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Estimating the timing of geophysical commitment to 1.5 and 2.0°C of global warming

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Abstract

Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming peak within a decade, followed by slow cooling as greenhouse-gas (GHG) concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels prior to reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2-4.5), we find that we are already committed to peak warming greater than 1.5°C with 42% probability, increasing to 66% by 2029 (340 $\mathrm{GtCO_2}$ relative to 2021). Probability of peak warming greater than 2.0°C is currently 2%, increasing to 66% by 2057 (1550 $\mathrm{GtCO_2}$ relative to 2021). Because climate will cool from peak warming as GHGs concentrations decline, committed warming of 1.5°C in 2100 won't occur with at least 66% probability until 2055.

The Paris Agreement has affirmed an international goal to hold global warming to well below 2°C and to pursue efforts to limit it to 1.5°C relative to pre-industrial temperatures. However, global warming is projected to exceed 1.5°C within decades, and 2°C by mid-century in all but the lowest emission scenarios [1]. That is, there is limited time and allowable carbon dioxide (CO_2) emissions (i.e., a remaining carbon budget) before these temperature thresholds are exceeded. Assessing the possibility of avoiding these global warming levels requires a clear understanding of the unrealized warming that is inevitable due to past emissions (a geophysical warming commitment), treated separately from the warming associated with future, and therefore theoretically avoidable, emissions (a socioeconomic warming commitment).

Here we provide a quantification of the geophysical warming commitment and its evolution over time in terms of the zero emissions commitment (ZEC) [°C], a common metric used to estimate the global temperature change that follows an abrupt cessation of emissions. The magnitude of the ZEC depends on the evolution of atmospheric greenhouse gas and aerosol concentrations after emissions cease, along with the multiple timescales of climate response to changes in radiative forcing. If only CO_2 emissions cease, global temperature is expected to remain relatively constant as both ocean heat uptake and atmospheric CO_2 forcing slowly decline by similar, and compensating, amounts [2, 3, 4, 5, 6]. Estimates of the ZEC following a cessation of only CO_2 emissions (referred to here as $\mathrm{ZEC}_{\mathrm{CO_2}}$) range from slight cooling to continued warming [6, 7] over multiple centuries, depending upon model representations of ocean heat uptake, carbon cycle, climate feedbacks and historical emissions pathways [4, 6, 8, 9, 10]. On average, $\mathrm{ZEC}_{\mathrm{CO_2}}$ is taken to be small throughout the 21st century when estimated from multi-model simulations [1, 8]. This suggests that future warming is primarily governed by future emissions rather than by past emissions, and thus society is not geophysically-committed to exceeding key global warming levels prior to reaching them.

However, the situation becomes more complex when the emissions of short-lived climate forcers, including non-CO_2 greenhouse gases (GHGs) and aerosols, are considered [11, 3, 12]. Tropospheric aerosols produced through the combustion of fossil fuels and biomass burning have atmospheric lifetimes of days to weeks and currently exert a strong net cooling effect on the climate (a negative radiative forcing). Thus, the ZEC associated with the cessation of all anthropogenic emissions (referred to here as $\mathrm{ZEC}_{\mathrm{anthro}}$) would include warming associated with the rapid reduction of aerosols and consequent ‘unmasking’ of a portion of GHG forcing. This warming is offset in small part by the removal of black carbon on snow (a positive surface albedo forcing) and in larger part by a decrease in tropospheric ozone, nitrous oxide and methane concentrations over the following weeks to decades, followed by a slower decline as GHG concentrations decrease until the global temperature stabilizes at a value determined by the residual forcing associated with the portion of anthropogenic CO_2 that remains in the atmosphere for millennia [3, 12, 13].

We thus focus on two measures of the climate commitment following a complete cessation of anthropogenic emissions: the peak temperature reached in the decades following emissions cessation ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$) and the eventual temperature reached in the year 2100 ($\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$). These two measures represent different aspects of committed warming that may be relevant to different components of the climate system and impacts thereupon; i.e., systems that respond quickly to global temperature change would be sensitive to peak warming (e.g., sea ice, the hydrological cycle, hurricanes, agriculture, and many ecosystems), while those that respond slowly to global temperature change would be sensitive to long-term warming (e.g., glaciers, ice sheets, and sea level).

Both measures of commitment ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$) depend on the magnitude and evolution of GHG and aerosol radiative forcing following emissions cessation, the sensitivity of climate to forcing changes (often characterized in terms of the equilibrium climate sensitivity (ECS) [°C]), and the timescales of climate adjustment associated with the oceans [3, 13]. Cessation of emissions from present-day levels generally results in a $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ of a few tenths of a degree Celsius above the current temperature, with an overshoot lasting approximately a decade before cooling to near-present temperatures [13, 14, 15]. However, a larger $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ with a more prolonged overshoot is possible if aerosol forcing is strong and climate sensitivity is high [3, 15]. Thus, a full accounting of past emissions suggests that society may be geophysically-committed to peak warming exceeding key global warming levels many years before those levels are reached – absent efforts to directly remove CO_2 from the atmosphere.

