One Earth

CellPress

Commentary

The risk of a hothouse Earth trajectory

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Earth's climate is now departing from the stable conditions that supported human civilization for millennia. Crossing critical temperature thresholds may trigger self-reinforcing feedbacks and tipping dynamics that amplify warming and destabilize distant Earth system components. Uncertain tipping thresholds make precaution essential, as crossing them could commit the planet to a hothouse trajectory with long-lasting and potentially irreversible consequences.

During the mid-to-late Pleistocene (∼1.2 million to 11,700 years before present), Earth's climate oscillated between ice ages and warmer interglacials, with temperatures ranging roughly between −6°C and +2°C relative to the pre-industrial mean of ∼14°C (Figure 1A). The Holocene, beginning ∼11,700 years ago, developed into a relatively stable climate that enabled agriculture, complex societies, and today's ecosystems to develop and thrive. Today, global temperatures are as warm as, or warmer than, any period in the last 125,000 years and it is likely that carbon dioxide levels are higher than at any time in at least the past two million years (Figures 1A and S1).[1] We are leaving the stable conditions of the Holocene, and entering a period of unprecedented climate change beyond the natural interglacial envelope, with outcomes that are difficult to predict.

In an effort to mitigate dangerous levels of warming, the Paris Agreement formalized the aim of limiting warming to 1.5°C above preindustrial levels, yet global temperatures have recently breached this limit for 12 consecutive months, coinciding with record-breaking heat, wildfires, floods, and other extremes.[2] Although temperature limit exceedance is typically evaluated using the 20-year centered mean global temperature, climate model simulations suggest the recent 12-month breach may indicate this long-term average is at or near 1.5°C.[2] Despite decades of research and sophisticated computational climate modeling, the magnitude and pace of these events have surprised scientists, raising questions about how well current climate projections capture risk. At the same time, research on climate tipping points, amplifying feedbacks, and cascading interactions shows that several Earth system components may be closer to destabilizing than once believed.[3] These processes are thought to be the precursors of a potential "hothouse trajectory": a pathway in which self-reinforcing feedbacks push the climate system past a point of no return, committing the planet to substantially higher long-term temperatures, even if emissions are later reduced.[4] Policymakers and the public, however, remain largely unaware of the risks posed by such a practically irreversible transition.[5] Importantly, a "hothouse trajectory" on human timescales is distinct from a "hothouse state," the possible far-future outcome in which the planet experiences sustained extreme warming and sea levels many meters higher than the present. The distinction is important as preventing the hothouse trajectory is far more achievable than trying to reverse it once the planet is committed to an eventual hothouse state. The severity of these looming changes highlight the urgent need for caution and much deeper investigation. Here, we explore the scientific evidence for the risk of a hothouse Earth trajectory, emphasizing the role of feedback loops, climate tipping points, interactions, and cascades that are likely important in shaping our planetary future. We explicitly link feedback dynamics with tipping point dynamics, clarifying the mechanisms by which a hothouse trajectory could unfold.

Predicting the future

Possible climate futures are projected by combining climate models with assumptions about how society might develop. Climate projections are often organized around Shared Socioeconomic Pathways (SSPs), scenarios that help inform Intergovernmental Panel on Climate Change (IPCC) assessments and policy choices by generating a series of futures that range from low-emission, sustainable worlds (SSP1) to "middle of the road" trends (SSP2), to high-emission, fossil-fueled societies (SSP5) (Figures 1A and S1).[6]

Present emission reduction pledges and policies may align with an SSP2-type world,[7] wherein warming would overshoot the 1.5°C limit and potentially lead to multi-degree warming this century and centuries of elevated temperatures thereafter. Under such an "overshoot" scenario, returning temperatures to safer levels below 1.5°C will require rapid decarbonization plus potentially unfeasible scales of carbon dioxide removal. The longer and higher the temperature overshoot, the greater the risk of strengthening self-reinforcing feedbacks and triggering tipping points that could commit the planet to a hothouse trajectory, even if emissions are later greatly reduced. Specifically, a major risk is from a cascading shift from largely dampening feedbacks to increasingly self-reinforcing feedbacks that alone accelerate warming.[4]

The uncertainty of change

Climate models provide valuable scenarios, but they cannot capture the full complexity of the climate system and despite decades of research, efforts to digitally replicate Earth's climate system remain affected by large uncertainties. The fact that the 1.5°C limit was surpassed in 2024 despite many climate projections forecasting a breach later, underscores how rapidly climate change is advancing. Modern historical increases in global surface temperatures have been tightly coupled with increases in carbon dioxide (Figure 1B). But, warming itself appears to be accelerating: the rate has risen from roughly 0.05°C per decade in the mid-20th century to about 0.31°C per decade today (Figure 1C). At this pace, warming may soon cross levels often seen as a limit against severe impacts and tipping cascades.[4] This rapid rise narrows the time frame available to prevent self-reinforcing processes from taking hold. Furthermore, declining aerosol emissions reduce the cooling effect that has masked greenhouse gas warming, potentially adding up to a further ~0.5°C to global temperatures.[1] This loss of aerosol masking explains part of the recent acceleration in warming. Emerging evidence suggests that other feedbacks may also be contributing, including cloud–albedo changes linked to aerosol declines, shifts in land surface reflectivity, and reduced carbon uptake on land, rather than a temporary response to changing external forcings such as greenhouse gases or aerosols.[1,8,9]

Feedback loops are processes where a change in the climate system amplifies or dampens further change. Amplifying feedbacks heighten the risks of accelerated warming (Figure 2A). For example, melting ice and snow, permafrost thaw, forest dieback, and soil-carbon loss can all magnify warming.[10] Some processes such as the ice-sheet-elevation effect, where melting accelerates as surfaces drop and absorb more heat, have the potential for escalating responses.[11] These feedbacks interact with the climate system's sensitivity to greenhouse gases (Figure S3). Equilibrium climate sensitivity is likely at least about 2.5°C–4°C per CO_2 doubling, but could exceed 4.5°C per CO_2 doubling.[1,8] Equilibrium climate sensitivity may have historically been underestimated due to limitations in modeling cloud dynamics, such as reduced low-level clouds, which has been tentatively linked to recent record-low planetary albedo.[9] Long-term Earth-system sensitivity, which includes slow amplifying feedbacks involving ice sheets and vegetation, may approach ~8°C per CO_2 doubling (Figure S3C).[12] If climate sensitivity is sufficiently high, even moderate overshoot or feedback-driven emissions could produce far greater warming than most baseline scenarios suggest and shift the Earth's climate system toward a hothouse trajectory, a point of no return.[8]

