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When will the world be committed to 1.5 and 2.0°C of global warming?

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Abstract

We investigate committed warming, i.e., the global mean temperature change that would follow complete cessation of anthropogenic emissions. The removal from the atmosphere of short-lived particulate aerosols, which have a cooling effect on the climate, leads to a peak in warming within a decade, followed by a slow decline over centuries to millennia to a relatively stable temperature determined by the residual CO_2 forcing. This has important consequences: temporary warming well beyond present-day levels without any additional emissions. We use an emissions-based climate model (FaIR) to estimate temperature change after abrupt cessation of all anthropogenic emissions in 2021 and in every year thereafter until 2080, assuming that emissions prior to cessation proceed along priority Shared Socioeconomic Pathways (SSPs). We find that society may already be committed to peak warming of greater than 1.5°C with approximately 40% probability, with a small (2%) probability of peak warming greater than 2.0°C. The probability of being committed to 1.5°C increases to at least 50% by 2024. Taking into account short-lived climate forcers advances warming commitments by a half a decade, considerably reducing the remaining carbon budget. While an abrupt cessation of all anthropogenic emissions is not likely to occur, this idealized scenario provides a quantification of when we will be committed to exceeding key global warming levels while following realistic emissions scenarios.

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, we have limited time and allowable carbon dioxide (CO_2) emissions (i.e., a remaining carbon budget) before these temperature thresholds are exceeded. Assessing our ability to avoid these global warming levels requires a clear understanding of the unrealized warming that is inevitable due to our past emissions (a geophysical warming commitment), treated separately from the warming associated with our future, and therefore 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 are considered, global temperature is expected to remain relatively constant from the time those emissions cease as CO_2 forcing declines by the same amount, and on the same timescale, as ocean heat uptake[2, 3, 4, 5, 6]. Estimates of the ZEC following a cessation of only CO_2 emissions (referred to here as ZEC_{CO_2}) range from slight cooling or no temperature change[7, 3, 2, 8] to slight warming[9, 10] over multiple centuries, with the lack of consensus arising from model differences in the representation of ocean heat uptake, carbon cycle, and climate feedbacks[6, 11, 12]. ZEC_{CO_2} is generally found to be small throughout the 21st century[4, 13], suggesting that future warming is primarily governed by our future emissions rather than by our past emissions, and thus we will not be geophysically-committed to exceeding key global warming levels prior to the time we reach 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[14, 3, 8]. Tropospheric aerosols produced through the combustion of fossil fuels and biomass burning have atmospheric lifetimes of days to weeks and currently exert a strong cooling effect on the climate (a negative radiative forcing). Thus, the ZEC associated with the cessation of all anthropogenic emissions (referred to here as $\text{ZEC}_{\text{anthro}}$) includes a warming effect associated with the rapid reduction of aerosols and consequent 'unmasking' of a portion of GHG forcing that today is estimated to be between 0.0 and 0.8°C[15]. This warming is offset by a decrease in methane, tropospheric ozone, and nitrous oxide 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, 8, 16].

The peak temperature reached in the decades following a cessation of all anthropogenic emissions ($\text{ZEC}^{\text{peak}}_{\text{anthro}}$) and the eventual temperature reached in the year 2100 ($\text{ZEC}^{2100}_{\text{anthro}}$) 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, 16]. Cessation of emissions from present-day levels generally results in a $\text{ZEC}^{\text{peak}}_{\text{anthro}}$ of a few tenths of a °C above the current temperature, with an overshoot lasting up to several decades before cooling to near-present temperatures[16, 13]. However, a larger $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ with a prolonged overshoot is possible if aerosol forcing is strong and climate sensitivity is high[3]. Thus, a full accounting of our past emissions suggests that we may be geophysically-committed to 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 our understanding of the instrumental record of global warming[17], Earth's energy imbalance[18, 19], aerosol radiative forcing[20, 19] and climate sensitivity[21, 19]. 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 we be geophysically-committed to crossing key global warming levels, such as 1.5 and 2.0°C, and how do these estimates depend upon the emissions scenario we follow?