Recent research has substantially advanced scientific understanding of the instrumental record of global warming [16], Earth's energy imbalance [17, 18], aerosol radiative forcing [19, 18] and climate sensitivity [20, 18]. In light of these advances, the current geophysical climate commitment needs to be revisited. Furthermore, both $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ will change over time as GHG emissions continue and the blend of radiative forcing agents in the atmosphere evolves. Key questions are – when will the world be geophysically-committed to reaching key global warming levels, such as 1.5 and 2.0°C, either temporarily (overshoot) or at the end-of-century, and how do these estimates depend upon the emissions trajectory?

We quantify both $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ associated with a cessation of all anthropogenic emissions using an emissions-based climate model, FaIR (Finite Amplitude Impulse Response Model, v1.3) [21, 22] with model parameters constrained by observations of global energy budget and temperature trends since the 1800s (Methods). FaIR produces effective radiative forcing from emissions time-series of 39 gases and short-lived climate forcers, with an intermediate concentration calculation for GHGs and a four-timescale carbon-cycle representation that is sensitive to changes in uptake efficiency with cumulative emissions and temperature. Changes in land-use forcing are excluded from this analysis because it is unclear how they should be represented in the ZEC framework (e.g., [23]), but sensitivity tests show that including land-use forcing has little impact on the results presented here (Methods and Supplementary Figure S1). Global temperature is calculated using a two-layer ocean model [24, 25] (Methods) which was also used for the global temperature projection assessment in the IPCC's Sixth Assessment Report (IPCC AR6) [1].

Priors for key model parameters, including the radiative feedback parameter (which governs ECS), the efficiency of ocean heat uptake, ocean effective heat capacities, the magnitude of GHG and aerosol forcing, and carbon cycle parameters are generated to match distributions of state-of the-art global climate models [25] and IPCC AR6 estimates [18, 26] (Methods; Extended Data Figs. E1-E4). Posterior model parameter distributions are then selected based on fits to observational records of global surface temperature, global energy accumulation and radiative forcing since 1850, as well as present-day CO_2 levels. These constraints result in a posterior FaIR model ensemble that accurately fits the historical temperature record to within an estimate of internal temperature variability (Fig. E5), and closely matches the projections of 21st century warming as assessed by IPCC AR6 [1] (Fig. 1a).

Posterior estimates of ECS and the transient climate response (TCR) are 2.9°C [1.8-4.7°C, 5-95% confidence] and 1.7°C [1.2-2.5°C], respectively. Median aerosol forcing is estimated to be -1.2 W m^{-2} [-1.8 to -0.6 W m^{-2}] in 2018 relative to 1765. These values are all in good agreement with recent assessments based on multiple lines of evidence [20, 19] including IPCC AR6 [18].

With the posterior FaIR ensemble, we first evaluate $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ associated with an abrupt cessation of anthropogenic emissions near the present day (taken as January 2021) (Fig. 1b). We find a median $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ of 0.22°C relative to 2020, with an overshoot that lasts for approximately 18 years before eventually cooling to several tenths of a degree Celsius below 2020 temperatures by the end-of-century (Fig. 1b, dashed line). Smith et al.[13], also using FaIR, estimated a median $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ of approximately 0.1°C above 2018, while Matthews and Zickfeld[15], using an intermediate complexity model, found median peak warming of 0.3 °C following a cessation of all emissions. This difference in results is due in large part to differences in aerosol forcing at the time of emissions cessation between ref[13] (-1.4 to -0.2 W m^{-2}, 90% confidence range), ref[15] (-1.9 to -0.8 W m^{-2}), and this study (-1.8 to -0.6 W m^{-2}), as well as larger climate sensitivity in ref[15].

Similar to Smith et al.[13], we find net cooling at the end-of-century following emissions cessation (a median $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ of -0.4°C below the 2020 temperature), which is in contrast to the end-of-century warming of approximately 0.3°C found in a previous study [12] – a difference that may be due to different assumptions about residual GHG and non-CO_2 forcing in the ZEC experiment, and the sensitivity of atmospheric CO_2 uptake to global temperatures [13]. An assessment of the effect of different emissions choices on the present-day $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ is provided in the Supplementary (Fig. S2).

The 2018 IPCC Special Report on global warming of 1.5°C concluded that past emissions alone are unlikely (less than 33% probability) to raise global temperature above 1.5°C relative to 1850-1900 [14]. We find that there is now a 42% probability that the world is committed to peak global warming ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$) of at least 1.5°C based on past emissions alone, and a 2% probability that $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ reaches at least 2.0°C (Fig. 1b). For sustained warming of greater than 1.5°C and 2.0°C at the end-of-century ($\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$), the probabilities are 5% and 0%, respectively, meaning that society is not yet committed to these levels of long-term warming.