Crossing critical thresholds

A central concern is the activation of climate tipping elements, large subsystems within the Earth system that can shift once critical temperature thresholds are crossed. Sixteen major tipping elements have been identified, ten of which could add to global temperature if triggered (Figure 2B).[3,13] Tipping may already be underway or could occur soon for the Greenland and West Antarctic ice sheets, boreal permafrost, mountain glaciers, and parts of the Amazon rainforest (Figure 2B). These processes could raise global temperatures, accelerate sea-level rise, release vast stores of carbon, and destabilize ecosystems. The precise threshold temperatures remain uncertain, but research shows that crossing one or more of these thresholds could trigger self-reinforcing processes that propel the Earth system onto a hothouse trajectory with long-lasting and potentially irreversible consequences (Figure 3A).[4] The interconnectedness of tipping elements compounds the risk they pose. There can even be remote interactions between spatially distant tipping elements (Figure 3B).[14] Most tipping interactions are destabilizing in nature (Figure S4). If one element tips, it can trigger a cascade effect, pushing other systems past their thresholds. Such tipping cascades have the potential to drive self-sustaining climate change adding to the risk of triggering a hothouse Earth trajectory.[15] Realistically, we are on a trajectory toward temperature overshoot, raising further concerns about crossing tipping points. While uncertainty remains, model results indicate that even a temporary overshoot could increase tipping risks by up to 72% compared to non-overshoot scenarios.[16]

Some feedback processes are themselves potential tipping points, and evidence suggests several may already be close to or beyond critical thresholds (Figure 2). The Earth system operates as a tightly coupled whole, where destabilization in one region can reverberate across oceans and continents (Figure S4). For example, as a relatively simple case study scenario (Figure 3B), where future human activities increase greenhouse gas concentrations, causing global temperatures to rise, which leads to further melting of Arctic sea ice and the Greenland Ice Sheet, which in turn accelerates warming by reducing Earth's albedo. With the decline of these northern ice sources, the resulting meltwater could perturb the Atlantic Meridional Overturning Circulation (AMOC), which is already showing signs of weakening.[3] A weakened AMOC could alter global atmospheric circulation, shifting tropical rain belts and drying parts of the Amazon. This cascade of events could trigger large-scale Amazon forest dieback, with major consequences for the region's carbon storage and biodiversity.[15] Compounding stressors, including global warming, deforestation, anthropogenic fires, and altered rainfall could push a portion of the Amazon toward a tipping point and a shift toward degraded savanna conditions.[17] Carbon released by Amazon dieback would further amplify global warming and interact with other feedbacks, triggering cascading effects among interconnected tipping elements (Figure S4). A web of amplifying feedbacks and destabilizing tipping elements could push the Earth system toward a hothouse pathway, locking in substantially higher long-term temperatures even if human emissions decline.[10,13,15] Quite concerning is the growing evidence that

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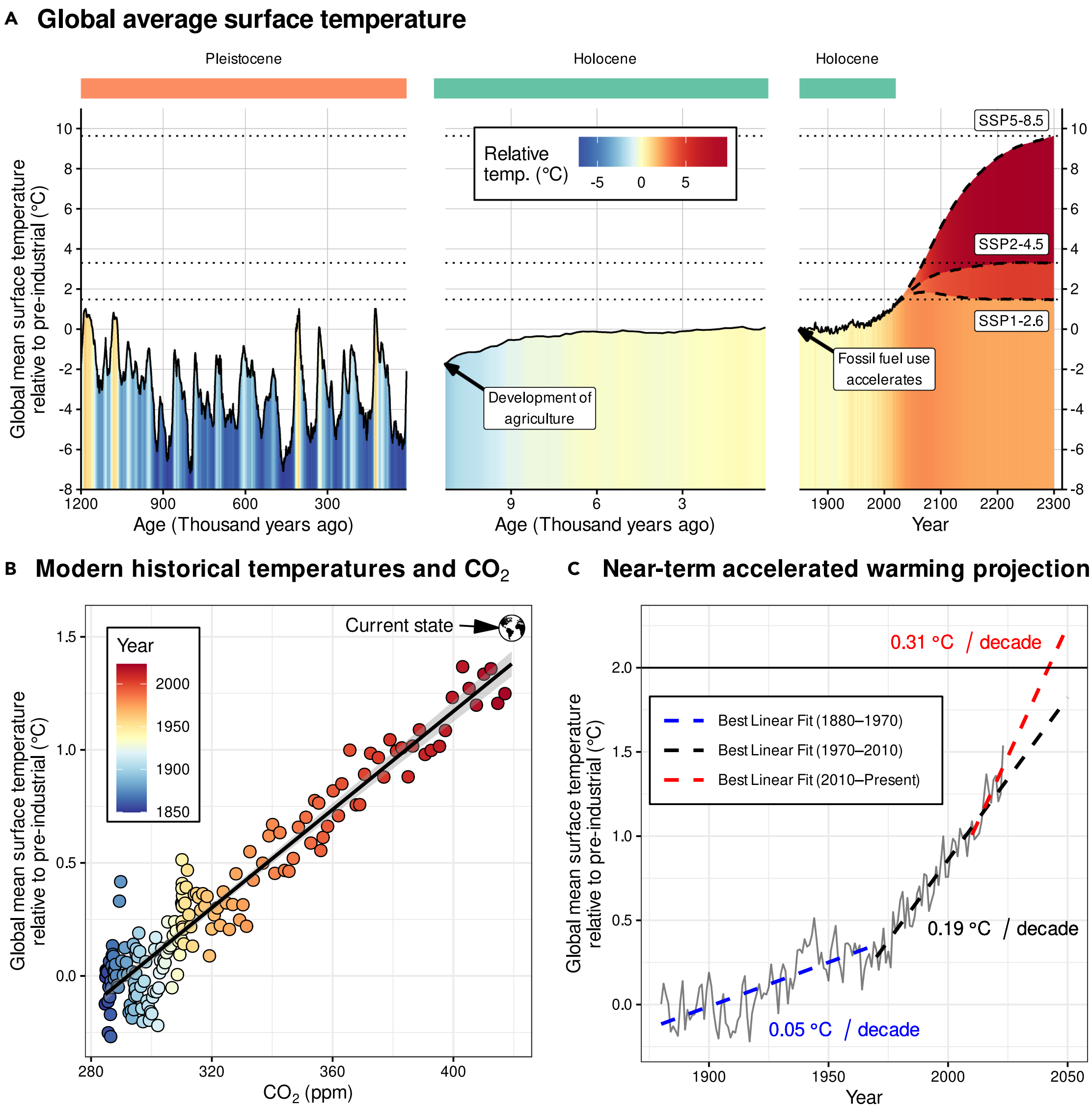