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)[22, 23] with model parameters constrained by observations of global energy budget and temperature trends since the 1800s (see Methods). FaIR uses biogeochemical feedbacks and an internal carbon cycle to produce atmospheric GHG concentrations and effective radiative forcing from emissions time-series of 39 gases and short-lived climate forcers. Global temperature is calculated using a two-layer ocean model[24, 25] (see Methods) which was also used for the global temperature projection assessment in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6)[1].

Priors (see Methods) 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[19, 26]. 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. 1a), and closely matches the projections of 21st century warming as assessed by IPCC AR6[1].

Posterior estimates of key climate response metrics, 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[21, 20] including IPCC AR6[19]. Some ocean model and carbon cycle parameters are not well-constrained by the historical record, but different choices of prior ranges for these parameters do not affect the results presented here (see Supplementary Information for a discussion of model parameters and sensitivity tests).

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 in 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 °C below 2020 temperatures by the end-of-century (Fig. 1b, dashed line). Smith et al.[16], also using FaIR, estimated a median $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ of approximately 0.1°C above 2018. This difference in results is likely due to a less-negative range of aerosol forcing around the time of emissions cessation (-1.4 to -0.2 W m^{-2}, 90% confidence range) compared to this study (-1.8 to -0.6 W m^{-2}) and AR6 estimates (-2.0 to -0.4 W m^{-2}) relative to pre-industrial. Similar to Smith et al.[16], we find net cooling at the end-of-century (a median $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ of -0.4°C below 2020), which is in contrast to the end-of-century warming of approximately 0.3°C found in a previous study[8] – 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[16]. An assessment of the effect of differing emissions choices on the present-day $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ is provided in the Supplementary (Fig. S10).

The 2018 IPCC Special Report on global warming of 1.5°C concluded that past emissions alone are unlikely (less than 66% probability) to raise global temperature to 1.5°C relative to 1850-1900[13]. In agreement with this, our result suggests that we specifically have a 42% probability of being committed to peak global warming ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$) of at least 1.5°C, while the probability that $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ reaches at least 2.0°C is about 2% (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.

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, 8, 7]. 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 $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ changes over time following a range of emissions pathways prior to cessation, as illustrated by four widely-used Shared Socioeconomic Pathway (SSP) emission scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. We conduct simulations of the climate response to a cessation of anthropogenic emissions within FaIR in every year for the period 2021-2080 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 $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ is reached occurs from five to seven years before that temperature would be exceeded following SSP2-4.5 (horizontal distance between orange and solid black lines in Fig. 2a): while we have a 50% probability of exceeding 1.5°C by 2031, we have a 50% probability of being committed to at least 1.5°C of warming by 2024 ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ in Fig. 1a; Table 1). For 2°C, this becomes 2053 and 2047, respectively ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ in Fig. 1a; Table 1). The number of years that $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ is reached before a given warming level is exceeded depends on the probability threshold considered, with the 17$^{\mathrm{th}}$ percentile of the ensemble (corresponding to high aerosol forcing and high climate sensitivity) producing the largest difference, and the 83$^{\mathrm{rd}}$ percentile of the ensemble (corresponding to low aerosol forcing and low climate sensitivity) producing the smallest difference (Table 1).

Figs. 3a,c,e show the same analysis for SSP1-2.6, SSP3-7.0 and SSP5-8.5 emissions scenarios. Independent of the scenario, we will be committed to 1.5 and 2°C of global warming ($\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$) roughly half a decade before those temperatures would actually be exceeded if emissions were never halted (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 ZEC^{peak}_{anthro} of 2°C earlier than lower emissions scenarios. Conversely, only high mitigation (SSP1-2.6) avoids ZEC^{peak}_{anthro} of 2°C over this century in the ensemble median. In all cases, the elevated warming relative to that in the year emissions cease (temperature overshoot) lasts for at least a decade.

