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Key Points:

- We conduct a thought experiment on equilibrium global warming and tipping point likelihood under constant greenhouse gas concentration scenarios
- Maintaining radiative forcing at or above current levels would commit multiple parts of the climate system to passing tipping points
- Only a lower emissions scenario, which would require rapidly reaching net-zero emissions, avoids crossing most climate tipping points

Supporting Information:

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

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Committed Global Warming Risks Triggering Multiple Climate Tipping Points

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Abstract Many scenarios for limiting global warming to 1.5°C assume planetary-scale carbon dioxide removal sufficient to exceed anthropogenic emissions, resulting in radiative forcing falling and temperatures stabilizing. However, such removal technology may prove unfeasible for technical, environmental, political, or economic reasons, resulting in continuing greenhouse gas emissions from hard-to-mitigate sectors. This may lead to constant concentration scenarios, where net anthropogenic emissions remain non-zero but small, and are roughly balanced by natural carbon sinks. Such a situation would keep atmospheric radiative forcing roughly constant. Fixed radiative forcing creates an equilibrium "committed" warming, captured in the concept of "equilibrium climate sensitivity." This scenario is rarely analyzed as a potential extension to transient climate scenarios. Here, we aim to understand the planetary response to such fixed concentration commitments, with an emphasis on assessing the resulting likelihood of exceeding temperature thresholds that trigger climate tipping points. We explore transients followed by respective equilibrium committed warming initiated under low to high emission scenarios. We find that the likelihood of crossing the 1.5°C threshold and the 2.0°C threshold is 83% and 55%, respectively, if today's radiative forcing is maintained until achieving equilibrium global warming. Under the scenario that best matches current national commitments (RCP4.5), we estimate that in the transient stage, two tipping points will be crossed. If radiative forcing is then held fixed after the year 2100, a further six tipping point thresholds are crossed. Achieving a trajectory similar to RCP2.6 requires reaching net-zero emissions rapidly, which would greatly reduce the likelihood of tipping events.

Plain Language Summary The importance of reaching net-zero greenhouse gas emissions to help avoid dangerous anthropogenic climate change is widely acknowledged. However, current national commitments do not align with this target and instead will lead to about 2.7°C warming by 2100. If the large-scale carbon dioxide removal needed to reach net-zero emissions is unfeasible and instead, the remaining hard-to-mitigate emissions approximately balance natural sinks, atmospheric greenhouse gas (GHG) concentrations will remain constant. Such fixed GHG levels will result in continued warming until the climate system reaches a state of radiative balance, which we call "committed warming." We investigate the committed warming associated with the CO_2 equivalent (CO_2e) for each year for three emission scenarios. Critically, we then examine the probability of breaching tipping point thresholds at different levels of committed warming, finding that under the scenario that best matches current national commitments, we will be committed to crossing the critical temperature threshold for six key climate tipping points by 2100. Maintaining radiative forcing at only slightly elevated levels above present GHG concentrations will substantially alter parts of the Earth System through such "locked-in" impacts. Society will only be able to avoid breaching tipping point thresholds through rapid and very substantial reduction of human emissions.

1. Introduction

The net zero approach to climate change is attaining worldwide recognition. With this goal in mind, there has been much discussion about whether global temperature will drop shortly after emissions abatement or if temperature commitment is already "locked in" and, if so, to what extent (MacDougall et al., 2020; Matthews

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& Caldeira, 2008; Matthews & Weaver, 2010; Zhou et al., 2021). Previous analyses show that stabilizing or "reversing" climate change is still possible if we are able to achieve net-zero or net-negative emissions (Anderson & Peters, 2016; MacDougall et al., 2020; Minx et al., 2018). Dropping to net-zero emissions where anthropogenic emissions are balanced by anthropogenic sinks or carbon removal technologies then allows natural sinks to bring down atmospheric greenhouse gas (GHG) concentrations. The approach to achieve this reduction that dominates in scenario literature is the use of massive GHG removal through negative emission technologies which are not proven at scale (Fuss et al., 2014). This approach is needed to stabilize global temperatures and the lower one wants to stabilize temperature the sooner net zero much be achieved. All other cases of even moderate emission reductions will result in either increasing or stable GHG concentrations—both of which will cause further increases in global temperatures. An alternative possibility is that of "concentration commitment" (called "constant composition commitment" in AR5, IPCC, 2014), where net anthropogenic emissions remain greater than zero but are broadly balanced by natural carbon sinks and human-driven carbon capture to keep atmospheric radiative forcing roughly constant from a given time forward (Figure 1). The balance would sustain a constant concentration of atmospheric CO_2 and could occur if the planetary-scale carbon dioxide removal projected to be necessary to reach net zero is not feasible for technical, environmental, political, or economic reasons. This would result in continuing GHG emissions from hard-to-mitigate sectors such as agriculture or cement production if they are not decarbonized (Anderson & Peters, 2016; Minx et al., 2018; Smith et al., 2015). Here, we aim to understand the planetary response to such fixed concentration commitments initiated after a period of different future emissions beforehand and during which GHGs rise.