Figure 1. Historical and projected future temperatures in context

(A) Temperatures since the mid Pleistocene, spanning the last 1.2 million years along with projections up to 2300. Over the course of this century and beyond, global temperatures could rise to levels that have not occurred in more than a million years. Horizontal dotted lines show the projected temperatures by 2300 for three different scenarios. In 2300, the median projected temperatures are 1.5°C (1°C–2.2°C), 3.3°C (2.3°C–4.6°C) and 9.6°C (6.6°C–14.1°C) for SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively, where the ranges provide the full 5%–95% confidence estimates.[1] The top bar shows geological epochs.

(B) Recent temperatures and CO_2 levels are strongly correlated. Continued CO_2 emissions greatly increase the risk of a hothouse Earth trajectory.

(C) Preliminary evidence suggests the rate of warming is accelerating and we could cross the 2°C limit before mid-century with current observed rates. See supplemental methods for details, including data sources.

the Greenland Ice Sheet shows signs of structural destabilization and is likely vulnerable to tipping between 0.8°C and 3.4°C, potentially significantly below 2°C warming, which could occur well before 2050 (Figures 1C and 2B).[18]

Moving forward

Are we now at risk of crossing planetary tipping points and triggering a hothouse Earth trajectory? Science doesn't have a precise answer, but this question requires urgent research, including exploring other hypotheses involving glacial/interglacial cycling and Holocene stability, and working to better understand climate dynamics. While the exact risk is uncertain, it is clear that current climate commitments, which have us on track for roughly 2.8°C peak warming by 2100,[7] are insufficient and greater climate mitigation efforts are needed.

In addition to feedbacks, rising anthropogenic emissions, driven by fossil fuel combustion, industrial activities, land-use change, and deforestation, are a major force behind accelerating climate change. In 2024, global energy-related CO_2 emissions rose by 0.8% to reach a record 37.8 gigatons,[19] pushing atmospheric CO_2 concentrations to an unprecedented 422.5 ppm, ~50% higher than pre-industrial levels.[16] These

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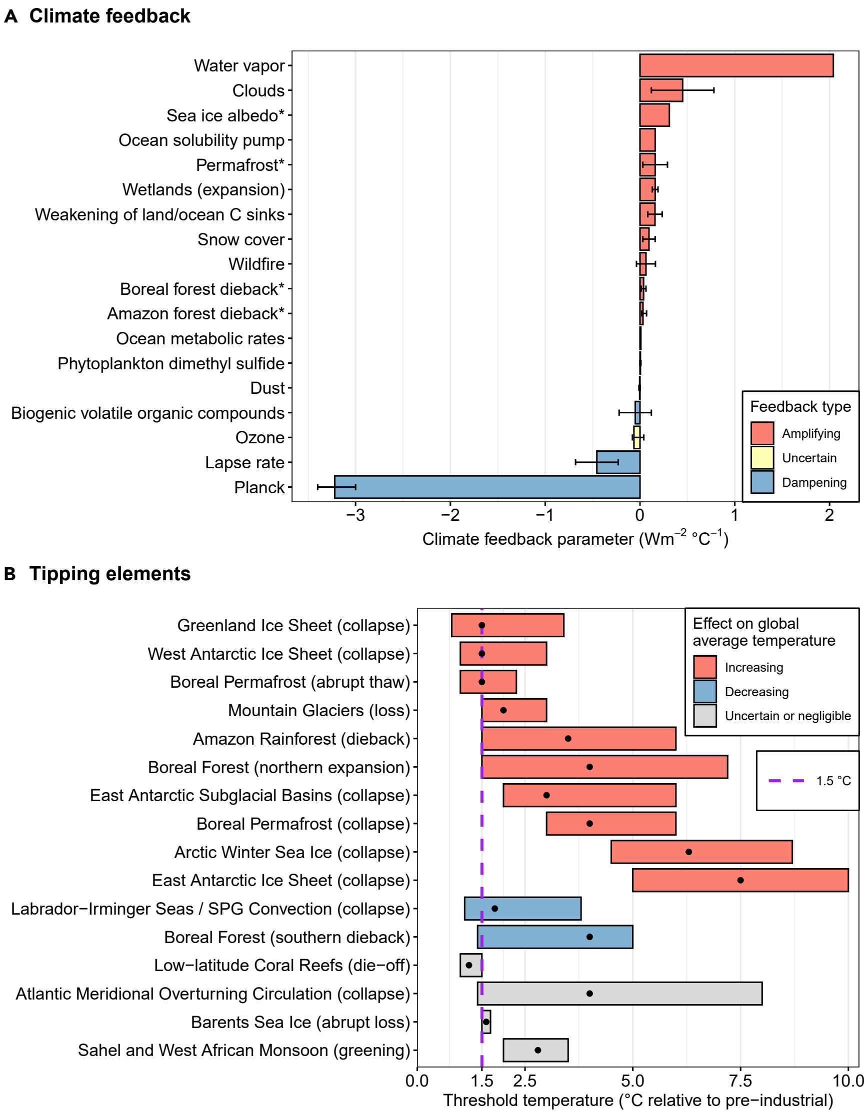

Figure 2. Overview of climate feedbacks and tipping elements

(A) The colored bars show central estimates and the lower and upper ends of the black error bars indicate minimum and maximum feedback strength estimates. Feedback strength parameters ($W/m^2/°C$) quantify how different climate processes amplify (positive value) or dampen (negative value) warming per degree of surface temperature change. Feedback loop strength estimates are primarily derived from the table of 41 physical and biological feedback loops in Ripple et al.[10] We did not include feedbacks where we did not know the strengths or where the units were not compatible or consistent with our graph. Feedback strength error bars indicate uncertainty intervals of various types (see Ripple et al.[10]). Feedback loops that may be associated with tipping elements are marked with asterisks (*). For an alternative grouping of feedbacks, see Figure S2.

