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We Are in the Anthropocene—Now What?

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Key Points:
- The Anthropocene's enormous consequences are of long-term nature, the slow pace of recovery currently under-appreciated among the public
- The smallest unavoidable residual emissions (e.g., from food sector) risk perpetuating global warming even without other human forcing
- Earth system feedbacks risk causing worse-than-expected impacts; should they shift, potentially surpassing human forcing in relevance

Supporting Information:
Supporting Information may be found in the online version of this article.

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Abstract

While the term "Anthropocene" is well established across scientific disciplines and social spheres, interpretations are diverse. Taking account of the 2024 rejection by a geological commission to accept the Anthropocene as a geological epoch and the related scientific debate, here we offer a future-oriented perspective from the viewpoint of Earth system science. We describe different pathways in the Anthropocene up to the year 3,000, systematically characterizing them according to impacts and causes. We discuss the enormous global consequences of anthropogenic pressures on the Earth system and quantify the corresponding long-term commitment to change. Regarding the causes, we conservatively explore best-case and middle-of-the road emission scenarios, in combination with climate sensitivities drawn from within the IPCC likely range. We also discuss implications for Earth system resilience that could result in what we call worst case scenarios for Anthropocene outcomes. We conclude that, beyond the slow pace of natural climate recovery spanning many millennia, even minimal, unavoidable residual emissions like from the food sector risk perpetuating global warming in the absence of other human forcing. One implication is that if climate or carbon cycle feedbacks shift toward reinforcing warming, they risk not only exacerbating climate impacts but to also surpassing human forcing in relevance. At that point, human influence on the Anthropocene would no longer play the dominant role.

Plain Language Summary

Most people have a general, intuitive understanding of the term "Anthropocene." And while it has not formally been declared as a new geological epoch, it is scientifically clear that these new times have only begun to fully unfold. The Anthropocene stresses both the enormity of the human imprint on Earth, as well as its long-term nature. That latter aspect, however, is highly underappreciated among the public. We describe several qualitatively different Anthropocene pathways for the next millennium, some of them depending on our cumulative actions as humanity, some on how the Earth system responds to these human pressures. We highlight how much we are already stuck in a figurative "Anthropocene quicksand", where only an active pull can free us from consequences like global heating—while even a very modest continuation of greenhouse gas emissions will keep us at high warming levels. Should Earth system resilience, the natural buffering capacity, significantly decline, the impacts of our actions would become even stronger. In a worst-case scenario, shifts in Earth system feedbacks could even surpass human forcing in relevance. But we are not there yet and can still pull ourselves out of the quicksand.

1. Introduction

One of the most fundamental questions of our time concerns the future of the Anthropocene. How will humanity shape its own future relationship with planet Earth, and how will the Earth system respond to the manifold human perturbations? At the same time, the concept of the Anthropocene itself is integral to help people realize the enormity—and the long-term consequences—of the human imprint on essentially all domains of natural life and the environment (Zalasiewicz et al., 2024). Yet, despite the idea of the Anthropocene being around for a quarter of a century (Crutzen, 2002; Crutzen & Stormer, 2000), the fact that the effects will be felt far beyond the immediate future, for centuries and millennia to come (Kaufhold, Willeit, Munhoven, et al., 2025; Zickfeld et al., 2013), is still hugely under-appreciated among the public and in the policy world.

The term Anthropocene was originally coined by Paul Crutzen as an "in many ways human-dominated, geological epoch" (Crutzen, 2002, 2006; Crutzen & Stormer, 2000; Steffen et al., 2020). From an Earth system science perspective, the Anthropocene has come to be defined as major, global scale deviations from Holocene conditions due to anthropogenic (human) pressures (Steffen et al., 2016; Zalasiewicz et al., 2021). These deviations are visible in global climate with all its components, the natural biosphere, and essential physical, chemical or biological properties of the ocean or land. Global mean temperature, for example, has clearly left the

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Holocene range of variability (Osman et al., 2021) since roughly the second half of the 20th century—with 1.24°C above preindustrial values during the 2015–2024 decade and 1.52°C in 2024 (Forster et al., 2025), and the latest 3-year average above 1.5°C as of the end of 2025 (Copernicus, European Centre for Medium-Range Weather Forecasts, ECMWF, 2026). This is why we, as Earth system scientists, refer to our current time as the Anthropocene. The Great Acceleration (Steffen, Broadgate, et al., 2015) not only marked a rapid rise in anthropogenic pressures like greenhouse gas emissions and land-use change, but also the onset of a resulting well-documented global departure from Holocene conditions (IPCC AR6 Synthesis Report, 2023; Pörtner et al., 2021).

There are many other striking features of the Anthropocene, which go some way to explaining the term's appeal across disciplines (Zalasiewicz et al., 2021) and in the general public. Just one example is the dominance of anthropogenic mass (from buildings and infrastructure to plastics) over living biomass: by weight, there is now twice as much plastic as animals on our planet (Elhacham et al., 2020). Despite compelling evidence (Head et al., 2022) going far beyond these kinds of striking quantitative measures, formal recognition of the Anthropocene as a geostratigraphic epoch was not granted by the International Commission on Stratigraphy (Witze, 2024).

In this perspective, however, we argue that the focus on definitions of the Anthropocene in terms of the present and the past is secondary. Neither the precise definition, nor the nature of human pressures (whether a "geological force" or not), or a specific onset date of the Anthropocene (in the mid-1950s or the industrial revolution) are the primary issues that deserve our attention, as long as one firmly stays with the definition of the term as marking departure from Holocene baseline conditions (Head et al., 2022, 2023). The primary question is rather where humanity is heading, in terms of life-support on Earth—not only in this or the next century, but in the longer term. Which doors are still open, and which are—or will be—closed for millennia (Clark et al., 2016; Lee et al., 2025)? Are there worst-case pitfalls (Kemp et al., 2022)?

Here, as outlined in Section 2, we explore possible futures in the Anthropocene landscape along the axes of established human forcing scenarios as well as known uncertainties in Earth system response (sections 3–5). But we also consider an even more fundamental question: will the Earth system continue to function within the narrow range of variability of the Holocene for biophysical processes like, for example, carbon uptake and release which regulates biosphere stocks of greenhouse gases, but also heat storage, global hydrology, and ice sheet dynamics? In terms of environmental conditions, the Anthropocene already now clearly deviates from Holocene-like conditions (Osman et al., 2021; Pörtner et al., 2021). Even more, it has been established that seven out of nine Planetary Boundaries have been transgressed (Sakschewski et al., 2025), leaving us in a zone of increasing risk of losing Earth system stability (Richardson et al., 2023; Rockström et al., 2009; Steffen, Richardson, et al., 2015).

But will this risk become reality? Will the Earth system of the Anthropocene, which up to now is under pressure, but at least in the above mentioned functional sense is still comparable to the Holocene, lose even that resemblance? In analytical terms, this means addressing the question of how plausible worst cases are (Section 6), where uncertain feedbacks of the Earth system to human pressures detrimentally not only add up, but reinforce each other (Ripple et al., 2026; Steffen et al., 2018). The associated concern is an irreversible lock-in of Earth's trajectory—leading us even faster and/or further away from the Holocene's range of variability in environmental conditions than known uncertainties, looked at individually, currently suggest.

2. Mapping the Anthropocene: Model Pathways and Resilience Considerations

The future Anthropocene can play out in very different ways. None of the options are "good", given the global environmental damage with negative impacts on Earth's life support systems (like for instance coastal regions, mountain glaciers, coral reefs, tropical rainforests and soils) that are irreversible on up to millennial time scales (Drenkhan et al., 2023; Eddy et al., 2021; Edwards et al., 2019; Geisen et al., 2019; Malhi et al., 2014; Owens, 2020; Woodhead et al., 2019; Zamrsky et al., 2024). Of the options remaining, we will show that they span a wide range in their degree of disruptiveness to the established ways human cultures are operating in. We explore three plausible, exemplary future pathways (Figure 1), with different levels of human forcing and climate sensitivity (Table 1), and beyond that discuss the possibility of worst-case type surprises in the Earth system.

Before we present model simulations of these pathways in Section 3, and discuss the properties of what we call the Anthropocene landscape resulting from these pathways in Section 4, we start with a qualitative description of our scope as sketched in Table 1.