For comparison, we find that a cessation of CO_2 emissions ($\mathrm{ZEC}_{\mathrm{CO_2}}$), while holding all other forcings fixed at present-day levels, results in temperatures remaining within approximately 0.1°C of the present-day temperature throughout the century (Fig. 1b, dotted line), consistent with previous studies [3, 12, 8]. The end-of-century $\mathrm{ZEC}_{\mathrm{CO_2}}$ is approximately 0°C [-0.02 to 0.12°C, 66% confidence] relative to present-day temperatures, in good agreement with the AR6 assessed likely range of 0°C ±0.19°C.

We next consider how $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ change over time following a range of emissions pathways prior to cessation, as illustrated by eight Shared Socioeconomic Pathway (SSP) emission scenarios: SSP1-1.9, SSP1-2.6, SSP4-3.4, SSP2-4.5, SSP4-6.0, SSP3-7.0-lowNTCF ('Near Term Climate Forcing'), SSP3-7.0, and SSP5-8.5 [27]. We conduct simulations of the climate response to a cessation of anthropogenic emissions within FaIR in every year for the period 2021-2080 or until CO_2 emissions reach net-zero, following each of these SSP scenarios, each run with 6,729 posterior ensemble members (Methods). Fig. 2a shows $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ relative to the pre-industrial period 1850-1900 as a function of the year in which emissions cease along a moderate mitigation scenario (SSP2-

4.5) (solid black and dashed black lines, respectively). A key result is that the time at which $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ is reached occurs from four to seven years before that temperature would be exceeded following SSP2-4.5 (horizontal distance between orange and solid black lines and shading in Fig. 2a); while there is a 66% probability of *exceeding* 1.5°C by 2035, there is a 66% probability of being *committed* to at least 1.5°C of warming by 2029 ($\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ in Fig. 2a; Table 1). For 2°C, this becomes 2061 and 2057, respectively ($\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ in Fig. 2a; Table 1). The number of years that $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ is reached before a given warming level is exceeded depends on the probability threshold considered, with the 17th percentile of the ensemble (corresponding to high aerosol forcing and high climate sensitivity) producing a larger difference, and the 83rd percentile of the ensemble (corresponding to low aerosol forcing and low climate sensitivity) producing a smaller difference (Table 1).

A similar assessment can be made for $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$, for which temperature thresholds are surpassed after the thresholds themselves are reached in the emissions scenario. We find that end-of-century warming commitments of 1.5 and 2.0°C are reached by 2055 and 2061 with 66% probability – 15 and 16 years after those temperatures are reached, respectively, when following SSP2-4.5 (Fig 2a). Since global temperature in 2100 after a cessation of emissions is relatively stable compared to peak warming, this implies that society is not committed to long-term warming of a given magnitude prior to when that temperature is reached following an emissions trajectory.

Considering the seven other emissions scenarios, results show that committed warming of 1.5 and 2°C ($\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$) occurs roughly half a decade before those temperatures would actually be exceeded if emissions were never halted (Figs. 3a,c,e; Table 1). The choice of emissions pathway becomes increasingly important with time, with high and very high emissions scenarios (SSP3-7.0, SSP5-8.5) generating a $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ of 2°C earlier than lower emissions scenarios. Conversely, only high mitigation (SSP1-1.9, SSP1-2.6) avoids $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ of 2°C over this century in the 66^{th} percentile. A $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$ exceeding 1.5°C and 2.0°C following a cessation of emissions in this century is avoided in low (SSP1-2.6) and in low to moderate (SSP4-3.4, SSP2-4.5) emissions scenarios, respectively.

The elevated warming following a cessation of emissions in 2021 (temperature overshoot) lasts 11-48 years (66% confidence range). The length of the temperature overshoot generally declines with aerosol forcing, and is therefore dependent upon the emissions trajectory; by 2060, a cessation of all emissions along medium-to-high aerosol forcing scenarios (SSP3-7.0, SSP4-6.0; Fig. E6) results in 6-31 year overshoots, while low aerosol forcing scenarios (SSP1-1.9, SSP1-2.6), result in 3-10 year overshoots (66% confidence range).

Committed warming as a function of cumulative emissions

The projected 21^{st} century warming following different SSP emissions scenarios (Fig. 3a) simplifies greatly when cast in terms of the cumulative CO_2 emissions (Fig. 3b; calculated as cumulative anthropogenic CO_2 emitted since January 2021). Consistent with previous studies [28, 29, 30], global warming is nearly proportional to cumulative CO_2 emissions, with small differences between scenarios arising from the assumed rate of emissions and the fractional contribution of non-CO_2 climate forcing to total forcing. A relevant measure of this proportionality is the Transient Climate Response to Emissions (TCRE), defined as the global temperature change per 1000 $GtCO_2$ emitted. We find that the constrained FaIR ensemble has TCRE = 0.44°C per 1000 $GtCO_2$ [0.33-0.59°C per 1000 $GtCO_2$, 66% confidence range] when calculated for SSP2-4.5 for the period 2018-2068 (Supplementary

Figure S4). These estimates are in line with Matthews et al.'s [31] estimate of 0.44°C per 1000 $GtCO_2$ [0.32-0.62 °C per 1000 $GtCO_2$, 90% range] and the IPCC AR6 [32] estimate of 0.45°C per 1000 $GtCO_2$ [0.27-0.63 °C per 1000 $GtCO_2$, 66% range].

