

# 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 GtCO<sub>2</sub> relative to 2021). Probability of peak warming greater than 2.0°C is currently 2%, increasing to 66% by 2057 (1550 GtCO<sub>2</sub> 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.

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

11 Here we provide a quantification of the geophysical warming commitment and its evolu-  
12 tion over time in terms of the zero emissions commitment (ZEC) [°C], a common metric used  
13 to estimate the global temperature change that follows an abrupt cessation of emissions.  
14 The magnitude of the ZEC depends on the evolution of atmospheric greenhouse gas and  
15 aerosol concentrations after emissions cease, along with the multiple timescales of climate  
16 response to changes in radiative forcing. If only CO<sub>2</sub> emissions cease, global temperature  
17 is expected to remain relatively constant as both ocean heat uptake and atmospheric CO<sub>2</sub>  
18 forcing slowly decline by similar, and compensating, amounts [2, 3, 4, 5, 6]. Estimates of  
19 the ZEC following a cessation of only CO<sub>2</sub> emissions (referred to here as ZEC<sub>CO<sub>2</sub></sub>) range  
20 from slight cooling to continued warming [6, 7] over multiple centuries, depending upon  
21 model representations of ocean heat uptake, carbon cycle, climate feedbacks and historical  
22 emissions pathways [4, 6, 8, 9, 10]. On average, ZEC<sub>CO<sub>2</sub></sub> is taken to be small throughout  
23 the 21<sup>st</sup> century when estimated from multi-model simulations [1, 8]. This suggests that  
24 future warming is primarily governed by future emissions rather than by past emissions,

25 and thus society is not geophysically-committed to exceeding key global warming levels  
26 prior to reaching them.

27 However, the situation becomes more complex when the emissions of short-lived climate  
28 forcers, including non-CO<sub>2</sub> greenhouse gases (GHGs) and aerosols, are considered [11, 3,  
29 12]. Tropospheric aerosols produced through the combustion of fossil fuels and biomass  
30 burning have atmospheric lifetimes of days to weeks and currently exert a strong net  
31 cooling effect on the climate (a negative radiative forcing). Thus, the ZEC associated with  
32 the cessation of all anthropogenic emissions (referred to here as  $ZEC_{\text{anthro}}$ ) would include  
33 warming associated with the rapid reduction of aerosols and consequent ‘unmasking’ of  
34 a portion of GHG forcing. This warming is offset in small part by the removal of black  
35 carbon on snow (a positive surface albedo forcing) and in larger part by a decrease in  
36 tropospheric ozone, nitrous oxide and methane concentrations over the following weeks  
37 to decades, followed by a slower decline as GHG concentrations decrease until the global  
38 temperature stabilizes at a value determined by the residual forcing associated with the  
39 portion of anthropogenic CO<sub>2</sub> that remains in the atmosphere for millennia [3, 12, 13].

40 We thus focus on two measures of the climate commitment following a complete ces-  
41 sation of anthropogenic emissions: the peak temperature reached in the decades following  
42 emissions cessation ( $ZEC_{\text{anthro}}^{\text{peak}}$ ) and the eventual temperature reached in the year 2100  
43 ( $ZEC_{\text{anthro}}^{2100}$ ). These two measures represent different aspects of committed warming that  
44 may be relevant to different components of the climate system and impacts thereupon;  
45 i.e., systems that respond quickly to global temperature change would be sensitive to peak  
46 warming (e.g., sea ice, the hydrological cycle, hurricanes, agriculture, and many ecosys-  
47 tems), while those that respond slowly to global temperature change would be sensitive to

48 long-term warming (e.g., glaciers, ice sheets, and sea level).

49 Both measures of commitment ( $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$ ) depend on the magnitude and  
50 evolution of GHG and aerosol radiative forcing following emissions cessation, the sensitivity  
51 of climate to forcing changes (often characterized in terms of the equilibrium climate sen-  
52 sitivity (ECS) [ $^{\circ}\text{C}$ ]), and the timescales of climate adjustment associated with the oceans  
53 [3, 13]. Cessation of emissions from present-day levels generally results in a  $ZEC_{\text{anthro}}^{\text{peak}}$  of  
54 a few tenths of a degree Celsius above the current temperature, with an overshoot lasting  
55 approximately a decade before cooling to near-present temperatures [13, 14, 15]. However,  
56 a larger  $ZEC_{\text{anthro}}^{\text{peak}}$  with a more prolonged overshoot is possible if aerosol forcing is strong  
57 and climate sensitivity is high [3, 15]. Thus, a full accounting of past emissions suggests  
58 that society may be geophysically-committed to peak warming exceeding key global warm-  
59 ing levels many years before those levels are reached – absent efforts to directly remove  
60  $\text{CO}_2$  from the atmosphere.

61 Recent research has substantially advanced scientific understanding of the instrumental  
62 record of global warming [16], Earth’s energy imbalance [17, 18], aerosol radiative forcing  
63 [19, 18] and climate sensitivity [20, 18]. In light of these advances, the current geophysical  
64 climate commitment needs to be revisited. Furthermore, both  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$   
65 will change over time as GHG emissions continue and the blend of radiative forcing agents  
66 in the atmosphere evolves. Key questions are – when will the world be geophysically-  
67 committed to reaching key global warming levels, such as 1.5 and 2.0 $^{\circ}\text{C}$ , either temporarily  
68 (overshoot) or at the end-of-century, and how do these estimates depend upon the emissions  
69 trajectory?