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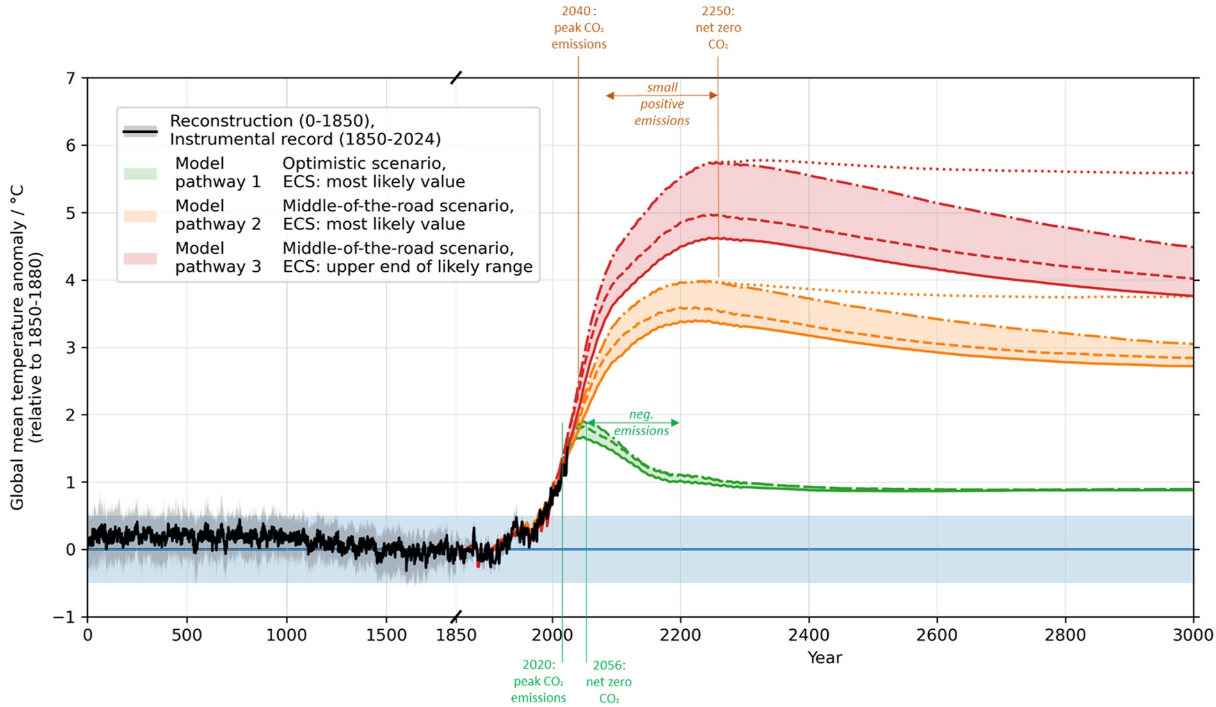

Figure 1. Global mean surface temperature anomaly from three sets of CLIMBER-X model runs. **Pathway 1**, green shading: SSP 1–1.9 with ECS = 3°C; **Pathway 2**, orange shading: SSP 2–4.5, ECS = 3°C; **Pathway 3**, red shading: SSP 2–4.5, ECS = 4°C. Black lines show reconstructions up to 1850 (PAGES2k (PAGES2k Consortium, 2017, 2019)) and instrumental records for 1850–2024 (HadCRUT5 (Morice et al., 2021)); blue shading indicates Holocene range of variability. Key emission landmarks are highlighted in green below/in orange above for scenarios SSP 1–1.9 (pathway 1) and SSP2-4.5 (pathways 2 and 3), respectively. Each modeled pathway consists of a reference run (model setup a, solid line), and runs where different model assumptions about the carbon cycle are added successively. Dashed line (setup b): like setup a, but with state-dependent methane residence time in the atmosphere (Kleinen et al., 2021); Dashed-dotted line (setup c): As setup b, with limited CO_2 fertilization effect (saturation above current CO_2 concentration). The experimental design is described in detail in Kaufhold et al. (2025); Kaufhold, Willeit, Talento, et al. (2025)). The dotted lines for pathways 2 and 3 represent a minimal deviation from SSP2-4.5, with continued residual CO_2 emissions of 0.5 Gt of carbon per year (equivalent to 5% of current emissions).

The pathways (Figure 1) range from best-case to high-risk scenarios, to illustrate different "versions" of the Anthropocene (Figure 2):

- A manageable Anthropocene—achieving sustainable stewardship on pathway 1;
- A dangerous Anthropocene—navigating the edge on pathway 2;
- An unmanageable Anthropocene—suffering a hostile Earth system mode on pathway 3.

Table 1
Overview of Exemplary Anthropocene Pathways, As Well As the Notable Eventuality Where the Earth System Behaves Unexpectedly

Human forcing	SSP1-1.9	SSP2-4.5
Earth system properties		
Constant ECS = 3°C	Pathway 1	Pathway 2
Constant ECS = 4°C		Pathway 3
Surprising Earth system behavior	Worst cases, outside of the range of influence from human forcing	

Note. SSP stands for the Shared Socioeconomic Pathways of the Intergovernmental Panel on Climate Change (IPCC), and ECS stands for Equilibrium Climate Sensitivity, see Section 3 for further elaboration. "Surprising Earth system behavior" refers to, for instance, changing ECS or major shifts in the global carbon cycle. The colors make reference to the color scheme of Figures 1 and 2.

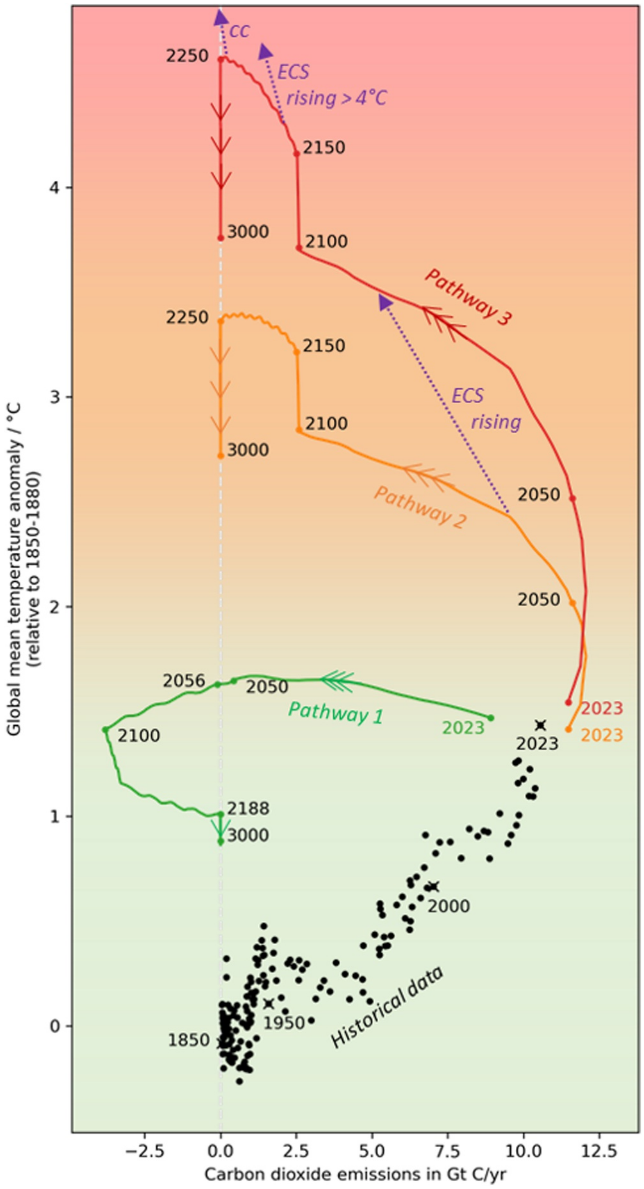

Figure 2. Anthropocene landscape of human action (horizontal axis) and Earth system response (vertical axis). Green, orange and red areas conceptually represent manageable, dangerous and unmanageable versions of the Anthropocene, respectively. The three illustrative pathways, as in Figure 1 (setup a), are depicted as lines. Human forcing (specifically, how fast the turnaround to net zero emissions happens) makes the difference between pathways 1 and 2, while climate sensitivity causes different temperature outcomes in pathways 2 and 3. A few worst-case type surprises involving feedbacks to warming within the carbon cycle (cc) and through rising equilibrium climate sensitivity (ECS) that are so far typically unaccounted for in Earth system models are illustrated by purple dotted arrows. Note that the upward vertical part of pathways 2 and 3 (2100–2150) is an effect by design of the prescribed extended emission scenario SSP 2-4.5, which holds emission levels constant during that period (land-use change emissions offsetting a decrease in industrial CO_2 emissions). Scenario data and temperatures as in Figure 1, with CMIP7 input data for CO_2 emissions (CEDS (Hoesly et al., 2025)) up to 2023.

Based on an assessment of where we currently stand and plausible developments of pressures from the human world and Earth system response, we are potentially already very close to a dangerous Anthropocene—**navigating the edge** (pathway 2) between pledges and lack of implementation (United Nations Environment Programme, 2025), between safety and loss of influence, between aiming for sustainable stewardship (manageable Anthropocene, pathway 1) and potentially transitioning to a hostile Earth system mode (unmanageable Anthropocene, pathway 3).

The best remaining option—the only remaining option to have a chance of staying on a trajectory in which the physical and biogeochemical conditions in the Anthropocene at least vaguely resemble that of the Holocene interglacial, as we will show in more detail in the next section—is a transformation toward **sustainable stewardship** (pathway 1). Such a transformation would entail a drastic reduction of human pressures, on all scales and in all domains (e.g., 7.5% annual greenhouse gas emission reduction (United Nations Environment Programme, 2024). Over time, it would bring the Earth system back from its current transgression of seven of nine Planetary Boundaries to the safe operating space (Richardson et al., 2023; Sakschewski et al., 2025) (albeit with an effectively permanent loss of biosphere integrity—both in terms of loss of species and loss of ecological functions). A major problem we are facing, however, is the long residence time of carbon dioxide (Archer & Brovkin, 2008) in the atmosphere: only part of our emissions is taken up by the ocean and the terrestrial biosphere on a timescale of decades to centuries, while much of it remains for tens of thousands of years until gradually removed by sedimentation in the deep sea (Cartapanis et al., 2018; DeVries, 2022). Our current actions will affect humanity's living conditions for thousands of years to come. So even the best outcome, pathway 1, cannot be considered “good”– it is merely “manageable” in the sense that the Earth system would continue to operate in a Holocene-like way and that there is hope that established ways of living overall could be preserved. But our environment would still deviate far away from what it was during the Holocene, and we would be burdened with committed change to both the physical/chemical and the living world for millennia to come.