Committed warming as a function of cumulative carbon emissions

The projected 21st 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 2021). Consistent with previous studies[27, 28, 29], global warming is nearly proportional to cumulative CO_2 emissions, with small calculated differences 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. Following the methods of Matthews et al.[30], which account for the role of non-CO_2 forcing by applying a scaling factor to temperatures estimated using emissions-driven experiments, 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; additional simulations using the same posterior model ensemble driven by only CO_2 emissions also produce TCRE = 0.44°C per 1000 $GtCO_2$ [0.34-0.55 °C per 1000 $GtCO_2$] (See Supplementary Fig. S6). These estimates are in line with Matthews et al.'s[30] estimate of 0.44°C per 1000 $GtCO_2$ [0.32-0.62 °C per 1000 $GtCO_2$, 90% range] and the IPCC AR6[31] estimate of 0.45°C per 1000 $GtCO_2$ [0.27-0.63 °C per 1000 $GtCO_2$, 66% range].

Using the FaIR simulations of emissions cessation at different times along the SSP scenarios, as described above, we evaluate how $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ scale with the cumulative CO_2 emitted until the year emissions cease. The evolution of $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ is nearly proportional to cumulative CO_2 emissions (Fig. 3b), despite its dependence on the 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. An exception is SSP1-2.6, wherein aerosols decrease rapidly during the first several decades of the 21$^{\mathrm{st}}$ century and decline more slowly thereafter (Supplementary Fig. S7), 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 $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$, 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[31]. A median $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ 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 $GtCO_2$ [470-1,150 $GtCO_2$]. At the end-of-century ($\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$), 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 $GtCO_2$ [1,170-2,700 $GtCO_2$]. 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[30].

Remaining carbon budgets estimated using the zero emissions commitment can be contrasted to those estimated following emissions pathways without a cessation of emissions (Table 2). 1.5°C is exceeded with 50% probability when cumulative emissions since the beginning of 2021 reach 420 $GtCO_2$ following SSP2-4.5 (orange line in Fig. 2b), a measure of the 'threshold exceedance budget'[31]. This is substantially larger than the median estimate of 120 $GtCO_2$ using ZEC^{peak}_{anthro} because it does not account for the additional warming that would occur as aerosol forcing is reduced upon cessation of emissions. The smaller carbon budget obtained using $ZEC^{peak}_{anthro}$is appropriate when considering the possibility of a temperature overshoot that may persist for decades, with subsequent impacts on those human and natural systems that respond quickly, and perhaps irreversibly, to global warming.

Including emissions since the beginning of 2020, the remaining carbon budget using ZEC^{peak}_{anthro} becomes 160 $GtCO_2$ [40-380 $GtCO_2$] – substantially smaller than the IPCC AR6 reported value of 500 ± 220 $GtCO_2$ relative to the same year, where the stated uncertainty depends on choices related to non-CO_2 emissions mitigation[31]. With similar values of TCRE and ZEC_{CO_2} presented here and in IPCC AR6, the difference between our findings and those of IPCC AR6 can be traced to the estimate of the non-CO_2 contribution to warming upon emissions cessation. IPCC AR6 assesses this using very low emissions pathways near the time of net-zero CO_2 emissions, when non-CO_2 radiative forcings are typically small, while the non-CO_2 contribution to warming can be substantial following the low to very high SSP emissions pathways that we consider here (as illustrated in Fig. 1b). Carbon budgets reported using ZEC^{peak}_{anthro}(Table 2) can be interpreted as a measure of when the remaining carbon budget will run out for a given warming level, following a given emissions pathway; they would provide an underestimate of remaining carbon budgets for emissions pathways that achieve net-zero CO_2 through the implementation of carbon dioxide removal technologies while maintaining some level of anthropogenic aerosol emissions.

