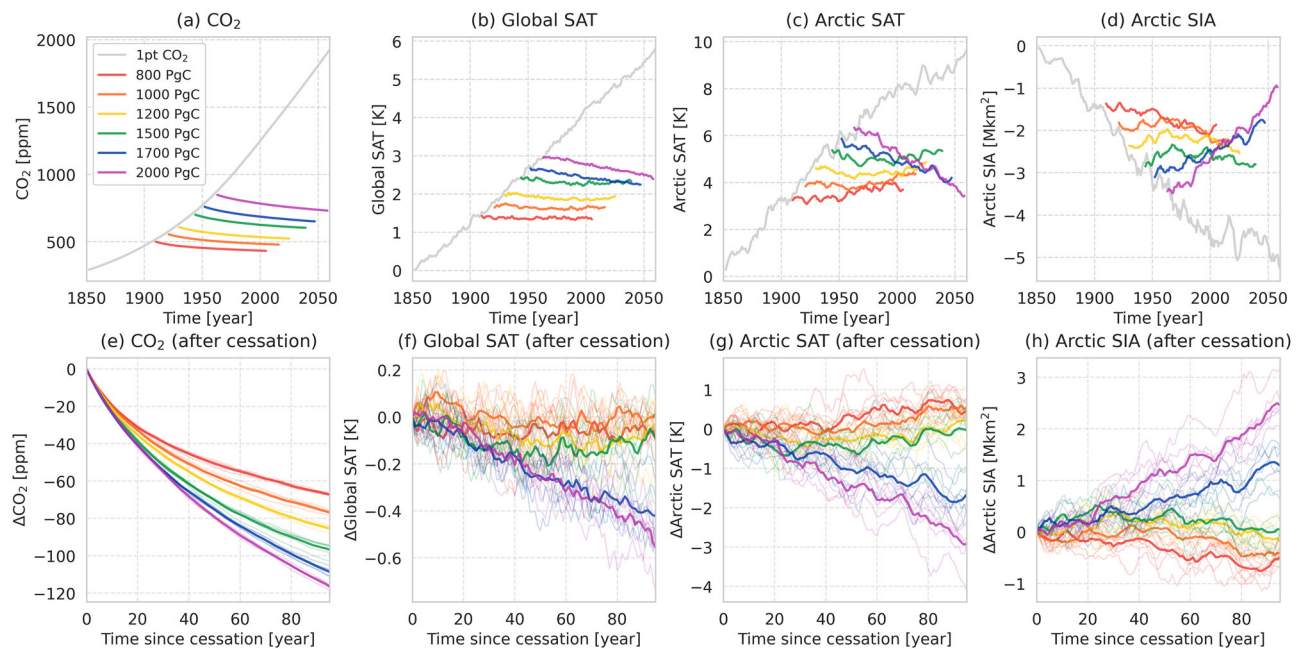


Fig. 1 | Global and Arctic climate responses to zero-CO₂ emissions in GISS

ModelE2.1-ESM2. **a–d** Time series of atmospheric CO₂ concentration, global mean surface air temperature (SAT) change, Arctic SAT change, and Arctic sea-ice area (SIA) change under an idealized one-percent-per-year CO₂ increase (grey) and zero-emission scenarios with cessation at 800, 1000, 1200, 1500, 1700, and 2000 PgC

(coloured lines), SAT and SIA changes are referenced to pre-industrial levels.

e–h Same as in **a–d**, but shown as anomalies relative to the year of CO₂ cessation, i.e. Zero emissions commitment (ZEC). All ZEC scenarios are run for 100 years post-cessation. Thick coloured curves denote ensemble means across six members, and thin lines indicate individual realizations.

Arctic climate changes, including potential tipping points, occur after CO₂ emissions cease, and what physical mechanisms drive these transitions? (2) How do these changes differ across cumulative emission levels? To address these questions, we use the NASA Goddard Institute for Space Studies (NASA-GISS) modelE version 2.1-G with fully interactive carbon cycle version 2 (GISS-ModelE2.1-G-CC2; see Methods). In these experiments, CO₂ emissions increase consistent with atmospheric concentration increases by 1% per year from preindustrial levels until cumulative totals reach 800, 1000, 1200, 1500, 1700, and 2000 PgC, and then emissions are abruptly set to zero. Each scenario includes six ensemble members. These experiments enable us to systematically examine the Arctic's post-emission climate trajectories and the underlying physical mechanisms, and to determine whether and when the Arctic climate stabilizes or transitions into an alternative climate state.