Understanding the response of the climate system to GHG levels requires distinguishing between short-term and long-term variations, including transient and equilibrium responses. Radiative forcing, a key concept in this context, is defined as the difference between incoming and outgoing energy (radiation) at the tropopause, which forces changes in the Earth's climate. It serves as a useful single overall metric for assessing combined alterations in radiative flux resulting from instantaneous changes in GHG concentrations. In the net zero scenario, once net zero is achieved, radiative forcing would slowly decline due to the continued action of land and ocean carbon sinks drawing down atmospheric CO_2 (MacDougall et al., 2020). This drawdown counters ongoing "lagged warming" from changing ocean heat uptake and results in a so-called "zero emission commitment" of negligible further warming.

In a fixed GHG scenario, initially—prior to achieving fixed GHG concentrations - GHG concentrations and global temperature will continue to rise during what we refer to as the "**pre-fixed transient period**." After achieving fixed GHG (i.e., invariant radiative forcing), global temperatures will not immediately stabilize (Matsuno et al., 2012). Instead, for fixed GHG, global temperatures will continue to rise because the Earth is transiently out of energy balance and the oceans must continue to take up heat until energy balance is achieved (Matsuno et al., 2012; Wigley, 2005). The slow uptake of heat predominantly by the oceans, also referred to as climate thermal inertia, ensures that global warming continues to rise for long periods after a given increase and then stabilization in radiative forcing during what we call the "**commitment transient period**" (Collins et al., 2013; IPCC, 2018). Over time, as the system reaches equilibrium, the oceans stop releasing accumulated heat, and an eventual global thermal balance is achieved. This final state represents the long-term or equilibrium response, where the Earth's energy balance is stable (IPCC, 2014, 2018), which we refer to as "**committed equilibrium warming**." The final committed equilibrium warming temperature, that warming asymptotes to, is determined by the equilibrium climate sensitivity (ECS) (Knutti & Hegerl, 2008). Higher ECS values indicate a greater amount of committed warming and likely a longer timeframe for the full warming to unfold (Hansen et al., 1984). Climate models yield a wide range of ECS values, and this uncertainty underscores the importance of considering their spread when assessing the level of committed warming (Knutti & Hegerl, 2008).

Committed long-term warming will lead to changes in the climate system additional to the ones experienced during the pre-fixed transient period, with the potential to substantially alter parts of the Earth System through such "locked-in" impacts. The long commitment transient period before global temperatures reaching equilibrium means that the impacts of anthropogenic climate change may be slow to become apparent. The potential of triggering tipping points in the climate system are of particular concern, as they correspond to a period of abrupt and/or irreversible change to a new state that might be difficult for society to adapt to. Tipping points are thresholds at which abrupt and/or irreversible qualitative changes in parts of the climate system are triggered by self-perpetuating feedback (Armstrong McKay et al., 2022; Lenton et al., 2008, 2019). The threat of negative impacts associated with abrupt and/or irreversible tipping point changes, and the potential for cascading effects,