Our calculation of the remaining carbon budget follows the best practices outlined by Matthews et al. (2020). We find that this methodology is relatively pathway-independent across priority SSPs, and therefore may be more robust to subjective choices of emissions trajectory; this provides an alternative to the IPCC AR6 approach to calculating carbon budgets, one which does not require an examination of only a subset of emissions trajectories that are calibrated to avoid 1.5 or 2°C, or that are constrained by socioeconomic feasibility[13, 32].

Two important insights are that: (i) the world will have a greater than 50% probability of being committed to peak warming above 1.5°C by 2024, independent of emission scenario, and 2°C by 2038-2040 in medium to high emissions scenarios, and (ii) these temperature commitments will occur over a half a decade before the 1.5 and 2°C warming levels will actually be exceeded along a given emissions scenario. 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 and albedo[33], methane hydrate dissociation due to thawing permafrost and ocean warming[34, 35], or a sea-surface temperature pattern effect that allows for a substantial shift toward more-positive cloud feedbacks in the future[36, 37, 38, 39, 12], our estimates of committed warming may become underestimates, and our estimates of carbon budgets may become overestimates, as global temperatures rise.

Methods

Model.

We use FaIR v1.3.6[22] 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 each SSP1-2.6, 2-4.5, 3-7.0 and 5-8.5 for the period 2016-2100, with an abrupt cessation of all anthropogenic emissions in every year along each pathway, where 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. 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[40]).

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

$$ECS = -\frac{F_2 x}{\lambda}$$

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 model 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 (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[19, 41, 42, 43].

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.[22, 16] All prior and posterior distributions for model parameters are presented in the Supplementary Information.

Constraining the model.

Following the methods of Armour[44], 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} [19]. Modeled CO_2 concentrations are additionally constrained to be within ± 2 ppm of the 2006-2018 mean (395.98 ppm)[45].

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.[21] 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 presented in Supplementary Figs. S3 and S4. 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) (Fig. S4c). The posterior distribution of ϵ used in this study is thus the same as the prior; however, sensitivity tests show that the choice of prior distribution in ϵ does not significantly affect the conclusions presented here (Fig. S10).

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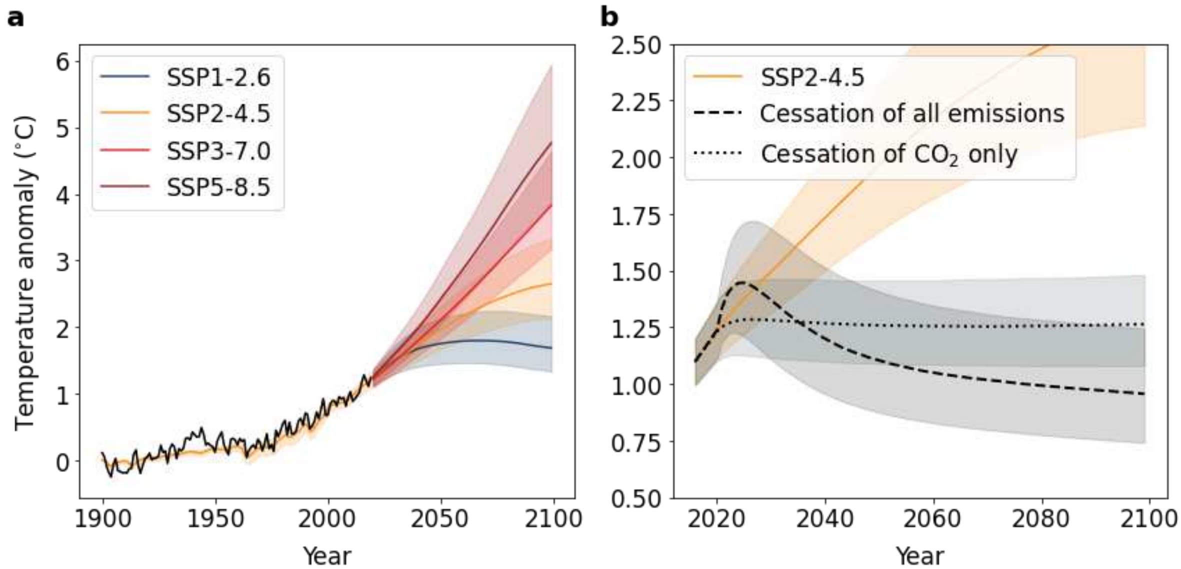