We next evaluate how ZEC^{peak}_{anthro} and ZEC^{2100}_{anthro} scale with the cumulative CO_2 emitted until the year emissions cease. The evolution of ZEC^{peak}_{anthro} is nearly proportional to cumulative CO_2 emissions (Fig. 3b), despite its dependence on aerosol forcing at the time emissions cease. This is likely due to the approximately constant fraction of aerosol forcing relative to total forcing over time for most individual SSP pathways. Exceptions are SSP1-2.6 and SSP1-1.9, wherein aerosols decrease rapidly during the first half of the 21st century and decline more slowly thereafter (Fig. E6), resulting in a non-linear response in peak warming as a function of emissions cessation year. The proportionality with cumulative CO_2 emissions is more evident for ZEC^{2100}_{anthro}, which is independent of the emissions scenario (Fig. 3c) because the residual CO_2 forcing dominates total forcing by 2100 following a cessation of emissions.

The proportionality of committed warming to cumulative CO_2 emissions permits the quantification of a remaining carbon budget for committed warming of 1.5, 1.7, and 2°C (Table 2). Total cumulative carbon emitted between 1850 and 2019 is approximately 2,290 $GtCO_2$, within the IPCC AR6 estimate of 2,390 +/- 240 $GtCO_2$ for the same period [32]. A median ZEC^{peak}_{anthro} of 1.5°C is reached after the emission of 120 $GtCO_2$ [0-340 $GtCO_2$, 66% confidence] relative to the beginning of 2021 (Fig. 2b); for 2°C the remaining carbon budget is 1,120 $GtCO_2$ [470-1,550 $GtCO_2$]. At the end-of-century (ZEC^{2100}_{anthro}), 1.5°C is reached after the emission of 1,080 $GtCO_2$ [420-1,470 $GtCO_2$]; for 2°C this remaining carbon budget is 1,980 $GtCO_2$ [1,170-not reached within the experiments]. Uncertainty in the remaining carbon budgets stems mainly from uncertainties in aerosol forcing and climate sensitivity. However, the results are consistent across the emissions scenarios (Table S2) – a key to maintaining consistency in the calculation of carbon budgets [31].

Remaining carbon budgets estimated using the ZEC can be contrasted to those estimated following emissions pathways without a cessation of emissions (Table 2). 1.5°C is exceeded with 66% probability when cumulative emissions since 2021 reach 600 $\mathrm{GtCO_2}$ following SSP2-4.5 (orange line in Fig. 2b), a measure of the 'threshold exceedance budget' [32]. This is substantially larger than the 66^{th} percentile estimate of 340 $\mathrm{GtCO_2}$ using $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ because it does not account for the additional warming that would occur as aerosol forcing is reduced upon abrupt cessation of emissions. The smaller carbon budgets obtained using $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ would provide an underestimate for emissions pathways that achieve net-zero $\mathrm{CO_2}$ through the implementation of carbon dioxide removal technologies while maintaining some level of anthropogenic aerosol emissions. However, compared to scenarios that phase out emissions more slowly and without net-negative $\mathrm{CO_2}$, $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ provides the smallest estimate of peak warming over the 21^{st} century, and therefore can be considered a lower bound on committed warming (Fig. E7).

These calculations are relatively pathway-independent across priority SSPs, and are therefore robust to choice of emissions trajectory. As such, they do not require an examination of only a subset of emissions trajectories that are calibrated to avoid 1.5 or 2°C (such as those presented in IPCC AR6), or that are constrained by socioeconomic feasibility [14, 33]. This methodology is appropriate when considering the possibility of a temperature overshoot that may persist for over a decade, with subsequent impacts on human and natural systems that respond quickly, and perhaps irreversibly, to global warming.

Two important insights are that: (i) the world will have a greater than 66% probability of being committed to peak warming above 1.5°C by 2027-2032 in all emissions scenarios, and 2°C by 2043-2057 in medium to high emissions scenarios (SSP2-4.5 to SSP5-8.5), and (ii) these temperature commitments will occur 4 to 6 years before the 1.5 and 2°C warming levels will actually be exceeded, assuming emissions follow SSP2-4.5. We find that the 1.5 and 2.0°C peak warming commitments ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$) correspond to median carbon budgets of approximately 120 and 1,120 Gt CO_2 relative to the beginning of 2021, respectively. Given that FaIR does not capture the possibility of future destabilizing climate feedbacks such as decreased ice sheet cover [34], thawing permafrost and methane hydrate dissociation due to ocean warming [35, 36], or a sea-surface temperature pattern effect that allows for a more substantial shift toward destabilizing cloud feedbacks in the future than modeled here [37, 38, 39, 40, 10], these estimates of the timing of geophysical warming commitments may become underestimates as global temperatures rise.