Results

Arctic ZEC and associated climate responses

We begin by examining the evolution of atmospheric CO₂ concentrations in our model experiments (Fig. 1a). In the 1% yr⁻¹ increase experiment (1pt CO₂), concentrations reach about 750 ppm after 100 years from the pre-industrial period (1850) and approach 1800 ppm after 200 years—roughly seven times the pre-industrial level. In the six ZEC experiments (coloured lines), CO₂ peaks between 500 ppm and 850 ppm, corresponding to cumulative emissions of 800–2000 PgC before starting to decline. Following emission cessation, atmospheric CO₂ concentrations decline at different rates across the six scenarios, with the highest-accumulation scenario showing nearly twice the post-cessation drawdown rate of the lowest-accumulation scenario (Fig. 1e). These emission pathways strongly influence global surface air temperature (SAT), which at the time of cessation ranges from 1.3 K to 3 K above the pre-industrial mean (Fig. 1b). In lower-accumulation scenarios (800–1500 PgC), global SATs exhibit an initial cooling followed by a recovery toward the cessation level about 60 years after zero emissions (Fig. 1f). In contrast, the higher-accumulation scenarios (1700–2000 PgC) show a persistent cooling of 0.4–0.6 K in the century following cessation.

The Arctic (60°–90°N) displays amplified temperature changes relative to the global mean (Fig. 1c,g). At the time of emissions cessation, Arctic SAT anomalies range from 3 K to 6 K higher than the pre-industrial stage, illustrating strong Arctic amplification. After cessation, the 800–1000 PgC scenarios continue to warm slightly (0.5 K), the 1200–1500 PgC scenarios cool briefly and then recover, and the 1700–2000 PgC scenarios undergo large cooling of 2–3 K over the following century. Changes in Arctic SAT are mirrored by opposite-signed trends in Arctic sea-ice area (SIA; Fig. 1d,h). Relative to pre-industrial conditions, SIA is reduced by 1–3.5 Mkm² at the time of cessation, but its evolution diverges thereafter: the 800 PgC scenario loses an additional 0.5 Mkm² of SIA, whereas the 2000 PgC scenario gains roughly 2.5 Mkm² of SIA by 100 years post-cessation. Notably, despite higher global temperatures, the 2000 PgC experiment reaches nearly the same Arctic SAT as the 800 PgC experiment case after a century post-cessation, yet with substantially greater ice cover. These results indicate that the Arctic responds more sensitively and nonlinearly to cumulative carbon emissions than the global mean, suggesting the existence of an emergent critical threshold (tipping point) beyond which Arctic climate trajectories bifurcate toward either continued warming or pronounced cooling after CO₂ emissions cease.

Arctic climate responses also exhibit strong spatial heterogeneity after CO₂ emissions cease. Figures 2a–f show ensemble-mean linear trends of SAT during the 100-year post-cessation period. In the lower-accumulation scenarios (Fig. 2a–d), SAT trends are slightly positive across most of the Arctic, indicating weak continued warming, while the higher-accumulation scenarios (Fig. 2e,f) display widespread cooling, with the Arctic-averaged SAT trend in the 2000 PgC case about four times stronger than the warming trend in the 800 PgC case. Corresponding trends in Arctic SIA (Fig. 2g–i) mirror these temperature changes. The average SIA increase in the 2000 PgC case is approximately 3.5 times larger than the decrease in the 800 PgC case, indicating a nonlinear, bifurcating Arctic response under different CO₂-mitigation levels. In addition, the regions showing the strongest sensitivity include the Barents-Kara Seas and the Greenland margins, where SAT and SIA trends diverge most sharply across CO₂-mitigation scenarios. Our results, therefore, suggest that the Arctic climate system crosses a