Figure 1. FaIR ensemble global temperature projections for priority Shared Socioeconomic Pathway (SSP) scenarios (**a**), with the historical temperature record from HadCRUT5[27] overlaid in black. **b)** FaIR ensemble temperature projections for SSP2-4.5 with no cessation of emissions (orange line), a cessation of only CO_2 emissions (dotted line, ZEC_{CO_2}) and of all anthropogenic emissions (dashed line, ZEC_{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.

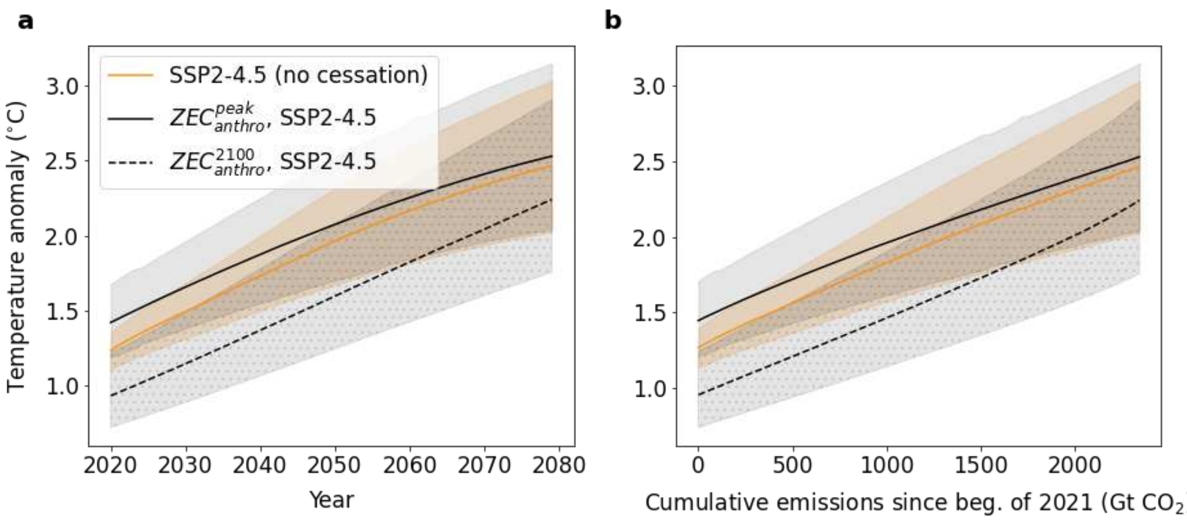

Figure 2. FaIR ensemble temperature projections assuming no cessation of emissions (orange line) and warming commitments $\mathrm{ZEC}^{\mathrm{peak}}_{\mathrm{anthro}}$ (solid black line) and $\mathrm{ZEC}^{2100}_{\mathrm{anthro}}$ (dashed black line) following the SSP2-4.5 scenario as functions of **a)**, emissions cessation year and **b)**, cumulative anthropogenic CO_2 emissions (relative to the beginning of 2021). Shading indicates the 66% confidence interval. Global temperature anomalies are taken relative to the 1850-1900 average.