The assumptions of reduced human forcing underlying pathway 1 are optimistic, not least given that due to lack of progress so far in reducing global GHG emissions, 2024 has been the first year above 1.5°C (Copernicus, European Centre for Medium-Range Weather Forecasts, ECMWF, 2026), which is indicative that, without very stringent climate mitigation, we have also entered the first 20 year period with an average warming of 1.5°C (Bevacqua et al., 2025).

Failing to bend the global curves of rising Anthropocene pressures, and thus continuing to figuratively **navigate the edge** on pathway 2, would seriously worsen the actual and committed damage to life-support on Earth, such that any resemblance to Holocene conditions is lost ((Rahmstorf, 2024), see also description in next section and Figure 1). Still, we are calling the Anthropocene of pathway 2 *dangerous* because beyond human forcing, it involves optimistic assumptions about the physical Earth system response to rising CO_2 concentrations (Table 1). And should these assumptions turn out to be incorrect, the danger of constraining warming to not even pathway 2 would become real.

Should the warming response to greenhouse gas forcing be on the upper end of known and plausible uncertainty ranges (Hansen et al., 2023; Myhre et al., 2025; Sherwood et al., 2020), that is, if ECS is 4°C instead of 3°C we would experience what we call a **hostile Earth System mode** (pathway 3), where even the most ambitious adaptation strategies would fall far short of what is needed to secure basic human needs (Callahan, 2025; Hanna & Tait, 2015)—we would have reached what we therefore call an unmanageable Anthropocene.

Even though these basic pathways cover essential conditions like human forcing and equilibrium climate sensitivity, not even they provide a guarantee of the outcomes. Depending on where the truth lies in other uncertainty ranges, for example, regarding the strength of carbon cycle processes and feedbacks (Kaufhold, Willeit, Talento, et al., 2025) see setups depicted as shadings in Figure 1), each pathway could turn out to describe an Earth system with a wide range in, for example, global peak temperatures.

Furthermore, these pathways are not separate, parallel tracks. There are risks for crossovers (compare Figure 2 and last row of Table 1). This aspect is crucial, as beyond the three illustrative basic pathways, we will argue in Section 6 that there is also a risk of worst-case type, functional surprises (Steffen et al., 2018): the response of some Earth system processes to the driving forces might change character along the way of the higher temperature pathways 2 and 3. Based on current scientific understanding, it is a plausible hypothesis that such a worst-case would include overall stronger positive (self-reinforcing/amplifying) feedbacks, combined with weaker negative (damping/buffering) feedbacks to global warming, exacerbating human pressures and pushing Earth along an even higher heating trajectory, for millennia, until a new equilibrium is reached. Carbon release from natural stocks that is unaccounted for in current models (Abramoff et al., 2022; Burke et al., 2020; Smith et al., 2022), failing carbon sinks after decades of enhancement (Gatti et al., 2021; Ruehr et al., 2023) or state-dependent climate sensitivity (Caballero & Huber, 2013; IPCC AR6 WGI Chapter 7, 2021; Knutti et al., 2017; Sanderson & Rugenstein, 2022) could play a role here. As a consequence, human pressures would no longer be the dominant characteristic of the Anthropocene, nor even the immediate damages: Even without any further anthropogenic push, the system itself would—having lost resilience and thereby reduced its capacity for pullback—perpetuate that new mode of operation. We would have reached a new functional state of the Anthropocene (Steffen et al., 2018).

The main characteristics of the three pathways (and additional worst-case scenarios of Earth resilience loss) fully play out over centuries to millennia and only then reveal the characteristics of a mature Anthropocene. In the following, we use global mean temperature as one of the key variables describing the overall state of the Earth system to explore in more detail the plausibility of the three basic, illustrative pathways. We then turn to the worst-case type surprises related to loss of Earth system resilience.

3. Global Temperatures—A Millennium Into the Anthropocene

The long-term perspective for global temperatures beyond 2300 was already explored systematically a decade ago (Zickfeld et al., 2013), but uncertainties remain high due to incomplete knowledge of both future human action and Earth system responses. The more recent Zero Emission Commitment Model Intercomparison Project (ZECMIP), with the objective to chart the possible Earth system responses when human forcing has ended, focuses on timescales of 50 or 100 years (MacDougall et al., 2020). However, the climate simulated by the participating models does not return to initial conditions even after a millennium. Climate stabilization has since been further discussed in the context of ZEC, with a special focus on the long-term uncertainties (Palazzo Corner et al., 2023). The bottom line is that uncertainties are tremendously high, such that a positive (warming) commitment for timescales of centuries to millennia is at least as plausible as a negative (cooling) one.

Here, we go a step further and combine the long-term perspective from models for the time after the bulk of human climate forcing has ceased until the year 3,000, with the possibility of continued minimal forcing from residual CO_2 emissions. To that end, we apply the extended version (Meinshausen et al., 2020) of two Shared Socioeconomic Pathways (SSPs) called "SSP1—Sustainability" and "SSP2-Middle of the Road." SSP'S are consistent narratives of global socio-economic developments providing the basis for projections in the most recent IPCC report (IPCC AR6 Synthesis Report, 2023).

We use the fast Earth system model CLIMBER-X (Willeit et al., 2022) to analyze the expected outcomes for the planet along the three Anthropocene pathways (Figure 1), focusing on the longer-term, up to the end of the current millennium. The model includes a global carbon cycle component (Willeit et al., 2023) and is designed for application on decadal up to glacial-interglacial timescales (Kaufhold, Willeit, Munhoven, et al., 2025; Kaufhold, Willeit, Talento, et al., 2025). Its performance generally lies within the range of state-of-the-art general circulation models, with the advantage of faster computation at a spatial resolution comparable to other Earth system models (5° × 5°). The model includes the frictional–geostrophic 3-D ocean model GOLDSTEIN for the ocean and a Semi-Empirical dynamical-Statistical Atmosphere Model (SESAM) for the atmosphere. Equilibrium Climate Sensitivity (ECS), defined as the steady-state global-mean surface air temperature change due to a doubling of atmospheric CO2, usually is an emerging property of numerical models of the climate system. In CLIMBER-X, however, it can be scaled within the radiation scheme of the model. These advantages together allow for the systematic investigation beyond the year 2100 of the joint impact of uncertainties in the climate-carbon cycle feedbacks as well as fast climate feedbacks (like water vapor, lapse rate, clouds and albedo) influencing ECS (Kaufhold, Willeit, Talento, et al., 2025). In ZECMIP experiments, the performance of CLIMBER-X lies within the set of participating models, supporting the applicability of the model in the context of this investigation (Supporting Information S1).

For each pathway, we present three sets of model assumptions. These setups, for which the CLIMBER-X temperature projections slightly differ, reflect uncertainties in the response of the climate system to carbon cycle feedbacks (see caption of Figure 1).

We apply the extended version of the most optimistic IPCC scenario (SSP1-1.9) to represent our pathway 1. It is important to note that from the 2025/2026 perspective we are not on that pathway anymore—compare gap between observations and scenario in Figure 2 and Figure S2 of Supporting Information S1. In this scenario, which nevertheless serves to illustrate the idea of sustainable stewardship for our pathway 1, greenhouse gas emissions and human pressures on land are reduced rapidly. CO_2 emissions experience a steep decline starting in 2020, limiting peak warming to well below 2°C above pre-industrial conditions (setup c), reached shortly ahead of net-zero emissions (compare Figure S2 of Supporting Information S1). Negative emissions from roughly the middle of the 21st to the end of the 22nd century (see Figure S1 in Supporting Information S1) bring warming back down to around 1°C. After that, the model shows that the Earth system, even along this "gentle" Anthropocene trajectory, ends up with a near constant, elevated global mean surface temperature of approximately 1°C up to year 3,000. This is due to both the scenario design (CH_4 and N_2O remain above their preindustrial values), and climate system properties as modeled with CLIMBER-X (long residence time of anthropogenic CO_2 in the atmosphere and the large thermal inertia of the climate system). So even with an optimistic "sustainable" Anthropocene future, Earth does not on its own return to within the Holocene range of climate variability (14°C ± 0.5°C) (Osman et al., 2021) for many centuries.

Pathway 2, characterized by stronger human forcing, is represented by the "middle of the road" scenario of the IPCC (SSP 2–4.5) which most closely tracks the current world development. In spite of an emissions peak in 2040 and a relatively steep decline thereafter, warming continues for almost 200 years. This effect is essentially due to the scenario-prescribed failure to rapidly reach net-zero emissions: even though CO_2 emissions drop from a peak of 12 Gt C (gigatons of carbon) per year down to 2.6 Gt C/yr in 2100, followed by a gradual decline to net-zero until 2250, these—compared to today's ∼10 Gt C/yr—low emission levels suffice to cause continued warming. Negative emissions are not part of this scenario. Warming peaks at up to 4°C (depending on model setup), shortly ahead of reaching net-zero emissions, followed by a very slow decline down to around 3°C at the end of this millennium. Continued residual emissions (potential causes are discussed below) of no more than 0.5 Gt C/yr, equivalent to ∼5% of current emissions, suffice to keep temperature near the 4°C peak for at least one thousand years.

Pathway 3 uses the same scenario, but with a "less cooperative" Earth system. Even if we knew exactly the degree of human disturbance to the climate, there is significant uncertainty regarding the warming response of the planet, stemming from incomplete knowledge about Earth system feedback processes. The wide range of ECS values in models at least partly reflects that uncertainty. In CLIMBER-X, pathway 3 is represented by an elevated ECS of 4°C per doubling of CO_2, which is at the upper end of the IPCC AR6 (IPCC AR6 WGI, 2021) likely range (2.5°C–4.0°C). Our results show that an Earth system with a higher ECS leads, for a "middle of the road" scenario, to global mean temperature in the year 3,000 reaching around 4–4.5°C above pre-industrial conditions, after a peak between 4.5 to close to 6°C (setup c, for setups see figure caption). As in pathway 2, the peak level is roughly maintained in the model for at least a millennium under the influence of very small residual emissions.