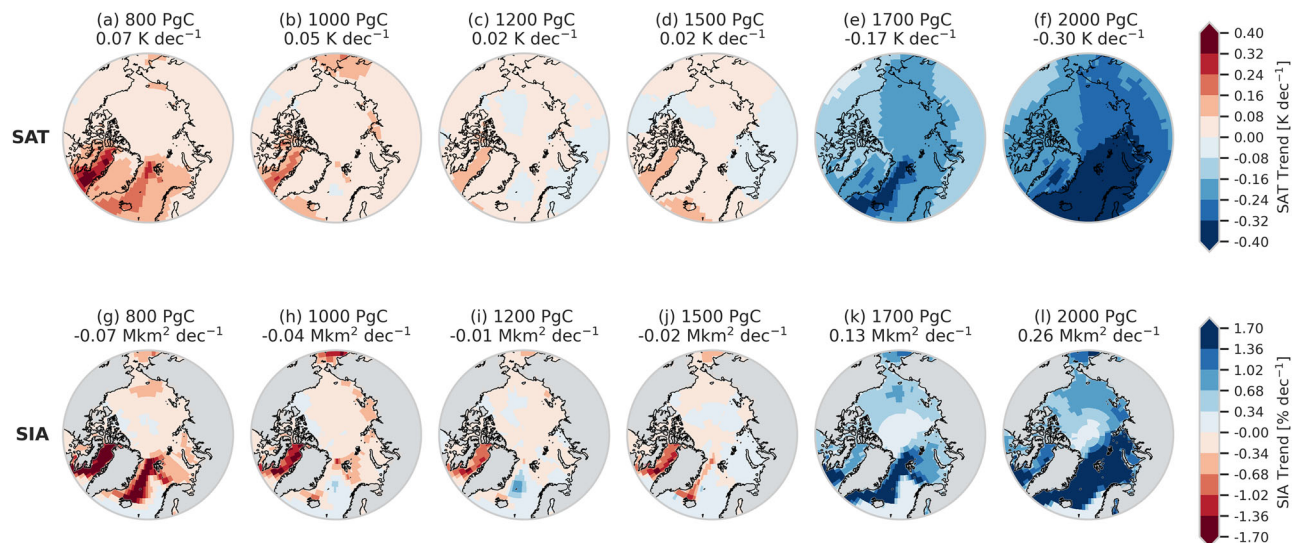


Fig. 2 | Spatial trend maps over Arctic region following zero CO₂ emissions. a–f Ensemble-mean trends in Arctic (60°–90°N) SAT during the 100 years following cessation of CO₂ emissions. g–l, As in a–f, but for Arctic SIA. Panel titles indicate the ZEC scenarios, and the value beneath each title is the ensemble-mean and Arctic-

mean trend (K dec^{−1} for SAT; Mkm² dec^{−1} for SIA). Warm colors indicate continued warming and sea-ice loss, while cool colors indicate Arctic cooling and sea-ice expansion.

tipping threshold wherein weak warming continued in the lower-accumulation scenarios transitions to strong cooling regimes under delayed mitigation. In the next section, we discuss the physical mechanisms underlying this tipping threshold.

Causes of Arctic tipping

We find that the divergent Arctic climate trajectories across CO₂-mitigation scenarios are associated with different responses of the AMOC (Fig. 3a), similar to those described in Romanou et al. (2023)³⁰. Whereas in the lower-accumulation scenarios the ensemble-mean AMOC strengthens post-cessation (red, orange, yellow and green lines), it declines steadily in the higher-accumulation scenarios (blue and purple lines). This divergent behavior indicates the existence of a tipping point in the AMOC response under ZEC conditions, shown in Fig. 3b, where we plot AMOC strength vs. CO₂. The Arctic tipping point behavior is particularly clear in Fig. 3c,d. Note how the blue and green curves overlap each other post-cessation but separate as CO₂ decreases past ~ 650 ppm and diverge thereafter (time increases to the left while CO₂ increases to the right in these plots). Both Arctic SAT and SIA bifurcate at around ~ 650 ppm, the tipping point value of CO₂. In terms of cumulative emissions, the tipping point is found somewhere between 1500 and 1700 PgC.