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Author contributions statement.

M.T.D., K.C.A., and C.P. designed the study. M.T.D. performed the analysis. K.C.A., C.P., D.M.W.F., M.B.B., and C.J.S. made suggestions to the analysis and helped interpret the results. M.T.D. wrote the manuscript with edits from all other authors.

Competing interests statement.

The authors declare no competing interests.

Tables.

Table 1. Year in which a cessation of anthropogenic emissions leads to $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ and $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$ of 1.5, 1.7 and 2°C following SSP2-4.5 at the 17th, 50th, 66th, and 83rd percent confidence levels. 'No cessation' refers to the year in which these temperatures are reached following the emissions scenario without a cessation of emissions. 'A/R' indicates that the temperature commitment has already been reached at that probability level as of the beginning of 2021, while 'N/R' indicates that the commitment is not reached at that probability level within the bounds of the experiment (up to year 2080).

Global warming since 1850-1900 (°C)	Temperature metric	Commitment year by ensemble percentile			
		17th	50th	66th	83rd
1.5	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	A/R	2024	2029	2037
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	2031	2046	2055	2065
	No cessation	2024	2031	2035	2040
1.7	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	A/R	2032	2040	2050
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	2038	2055	2064	2076
	No cessation	2031	2039	2044	2052
2.0	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	2032	2047	2057	2074
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	2048	2068	N/R	N/R
	No cessation	2040	2052	2061	2077

Table 2. Estimated remaining carbon budget ($\mathrm{GtCO_2}$) relative to the beginning of 2021

for $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ and $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$ of 1.5, 1.7 and 2°C following SSP2-4.5 at the 17th, 50th, 66th, and 83rd percent confidence levels. 'No cessation' and 'N/R' are as in Table 1.

Global warming since 1850-1900 (°C)	Temperature metric	Estimated remaining carbon budget			
		17th	50th	66th	83rd
1.5	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	0	120	340	680
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	420	1080	1470	1870
	No cessation	120	420	600	820
1.7	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	0	470	820	1260
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	730	1470	1830	2250
	No cessation	420	770	990	1340
2.0	$\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$	470	1120	1550	2190
	$\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$	1170	1980	N/R	N/R
	No cessation	820	1340	1720	2280

Figure Legends.

Figure 1. Constrained FaIR ensemble global temperature projections. a) Global warming following Shared Socioeconomic Pathways (SSPs) with the historical temperature record from HadCRUT5 [41] overlaid in black. b) SSP2-4.5 with no cessation of emissions (orange line), a cessation of only CO_2 emissions (dotted line, ZEC_{CO_2}) and of all anthropogenic emissions (dashed line, $\mathrm{ZEC}_{\mathrm{anthro}}$) in the beginning of 2021. Shading represents the 66% confidence interval obtained from a 6729 posterior member ensemble (Methods). Global temperature anomalies are taken relative to the 1850-1900 average.

Figure 2. Committed warming and scenario warming following SSP2-4.5. FaIR ensemble temperature projections assuming no cessation of emissions (orange line) and warming commitments, $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ (solid black line) and $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$ (dashed black line), as functions of emissions cessation year (a) and cumulative anthropogenic CO_2 emissions since the

beginning of 2021 (b). For SSP2-4.5 in (a), the x-axis is ‘Year’. Shading indicates the 66% confidence interval. Global temperature anomalies are taken relative to the 1850-1900 average.

Figure 3. Committed warming and scenario warming relative to 1850-1900 for all SSPs. Temperature response following each SSP with no cessation of emissions as a function of year (a); $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ (b) and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ (c) as a function of shut-off year until 2080 or when emissions reach net-zero. d-f are as in a-c, but as functions of cumulative emissions since the beginning of 2021. Note that a, b, and c correspond to the orange, solid black and dashed black lines presented in Fig. 2, respectively, but for all SSPs. Shading represents the 66% confidence interval.

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Methods

Model.

We use FaIR v1.3.6 [21] for all historical and future climate simulations. Historical simulations are run using the Reduced-Complexity Model Intercomparison Project (RCMIP)-generated SSP emissions time-series for the period 1765-2016; future scenarios are run for SSP1-1.9, SSP1-2.6, SSP4-3.4, SSP2-4.5, SSP4-6.0, SSP3-7.0-lowNTCF, SSP3-7.0, and SSP5-8.5 for the period 2016-2100, with an abrupt cessation of all anthropogenic emissions in every year along each pathway until 2080 or until CO_2 emissions reach net zero; CO_2 emissions are set to zero while all other emissions are set to pre-industrial (1765) levels in order to retain background sources. Background emissions of N_2O and CH_4 for the historical period and into the future are prescribed using the default time-series in FaIR, where emissions vary over the historical period but are constant from 2005 onwards as a proxy for natural sources.