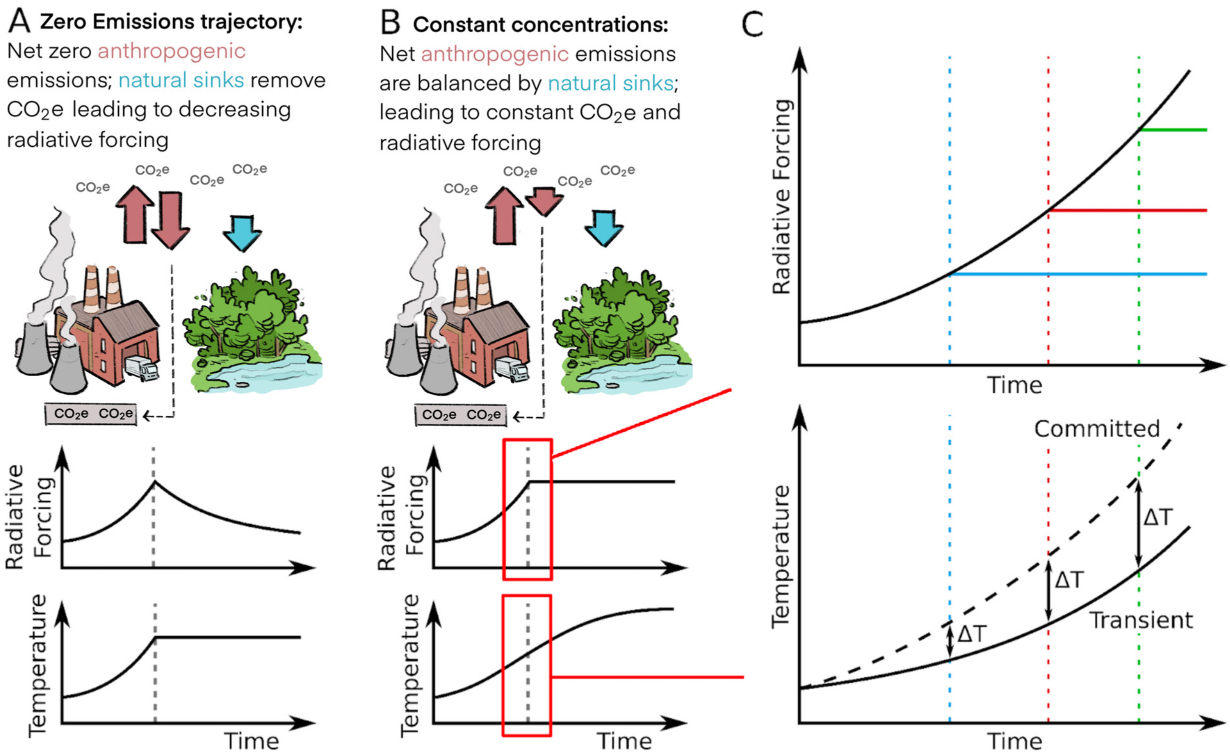

Figure 1. Schematic figure illustrating (a) the main carbon sources and sinks, and with radiative forcing described in terms of an effective CO_2e concentration, accounting additionally for non-CO_2 greenhouse gases. (b) The conceptual differences between net zero and constant-concentration commitments. In net zero scenarios human emissions are reduced, allowing for the change in radiative forcing to be negative and stabilizing global mean temperature (GMT). In constant concentration scenarios, atmospheric radiative forcing is held constant and GMT continues to rise until equilibrium is reached. (c) The constant concentration scenarios are explored in this study, where we branch off at a given year from the Representative Concentration Pathway emission scenarios, leading to a potentially higher committed temperature than the transient temperature projected for that year.

including amplification of global warming, make the prospect of breaching tipping points an existential risk (Lenton et al., 2019; Wunderling et al., 2021). Candidate "tipping elements" include the Amazon rainforest (Staal et al., 2020), the Atlantic meridional overturning circulation (AMOC) (Lohmann & Ditlevsen, 2021) and major ice sheets (Boers & Rypdal, 2021; Garbe et al., 2020; Wunderling et al., 2020). Additional warming in a concentration commitment scenario may trigger additional climate tipping points as the Earth system moves toward equilibrium to those initiated during the pre-fixed transient period when GHGs were rising.

Here, to quantify these concepts, we present a thought-experiment to explore the temperature gap between transient and committed global temperatures that occurs after GHGs are fixed. We calculate committed equilibrium warming by fixing atmospheric GHG in any given year and calculating the resulting committed equilibrium temperature utilizing the ECS values of the recent CMIP6 Earth System Models (ESMs) (Meehl et al., 2020). This analysis builds on previous work which focused on committed equilibrium warming associated with different levels of GHG observed during the historical period (Huntingford et al., 2020). Here, we extend that analysis to three future Representative Concentration Pathway (RCP) emissions scenarios. We then assess under which conditions the committed equilibrium warming would be sufficient to breach critical temperature thresholds for different climate tipping elements, discussing the associated accumulation of risk for increased (but fixed) GHG concentrations.

2. Methods

2.1. Modeling of Global Temperature

To determine the equilibrium temperature at various levels of GHG concentrations, which vary across different climate models, we follow the method presented by Huntingford et al. (2020) which relies on knowledge of the ECS values that have been calculated for the most up-to-date set of climate models in the CMIP6 ensemble

(Eyring et al., 2016). ECS refers to the amount of warming that is projected for a specific ESM when atmospheric CO_2 is doubled while keeping all other non-CO_2 greenhouse gasses constant (Huntingford et al., 2020). However, ECS can also be used to estimate equilibrium warming when other non-CO_2 greenhouse gasses are included. To accomplish this, we utilize the metric of carbon dioxide equivalent concentrations, CO_2e (ppm), which takes into account, additively, the radiative forcing of CO_2 and other radiatively active gasses in the atmosphere. Knowledge of ECS enables us to scale and estimate committed equilibrium warming, ΔT_{com}, for any given CO_2e level according to:

$$\Delta T_{\mathrm{com}} = \log\left[\frac{\mathrm{CO_2e}}{\mathrm{CO_2e_{PI}}}\right] \times \frac{\mathrm{ECS}}{\log 2} \tag{1}$$

where "PI" denotes pre-industrial conditions. Hence, what we refer to as committed warming describes the eventual warming relative to pre-industrial times if the radiative forcing is held constant at any year. Such GHG constancy implies residual anthropogenic emissions are balanced by natural sinks leading to no further changes in atmospheric gas concentration.

The conventional approach to determine ECS values involves inferring them from relatively short ESM simulations that do not reach equilibrium (Gregory, 2004). However, the recent availability of longer model simulations indicate that this method tends to underestimate the true ECS values (Rugenstein et al., 2019). Consequently, our calculations of committed warming are also likely underestimates of the actual values. The typical times to reach the full committed warming values from the transient runs are slow, dictated by the long time scale response of the deep ocean. Idealized model runs reach 90% of the final projected committed warming in around 300 years, however the majority of the warming (60%) happens much faster, in the first 25–50 years (Hansen et al., 2005). These timescales and warming percentages are applicable to our time periods between society achieving fixed GHGs and the realization of equilibrium warming levels associated with them, as noted in the analysis that follows.