(B) Tipping point threshold temperature estimates are shown with black dots; floating bars indicate lower and upper estimates. Note that the estimated tipping threshold of 1.2°C for low-latitude coral reefs has likely already been crossed.[3] The dashed purple vertical line indicates 1.5°C above pre-industrial levels; a sustained global average temperature at this level is likely in the near future.[2] Tipping point thresholds are adapted from Armstrong McKay et al.[13] with updates from Lenton et al.[3] Tipping impacts and timescales vary greatly. In some cases, effects on global temperatures may be uncertain or negligible (gray bars). Note that overlap can occur among feedbacks and/or tipping points, so their effects are not necessarily independent. See supplemental methods for further details, including data sources.

energy-related CO_2 emissions are expected to rise even higher for the year 2025. Methane levels also continued to increase, further compounding near-term warming due to methane's high global warming potential. Nitrous oxide, another potent long-lived greenhouse gas, is also rising steadily. Looking ahead, the outlook for emissions remains deeply concerning. Emerging economies continue to invest in coal and gas infrastructure, and overall fossil fuel subsidies are at record levels. At the same time, geopolitical shifts, including weakened climate commitments in some major economies, may be slowing international climate mitigation. For example, policy shifts in major economies may block progress on emissions cuts, threatening climate stabilization. The window to limit global temperatures below critical thresholds may be rapidly closing.

The risks we describe are troubling not only for their magnitude but also for their

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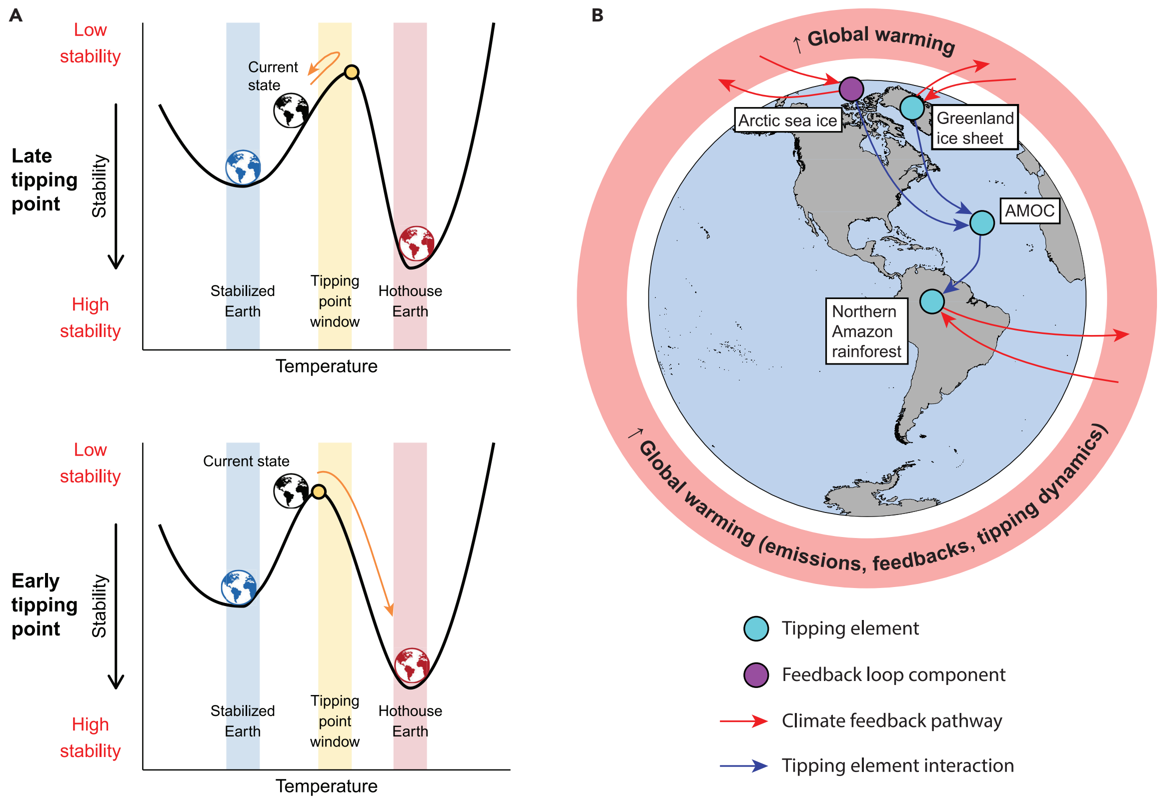

Figure 3. Tipping point uncertainty and hothouse trajectory risk

(A) The Earth's current state (globe shown in black) is nearing tipping point thresholds (within yellow band). The yellow dot depicts a tipping point threshold, and the blue and red vertical bands on the left and right of the graphs indicate troughs that represent relatively stable cooler or hothouse Earth states, respectively. Depending on the tipping threshold, a small increase in warming could still allow for a transition back to a cool, stabilized Earth (orange arrow in upper graph) or place the Earth system on a hothouse trajectory (orange arrow in lower graph). If a critical tipping point threshold is crossed at a relatively low temperature, then a hothouse trajectory could occur even assuming fairly low future emissions. The tipping point window (vertical yellow band) reflects the uncertainty of the tipping point temperature threshold.