Forcing associated with land-use change is not included over the historical record or in future projections due to the lack of a dynamic vegetation model and its overestimation in FaIR relative to AR6 estimates [18]. Land-use change associated with the zero emissions commitment was also not modeled in intermediate complexity models participating in

ZECMIP [23]. Including land-use forcing does not substantially change the results (Fig. S1). Volcanic and solar forcing are not included in future emissions scenarios in order to isolate anthropogenic warming. Volcanic forcing for the historical period is scaled by a factor of 0.6 in order to obtain better agreement with historical aerosol forcing and global temperatures (similar scaling-down of volcanic efficacy has previously been performed in the MAGICC simple climate model for better correspondence to observed temperatures [42]).

We modify FaIR to use the Held et al. [24] two-layer energy balance model (EBM) to calculate global temperatures from radiative forcing. The equations for this EBM are:

$$\begin{aligned} C\frac{dT}{dt} &= F + \lambda T - \epsilon\gamma(T - T_0) \\ C_0\frac{dT_0}{dt} &= \gamma(T - T_0) \end{aligned}$$

where C and C_0 are, respectively, the heat capacities of the first layer (representing the surface components of the climate system including the atmosphere, land, sea ice, and ocean mixed layer) and second layer (representing the deep ocean); γ is the coefficient of heat exchange between the two layers, representing a measure of the ocean heat uptake efficiency; λ is the radiative feedback parameter; and ϵ is a deep ocean efficacy factor that expresses the time dependence of the global radiative feedback (see Held et al. [24], Geoffroy et al. [25]). The equilibrium climate sensitivity is given by

$$ECS = -\frac{F_2x}{\lambda}$$

where F_{2x} is the forcing for CO_2 doubling. Retaining the Held formulation of energy balance in FaIR allows us to diagnose heat uptake, account for feedback time dependence, and model feedback parameters estimated from general circulation models [25].

Ensemble development.

A 300,000 member FaIR ensemble is generated by drawing random values from prior probability distributions of ECS (uniform from 1 to 6°C), ocean model variables, and carbon cycle parameters. Normal prior distributions of γ, C and C_0 are generated using distributions from GCMs (Global Climate Models) (Geoffroy et al.) [25], but with standard deviations (σ) expanded by 50%; the distribution in γ is truncated to avoid values less than 0.1, while C_0 is truncated to avoid sampling deep ocean heat capacities less than 10 W m^{-2} $°C^{-1}$ yr (γ: mean = 0.67 W m^{-2} $°C^{-1}$, σ = 0.225 W m^{-2} $°C^{-1}$; C: mean = 8.2 W m^{-2} $°C^{-1}$ yr, σ = 1.4 W m^{-2} $°C^{-1}$ yr; C_0: mean = 124.7 W m^{-2} $°C^{-1}$ yr, σ = 65.8 W m^{-2} $°C^{-1}$ yr). A lognormal prior distribution for ϵ is generated using distributions from GCMs [25] (mean = 1.28, σ = 0.375), with values of ϵ above unity reflecting the fact that the effective climate sensitivity is expected to become larger in the future as the geographic pattern of warming changes on timescales of multiple centuries [18, 43, 44, 45].

We scale GHG forcing due to CO_2, CH_4, and N_2O in every year by a constant amount generated from normal distributions that match the updated IPCC AR6 "very likely" range (90% confidence interval) of radiative forcing over the industrial period (1750-2018; CO_2: mean = 2.15 W m^{-2}, σ = 0.16 W m^{-2}; CH_4: mean = 0.54 W m^{-2}, σ = 0.07 W m^{-2}; N_2O: mean = 0.19 W m^{-2}, σ = 0.02 W m^{-2}). Aerosol forcing is also scaled by a constant amount by values drawn from a uniform distribution ranging from -2.2 to -0.1 W m^{-2} in order to adequately sample the full range of possible forcing values. All other gases and short-lived climate forcers (SLCFs) are treated using default parameterizations in FaIR (not scaled).

Uncertainty in FaIR carbon cycle parameters associated with various uptake processes is treated as in Smith et al. [21, 13]. Because FaIR has no representation of internal variablity, $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ are quantified based on annual mean temperature values.

Constraining the model.

Following the methods of Armour [46], a Bayesian framework is used to constrain model outputs to observational estimates of global mean sea surface temperature (T), ocean heat uptake (Q), and radiative forcing (F) for the 2006-2019 mean relative to the 1850-1900 baseline, reducing the model ensemble to 6,729 members. Specifically, only ensemble members that satisfy the condition:

$$\sqrt{\left(\frac{\delta T}{\sigma T}\right)^2 + \left(\frac{\delta Q}{\sigma Q}\right)^2 + \left(\frac{\delta N}{\sigma N}\right)^2} < 1.65$$

are kept, where δT, δQ and δF are the differences between the model-derived estimates of global surface temperature, ocean heat uptake and total radiative forcing anomalies (2006-2019 mean relative to the 1850-1900 baseline) and observational estimates, with σ_T, σ_Q and σ_N representing one standard deviation of the mean for each of these values, and 1.65 corresponding to the 90% confidence level. Observational values are taken from the IPCC AR6: $\Delta T_{obs} = 1.03 \pm 0.2$°C, $\Delta Q_{obs} = 0.59 \pm 0.35$ W m^{-2} and $\Delta N_{obs} = 2.20 \pm 0.7$ W m^{-2} [18]. Modeled CO$_2$ concentrations are additionally constrained to be within ± 2 ppm of the 2006-2018 mean (395.98 ppm) [47].