To physically connect the divergent AMOC responses to the corresponding Arctic SAT and SIA responses, we examine the changes in the Arctic energy budget (see Methods) 100 years after emission cessation relative to the onset of zero emissions (Fig. 4). The analysis reveals ocean heat transport (OHT) changes that are consistent with the AMOC changes across the CO₂-mitigation scenarios. For example, in the 2000 PgC scenario, in which the AMOC nearly collapses (Fig. 3), the OHT response is strongly negative, indicating a substantial reduction in OHT into the Arctic that contributes to the strong Arctic cooling and sea-ice expansion in this scenario. OHT responses across the scenarios are compensated, at least in part, by the atmospheric heat transport (AHT) responses. Our analysis further highlights that lapse-rate and surface-albedo feedbacks are the leading amplifiers of the Arctic temperature response^{1,32,33}, particularly in the 2000 PgC scenario, where their magnitudes (in Wm^{−2}) far exceed those in lower-accumulation cases. Other terms in the energy budget are typically smaller in magnitude, although we note that the remaining feedbacks (Planck, water vapor, and cloud) generally reinforce the effect of the OHT response and the lapse-rate and surface-albedo feedbacks. In summary, the Arctic energy

budget reveals a clear process hierarchy: OHT acts as the primary driver, with anomalies ranging from + 1.5 to + 2 Wm^{−2} in the lower-accumulation cases and reaching − 3 Wm^{−2} in the 2000 PgC scenario, while lapse-rate and surface-albedo feedbacks serve as secondary amplifiers (0 to + 1 Wm^{−2} and − 1.5 to − 2.5 Wm^{−2}, respectively).

Discussion

In summary, the Arctic climate exhibits a distinctly nonlinear response to the cessation of CO₂ emissions, diverging into two different pathways—continued warming or abrupt cooling—depending on the timing of emission cessation. The abrupt Arctic cooling emerges for cumulative CO₂ emissions at above 1700 PgC, marking a tipping threshold within the Arctic climate system. This cooling coincides with a significant weakening or collapse of the AMOC, consistent with previous studies linking North Atlantic circulation slowdowns to high-latitude cooling and sea-ice expansion^{34,35}. Notably, individual realizations of a given ZEC experiment reveal stochastic divergence due to internal variability: one member of the 1500 PgC scenario undergoes a near-complete AMOC collapse, in contrast to the ensemble mean, whereas one member of the 1700 PgC scenario shows AMOC recovery, again in contrast to the ensemble mean. AMOC weakening cools the Arctic by reducing the poleward OHT, and this is further amplified by lapse-rate and surface-albedo feedbacks over the Arctic.

Despite this robust physical mechanism, one might question the potential model dependence of our results. Model intercomparison with ZECMIP (see Methods) shows that our simulations, across both lower-accumulation cases (800 or 1000 PgC, Figs. S1 and S2) and higher-accumulation cases (2000 PgC, Fig. S3), generally lie within the mid-range of other Earth system models, yet different models exhibit divergent Arctic temperature and sea-ice trajectories for the same emissions scenario. In addition, the divergent AMOC behavior is further supported by Oh et al. (2025)³⁶ who identified AMOC bifurcation under zero-emission scenarios using Community Earth System Model (CESM), an independent model with different ocean physics, suggesting that AMOC tipping under delayed mitigation may not be unique to this model. Future work should therefore further examine the Arctic ZEC using additional models, finer cumulative emission increments (e.g. 1600 PgC), and larger ensembles to better quantify the likelihood of passing Arctic tipping thresholds, and to better constrain how model differences in the pre-industrial AMOC strength and climate sensitivity affect the location of the stochastic tipping zone.