While ECS (and therefore the difference between pathways 2 and 3) represents uncertainty in physical climate feedbacks, uncertainties in some elements of the global carbon cycle are shown as the shaded spread of the pathways in Figure 1. It is important to note that the spread in pathway 3 is larger than in the other pathways, because feedbacks of physical nature (different ECS in pathways 2 and 3) and carbon cycle feedbacks (creating the shaded spread) can enhance each other. This should serve as a reminder that, as mentioned above, the pathways are not separate tracks without the risk of cross-over: One level of warming can trigger additional self-amplified warming (Wunderling et al., 2024) (compare Section 6 on worst cases and purple arrows in Figure 2).

4. The Two Faces of the Anthropocene

In the real world, the future path of the Earth system in the Anthropocene landscape depends on both our further actions as human societies in terms of direct pressure (forcing), and on the response of the Earth system (horizontal and vertical axes in Figure 2). While the former is exemplified by the scenario difference between pathways 1 and 2, the different ECS's in pathways 2 and 3 represent variations in Earth system resilience related to the physical response to rising CO_2 concentrations. These two dimensions span a landscape where manageability conceptually divides the Anthropocene into two realms (green and red background in Figure 2) that we qualitatively describe here.

The ultimate concern, however, is that Earth system resilience could, within the intermediate "dangerous Anthropocene", become weaker as it progresses along the path. Such a shift could change the face of the Anthropocene from manageable to unmanageable, irrespective of how humanity reacts (see purple arrows in Figure 2 and section "worst cases", below).

Pathway 1 illustrates that it is still within our influence to avoid fully entering the dangerous transition zone between those two Anthropocene versions. We can still manage to steer away from temperatures above the Paris range (1.5°C to well below 2°C)—at least if global emissions peak now and reach zero by mid-century, and we additionally realize the very optimistic assumptions on carbon dioxide removal that generally are incorporated in 1.5°C-compatible pathways (Warszawski et al., 2021), without disregarding potential negative impacts (Zickfeld et al., 2023).

It is important to stress again, however, that even this very optimistic pathway cannot be considered a "good" one by any social standard—neither with respect to human suffering nor to the effects on non-human life on Earth. Regarding the human dimension, the Earth Commission draws the line for the *just* boundary for climate change at just 1°C of GMST rise, as higher temperatures inflict unacceptable levels of significant harm to people (Rockström et al., 2023). For the Earth system, the implications of pathway 1 include continued sea-level rise due to thermal expansion and land ice loss, including from Greenland and Antarctica (Stokes et al., 2025), and seemingly unavoidable biodiversity loss on par with past mass extinctions (Ceballos & Ehrlich, 2018). For example, tropical coral reefs have already crossed a threshold, with massive die-off in recent years (Henley et al., 2024). Another example is the increasing vulnerability of intact tropical rainforests to droughts (Tao et al., 2022). Of those impacts, some are irreversible (or reversible only on timescales of at least tens of millennia), leaving an undesirable Anthropocene imprint on even our most optimistic pathway 1. Yet, if we at least adhere to the Paris Agreement and manage to limit the extent and duration of overshoot of 1.5°C (Möller et al., 2024; Wunderling et al., 2023), we could—with a stroke of luck—avoid crossing global-scale climate tipping points (Armstrong McKay et al., 2022; Lenton et al., 2023) like irreversible, long-term melting of the ice sheets (Stokes et al., 2025). In that case, we remain in a manageable Anthropocene, albeit with an Earth system that, for the next 1,000 years, deviates in terms of global temperature variability by at least 100% more from the Holocene mean state than at any moment over the past 12,000 years. But it could still be possible for us to sustainably steward our wounded planet, at least close to a safe operating space and with a reasonably intact Earth system resilience. Our environment would be to some degree recognizable, therefore manageable, and the best on offer.

Pathway 2, instead, a scenario with "middle of the road" human climate forcing (essentially the path we are following today, with insufficient climate protection), brings us into dangerous territory. Four degrees of warming (as in setup c) would entail catastrophic consequences (in terms of multi-meter sea-level rise on millennial time scales (Clark et al., 2016) and, as thoroughly assessed by working group II of the IPCC (IPCC AR6 WGII, 2022), in many areas beyond). In pathway 3, where peak warming climbs to almost 6°C (setup c), we have to expect a substantial worsening of all of these adverse consequences, for example, (Coulon et al., 2025), making the Anthropocene globally unmanageable. Within our pathway-based illustration, this shift into the unmanageable

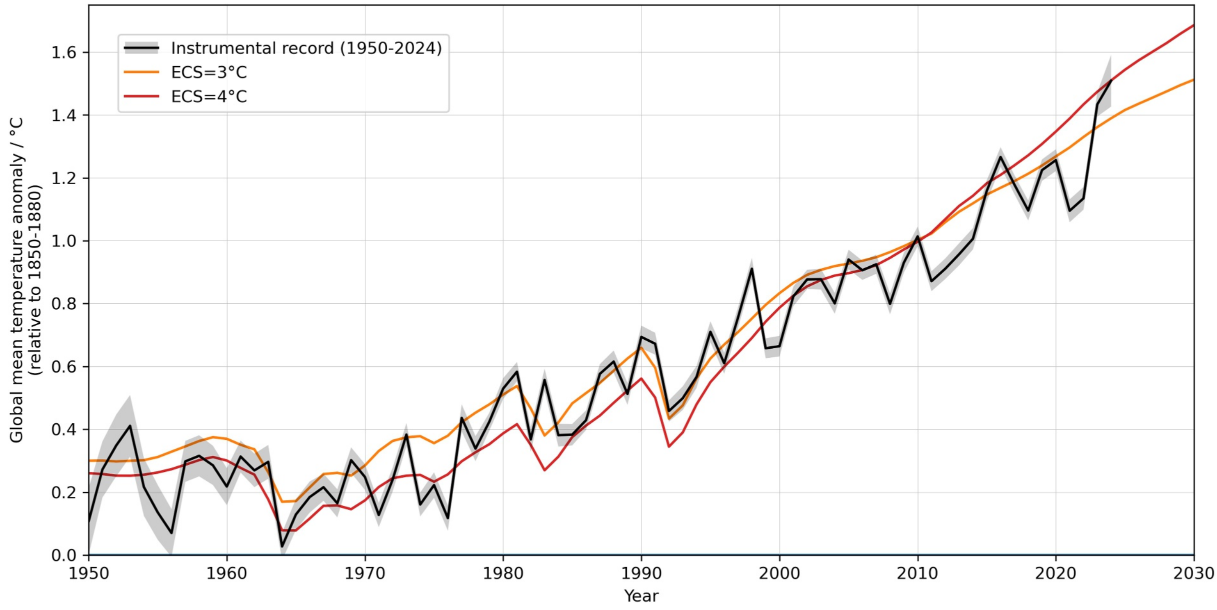

Figure 3. CLIMBER-X model runs with most likely value for ECS (ECS = 3°C), and the upper end of the likely range, (ECS = 4°C), compared to the instrumental record. For each value of ECS, aerosol forcing was tuned to achieve the best agreement with historical data. While this short-term comparison cannot be used to argue that one or the other value for ECS is more likely correct, it is likely that within the next few decades, the observational record will be long enough to disentangle aerosol and other climate forcing, leading to better constraints on current climate sensitivity.

face of the Anthropocene is caused simply by assuming a slightly higher but still reasonably inferred (according to the likely range given by IPCC (IPCC AR6 WGI, 2021)) equilibrium climate sensitivity. Even though reducing uncertainties of current climate sensitivity is difficult due to insufficient knowledge about effects involving aerosols and clouds in particular, satellite-based CERES data of the Earth's Energy imbalance cannot be reproduced by models with climate sensitivity below 2.5 K (Myhre et al., 2025), and an ECS of 4°C does at least not contradict the observed warming rate of the past 2 decades (Figure 3).

5. Climate Recovery Within the Anthropocene

Importantly, in all pathways presented here Earth's climate does not on its own return back to the original climate state, even after minimizing human pressures. There is no easy recovery—we get “stuck” in a warmer state for millennia, unless massive carbon drawdown (via negative emissions) is achieved. A doubling of current cumulative carbon emissions to 1,000 PgC (a value expected to be reached by ~2070 in SSP2-4.5) would delay the next glacial inception by 50,000 years (Kaufhold, Willeit, Munhoven, et al., 2025). Even after hundreds of thousands of years into the deep future, the Earth system may not return to its natural orbitally driven cycling between glacial and interglacial states (Ganopolski et al., 2016; Summerhayes et al., 2024), suggesting that a truly long-term Anthropocene trajectory may be triggered. Notably, any robust predictions of such a development would entail the renewed question to formal bodies of the geological community, whether the Anthropocene is not only a new epoch following the Holocene, but rather to be located on the period-scale, given that such a trajectory would imply a departure of the Earth system from Quaternary conditions with its robust glacial-interglacial cycle of 100,000 years.

In the virtual absence of natural climate recovery on human timescales, however, any attempts to actively steer the Earth system back toward its pre- or early Anthropocene state using negative emissions would be directly counteracted by involuntary residual emissions. These residual emissions may be indirectly caused by an Earth system response to warming, but could just as easily directly stem from human activities leading to the release of fossil CO_2 from sectors like agriculture and industry (Buck et al., 2023), which add up to far more than the minimal value of 0.5 Gt of carbon per year assumed in the model runs presented in Figure 1 (dotted lines).