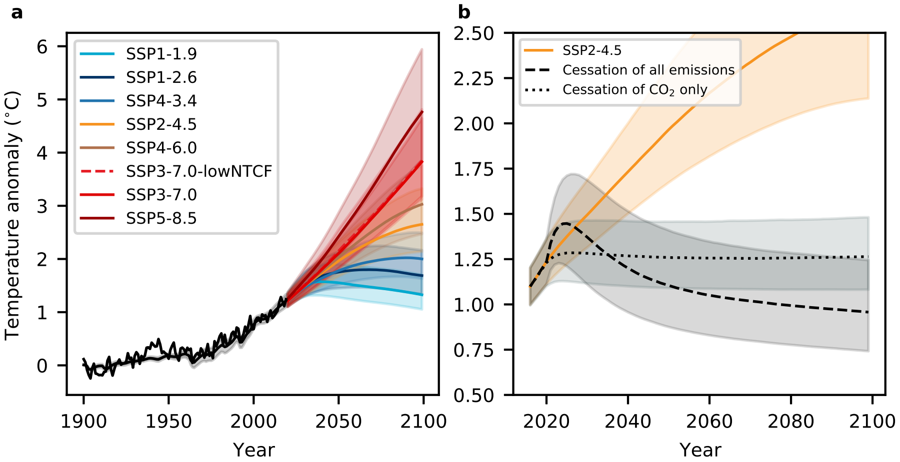
This method produces a posterior estimate on the equilibrium climate sensitivity of 2.9°C [1.8-4.7°C], which is consistent with the most recent estimate of 2.3-4.7°C provided by Sherwood et al. [20] and 2-5°C as assessed in IPCC AR6. Posterior estimates of aerosol forcing and the remaining four free parameters in the two-layer ocean model (γ, ϵ, C and C_0) are shown in Figs. E1-E4). However, the observational record is not long enough to adequately constrain ϵ owing to the slow adjustment of the deep ocean (the timescale on which the value of ϵ becomes relevant for surface warming). The posterior distribution of ϵ used in this study is thus the same as the prior (Fig. E2c); however, sensitivity tests show that the choice of prior distribution in ϵ does not significantly affect the conclusions presented here (Supplementary Fig. S3).

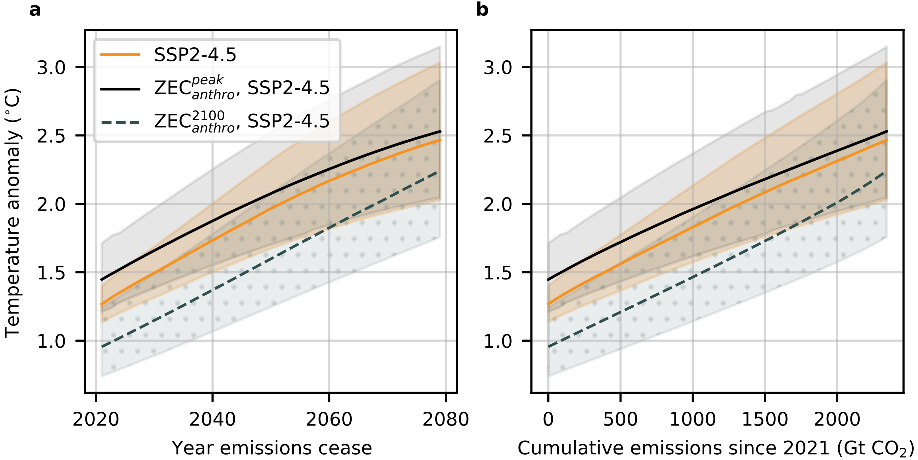
Data availability.