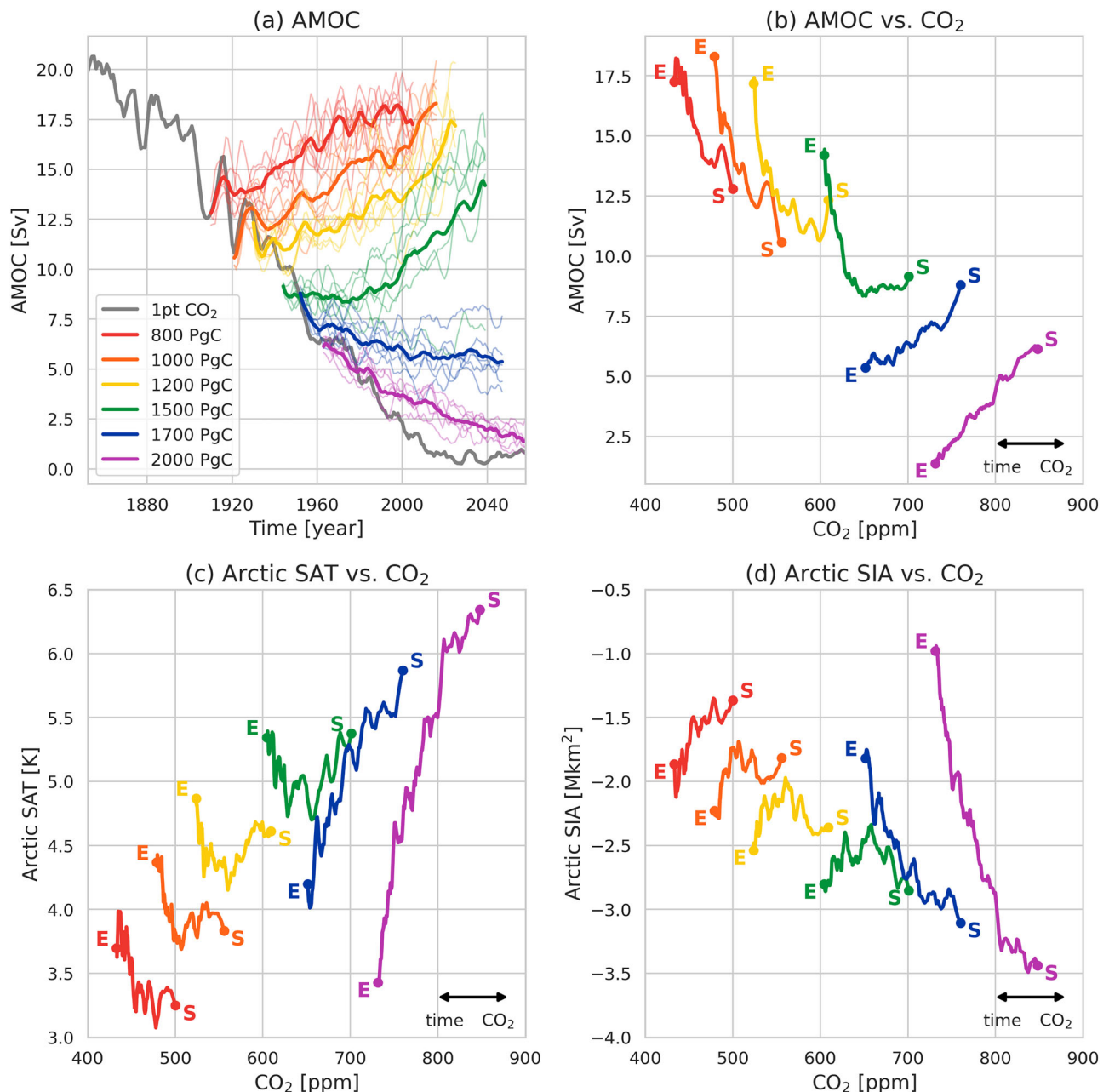


Fig. 3 | AMOC and Arctic climate response to zero-CO₂ emissions. **a** Time series of Atlantic Meridional Overturning Circulation (AMOC) strength at 48°N (Sv) under the emission-cessation scenarios shown in Fig. 1. Thick coloured curves denote ensemble means, with thin lines indicating individual ensemble members. **b** AMOC strength as a function of atmospheric CO₂ concentration. **c, d**, As in **b**, but

for Arctic SAT and Arctic SIA, respectively. In **b–d**, only ensemble-mean trajectories are shown; filled circles mark the beginning and end of each trajectory, labelled by S (start) and E (end). The double-headed arrow indicates the progression in time and atmospheric CO₂.