(B) Case study scenario of interconnected feedbacks and tipping cascades linking Arctic and Atlantic processes to the Amazon. Warming from greenhouse gas emissions accelerates Arctic sea ice and Greenland Ice Sheet loss, reducing albedo and adding meltwater that weakens the Atlantic Meridional Overturning Circulation (AMOC). A weakened AMOC shifts tropical rainfall patterns, increasing drought risk and potential dieback in the northern Amazon forest, further amplifying global warming through the feedback involving carbon loss. Note that once one tipping point is crossed, it will likely impact the timing and temperature thresholds for other tipping points.

uncertainty. We do not yet know the exact thresholds for many tipping elements, how feedbacks will interact with climate sensitivity, or how quickly tipping cascades might unfold. Evidence nevertheless shows that overshooting 1.5°C or even the current temperatures increases their probability. Uncertainty about where tipping thresholds lie is therefore not a reason for delay, but a compelling reason for immediate precautionary action. In short, we may be approaching a perilous threshold, with rapidly dwindling opportunities to prevent dangerous and unmanageable climate outcomes.

Addressing the various threats requires stronger policy frameworks that accelerate emissions reductions and integrate tipping-point risks into global climate planning. In addition to quickly and drastically reducing anthropogenic emissions, novel approaches such as coordinated global tipping-point monitoring, advances in high-resolution Earth-system models, and anticipatory governance to manage cascading risks could improve our ability to detect early warning signs and prevent an irreversible shift toward a hothouse world. Confronting climate change demands policies resilient to deep uncertainty and capable of safeguarding the Earth system against catastrophic outcomes.

ACKNOWLEDGMENTS

This paper is dedicated to the memory of Will Steffen (1947–2023), whose groundbreaking work on Earth system science continues to inspire essential climate research and action. His insights into the risks of a hothouse Earth trajectory remain a crucial guide for safeguarding our planet's future. We thank David Armstrong Mckay for reviewing an early draft.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2025.101565.

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Supplemental information

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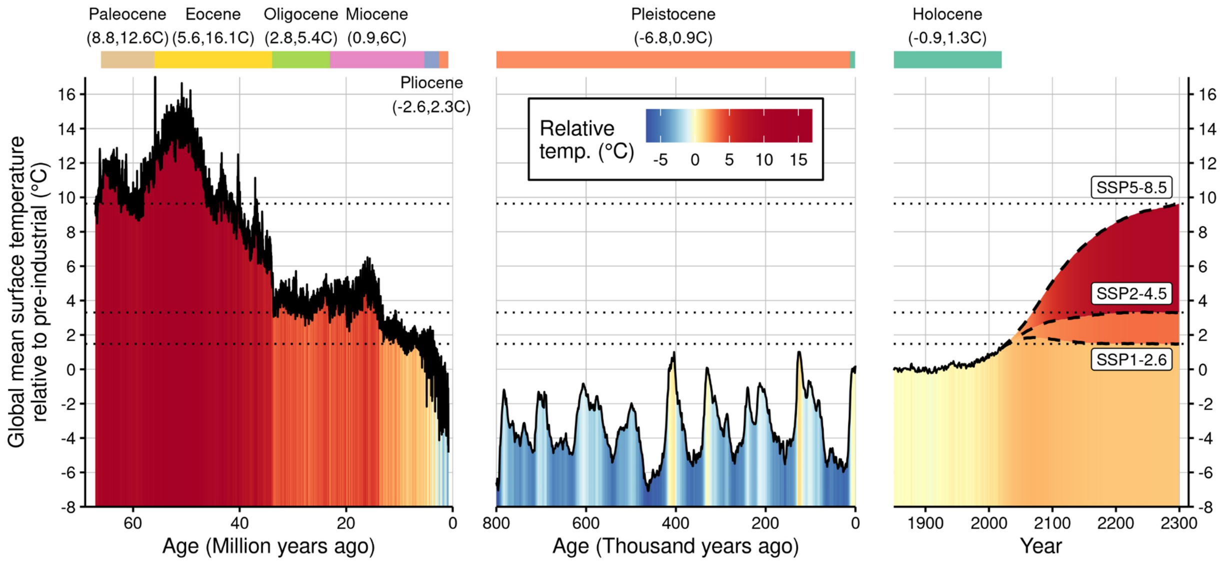

Figure S1. Changes in global temperature (relative to 1850–1900) from 55 million years ago up to 2300. Future temperature projections are based on the SSPs. In 2300, the 5–95% temperature range for SSP1-2.6 is 1.0°C to 2.2°C, the range for SSP2-4.5 is 2.3°C to 4.6°C and the range for SSP5-8.5 is 6.6°C to 14.1°C.[1] The three median projected temperatures for 2300 are 1.5°C, 3.3°C, and 9.6°C respectively.[1] Uncertainty increases further back in time. The Cenozoic Era, spanning the last 66 million years, has experienced significant climatic shifts.[2] It began with a very hot climate (relative to the rest of the era) during the Paleocene and Eocene (~66–34 million years ago), a period when the Earth was largely free of large polar ice sheets, with high atmospheric CO_2 levels (above ~500 ppm) and tropical forests extending into high latitudes. The next three eras (Oligocene, Miocene, and Pliocene) had relatively cooler temperatures, but were still fairly warm. The more recent Pleistocene epoch (~2.58 million to ~11,700 years ago) exhibited glacial/interglacial cycling. What has been demonstrated already though is the systemic disruption of the natural glacial cycle by human interference; that is, the suppression of the next ice ages as generated by Milankovitch forcing.[3] The current epoch, the Holocene, began ~11,700 years ago and has been characterized by an unusually stable climate. The top bar shows geological epochs with approximate temperature ranges in parentheses. Temperature data sources: left panel—Westerhold et al.[4], middle panel—Clark et al.[2], right panel—IPCC[1]. See supplementary methods for details.