Following (Huntingford et al., 2020), we derive the change in temperature for different ECS values, from different models in the CMIP6 ensemble using estimates of historical and future GHG concentrations (Meinshausen et al., 2011). We compare expected equilibrium temperatures to the modeled transient temperatures from the CMIP6 ensemble of ESMs, at the point where we branch off from RCP scenarios and start constant GHGs. This comparison allows us to quantify the "commitment temperature gap" and "committed tipping." The CO_2e data set we use is based on atmospheric measurements until the year 2014, followed by the RCP scenarios. Here, we focus on presenting RCPs representing the highest and lowest emission scenarios and for which numerous model runs are available (RCP8.5 and RCP2.6), as well as the scenario that best approximates our current future trajectory (RCP4.5). RCP8.5 is a high future emissions scenario which is now unlikely but provides a good approximation of historical GHG concentration changes (Hausfather & Peters, 2020; Schwalm et al., 2020). RCP8.5 marks the upper edge of the RCP scenario spectrum representing a high fossil fuel development world and a reversal of climate policies throughout the 21st century, leading to an eventual year 2100 radiative forcing level of +8.5 W m^{-2} (relative to the radiative forcing in 1750). RCP2.6 is a more optimistic version of the future—with the assumption of a societal wish to lower emissions and incur transformative social change—is presented. In RCP2.6 radiative forcing exceeds the threshold for 1.5°C warming and then declines to a 2,100 radiative forcing of +2.6 W m^{-2}—a concept that is referred to as climate overshoot. RCP4.5 stabilizes radiative forcing at 4.5 W m^{-2} in the year 2100 without ever exceeding that value. For comparison, the radiative forcing in the year 2020 was approximately +3.2 W m^{-2} (NOAA, 2021).

2.2. Modeling of Tipping Point Thresholds

To estimate tipping point probability, we assume a uniform distribution for each of the nine tipping elements identified as "global core" elements by Armstrong McKay et al. (2022), using the estimates for the minimum T_{min} and maximum T_{max} threshold temperatures for each climate tipping point:

$$P(\mathrm{tip}|T) = \mathrm{Unif}(T_{\mathrm{min}}, T_{\mathrm{max}}) \tag{2}$$

Temperature probabilities are estimated using output from the CMIP6 model ensemble. We calculate a probability distribution for the temperature in each year (Y) under each RCP scenario (S) as a log-normal distribution:

$$P(T|Y, S) = \mathrm{Lognorm}\left(\mu_{Y,S}, \sigma^2_{Y,S}\right) \tag{3}$$

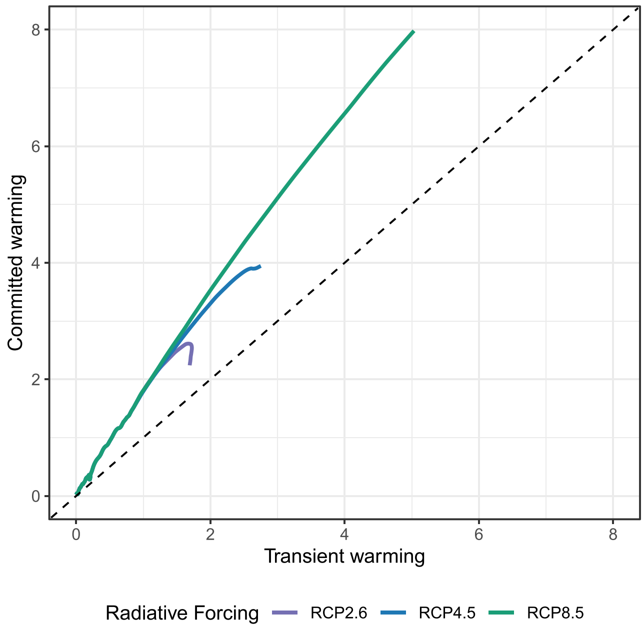

Figure 2. Mean modeled committed equilibrium warming versus mean pre-commitment transient warming above pre-industrial levels for the CMIP6 ensemble of models. Given are the mean committed equilibrium temperatures above pre-industrial temperatures for RCP2.6 (purple), RCP4.5 (blue), and RCP8.5 (green), compared to the mean of the modeled pre-commitment transient temperatures from the CMIP6 ensemble of Earth System Models. Committed equilibrium warming is always higher than transient warming.

where $\mu_{Y,S}$, and $\sigma_{Y,S}$ are the mean and standard deviation of the CMIP6 ensemble temperature for the given RCP and year. We perform Monte Carlo simulations in which we sample the tipping point threshold temperature from the $P(\text{tip}|T)$ and compare this to samples from the temperature distribution $P(T|Y, S)$ for Y and S. The realization is assigned a one if $P(T|Y, S) > P(\text{tip}|T)$, otherwise it is assigned a 0. We compute the mean of the realizations as the probability of tipping. We repeat this for each year (Y) under each RCP (S) for each climate tipping point to generate a probability distribution time series for each climate tipping point. We then perform bootstrapping to generate 95% confidence intervals (95CI). We present the results of the committed tipping probabilities, hereafter referred to as committed tipping.

3. Results

Based on the commitment scenarios explored here, we find that although transient global mean temperature (GMT) change is currently ∼1.2°C above pre-industrial levels, if the atmospheric radiative forcing is kept constant at present levels (year 2022), the likelihood of crossing the 2.0°C and 1.5°C warming goals during the commitment transient phase is 55% and 83%, respectively. In RCP4.5 (Figure 3, for individual model predictions see Figure S1 in Supporting Information S1), the planet will cross 2.0°C warming well before 2100 and the committed equilibrium warming will be double the 2.0°C target at approximately 3.9°C. Treating all CMIP6 models as equally reliable, under RCP4.5 in 2100 there is a 93% likelihood of being committed to exceeding 2.0°C committed equilibrium warming. Under RCP4.5 the gap between committed equilibrium warming and pre-commitment transient temperatures is estimated to be 1.2°C in 2100. Under RCP4.5, many tipping elements will already be at risk during to pre-commitment transient phase, with even more (including some of the high threshold tipping elements) at risk due to the higher committed equilibrium warming.