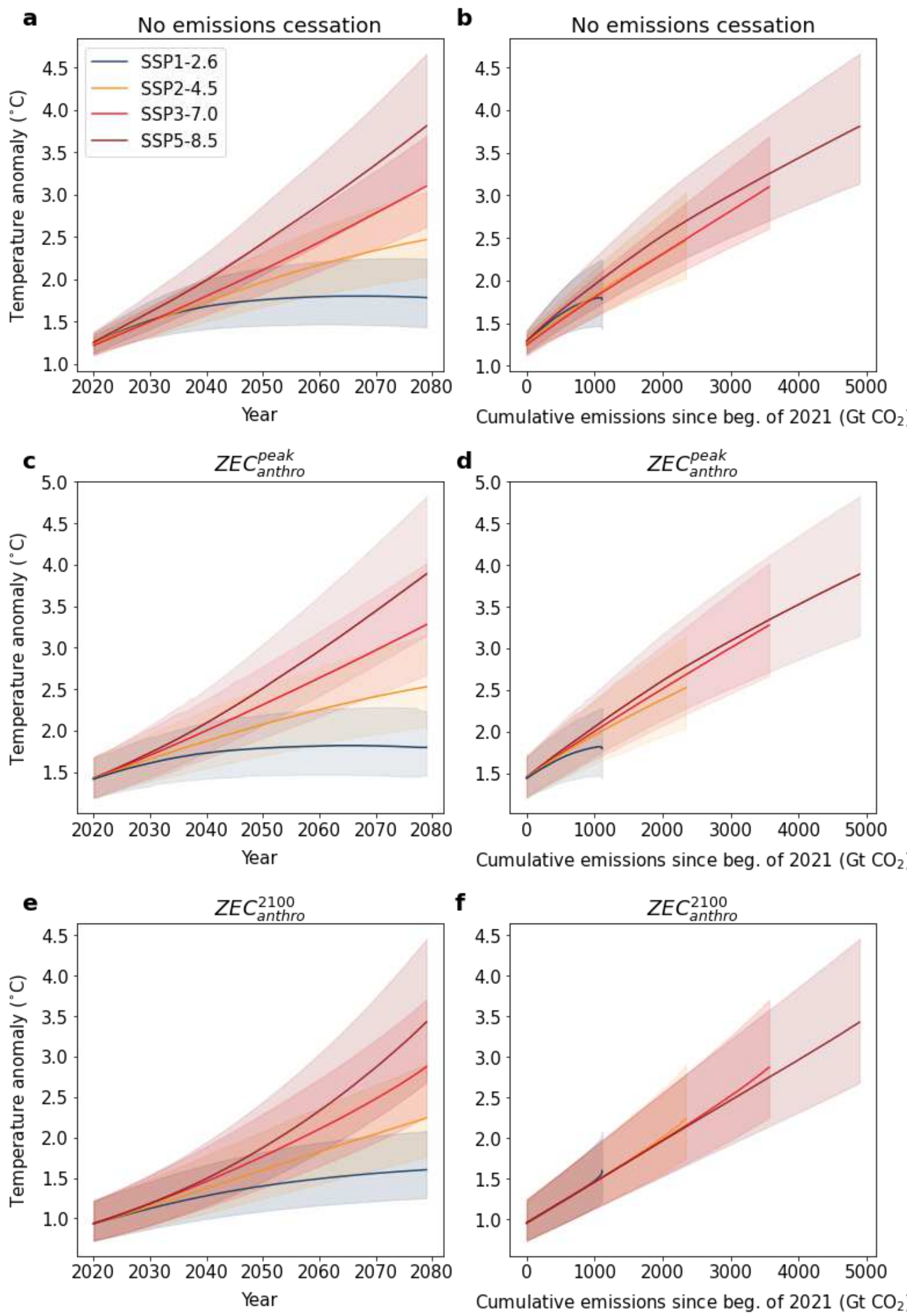

Figure 3. Global temperature anomalies relative to 1850-1900 for priority SSPs given no emissions cessation as a function of year **(a)**, and cumulative CO_2 emissions since 2021 **(b)**; $\mathrm{ZEC}_{\mathrm{anthro}}^{\mathrm{peak}}$ as a function of shut-off year **(c)**, and cumulative CO_2 emissions up to the shut-off year **(d)**. **e)** and **f)** are as with **c)** and **d)**, but for $\mathrm{ZEC}_{\mathrm{anthro}}^{2100}$. Note that **b)**, **d)**, and **f)** 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.