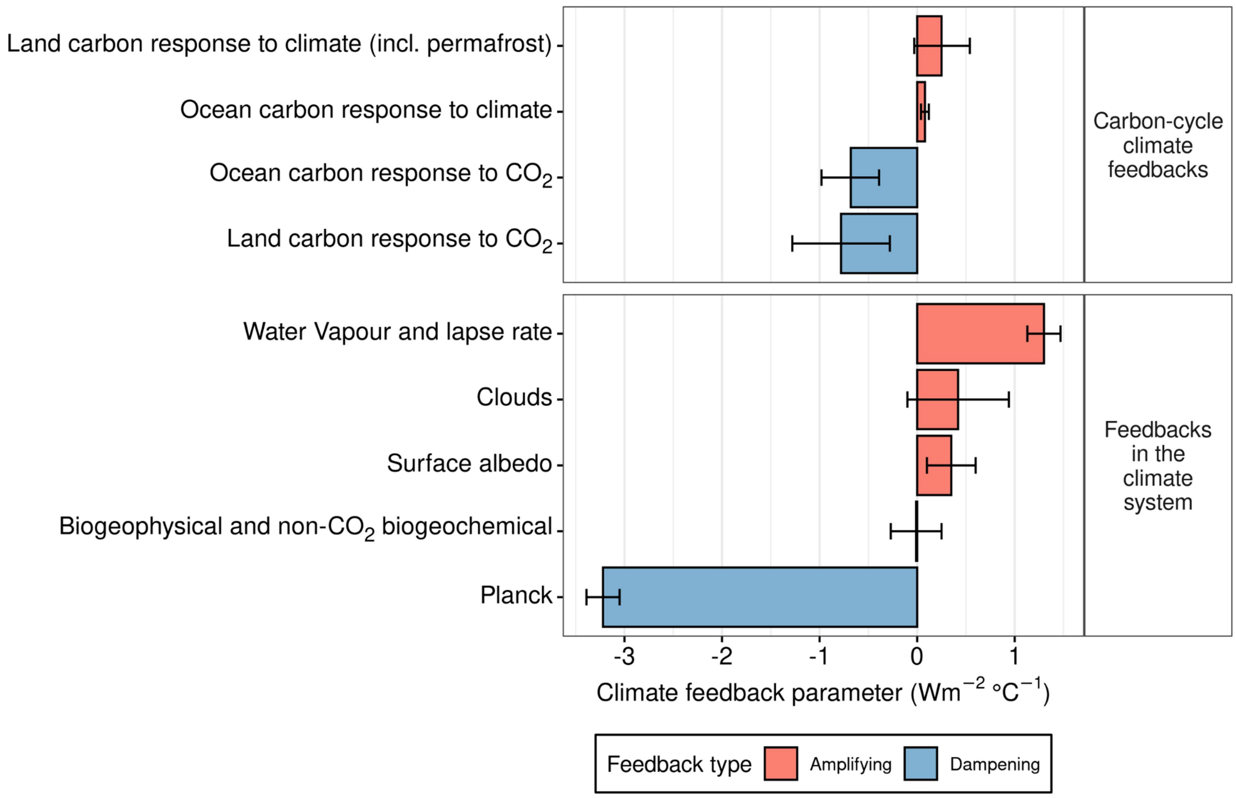

Figure S2. Overview of climate feedbacks. The colored bars show central estimates and the lower and upper ends of the black error bars indicate minimum and maximum feedback strength estimates. Feedback strength parameters (W/m²/°C) quantify how different climate processes amplify (positive value) or dampen (negative value) warming per degree of surface temperature change. All data are from Arias et al. 2021[5].