6. Worst Cases: Loss of Earth System Resilience

Several issues raise concerns that our illustrative pathways may actually not represent the worst cases in terms of climate outcome and manageability: Firstly, human action could fall behind: in our pathways 2 and 3, we "only" burden the planet with middle-of-the-road-type human pressure, not even considering more extreme emission scenarios above SSP2-4.5. As warned by the IPCC (IPCC AR6 Synthesis Report, 2023), SSP2-4.5 alone will cause temperatures higher than the warmest the planet has seen in over 2.5 million years (Burke et al., 2018)—or even 40 million years (Kaufhold, Willeit, Talento, et al., 2025)—both long before modern humans developed.

The second point of concern, involving resilience, covers several potential surprises in the Earth system response to such warming: current Earth system models may lack or underestimate the strength of some important climate-related positive feedbacks under these high-temperature conditions. The warming response could be stronger than commonly anticipated. These cases are conceptually sketched as purple arrows in Figure 2. They are an attempt to address the open question to what extent the Earth system will conserve its Holocene resilience under human pressures. Put another way, to what degree will the Earth system continue to physically and biologically buffer Anthropocene stress (i.e., to which degree it continues to be constantly dominated by negative feedbacks to warming that either take energy out of the system (like the Planck radiation feedback) or greenhouse gases out of the atmosphere (like CO_2 fertilization)?

The first kind of surprise involves (positive) carbon cycle feedbacks to warming beyond those implemented in CLIMBER-X or other Earth system models. Warming would get an extra push if natural carbon sinks significantly weaken, for example, if the export of CO_2 into the deep ocean via the biological (Henson et al., 2022) or physical (Joos et al., 1999) pumps (Gruber et al., 2023) slows, or if anthropogenic warming triggers additional carbon release from natural stocks. That might happen, for example, in the case of large-scale dying or burning of forests (Reyer et al., 2015), or when carbon release from thawing permafrost (Turetsky et al., 2020) or gas hydrates on the ocean floor (Minshull et al., 2016) increases beyond current expectations. If such "natural" carbon release exceeds a potentially modest threshold (compare residual emissions experiment, Figure 1), warming may continue even if human forcing from GHG emissions or further land-use changes are virtually stopped. These human efforts would then be thwarted by the Earth system itself. An exemplary illustration is given by the purple arrow "cc" in Figure 2.

Another kind of surprise could involve the sensitivity of the Earth system to a specific (fixed) level of greenhouse gases in the atmosphere. Equilibrium climate sensitivity might be strongly state-dependent (compare Section 7.4.3 in (IPCC AR6 WGI, 2021)), such that on a warming planet ECS rises (continually or step-wise due to shifts in Earth system functioning; purple arrow "ECS rising" in Figure 2), potentially even beyond the upper end of the IPCC likely range (purple arrow "ECS rising >4°C" in Figure 2). This concern raises the question of whether the historic ECS in the Holocene and early Anthropocene, during a phase of high Earth resilience, also applies to the future, in a dangerous Anthropocene where Earth resilience may be in decline. It is important to note that elevated equilibrium climate sensitivity has an effect irrespective of anthropogenic forcing at that time—remaining elevated greenhouse gas concentrations in the atmosphere would lead to elevated warming even with net-zero emissions. A state-dependent ECS (with higher sensitivity at higher temperatures) can therefore be regarded as a positive feedback acting independently of current human forcing. In past warm phases on our planet there are hints that equilibrium climate sensitivity might have been higher than in cooler climates (Anagnostou et al., 2020).

We therefore argue that both kinds of surprises, and with them a shift in the functional character of the Anthropocene, are at least plausible. We even cannot rule out that we are already approaching a dangerous Anthropocene. One example of the first surprise category is the current state of global carbon sinks on land. In spite of a regionally differentiated, but overall stable trend so far (Pan et al., 2024), 2023 was an extraordinarily weak year, with the lowest carbon uptake since 2015 (Friedlingstein et al., 2025) due to the impact of record warming on terrestrial ecosystems through drought and fire (Jain et al., 2024; Ke et al., 2024). Whether or not this is the first indication of a globally weakening sink is not clear yet, but there are signs that models used for projections are overly optimistic (Wang et al., 2020). In terms of equilibrium climate sensitivity to specific anthropogenic forcing: If there currently is a tendency of higher rate of global warming, as implied by the observed increase of the Earth's energy imbalance over the last 2 decades (Loeb et al., 2024) and as seen in the global temperature record when corrected for "noise" such as ENSO (Foster & Rahmstorf, 2026), it is probably an effect of multiple causes including reduced aerosol forcing due to political measures against pollution (Yuan

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et al., 2024), the subsequent climate response (Hodnebrog et al., 2024), and natural variability (like El Nino) (Raghuraman et al., 2024; Schoeberl et al., 2024). A feedback to warming, however, could play a causal role as well: It is one of the possible explanations for an observed trend of reduced low-cloud cover (Goessling et al., 2024) causing reductions in Earth albedo and therefore additional warming, with implications for equilibrium climate sensitivity.

So, even if there is no definite explanation yet for the recent trends, there is reason for concern that at some (still unspecified) point, the dominant Holocene-type functioning of the Anthropocene might shift. Pathways 1 and 2 illustrate the current situation, where the Earth system responds linearly to human pressures, while pathway 3 illustrates a more sensitive situation where feedbacks add to the pressure, aggravating warming even in the absence of any further *direct* human pressure. In other words, entering the "dangerous" Anthropocene means risking a stronger Earth system response to warming, which in turn would entail a shift in the Anthropocene: its manageable face would—gradually or abruptly—become unmanageable. If and when this happens is unclear, as represented by the orange zone in Figure 2. The risk of crossing tipping points, both large-scale or of regional type, increases with every tenth of a degree, starting with thresholds as low as 1.5° of warming (Armstrong McKay et al., 2022; Lenton et al., 2023). We stress, however, that the illustrative pathways or the color transitions presented in Figures 1 and 2 are not meant to suggest that the specific temperature levels shown represent a well-resolved boundary between these two faces of the Anthropocene. That a danger zone exists, though, is a reasonable concern.

To be clear: while we are already seeing worrying signs of degrading buffering capacity (Ke et al., 2024), the planet is still operating according to what we call a "Holocene-like logic", where Earth resilience is maintained largely intact with active land and ocean carbon sinks (Friedlingstein et al., 2025) and no clear sign that ECS is on the rise. Also, while positive feedbacks have clearly amplified past warming events in the Earth system, there is no solid evidence for a transition from a warm to a hot mode in which such feedbacks dominated the climate dynamics over extended periods without continued external forcing. Nevertheless, a dire situation where the Earth system itself (responding indirectly to earlier human disturbances) elevates global mean temperature—or at least permanently keeps it—above 5 or 6°C of warming cannot be excluded and therefore is within reasonable estimates of known uncertainties.

We place this self-amplifying situation, our second point of concern, among the worst cases, because it implies loss of foresight (due to the surprises) but also because it can imply loss of agency in those cases in which these surprises take effect even after human forcing has stopped: We would then leave the forcing-driven realm of the Anthropocene (where temperature changes, for instance, are mainly directly driven by anthropogenic forcing) and instead transition to a situation where changes in characteristics of the Earth system state, like global temperature, are dominated by shifts in feedback strength and feedback relevance.

7. Coping With the Anthropocene

The IPCC acknowledges that, with high confidence, the choices and actions implemented in this decade will have impacts for thousands of years (IPCC AR6 Synthesis Report, 2023). Nevertheless, it puts a focus on the time until 2100, while discussing scenarios extending to 2300 more on the sideline, as for instance in Section 4.7.1 in AR6, WG1. Particularly policy-guiding scenarios, as in working Group 3 (IPCC AR6 WGIII, 2022) lack a longer-term perspective.

That longer-term perspective, which we have tried to highlight here, is tightly connected to planetary resilience. And resilience of the Earth system, in turn, depends on dynamic system properties that are not yet fully understood, or even essentially unknown (see the large span of estimates for ECS, and the different estimates for the climate commitment after zero emissions are reached (ZEC) (Palazzo Corner et al., 2023). However, we do know that the system's resilience is itself strongly influenced by our actions—it depends, for example, on how well we take care of natural carbon stocks or buffering systems like land carbon sinks (Friedlingstein et al., 2025). But we need to improve our understanding of the currently accessible Anthropocene pathways: how exactly is Earth system resilience degraded by human pressures (including tipping point research, and exploring the less likely but high impact tails of the probability distribution for feedbacks such as carbon cycling under higher temperatures)? And how can Earth's resilience be regenerated? Most pressing is the need to understand how to implement sustainable stewardship in our global societies: which instruments (Stechemesser et al., 2024) can be successfully used to realize long-established requirements like carbon neutrality (or active drawdown needed for recovery) and protection of the biosphere (Lenton et al., 2022; Otto et al., 2020).

On the scientific side, we therefore argue that forward-looking Anthropocene research questions should be given priority, irrespective of academic debates about formal Anthropocene definitions and starting dates (Gibbard et al., 2022; Head et al., 2022, 2023). Our key message here is that the Anthropocene matters even without a formal geological definition (IPCC AR6 WGII, 2022; Zalasiewicz et al., 2024). Whether we like it or not: from an Earth system perspective, we are deep into the Anthropocene. An unmanageable Anthropocene would—from a backward-looking geological perspective in the far future—undoubtedly provide ample reference spikes, in addition to the radioactive "golden spike" already discussed in the literature (Vince, 2011). The question though is whether by that time we would still have any civilization interested in mapping geological epochs.