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

Global warming since 1850-1900 (°C)	SSP emissions scenario	Temperature metric	Commitment year by ensemble percentile			
			17th	*50th*	*66th*	*83rd*
1.5	1-2.6	ZEC^{peak}_{anthro}	A/R	2024	2032	N/R
		ZEC^{2100}_{anthro}	2032	2062	N/R	N/R
		No cessation	2024	2030	2036	N/R
	2-4.5	ZEC^{peak}_{anthro}	A/R	2024	2029	2037
		ZEC^{2100}_{anthro}	2031	2046	2055	2065
		No cessation	2024	2031	2035	2040
	3-7.0	ZEC^{peak}_{anthro}	A/R	2023	2028	2034
		ZEC^{2100}_{anthro}	2030	2042	2048	2055
		No cessation	2026	2031	2034	2037
	5-8.5	ZEC^{peak}_{anthro}	A/R	2023	2027	2033
		ZEC^{2100}_{anthro}	2029	2041	2046	2052
		No cessation	2023	2027	2030	2034
1.7	1-2.6	ZEC^{peak}_{anthro}	A/R	2037	N/R	N/R
		ZEC^{2100}_{anthro}	2043	N/R	N/R	N/R
		No cessation	2029	2043	N/R	N/R
	2-4.5	ZEC^{peak}_{anthro}	A/R	2032	2040	2050
		ZEC^{2100}_{anthro}	2038	2055	2064	2076
		No cessation	2031	2039	2044	2052
	3-7.0	ZEC^{peak}_{anthro}	A/R	2030	2036	2042
		ZEC^{2100}_{anthro}	2035	2048	2055	2062
		No cessation	2031	2037	2041	2045
	5-8.5	ZEC^{peak}_{anthro}	A/R	2029	2034	2039
		ZEC^{2100}_{anthro}	2035	2046	2052	2057
		No cessation	2028	2033	2036	2040
2.0	1-2.6	ZEC^{peak}_{anthro}	2035	N/R	N/R	N/R
		ZEC^{2100}_{anthro}	2067	N/R	N/R	N/R
		No cessation	2041	N/R	N/R	N/R
	2-4.5	ZEC^{peak}_{anthro}	2032	2047	2057	2074
		ZEC^{2100}_{anthro}	2048	2068	N/R	N/R
		No cessation	2040	2052	2061	2077
	3-7.0	ZEC^{peak}_{anthro}	2030	2040	2046	2054
		ZEC^{2100}_{anthro}	2043	2057	2064	2072
		No cessation	2040	2047	2052	2057
	5-8.5	ZEC^{peak}_{anthro}	2029	2038	2043	2049
		ZEC^{2100}_{anthro}	2042	2053	2059	2065
		No cessation	2034	2041	2044	2049

Table 2. Cumulative emissions ($GtCO_2$) relative to the beginning of 2021 that correspond to the year in which a cessation of anthropogenic emissions leads to committed warming of 1.5, 1.7 and 2°C at the 17th, 50th, 66th, and 83rd percent confidence levels. As in Table 1, 'No cessation' refers to the year in which these temperatures are exceeded following SSP2-4.5 without a cessation of emissions, 'A/R' indicates that the temperature commitment has already been reached at that probability level, and '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	Estimated remaining carbon budgets ($GtCO_2$ relative to the beginning of 2021) following SSP2-4.5			
		17th	*50th*	*66th*	*83rd*
1.5	ZEC_{anthro}^{peak}	0	120	340	680
	ZEC_{anthro}^{2100}	420	1080	1470	1870
	No cessation	120	420	600	820
1.7	ZEC_{anthro}^{peak}	0	470	820	1260
	ZEC_{anthro}^{2100}	730	1470	1830	2250
	No cessation	420	770	990	1340
2.0	ZEC_{anthro}^{peak}	470	1120	1550	2190
	ZEC_{anthro}^{2100}	1170	1980	N/R	N/R
	No cessation	820	1340	1720	2280

Supplementary Files

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