Under the highest emissions scenario RCP8.5, the projected pre-commitment transient global temperature is 5.1°C above pre-industrial in 2100 (Figure 2, for individual model predictions see Figure S2 in Supporting Information S1). Hence by the end of the century, several critical tipping points in the Earth system could already have been crossed, including Amazon Rainforest dieback, the collapse of the AMOC, and sustained, irreversible ice loss from Greenland and West Antarctica. There is a substantial difference between pre-commitment transient and committed equilibrium global warming in RCP8.5 (Figure 2). Under RCP8.5 at the end of the century committed equilibrium warming reaches approximately 8°C (Figure 3a, for individual model predictions see Figure S1 in Supporting Information S1)—an additional 3.6°C when compared to the pre-commitment transient temperature. This additional committed warming (if realized) could push the planet past further climate tipping points, including the abrupt loss of Arctic winter sea-ice and the collapse of the East Antarctic Ice Sheet.

For RCP2.6 (Figure 3, for individual model predictions see Figure S3 in Supporting Information S1) the CMIP6 projections lead to a mean pre-commitment transient warming of more than 1.5°C by the end of the century, but likely below 2.0°C. Treating all CMIP6 models as equally likely, under RCP2.6 there is a 74% chance of committed equilibrium warming exceeding 2.0°C by the end of the century if concentrations stabilize rather than fall. RCP2.6 shows a peak in mean committed equilibrium warming in 2044 of 2.6°C. Following this there is a reduction toward the end of the century because radiative forcing declines in this scenario. Due to this GHG drawdown, the maximum committed equilibrium temperature In RCP2.6 will most likely not be reached. Under RCP2.6, in 2100 committed equilibrium warming is 2.2°C, indicating a gap between full committed and pre-commitment transient temperatures of 0.6°C. While many tipping point thresholds will most likely be avoided under RCP2.6, some that appear safe according to pre-commitment transient temperatures—notably East Antarctic Subglacial Basins—may be at risk considering the higher committed equilibrium warming. Furthermore, those already at risk due to pre-commitment transient warming, such as Labrador Sea convection collapse, are at greater risk when considering committed equilibrium warming.

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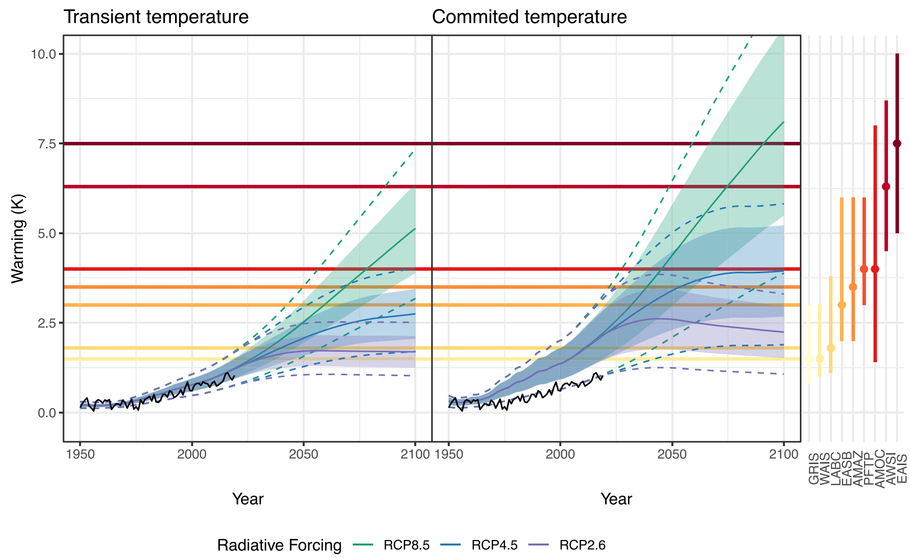

Figure 3. (a) Pre-commitment transient and (b) committed equilibrium warming temperatures for RCP8.5 (green curves), RCP4.5 (blue), and RCP2.6 (purple). The shaded area represents the uncertainty (standard deviation) of the model ensemble, while the dashed lines represent minimum and maximum modeled values. The black line is an overlay of historic temperature observations. Tipping point threshold best estimates from Armstrong McKay et al. (2022) are shown as the horizontal colored lines with the threshold range shown in panel (c) Tipping point abbreviations as follows: GRIS—Greenland Ice Sheet collapse, LABC—Labrador/SPG Convection collapse, AMAZ—Amazon Rainforest dieback, AMOC—Atlantic Meridional Overturning Circulation collapse, AWSI—Arctic Winter Sea Ice collapse, EAIS East Antarctic Ice Sheet collapse, PFTP—Boreal Permafrost collapse, WAIS—West Antarctic Ice Sheet collapse, EASB–East Antarctic Subglacial Basins collapse.