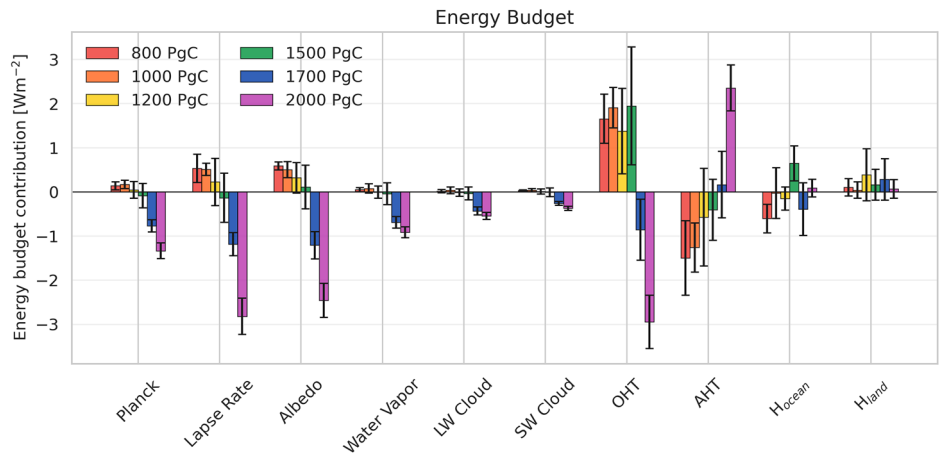
The existence of Arctic climate tipping points carries significant implications for mitigation policy. The tipping threshold in our model of ~ 1700 PgC corresponds to a global warming of 2.7°C at the time of cessation, exceeding the 2°C Paris Agreement climate target. Our results demonstrate very clearly that if CO₂ emissions mitigation is delayed beyond the point where the Paris Agreement climate target (2°C global warming) is breached, the Arctic is increasingly likely to transition into an alternative climate state characterized by cooling and sea-ice expansion, which may persist for decades or longer. Such nonlinear and abrupt transitions will complicate projections of regional climate, ecosystem stability, and socio-economic planning across the polar domain.

Methods

NASA-GISS modelE2-1-G-CC2

We utilize the NASA Goddard Institute for Space Studies (GISS) ModelE2-1-G-CC2²⁷, which is based on the NASA-GISS ModelE2.1^{37,38} that was included in the sixth phase of the Coupled Model Intercomparison Project (CMIP6)³⁹, but implemented here in an emissions-driven configuration that includes a fully interactive carbon cycle coupled to the atmosphere, ocean, and land components. The atmospheric component of the model has a horizontal resolution of 2° latitude by 2.5° longitude with 40 vertical layers extending from the surface to 0.1 hPa in the lower mesosphere. It is coupled to the GISS Ocean V1 (E2.1-G) general circulation model, which has a horizontal resolution of 1° latitude by 1.25° longitude and 40 vertical layers,

Fig. 4 | Arctic energy budget response to zero-CO₂ emissions. Contributions of individual feedbacks, heat transports, and heat uptake to the perturbation Arctic energy budget (see Methods). Values are calculated as differences between years 91–100 and years 1–10 after emission cessation, shown as ensemble means with error bars denoting one standard error across $n = 6$ independent ensemble members. Feedback terms include Planck, lapse rate, albedo, water vapor, and longwave (LW) and shortwave (SW) cloud; transport terms include ocean heat transport (OHT) and atmospheric heat transport (AHT); uptake terms include ocean and land heat uptake (H_{ocean} , H_{land}). Positive values indicate energy input to the Arctic.



refined to 5–20 m layer thickness near the surface and about 200 m layer thickness at depth. The model features fully interactive land and ocean carbon cycles. The land component follows the standard CMIP6 implementation²⁷, while the ocean biogeochemical module has been updated to include dissolved oxygen tracers that interact with organic matter remineralization, allowing transitions between aerobic respiration and denitrification⁴⁰.

ZECMIP

To compare with our NASA-GISS simulations (see below), we use additional model output from the Zero Emissions Commitment Model Inter-comparison Project (ZECMIP)²². ZECMIP investigates idealized CO₂ emissions trajectories through two classes of experiments: type-A and type-B. Type-A experiments, which we analyze here, branch from the 1% yr⁻¹ CO₂ increase experiment of CMIP6. After a target cumulative emission is reached, emission are abruptly set to zero and the model is integrated for an additional 100 years. We analyze three type-A experiments with cumulative emissions of 750, 1000, and 2000 PgC. In all ZECMIP experiments, only atmospheric CO₂ is varied, while non-CO₂ forcings (e.g., CH₄, aerosols) are held fixed at preindustrial levels.