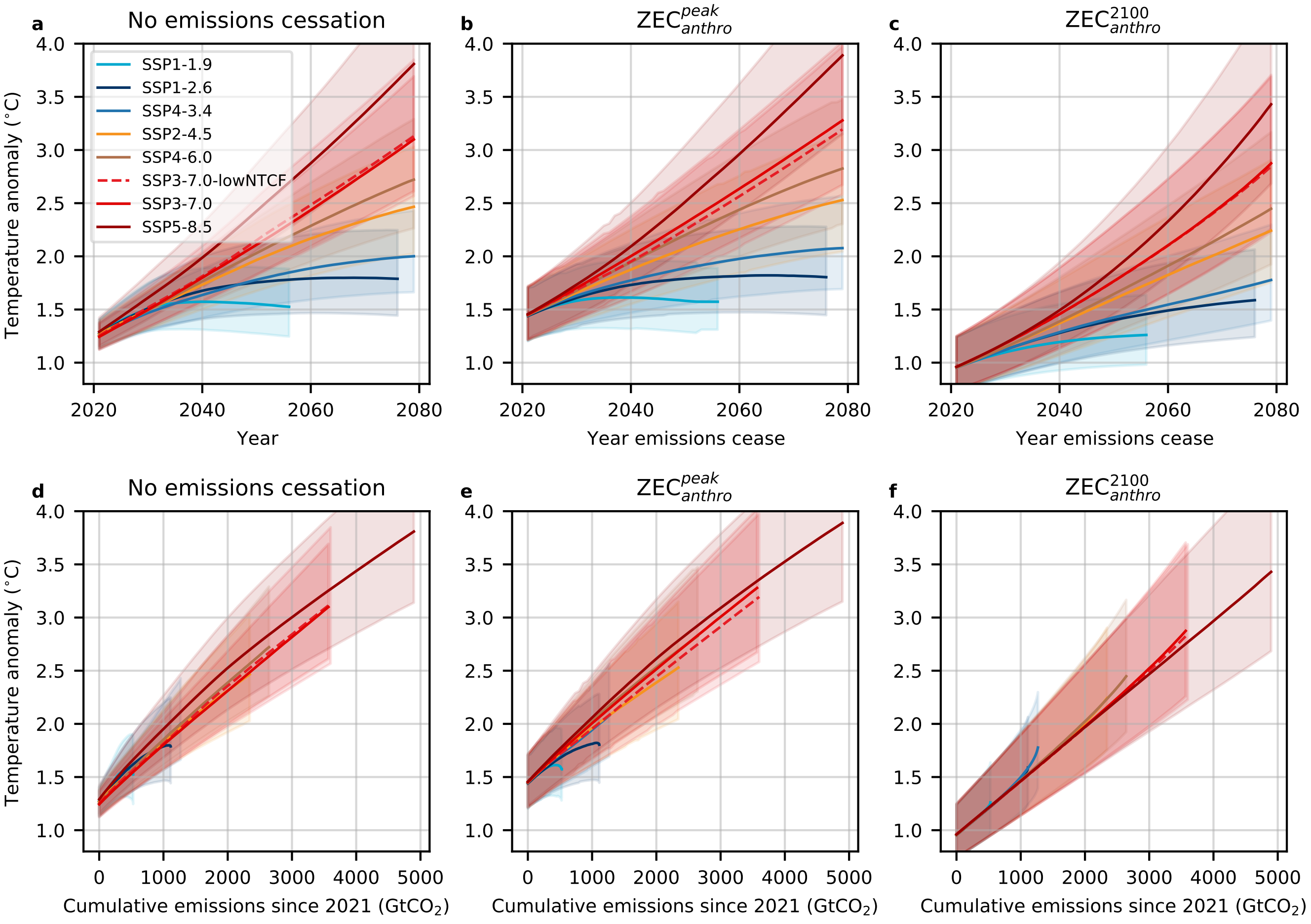
All data necessary to interpret, verify and extend the research in this article are available to download from the online repository, Zenodo [48].

Code availability.

The FaIR model is available to download from the public code repository, GitHub (https://github.com/OMS-NetZero/FAIR). All other code used to used to set up model simulations, analyze model output and create figures, are available to view and download from GitHub [49].


a
b
Temperature anomaly (°C)
6
5
4
3
2
1
0
1900
1950
2000
2050
2100
Year
SSP1-1.9
SSP1-2.6
SSP4-3.4
SSP2-4.5
SSP4-6.0
SSP3-7.0-lowNTCF
SSP3-7.0
SSP5-8.5
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
2020
2040
2060
2080
2100
Year
SSP2-4.5
Cessation of all emissions
Cessation of CO_2 only


a
b
SSP2-4.5
ZEC^{peak}_{anthro}, SSP2-4.5
ZEC^{2100}_{anthro}, SSP2-4.5
Temperature anomaly (°C)
3.0
2.5
2.0
1.5
1.0
2020
2040
2060
2080
Year emissions cease
0
500
1000
1500
2000
Cumulative emissions since 2021 (Gt CO_2)



a
No emissions cessation
b
ZEC$^{peak}_{anthro}$
c
ZEC$^{2100}_{anthro}$
SSP1-1.9
SSP1-2.6
SSP4-3.4
SSP2-4.5
SSP4-6.0
SSP3-7.0-lowNTCF
SSP3-7.0
SSP5-8.5
Temperature anomaly (°C)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
2020
2040
2060
2080
Year
Year emissions cease
Year emissions cease
d
No emissions cessation
e
ZEC$^{peak}_{anthro}$
f
ZEC$^{2100}_{anthro}$
Temperature anomaly (°C)
0
1000
2000
3000
4000
5000
Cumulative emissions since 2021 (GtCO$_2$)
Cumulative emissions since 2021 (GtCO$_2$)
Cumulative emissions since 2021 (GtCO$_2$)