We present the results for tipping commitment (Figure 4) as the probability to tip according to the committed equilibrium temperature (the long-term equilibrium warming if radiative forcing remained fixed from that year, rather than the transient warming that would be observed in that year) in a given year (not as the cumulative probability of tipping over time). Overall, the likelihood of crossing climate tipping points typically increases with time, as radiative forcing and committed equilibrium temperatures increase (Figure 4). However, in RCP2.6 there is a peak and then decrease in committed tipping post 2030, reflecting the ambition in RCP2.6 to generate negative emissions resulting in a reduction in atmospheric radiative forcing and, therefore, committed temperatures. Committed tipping for lower threshold tipping points, such as Labrador Convection collapse and Greenland Ice Sheet collapse become virtually certain by the middle of the century in all but the lowest emission scenario (RCP2.6). In the highest emission scenario (RCP8.5) high threshold tipping events such as the collapse of the East Antarctic Ice Sheet or the disappearance of Arctic Winter Sea Ice become more likely if committed warming is realized, with a 57% (45%–70% 95BCI) and 61% (50%–73% 95BCI) likelihood in 2100, respectively (Figure 4). In the emission scenario most representative of current global policy and pledges (RCP4.5) committed tipping for high threshold tipping events such as the collapse of the East Antarctic Ice Sheet or the disappearance of Arctic Winter Sea Ice are less likely, with a 32% (22%–44% 95BCI) and 35% (27%–48% 95BCI) likelihood in 2100, respectively (Figure 4).

Mean projected warming during the pre-commitment transient phase will risk triggering three, five, and nine climate tipping points by the end of the century under RCP2.6, RCP4.5, and RCP8.5, respectively (Figure 3). The best-estimate threshold will be passed for one, two, and six climate tipping points by the end of the century for the pre-commitment transient phase under RCP2.6. RCP4.5, and RCP8.5, respectively. The extra warming of the climate system during the commitment transient phase until reaching the full committed equilibrium warming will increase the risk of triggering climate tipping points, pushing mean temperatures into the possible tipping threshold range for five, six, and nine climate tipping points under RCP2.6, RCP4.5, and RCP8.5, respectively. Mean committed equilibrium warming temperatures will cross the best-estimate temperature threshold for three, six, and nine climate tipping points under RCP2.6, RCP4.5, and RCP8.5, respectively.

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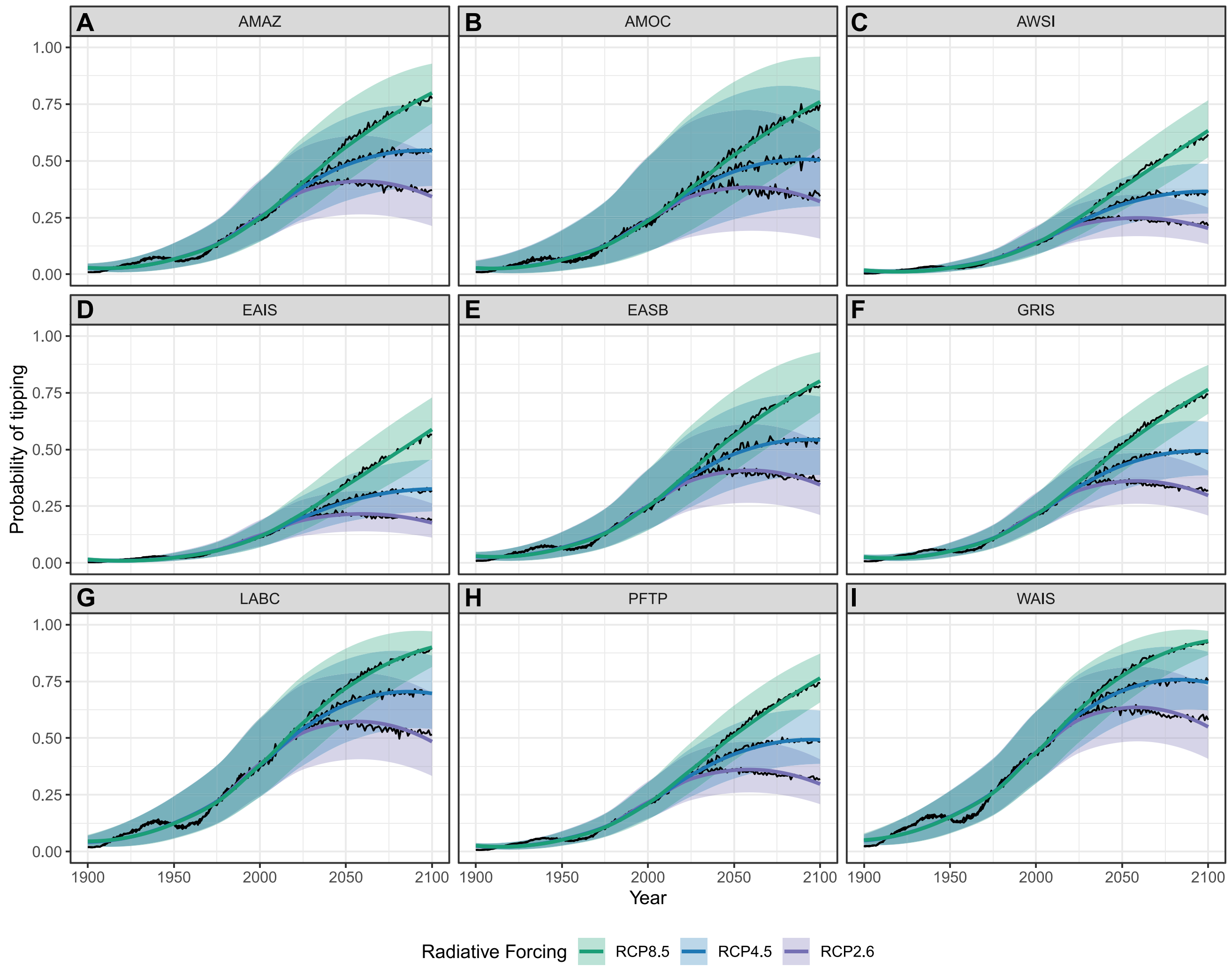