NASA-GISS simulations

We conducted a suite of emissions-driven simulations following the type-A experiments of ZECMIP using NASA-GISS ModelE2.1-G-CC2. Starting from a preindustrial climate state, CO₂ emissions are prescribed such that CO₂ concentrations increase along a 1% yr⁻¹ trajectory until cumulative emissions reach values between 800 and 2000 PgC. At these points, emissions are instantaneously set to zero and the model is integrated for an additional 100 years. Non-CO₂ forcings, including other well-mixed greenhouse gases, aerosols, ozone, and land cover, are held constant at preindustrial levels throughout all simulations. In total, we analyze six zero-emission CO₂ scenarios (800, 1000, 1200, 1500, 1700, and 2000 PgC), each including six ensemble members with slightly different atmospheric initial conditions to sample internal climate variability.

AMOC

We define the strength of the Atlantic Meridional Overturning Circulation (AMOC) as the maximum value of the annual-mean meridional overturning streamfunction below 500 m depth at 48°N in the North Atlantic.

Energy budget analysis

We apply an energy budget analysis for the Arctic domain (60°–90°N) to quantify the contributions of radiative feedbacks and changes in horizontal heat transport to Arctic temperature change in our simulations. For the energy budget of an atmosphere-ocean column, the change in net top-of-atmosphere radiation (ΔR) balances the sum of net horizontal heat

transport change (ΔF) and total column heat uptake (ΔH):

$$\Delta R + \Delta F = \Delta H \quad (1)$$

Here, Δ represents the difference between years 1–10 and 90–100 following CO₂ emissions cessation. ΔR can be decomposed into radiative forcing (ΔQ) and the sum of individual climate feedbacks ($\sum_i \lambda_i \Delta T_s$):

$$\Delta R = \Delta Q + \sum_i \lambda_i \Delta T_s \quad (2)$$

where ΔT_s denotes the change in Arctic near-surface air temperature, and λ_i represents the feedback parameters, including surface albedo, Planck, lapse-rate, water vapor, shortwave cloud, and longwave cloud feedbacks. These feedbacks are computed using the radiative kernels method⁴¹, employing CAM5 kernels⁴² implemented as part of the ClimKern package⁴³. The Planck feedback is defined as the local deviation from the global mean. Note that although ΔQ is not available for our simulations, we infer the radiative effect of CO₂, in a qualitative sense, from changes in its atmospheric concentration (Fig. 1a,e). Based on this, we conclude that CO₂ variations contribute to Arctic cooling in the high-accumulation scenarios but oppose Arctic warming in the low-accumulation scenarios.

ΔH is separated into oceanic (ΔH_{ocean}) and terrestrial (ΔH_{land}) components:

$$\Delta H = \Delta H_{\text{ocean}} + \Delta H_{\text{land}} \quad (3)$$

where ΔH_{ocean} is calculated from vertically integrated Arctic ocean temperature changes, and ΔH_{land} from changes in net surface heat flux over Arctic land grid cells. We neglect heat uptake by atmosphere, which is small compared to the ocean and land. Finally, ΔF is calculated as a residual from equation (1), and is partitioned into oceanic (ΔOHT) and atmospheric (ΔAHT) contributions:

$$\Delta F = \Delta \text{OHT} + \Delta \text{AHT} \quad (4)$$

where ΔOHT is computed from the meridional convergence of ocean heat flux in the Arctic, and ΔAHT is computed as the residual in equation (4).

Data availability

The ZECMIP simulations used in this study are available through the Earth System Grid Federation (<https://esgf.llnl.gov>). The NASA-GISS ModelE2.1-G-CC2 simulation output for this study is available on the Y.-T. Wu's Zenodo repository (<https://zenodo.org/records/21142617>).

Code availability

The Python scripts for processing data and plotting figures are available on Y.-T. Wu's Zenodo repository (<https://zenodo.org/records/21142650>).

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Competing interests

The authors declare no competing interests.

Additional information

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