The Anthropocene can be compared to quicksand: after unintentionally slipping in, it is difficult to get out. And it takes time—evidence from Earth system science clearly shows that while exiting the Anthropocene is only possible in the far future (Summerhayes et al., 2024) (vividly illustrated by the prospect of the next glaciation being postponed by 100 thousand years (Ganopolski et al., 2016)), possible pathways *through* the Anthropocene are neither "good" nor necessarily "apocalyptic."

With our knees in the sand but a rope in our hands, the currently best available, although far from "good", Anthropocene option is to make a brave pull toward sustainable stewardship, a manageable situation, albeit stuck with committed damage. It is in our hands to make that pull. Otherwise, we risk to continue sinking deeper, toward a dangerous Anthropocene, where we approach an unmanageable situation by crossing global-scale tipping points, activating positive feedbacks, and substantially worsening the committed change. It is unlikely, however, that we have already crossed a hypothetical point of no return, where the rope slips through our hands. Earth continues to operate in a way that buffers the stressors, shielding us from the worst impacts. We still have a choice, and are not yet destined to bequeath a much less habitable planet to future generations.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The model output from CLIMBER-X is archived and publicly available at Zenodo (Ganopolski et al., 2026). The other data, created by others but used in this article is accessible via the following publications:

- (PAGES 2k Consortium, 2019; PAGES2k Consortium, 2017) for global temperature reconstruction data (Neukom et al., 2019) shown in Figure 1,
- (Morice et al., 2021) for HadCRUT5 historical global surface temperature anomaly data (Met Office Hadley Centre, 2019) shown in Figure 1,
- and (Hoesly et al., 2025) for CEDS CO_2 emission data (Hoesly et al., 2025) in Figure 2.

Software availability: The CLIMBER-X model is available at https://github.com/cxesmc/climber-x/releases/tag/v1.3.0. For this study, we used the tagged v1.3.0 of the model. Data visualization was done using Python: https://github.com/python.

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References

Abramoff, R. Z., Guenet, B., Zhang, H., Georgiou, K., Xu, X., Viscarra Rossel, R. A., et al. (2022). Improved global-scale predictions of soil carbon stocks with Millennial version 2. *Soil Biology and Biochemistry*, *164*, 108466. https://doi.org/10.1016/j.soilbio.2021.108466

Anagnostou, E., John, E. H., Babila, T. L., Sexton, P. F., Ridgwell, A., Lunt, D. J., et al. (2020). Proxy evidence for state-dependence of climate sensitivity in the Eocene greenhouse. *Nature Communications*, *11*(1), 4436. https://doi.org/10.1038/s41467-020-17887-x

Archer, D., & Brovkin, V. (2008). The millennial atmospheric lifetime of anthropogenic CO_2. *Climatic Change*, *90*(3), 283–297. https://doi.org/10.1007/s10584-008-9413-1

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science. (World)*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Bevacqua, E., Schleussner, C.-F., & Zscheischler, J. (2025). A year above 1.5°C signals that Earth is most probably within the 20-year period that will reach the Paris agreement limit. *Nature Climate Change*, *15*(3), 262–265. https://doi.org/10.1038/s41558-025-02246-9

Buck, H. J., Carton, W., Lund, J. F., & Markusson, N. (2023). Why residual emissions matter right now. *Nature Climate Change*, *13*(4), 351–358. https://doi.org/10.1038/s41558-022-01592-2

Burke, E. J., Zhang, Y., & Krinner, G. (2020). Evaluating permafrost physics in the coupled model intercomparison project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere*, *14*(9), 3155–3174. https://doi.org/10.5194/tc-14-3155-2020

Burke, K. D., Williams, J. W., Chandler, M. A., Haywood, A. M., Lunt, D. J., & Otto-Bliesner, B. L. (2018). Pliocene and Eocene provide best analogs for near-future climates. *Proceedings of the National Academy of Sciences*, *115*(52), 13288–13293. https://doi.org/10.1073/pnas.1809600115

Caballero, R., & Huber, M. (2013). State-dependent climate sensitivity in past warm climates and its implications for future climate projections. *Proceedings of the National Academy of Sciences*, *110*(35), 14162–14167. https://doi.org/10.1073/pnas.1303365110

Callahan, C. W. (2025). Present and future limits to climate change adaptation. *Nature Sustainability*, *8*(4), 336–342. https://doi.org/10.1038/s41893-025-01519-7

Cartapanis, O., Galbraith, E. D., Bianchi, D., & Jaccard, S. L. (2018). Carbon burial in deep-sea sediment and implications for oceanic inventories of carbon and alkalinity over the last glacial cycle. *Climate of the Past*, *14*(11), 1819–1850. https://doi.org/10.5194/cp-14-1819-2018

Ceballos, G., & Ehrlich, P. R. (2018). The misunderstood sixth mass extinction. *Science*, *360*(6393), 1080–1081. https://doi.org/10.1126/science.aau0191

Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., et al. (2016). Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, *6*(4), 360–369. https://doi.org/10.1038/nclimate2923

Copernicus, European Centre for Medium-Range Weather Forecasts, ECMWF. (2026). 2025 global climate highlights. Retrieved from https://climate.copernicus.eu/sites/default/files/custom-uploads/GCH-2025/GCH2025-full-report.pdf

Coulon, V., Klose, A. K., Edwards, T., Turner, F., Pattyn, F., & Winkelmann, R. (2025). From short-term uncertainties to long-term certainties in the future evolution of the Antarctic Ice Sheet. *Nature Communications*, *16*(1), 10385. https://doi.org/10.1038/s41467-025-66178-w

Crutzen, P. J. (2002). Geology of mankind. *Nature*, *415*(6867), 23. Article 6867. https://doi.org/10.1038/415023a

Crutzen, P. J. (2006). The "Anthropocene.". In E. Ehlers & T. Krafft (Eds.), *Earth system science in the Anthropocene* (pp. 13–18). Springer. https://doi.org/10.1007/3-540-26590-2_3

Crutzen, P. J., & Stormer, E. F. (2000). The "Anthropocene.". *IGBP Newsletter*, *41*, 17–18. http://www.igbp.net/download/18.316f18321323470177580001401/1376383088452/NL41.pdf

DeVries, T. (2022). The ocean carbon cycle. *Annual Review of Environment and Resources*, *47*(47), 317–341. https://doi.org/10.1146/annurev-environ-120920-111307

Drenkhan, F., Buytaert, W., Mackay, J. D., Barrand, N. E., Hannah, D. M., & Huggel, C. (2023). Looking beyond glaciers to understand mountain water security. *Nature Sustainability*, *6*(2), 130–138. https://doi.org/10.1038/s41893-022-00996-4

Eddy, T. D., Lam, V. W. Y., Reygondeau, G., Cisneros-Montemayor, A. M., Greer, K., Palomares, M. L. D., et al. (2021). Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*, *4*(9), 1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016

Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of tropical forests in the Anthropocene. *Current Biology*, *29*(19), R1008–R1020. https://doi.org/10.1016/j.cub.2019.08.026

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., & Milo, R. (2020). Global human-made mass exceeds all living biomass. *Nature*, *588*(7838), 442–444. https://doi.org/10.1038/s41586-020-3010-5

Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., et al. (2025). Indicators of global climate change 2024: Annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, *17*(6), 2641–2680. https://doi.org/10.5194/essd-17-2641-2025

Foster, G., & Rahmstorf, S. (2026). Global warming has accelerated significantly. *Geophysical Research Letters*, *53*(5), e2025GL118804. https://doi.org/10.1029/2025GL118804

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., et al. (2025). Global carbon budget 2024. *Earth System Science Data*, *17*(3), 965–1039. https://doi.org/10.5194/essd-17-965-2025

Ganopolski, A., Kaufhold, C., & Willeit, M. (2026). Data set for the study "we are in the Anthropocene – Now what? [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.19696770

Ganopolski, A., Winkelmann, R., & Schellnhuber, H. J. (2016). Critical insolation–CO_2 relation for diagnosing past and future glacial inception. *Nature*, *529*(7585), 200–203. https://doi.org/10.1038/nature16494

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature*, *595*(7867), 388–393. https://doi.org/10.1038/s41586-021-03629-6

Geisen, S., Wall, D. H., & van der Putten, W. H. (2019). Challenges and opportunities for soil biodiversity in the Anthropocene. *Current Biology*, *29*(19), R1036–R1044. https://doi.org/10.1016/j.cub.2019.08.007

Gibbard, P., Walker, M., Bauer, A., Edgeworth, M., Edwards, L., Ellis, E., et al. (2022). The Anthropocene as an event, not an epoch. *Journal of Quaternary Science*, *37*(3), 395–399. https://doi.org/10.1002/jqs.3416

Goessling, H. F., Rackow, T., & Jung, T. (2024). Recent global temperature surge intensified by record-low planetary albedo. *Science*, 68–73. https://doi.org/10.1126/science.adq7280

Gruber, N., Bakker, D. C. E., DeVries, T., Gregor, L., Hauck, J., Landschützer, P., et al. (2023). Trends and variability in the ocean carbon sink. *Nature Reviews Earth & Environment*, *4*(2), 119–134. https://doi.org/10.1038/s43017-022-00381-x

Hanna, E. G., & Tait, P. W. (2015). Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. *International Journal of Environmental Research and Public Health*, *12*(7), 8034–8074. https://doi.org/10.3390/ijerph120708034