Figure 4. The committed probabilities of crossing critical temperature thresholds for nine tipping elements in the climate system if forcing remains fixed at that year's value for RCP2.6 (purple), RCP4.5 (blue), and RCP8.5 (green). The colored solid lines are the spline fit line to the raw data (black sinuous lines). The shaded area is the uncertainty shown as 95% Bayesian CI. Tipping point abbreviations as follows: (a) AMAZ—Amazon Rainforest dieback, (b) AMOC—Atlantic Meridional Overturning Circulation collapse, (c) AWSI—Arctic Winter Sea Ice collapse, (d) EAIS East Antarctic Ice Sheet collapse, (e) EASB—East Antarctic Subglacial Basins collapse, (f) GRIS—Greenland Ice Sheet collapse, (g) LABC—Labrador/SPG Convection collapse, (h) PFTP—Boreal Permafrost collapse, and (i) WAIS—West Antarctic Ice Sheet collapse.

4. Discussion

Our findings show that even GHG levels that reflect relatively small increases above current concentrations will lead to committed equilibrium temperature levels that are higher than the thresholds expected to trigger multiple Earth system tipping points. This highlights that the choices and policy decisions made today regarding emissions of GHG will affect changes in the climate system and the biogeophysical Earth System for centuries or even millennia to come (Clark et al., 2016). If we are not able to reach net zero rapidly then we will commit ourselves to a world that is drastically different then present day—a possibility that warrants critical evaluation.

Most scenarios used to force climate models generate global warming that increases monotonically. Yet, one notable exception is RCP2.6, which envisions negative CO_2 emissions and suggests that to achieve temperature stability at lower levels, an initial overshoot may be unavoidable—a concept recognized for some time (Huntingford & Lowe, 2007). Our findings from the RCP2.6 scenario underscore that in an overshoot scenario reducing committed warming later this century is possible but represents a formidable challenge. It would require significant transformations in the global economic landscape (Riahi et al., 2017), emphasizing demand-side interventions

(Grubler et al., 2018). The success of this endeavor hinges on our ability to effectively remove GHGs from the atmosphere using unproven technologies and sustain these efforts beyond 2100. In RCP8.5—which has served as a close approximation of reality in the past (Schwalm et al., 2020) but is now considered unlikely in the future (Hausfather & Peters, 2020) - committed warming could reach 8°C by the end of the century significantly exceeding transient warming (3°C or 60% higher) during the pre-fixed transient period. Our analysis indicates that there is an 80% chance that at today's radiative forcing we are already committed to 1.5°C warming, supporting a similar finding by Huntingford et al. (2020).

To stabilize radiative forcing, we must strike a balance between ongoing emissions and CO_2 absorption by natural sinks (Wigley, 2005, 2006) which act as natural buffers, limiting the increase of CO_2 in the atmosphere (Friedlingstein et al., 2022). Initially, natural sinks will absorb around 30% of current global emissions. However, these emissions must continually decrease over time, as natural carbon sinks are anticipated to weaken, potentially even shifting from sinks to sources in future scenarios (C. D. Jones et al., 2016; Keller et al., 2018). This is because the magnitude of current carbon sinks is a response to disequilibrium between the atmosphere and either the surface ocean pCO_2 level or the land carbon stores. To date, this natural climate change mitigation has proportionally kept pace with emissions, limiting global warming to a certain extent. Some research suggests that increased sequestration by the terrestrial biosphere may, in reality, have quite a dramatic effect in reducing atmospheric carbon due to the impact of CO_2 fertilization (Haverd et al., 2020). However, evidence indicates that the strength of some natural carbon sinks may be overestimated (Terrer et al., 2021) and that climate change may make natural carbon sinks less effective (IPCC, 2021). Observational evidence points toward weakening of the fertilization effect (Wang et al., 2020) and a recent decline of the tropical forest carbon sink (Hubau et al., 2020; Yang et al., 2018). Recent research has suggested that a temperature limit - which we are getting close to reaching—exists for the terrestrial carbon sink, above which trees will start to emit more CO_2 than they can take in through photosynthesis, at which point the land system will act to accelerate climate change rather than slow it down (Duffy et al., 2021). Additional evidence from ESMs indicates that climate change will lead to a weakening of the ocean carbon uptake rate as warm water holds less dissolved CO_2 and as biological productivity declines (Armstrong McKay et al., 2021). In this study we do not directly consider this change and do not model the changing role of natural CO_2 sinks as we prescribe the GHG concentrations.