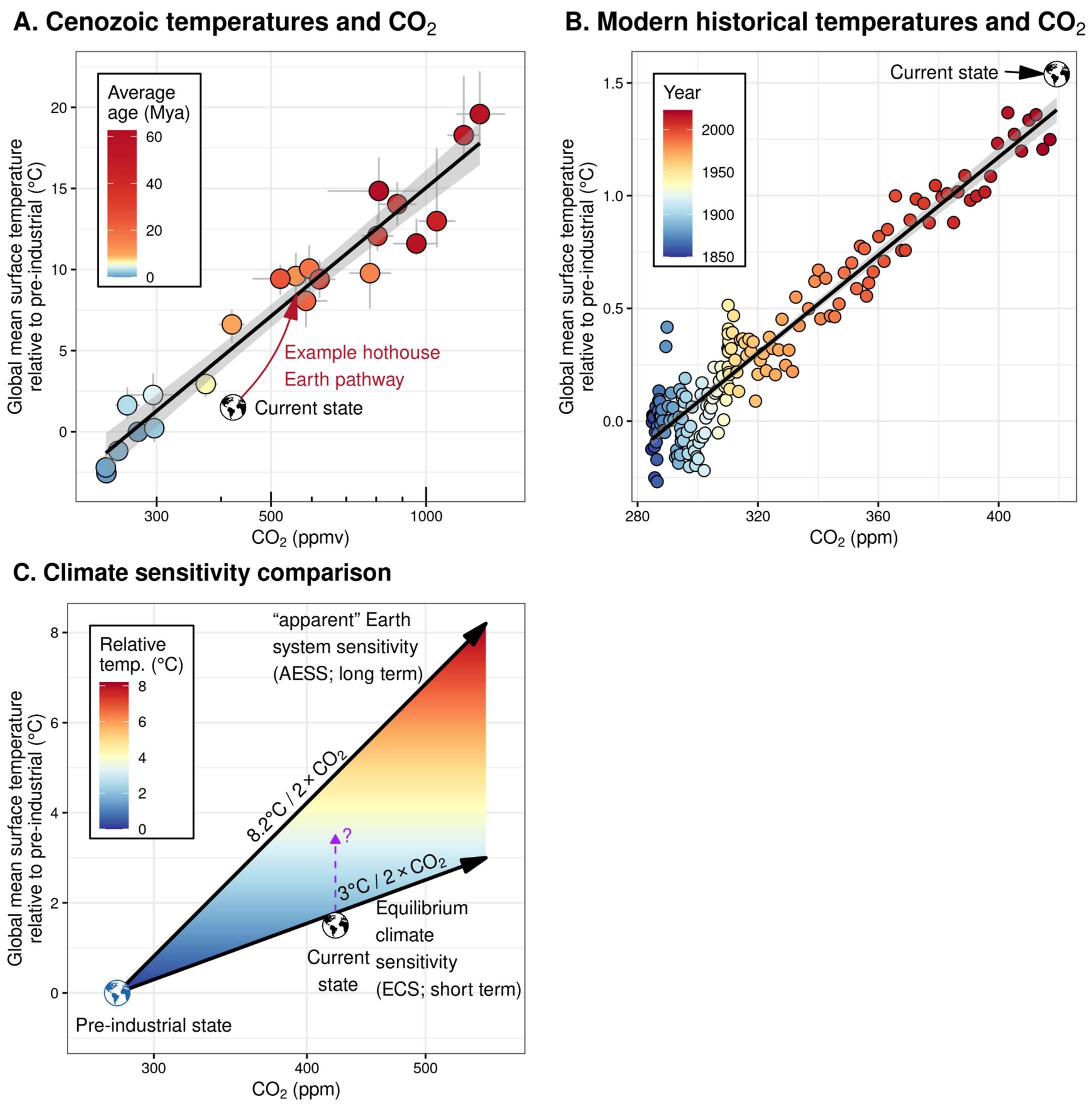

Figure S3. (A) The relationship between global mean surface temperature (GMST) and CO_2 concentration for the Cenozoic era (~66 million years ago to present). Each point corresponds to a different geochronologic age (i.e., chronostratigraphic stage). (B) Recent temperatures and CO_2 levels are strongly correlated. Continued CO_2 emissions greatly increase the risk of a hothouse Earth trajectory. (C) The "apparent" Earth system sensitivity (AESS)—long-term temperature rise per doubling in CO_2—is approximately 8.2° ± 0.4°C (Judd et al.[6]). In contrast to AESS, the equilibrium climate sensitivity (ECS) is approximately 3°C per doubling in CO_2; this does not account for very long-term feedback loops.[7] Although the exact value of ECS is unknown, it is very unlikely to be below 2.9°C based on observational constraints.[8] The dashed purple arrow indicates a hypothetical pathway showing how temperature could rise over time even if CO_2 concentration is fixed. Cenozoic data (A) come from Judd et al.[6], with relative temperatures calculated assuming a pre-industrial average of 14 °C (Lamperti et al.[9]). Modern CO_2 data (B) were obtained from Etheridge et al.[10,11] for 1850–1978 and from Lan et al.[12] for 1979–2023. Modern (1850–present) temperature data (B) were obtained from Rohde and Hausfather[13].

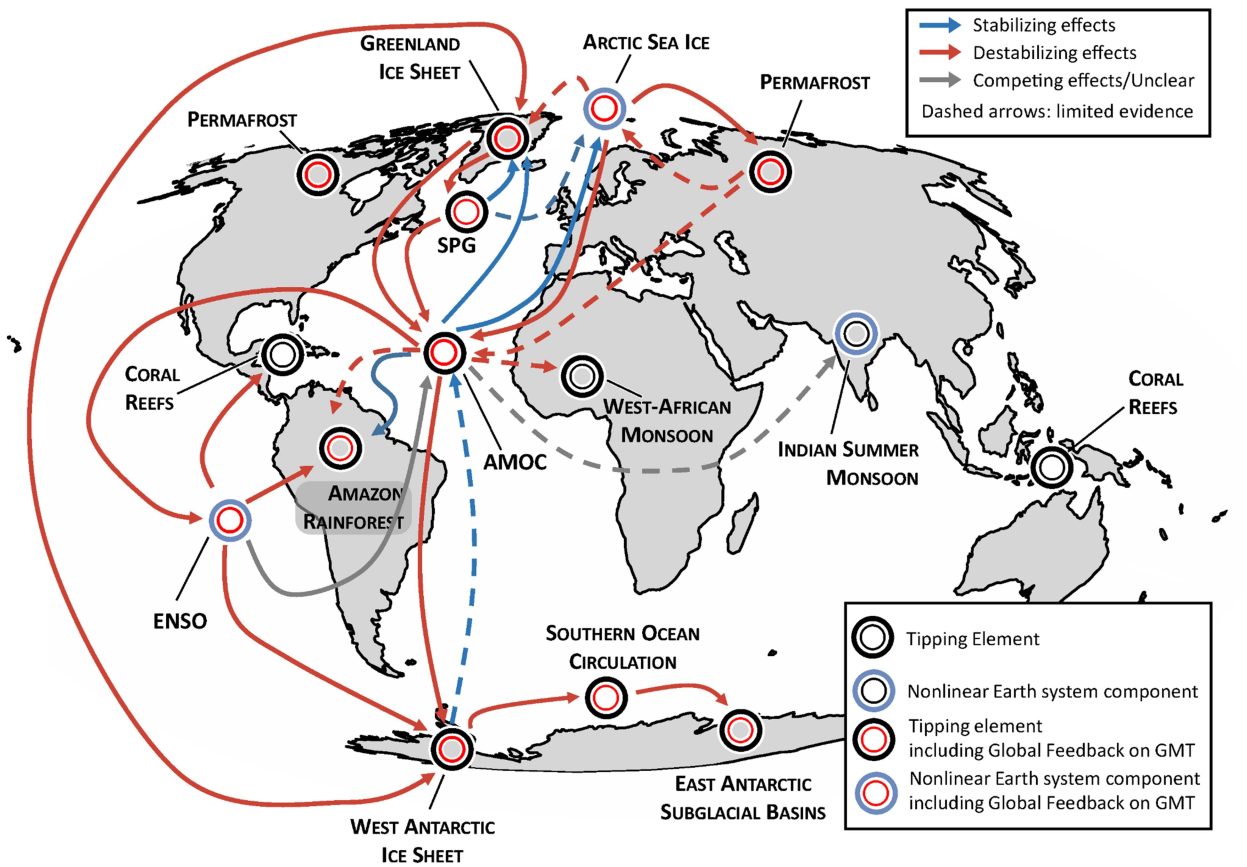

Figure S4. Overview of tipping systems including their interactions. Stabilizing interactions are shown with blue arrows and destabilizing interactions are shown with red arrows. Tipping elements are shown with black outer circles. Other elements are labeled as nonlinear Earth system components (blue outer circles). Red inner circles indicate tipping elements or nonlinear Earth system components that can affect global mean temperature (GMT); black inner circles indicate elements or components that may not affect global mean temperatures. Abbreviations correspond to the Atlantic Meridional Overturning Circulation (AMOC), the El Niño-Southern Oscillation (ENSO), and the North Atlantic Subpolar Gyre (SPG). This figure is adapted and updated from Wunderling et al.[14] and Lenton et al.[15]. See supplementary methods for more details.