Hansen, J. E., Sato, M., Simons, L., Nazarenko, L. S., Sangha, I., Kharecha, P., et al. (2023). Global warming in the pipeline. *Oxford Open Climate Change*, *3*(1), kgad008. https://doi.org/10.1093/oxfclm/kgad008

Head, M. J., Zalasiewicz, J. A., Waters, C. N., Turner, S. D., Williams, M., Barnosky, A. D., et al. (2023). The Anthropocene is a prospective epoch/series, not a geological event. *Episodes Journal of International Geoscience*, *46*(2), 229–238. https://doi.org/10.18814/epiiugs/2022/022025

Head, M. J., Zalasiewicz, J. A., Waters, C. N., Turner, S. D., Williams, M., Barnosky, A. D., et al. (2022). The proposed Anthropocene Epoch/Series is underpinned by an extensive array of mid-20th century stratigraphic event signals. *Journal of Quaternary Science*, *37*(7), 1181–1187. https://doi.org/10.1002/jqs.3467

Henley, B. J., McGregor, H. V., King, A. D., Hoegh-Guldberg, O., Arzey, A. K., Karoly, D. J., et al. (2024). Highest ocean heat in four centuries places Great Barrier Reef in danger. *Nature*, *632*(8024), 320–326. https://doi.org/10.1038/s41586-024-07672-x

Henson, S. A., Laufkötter, C., Leung, S., Giering, S. L. C., Palevsky, H. I., & Cavan, E. L. (2022). Uncertain response of ocean biological carbon export in a changing world. *Nature Geoscience*, *15*(4), 248–254. https://doi.org/10.1038/s41561-022-00927-0

Hodnebrog, Ø., Myhre, G., Jouan, C., Andrews, T., Forster, P. M., Jia, H., et al. (2024). Recent reductions in aerosol emissions have increased Earth's energy imbalance. *Communications Earth & Environment*, *5*(1), 1–9. https://doi.org/10.1038/s43247-024-01324-8

Hoesly, R., Smith, S. J., Ahsan, H., Prime, N., O'Rourke, P., Crippa, M., et al. (2025). CEDS v_2025_03_18 aggregate data (version v_2025_03_18) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.15059443

IPCC AR6 Synthesis Report. (2023). IPCC, 2023: Climate change 2023: Synthesis report. In H. Lee, & J. Romero (Eds.), *Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team*. IPCC, Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

IPCC AR6 WGI. (2021). Climate change 2021: The physical science basis. In *Contribution of working Group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC AR6 WGI Chapter 7. (2021). Chapter 7 the Earth's energy budget, climate feedbacks and climate sensitivity—IPCC_AR6_WGI_Chapter07.

IPCC AR6 WGII. (2022). Climate change 2022: Impacts, adaptation, and vulnerability. In *Contribution of working Group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009325844

IPCC AR6 WGIII. (2022). Climate change 2022: Mitigation of climate change. In *Contribution of working Group III to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

Jain, P., Barber, Q. E., Taylor, S. W., Whitman, E., Castellanos Acuna, D., Boulanger, Y., et al. (2024). Drivers and impacts of the record-breaking 2023 wildfire season in Canada. *Nature Communications*, *15*(1), 6764. https://doi.org/10.1038/s41467-024-51154-7

Joos, F., Plattner, G.-K., Stocker, T. F., Marchal, O., & Schmittner, A. (1999). Global warming and marine carbon cycle feedbacks on future atmospheric CO_2. *Science*, *284*(5413), 464–467. https://doi.org/10.1126/science.284.5413.464

Kaufhold, C., Willeit, M., Munhoven, G., Klemann, V., & Ganopolski, A. (2025). Timing of a future glaciation in view of anthropogenic climate change. *Communications Earth & Environment*, *6*(1), 1016. https://doi.org/10.1038/s43247-025-02867-0

Kaufhold, C., Willeit, M., Talento, S., Ganopolski, A., & Rockström, J. (2025). Interplay between climate and carbon cycle feedbacks could substantially enhance future warming. *Environmental Research Letters*, *20*(4), 044027. https://doi.org/10.1088/1748-9326/adb6be

Ke, P., Ciais, P., Sitch, S., Li, W., Bastos, A., Liu, Z., et al. (2024). Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023. *National Science Review*, *11*(12), nwae367. https://doi.org/10.1093/nsr/nwae367

Kemp, L., Xu, C., Depledge, J., Ebi, K. L., Gibbins, G., Kohler, T. A., et al. (2022). Climate endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences*, *119*(34), e2108146119. https://doi.org/10.1073/pnas.2108146119

Kleinen, T., Gromov, S., Steil, B., & Brovkin, V. (2021). Atmospheric methane underestimated in future climate projections. *Environmental Research Letters*, *16*(9), 094006. https://doi.org/10.1088/1748-9326/ac1814

Knutti, R., Rugenstein, M. A. A., & Hegerl, G. C. (2017). Beyond equilibrium climate sensitivity. *Nature Geoscience*, *10*(10), 727–736. https://doi.org/10.1038/ngeo3017

Lee, S.-S., Sharma, S., Rosenbloom, N., Rodgers, K. B., Kim, J.-E., Kwon, E. Y., et al. (2025). Multi-centennial climate change in a warming world beyond 2100. *Earth System Dynamics*, *16*(5), 1427–1451. https://doi.org/10.5194/esd-16-1427-2025

T. M. Lenton, D. I. Armstrong McKay, S. Loriani, J. F. Abrams, S. J. Lade, J. F. Donges, et al. (Eds.) (2023). *The global tipping points report 2023*. University of Exeter.

Lenton, T. M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., et al. (2022). Operationalising positive tipping points towards global sustainability. *Global Sustainability*, *5*, e1. https://doi.org/10.1017/sus.2021.30

Loeb, N. G., Ham, S.-H., Allan, R. P., Thorsen, T. J., Meyssignac, B., Kato, S., et al. (2024). Observational assessment of changes in Earth's energy imbalance since 2000. *Surveys in Geophysics*, *45*(6), 1757–1783. https://doi.org/10.1007/s10712-024-09838-8

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., et al. (2020). Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from CO_2. *Biogeosciences*, *17*(11), 2987–3016. https://doi.org/10.5194/bg-17-2987-2020

Malhi, Y., Gardner, T. A., Goldsmith, G. R., Silman, M. R., & Zelazowski, P. (2014). Tropical forests in the Anthropocene. *Annual Review of Environment and Resources*, *39*(39), 125–159. https://doi.org/10.1146/annurev-environ-030713-155141

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Met Office Hadley Centre. (2019). HadCRUT: Gridded dataset of global historical surface temperature anomalies [Dataset]. *Centre for Environmental Data Analysis*. Retrieved from https://catalogue.ceda.ac.uk/uuid/f7189fabb084452c9818ba41e59ccabd/

Minshull, T. A., Marín-Moreno, H., Armstrong McKay, D. I., & Wilson, P. A. (2016). Mechanistic insights into a hydrate contribution to the Paleocene-Eocene carbon cycle perturbation from coupled thermohydraulic simulations. *Geophysical Research Letters*, *43*(16), 8637–8644. https://doi.org/10.1002/2016GL069676

Möller, T., Högner, A. E., Schleussner, C.-F., Bien, S., Kitzmann, N. H., Lamboll, R. D., et al. (2024). Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nature Communications*, *15*(1), 6192. https://doi.org/10.1038/s41467-024-49863-0

Morice, C. P., Kennedy, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., et al. (2021). An updated assessment of near-surface temperature change from 1850: The HadCRUT5 data set. *Journal of Geophysical Research: Atmospheres*, *126*(3), e2019JD032361. https://doi.org/10.1029/2019JD032361

Myhre, G., Hodnebrog, Ø., Loeb, N., & Forster, P. M. (2025). Observed trend in Earth energy imbalance may provide a constraint for low climate sensitivity models. *Science*, *388*(6752), 1210–1213. https://doi.org/10.1126/science.adt0647

Neukom, R., Barboza, L. A., Erb, M. P., Shi, F., Emile-Geay, J., Evans, M. N., et al. (2019). NOAA/WDS Paleoclimatology—PAGES2k common era surface temperature reconstructions [Dataset]. *NOAA National Centers for Environmental Information*. https://doi.org/10.25921/TKXP-VN12

Osman, M. B., Tierney, J. E., Zhu, J., Tardif, R., Hakim, G. J., King, J., & Poulsen, C. J. (2021). Globally resolved surface temperatures since the last glacial maximum. *Nature*, *599*(7884), 239–244. https://doi.org/10.1038/s41586-021-03984-4

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., et al. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences*, *117*(5), 2354–2365. https://doi.org/10.1073/pnas.1900577117

Owens, P. N. (2020). Soil erosion and sediment dynamics in the Anthropocene: A review of human impacts during a period of rapid global environmental change. *Journal of Soils and Sediments*, *20*(12), 4115–4143. https://doi.org/10.1007/s11368-020-02815-9

PAGES2k Consortium. (2017). A global multiproxy database for temperature reconstructions of the Common era. *Scientific Data*, *4*(1), 170088. https://doi.org/10.1038/sdata.2017.88

PAGES 2k Consortium. (2019). Consistent multidecadal variability in global temperature reconstructions and simulations over the Common era. *Nature Geoscience*, *12*(8), 643–649. https://doi.org/10.1038/s41561-019-0400-0

Palazzo Corner, S., Siegert, M., Ceppi, P., Fox-Kemper, B., Frölicher, T. L., Gallego-Sala, A., et al. (2023). The zero emissions commitment and climate stabilization. *Frontiers in Science*, *1*, 1170744. https://doi.org/10.3389/fsci.2023.1170744