A key implication of the possibility of long-term committed warming is that it will lead to the committed crossing of climate tipping points additional to those crossed under transient warming this century. We find that even GHG levels that reflect relatively small increases above current concentrations lead to committed equilibrium temperatures that are higher than the thresholds expected to trigger multiple climate tipping points (with all tipping elements committed to a more than 25% chance of tipping as seen in Figure 4). There are a range of underlying mechanisms (physical, structural, thermal, biophysical, and biogeochemical) driving climate tipping points processes (Armstrong McKay et al., 2022; Wang et al., 2023), some possibly rate-dependent or operating on long timescales (Ashwin et al., 2012; Ritchie et al., 2021, 2023). Some evidence even suggests that certain tipping points may be closer than previously thought (Boers & Rypdal, 2021). These complex systems exhibit hysteresis, meaning they may have different thresholds for triggering and reversing the associated changes. Hence the precise global temperature at which tipping points may be crossed may not be fully independent of the prescription of GHG (and thus global warming) trajectory. This means that the timing of tipping points is uncertain. In fact, a series of recent studies suggest that some climate tipping points may be closer than previously thought (Boers, 2021; Boers & Rypdal, 2021; Boulton et al., 2022; Cesar et al., 2018; Staal et al., 2020). One implication of hysteresis is that tipping points may be “silently” passed, only to realize the impact years later. For example, in simulations the Amazon rainforest can appear stable for many decades after temperatures have stabilized, before showing evidence of strong dieback (Boulton et al., 2017; Huntingford et al., 2013; C. Jones et al., 2009). The AMOC can also appear stable in simulations under the same conditions that it would collapse in if run to equilibrium (Boulton et al., 2014; Hawkins et al., 2011).

Here, we consider the full range of temperature thresholds for each tipping point, but do not account for rate-induced or noise-induced tipping. In this analysis, we examine only one driver of climate tipping points - GMT. We do not consider other potential drivers such as land cover change or human encroachment, or other potential tipping points that are not driven by GMT. In the real world there is an important interplay between these driving forces. Furthermore, we limit our analysis to the possibility of climate tipping points happening in isolation and do not investigate the potential cascading effects or tipping cascades.

Further, the idea of long-term committed warming raises concerns about the increasing probability of other cascading and irreversible climate impacts as the global temperature rises above 1.5°C (Wunderling et al., 2023). When warming reaches 2°C, numerous human and natural systems would face severe strain, and certain ecosystems may struggle for survival even if temperatures were to subsequently fall (IPCC, 2018, 2021). 1.5°C and 2°C are not definitive thresholds though; rather, the risks escalate based on the magnitude and duration of the overshoot. In practice, rapid near-term implementation of carbon capture and storage might allow stabilization at 2°C warming with no overshoot, while using the same technology to reduce temperature levels following a breach of 1.5°C overshoot may prove challenging. Even if this were possible, overshoot will increase tipping risk by up to 72% compared with non-overshoot scenarios (Wunderling et al., 2023). This all points to the impossibility of resetting complex system properties through remediation efforts. Therefore, following a pathway avoiding overshoot should be a priority and can enable achieving several development objectives jointly (Grubler et al., 2018).

Our model framework presents a highly idealized yet illustrative description of how different atmospheric GHG concentrations relate to equilibrium temperatures that could trigger a range of climate tipping points. Our presentation is conceptual, and it implies two potentially major timescales. First, a long timescale over which atmospheric GHGs are held invariant, such that the related equilibrium temperatures are realized. This period would consist of many generations of people deliberately supporting an emissions policy that closely matches the natural drawdown of radiatively active gasses. Eventually this constant GHG concentration commitment would correspond to net-zero emissions as natural offsets saturate and asymptote to zero. The second timescale is related to the internal timescale of each tipping element, some of which could take centuries to millennia to fully tip. For slow-onset tipping elements, Ritchie et al. (2021) have shown that tipping could be avoided in an overshoot scenario, but this remains uncertain. Whilst in reality, this precise situation of fixed GHG commitment over very long periods may be unlikely, such a presentational format captures a sense of the risks, in terms of passing tipping point thresholds, for different levels of radiatively active gasses.

We emphasize that even maintaining radiative forcing at or slightly above current levels could substantially alter the Earth's system. Importantly, our analysis shows that committed warming considerably increases the likelihood of breaching key tipping point thresholds. The economic, ecological and societal damage presented by passing tipping points is high, hence following an emissions profile that could trigger them is highly risky (Lenton et al., 2019). Gradual reductions to net zero or allowing any remnant emissions may not be enough to ensure that such catastrophic consequences for humanity and nature are avoided. To avoid these circumstances, immediate and aggressive emissions cuts are required and may ultimately motivate the use of technologies that can extract CO_2 from the atmosphere if they prove to be feasible. We have a rapidly closing window to avoid triggering self-reinforcing climate tipping points through rapid decarbonization of the global economy and society.

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Data Availability Statement

The ranges for tipping point thresholds are taken from Armstrong McKay et al. (2022). RCP CO_2e emissions are available from Meinshausen et al. (2011). The code and scripts used to calculate the commitment temperatures and perform the Bayesian analysis for tipping probabilities are available from Abrams (2022).

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