Supplementary Methods

Global average surface temperature (Figure 1a)

Pleistocene temperature data from 11,700 to 1.2 million years ago are from Clark et al.[2].

Holocene temperature data are from the LGMR 50th percentile temperature estimates provided by Osman et al.[16], converted from the 1000–1850 to the 1850–1900 reference period using the 50th percentile temperature estimates from the Tardif et al.[17] LMR dataset.

Recent (1850–2020) temperature data and SSP projections (2020–2300) (right side of panel) come from Figure 4.40 of IPCC[1]. Specifically, the historical temperature data are from the "Consolidated GMST time series.csv" provided by Trewin et al.[18] and the SSP projection data are from the "MAGICCv7.5.0_Surface-Air-Temperature-Change_World_ssp[...]" files provided by Nicholls et al.[19].

Modern historical temperatures and CO_2 (Figure 1c)

This panel is the same as in Figure S3B. See the caption of that figure for details.

Near-term accelerated warming projection (Figure 1c)

Modern (1850–present) temperature data (E) were obtained from Rohde and Hausfather[13]. We converted these data to actual (i.e., unadjusted) air temperatures by adding 14.101°C based on the metadata description and then subtracted the 1850–1900 average temperature so that the resulting temperatures are relative to the 1850–1900 reference, matching the other data that we present.

Accelerated warming graph is adapted from Hansen et al.[20].

Figure 2

Feedback loop data are primarily derived from the table of 41 physical and biological feedback loops compiled by Ripple et al.[21], and we considered only climate feedback loops for which strengths were given in units that could be expressed as $W/m^2/°C$. For the wildfire feedback loop, the original strength was provided in units of change in radiative forcing (W/m^2) by 2100. We converted this strength estimate (and confidence interval) to $W/m^2/°C$ by assuming a temperature increase of 2.7°C (relative to pre-industrial conditions) by 2100.[22] Similarly, the strength of the "ocean metabolic rates" feedback was originally given as ~0.02°C by 2100, which we first converted to W/m^2 by 2100 using a specific climate sensitivity of 0.79 °C/(W/m^2), which corresponds to the expected warming per unit radiative forcing after a century[23], and then converted to W/m2/°C as described above. Feedback strength estimates were from various sources; for information on specific strengths, see the original sources listed in Table S1 of Ripple et al.[21]. We also included three feedbacks listed in Steffen et al.[24]: boreal forest dieback, Amazon forest dieback, and weakening of land/ocean carbon sinks. Following equilibrium climate sensitivity (ECS) conventions, we treated Planck, water vapor, lapse rate, clouds, and albedo as temperature-driven feedbacks, even though clouds and humidity can contribute to effective radiative forcing (ERF) when altered by external forcings.[1] We marked feedback loops that may be associated with tipping elements based on Ripple et al.[21]. Note that overlap can occur among feedbacks, among tipping points, or between feedbacks and tipping points; thus, their effects are not necessarily independent and additive. Predicted tipping point effects on global temperature (Decreasing, Increasing, or N/A) come from Armstrong McKay et al.[25], except we classified the Atlantic meridional overturning circulation (AMOC) as N/A because AMOC collapse can affect many parts of the biosphere in complex ways.[26]

Figure S1

Temperature data sources and methods are the same as for Figure 1a above except we used Clark et al.[2] data going back to 0.8 million years before present and Westerhold et al.[4] CENOGRID temperature data from 66 million to 0.8 million years before present as described below.

Cenozoic temperature data for the period between 66 million years ago (Mya) and 0.8 Mya are from Westerhold et al.[4]. Specifically, we converted the “ISOBENd18oLOESSsmooth” variable in the “CENOGRID_Loess_20” dataset” to delta temperature relative to 1961–1990 using the equations in Table S7 of Westerhold et al.[4], which are from Hansen et al.[20]. We then converted this time series to delta temperature relative to 1850–1900 using the difference between the average temperatures for these reference periods based on Rohde and Hausfather[13]. Finally, we linearly interpolated this time series to 10,000 year resolution for plotting and quantile calculation (see below). For plotting, we clipped the upper limit to 16.5°C so that the rest of the data would be easier to see.

Epoch timespan data are from Cohen et al.[27]. Temperature ranges shown for the epochs are based on the 0.5% and 99.5% quantiles (i.e., the middle 99% of the data) calculated using the time series described above. These ranges are intended only as rough approximations of the temperature extents for each epoch since there can be significant uncertainty in the underlying time series, differences in estimation methodology, differences in temporal resolution, and so on.

Figure S4

Update of tipping element interactions based on recent evidence from literature. In particular, the following interactions were updated since Wunderling et al.[14]: (i) AMOC → Amazon rainforest: Recent evidence from Earth System Models and observational data indicate that a weakening AMOC offsets part of the precipitation decrease due to global warming leading in the southern Amazon rainforest.[28,29] At the same time, pollen and microcharcoal data indicates that the northern Amazon rainforest may have become drier in response to higher temperatures in the past.[30] Therefore, the interaction between AMOC and the Amazon rainforest is likely regiondependent with currently more evidence for a stabilizing interaction for the southern Amazon part. (ii) WAIS (West Antarctic Ice Sheet) → AMOC: Based on simulations with Earth system models of intermediate and high complexity (CLIMBER-X and CESM), and accounting for realistic meltwater input from both the Greenland and West Antarctic Ice Sheet, recent literature indicates a potential stabilizing effect overall.[31,32] (iii) Arctic Sea Ice → Permafrost: Studies suggest a destabilizing feedback from Arctic (winter) sea ice retreat to inland permafrost thaw[15] supported by paleoclimate records[33] and climate model simulations[34].

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