Pan, Y., Birdsey, R. A., Phillips, O. L., Houghton, R. A., Fang, J., Kauppi, P. E., et al. (2024). The enduring world forest carbon sink. *Nature*, *631*(8021), 563–569. https://doi.org/10.1038/s41586-024-07602-x

Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., et al. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. IPBES and IPCC. (p. 234). https://doi.org/10.5281/zenodo.4782538

Raghuraman, S. P., Soden, B., Clement, A., Vecchi, G., Menemenlis, S., & Yang, W. (2024). The 2023 global warming spike was driven by the El Niño–Southern oscillation. *Atmospheric Chemistry and Physics*, *24*(19), 11275–11283. https://doi.org/10.5194/acp-24-11275-2024

Rahmstorf, S. (2024). Climate and weather at 3 degrees more: Earth as we don't (want to) know it. In K. Wiegandt (Ed.), *3 degrees more* (pp. 3–17). Springer Nature. https://doi.org/10.1007/978-3-031-58144-1_1

Reyer, C. P. O., Brouwers, N., Rammig, A., Brook, B. W., Epila, J., Grant, R. F., et al. (2015). Forest resilience and tipping points at different spatio-temporal scales: Approaches and challenges. *Journal of Ecology*, *103*(1), 5–15. https://doi.org/10.1111/1365-2745.12337

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., et al. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Ripple, W. J., Wolf, C., Rockström, J., Richardson, K., Wunderling, N., Gregg, J. W., et al. (2026). The risk of a hothouse Earth trajectory. *One Earth*, 101565. https://doi.org/10.1016/j.oneear.2025.101565

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., et al. (2023). Safe and just Earth system boundaries. *Nature*, *619*(7968), 102–111. Article 7968. https://doi.org/10.1038/s41586-023-06083-8

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 7263–7475. https://doi.org/10.1038/461472a

Ruehr, S., Keenan, T. F., Williams, C., Zhou, Y., Lu, X., Bastos, A., et al. (2023). Evidence and attribution of the enhanced land carbon sink. *Nature Reviews Earth & Environment*, *4*(8), 518–534. https://doi.org/10.1038/s43017-023-00456-3

Sakschewski, B., Caesar, L., Andersen, L., Bechthold, M., Bergfeld, L., Beusen, A., et al. (2025). Planetary Health Check 2025: A scientific assessment of the state of the planet. In N. H. Kitzmann, L. Caesar, B. Sakschewski, & J. Rockström (Eds.), *Planetary boundaries science (PBScience)*. Potsdam Institute for Climate Impact Research (PIK). [Application/pdf]. https://doi.org/10.48485/PIK.2025.017

Sanderson, B. M., & Rugenstein, M. (2022). Potential for bias in effective climate sensitivity from state-dependent energetic imbalance. *Earth System Dynamics*, *13*(4), 1715–1736. https://doi.org/10.5194/esd-13-1715-2022

Schoeberl, M. R., Wang, Y., Taha, G., Zawada, D. J., Ueyama, R., & Dessler, A. (2024). Evolution of the climate forcing during the two years after the Hunga Tonga-Hunga Ha'apai eruption. *Journal of Geophysical Research: Atmospheres*, *129*(14), e2024JD041296. https://doi.org/10.1029/2024JD041296

Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, *58*(4), e2019RG000678. https://doi.org/10.1029/2019RG000678

Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J., & Romanovsky, V. E. (2022). The changing thermal state of permafrost. *Nature Reviews Earth & Environment*, *3*(1), 10–23. https://doi.org/10.1038/s43017-021-00240-1

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L., et al. (2024). Climate policies that achieved major emission reductions: Global evidence from two decades. *Science*, *385*(6711), 884–892. https://doi.org/10.1126/science.adl6547

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81–98. https://doi.org/10.1177/2053019614564785

Steffen, W., Leinfelder, R., Zalasiewicz, J., Waters, C. N., Williams, M., Summerhayes, C., et al. (2016). Earth's future stratigraphic and earth system approaches to defining the Earth's future. *Earth's Future*, *4*(8), 324–345. https://doi.org/10.1002/2016ef000379

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H. J., Dube, O. P., Dutreuil, S., et al. (2020). The emergence and evolution of Earth system science. *Nature Reviews Earth & Environment*, *1*, 54–63. https://doi.org/10.1038/s43017-019-0005-6

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., et al. (2018). Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Stokes, C. R., Bamber, J. L., Dutton, A., & DeConto, R. M. (2025). Warming of +1.5°C is too high for polar ice sheets. *Communications Earth & Environment*, *6*(1), 1–12. https://doi.org/10.1038/s43247-025-02299-w

Summerhayes, C. P., Zalasiewicz, J., Head, M. J., Syvitski, J., Barnosky, A. D., Cearreta, A., et al. (2024). The future extent of the Anthropocene epoch: A synthesis. *Global and Planetary Change*, *242*, 104568. https://doi.org/10.1016/j.gloplacha.2024.104568

Tao, S., Chave, J., Frison, P.-L., Le Toan, T., Ciais, P., Fang, J., et al. (2022). Increasing and widespread vulnerability of intact tropical rainforests to repeated droughts. *Proceedings of the National Academy of Sciences*, *119*(37), e2116626119. https://doi.org/10.1073/pnas.2116626119

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., et al. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, *13*(2), 138–143. https://doi.org/10.1038/s41561-019-0526-0

United Nations Environment Programme. (2024). *Emissions gap report 2024*. UNEP—UN Environment Programme. Retrieved from https://www.unep.org/resources/emissions-gap-report-2024

United Nations Environment Programme. (2025). Emissions gap report 2025: Off target—Continued collective inaction puts global temperature goal at risk. https://doi.org/10.59117/20.500.11822/48854

Vince, G. (2011). A sign of our times. *Science*, *334*(6052), 37. https://doi.org/10.1126/science.334.6052.37

Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., et al. (2020). Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. *Science*, *370*(6522), 1295–1300. https://doi.org/10.1126/science.abb7772

Warszawski, L., Kriegler, E., Lenton, T. M., Gaffney, O., Jacob, D., Klingenfeld, D., et al. (2021). All options, not silver bullets, needed to limit global warming to 1.5°C: A scenario appraisal. *Environmental Research Letters*, *16*(6), 64037. https://doi.org/10.1088/1748-9326/abfeec

Willeit, M., Ganopolski, A., Robinson, A., & Edwards, N. R. (2022). The Earth system model CLIMBER-X v1.0 – Part 1: Climate model description and validation. *Geoscientific Model Development*, *15*(14), 5905–5948. https://doi.org/10.5194/gmd-15-5905-2022

Willeit, M., Ilyina, T., Liu, B., Heinze, C., Perrette, M., Heinemann, M., et al. (2023). The Earth system model CLIMBER-X v1.0 – Part 2: The global carbon cycle. *Geoscientific Model Development*, *16*(12), 3501–3534. https://doi.org/10.5194/gmd-16-3501-2023

Witze, A. (2024). Geologists reject the Anthropocene as Earth's new epoch—After 15 years of debate. *Nature*, *627*(8003), 249–250. https://doi.org/10.1038/d41586-024-00675-8

Woodhead, A. J., Hicks, C. C., Norström, A. V., Williams, G. J., & Graham, N. A. J. (2019). Coral reef ecosystem services in the Anthropocene. *Functional Ecology*, *33*(6), 1023–1034. https://doi.org/10.1111/1365-2435.13331

Wunderling, N., von der Heydt, A. S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., et al. (2024). Climate tipping point interactions and cascades: A review. *Earth System Dynamics*, *15*(1), 41–74. https://doi.org/10.5194/esd-15-41-2024

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D. I., Ritchie, P. D. L., et al. (2023). Global warming overshoots increase risks of climate tipping cascades in a network model. *Nature Climate Change*, *13*(1), 75–82. Article 1. https://doi.org/10.1038/s41558-022-01545-9

Yuan, T., Song, H., Oreopoulos, L., Wood, R., Bian, H., Breen, K., et al. (2024). Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming. *Communications Earth & Environment*, *5*(1), 1–8. https://doi.org/10.1038/s43247-024-01442-3

Zalasiewicz, J., Adeney Thomas, J., Waters, C. N., Turner, S., & Head, M. J. (2024). The meaning of the Anthropocene: Why it matters even without a formal geological definition. *Nature*, *632*(8027), 980–984. https://doi.org/10.1038/d41586-024-02712-y

Zalasiewicz, J., Waters, C. N., Ellis, E. C., Head, M. J., Vidas, D., Steffen, W., et al. (2021). The Anthropocene: Comparing its meaning in geology (chronostratigraphy) with conceptual approaches arising in other disciplines. *Earth's Future*, *9*(3), e2020EF001896. https://doi.org/10.1029/2020EF001896

Zamrsky, D., Oude Essink, G. H. P., & Bierkens, M. F. P. (2024). Global impact of sea level rise on coastal fresh groundwater resources. *Earth's Future*, *12*(1), e2023EF003581. https://doi.org/10.1029/2023EF003581

Zickfeld, K., Eby, M., Weaver, A. J., Alexander, K., Crespin, E., Edwards, N. R., et al. (2013). Long-term climate change commitment and reversibility: An EMIC Intercomparison. *Journal of Climate*, *26*(16), 5782–5809. https://doi.org/10.1175/JCLI-D-12-00584.1

Zickfeld, K., MacIsaac, A. J., Canadell, J. G., Fuss, S., Jackson, R. B., Jones, C. D., et al. (2023). Net-zero approaches must consider Earth system impacts to achieve climate goals. *Nature Climate Change*, *13*(12), 1298–1305. https://doi.org/10.1038/s41558-023-01862-7