70 We quantify both  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  associated with a cessation of all anthro-

71 pogenic emissions using an emissions-based climate model, FaIR (Finite Amplitude Impulse  
72 Response Model, v1.3) [21, 22] with model parameters constrained by observations of global  
73 energy budget and temperature trends since the 1800s (Methods). FaIR produces effec-  
74 tive radiative forcing from emissions time-series of 39 gases and short-lived climate forcers,  
75 with an intermediate concentration calculation for GHGs and a four-timescale carbon-cycle  
76 representation that is sensitive to changes in uptake efficiency with cumulative emissions  
77 and temperature. Changes in land-use forcing are excluded from this analysis because it  
78 is unclear how they should be represented in the ZEC framework (e.g., [23]), but sensi-  
79 tivity tests show that including land-use forcing has little impact on the results presented  
80 here (Methods and Supplementary Figure S1). Global temperature is calculated using a  
81 two-layer ocean model [24, 25] (Methods) which was also used for the global temperature  
82 projection assessment in the IPCC’s Sixth Assessment Report (IPCC AR6) [1].

83 Priors for key model parameters, including the radiative feedback parameter (which  
84 governs ECS), the efficiency of ocean heat uptake, ocean effective heat capacities, the  
85 magnitude of GHG and aerosol forcing, and carbon cycle parameters are generated to  
86 match distributions of state-of-the-art global climate models [25] and IPCC AR6 estimates  
87 [18, 26] (Methods; Extended Data Figs. E1-E4). Posterior model parameter distributions  
88 are then selected based on fits to observational records of global surface temperature,  
89 global energy accumulation and radiative forcing since 1850, as well as present-day CO<sub>2</sub>  
90 levels. These constraints result in a posterior FaIR model ensemble that accurately fits  
91 the historical temperature record to within an estimate of internal temperature variability  
92 (Fig. E5), and closely matches the projections of 21<sup>st</sup> century warming as assessed by  
93 IPCC AR6 [1] (Fig. 1a).

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

99 With the posterior FaIR ensemble, we first evaluate  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  associated  
100 with an abrupt cessation of anthropogenic emissions near the present day (taken as January  
101 2021) (Fig. 1b). We find a median  $ZEC_{\text{anthro}}^{\text{peak}}$  of 0.22°C relative to 2020, with an overshoot  
102 that lasts for approximately 18 years before eventually cooling to several tenths of a degree  
103 Celsius below 2020 temperatures by the end-of-century (Fig. 1b, dashed line). Smith et  
104 al.[13], also using FaIR, estimated a median  $ZEC_{\text{anthro}}^{\text{peak}}$  of approximately 0.1°C above 2018,  
105 while Matthews and Zickfeld[15], using an intermediate complexity model, found median  
106 peak warming of 0.3 °C following a cessation of all emissions. This difference in results is  
107 due in large part to differences in aerosol forcing at the time of emissions cessation between  
108 ref[13] (-1.4 to -0.2 W m<sup>-2</sup>, 90% confidence range), ref[15] (-1.9 to -0.8 W m<sup>-2</sup>), and this  
109 study (-1.8 to -0.6 W m<sup>-2</sup>), as well as larger climate sensitivity in ref[15].

110 Similar to Smith et al.[13], we find net cooling at the end-of-century following emissions  
111 cessation (a median  $ZEC_{\text{anthro}}^{2100}$  of -0.4°C below the 2020 temperature), which is in contrast  
112 to the end-of-century warming of approximately 0.3°C found in a previous study [12] –  
113 a difference that may be due to different assumptions about residual GHG and non-CO<sub>2</sub>  
114 forcing in the ZEC experiment, and the sensitivity of atmospheric CO<sub>2</sub> uptake to global  
115 temperatures [13]. An assessment of the effect of different emissions choices on the present-  
116 day  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  is provided in the Supplementary (Fig. S2).

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

125 For comparison, we find that a cessation of CO<sub>2</sub> emissions ( $ZEC_{\text{CO}_2}$ ), while holding  
126 all other forcings fixed at present-day levels, results in temperatures remaining within  
127 approximately 0.1°C of the present-day temperature throughout the century (Fig. 1b,  
128 dotted line), consistent with previous studies [3, 12, 8]. The end-of-century  $ZEC_{\text{CO}_2}$  is  
129 approximately 0°C [-0.02 to 0.12°C, 66% confidence] relative to present-day temperatures,  
130 in good agreement with the AR6 assessed likely range of 0°C ±0.19°C.

131 We next consider how  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  change over time following a range of  
132 emissions pathways prior to cessation, as illustrated by eight Shared Socioeconomic Path-  
133 way (SSP) emission scenarios: SSP1-1.9, SSP1-2.6, SSP4-3.4, SSP2-4.5, SSP4-6.0, SSP3-  
134 7.0-lowNTCF (‘Near Term Climate Forcing’), SSP3-7.0, and SSP5-8.5 [27]. We conduct  
135 simulations of the climate response to a cessation of anthropogenic emissions within FaIR  
136 in every year for the period 2021-2080 or until CO<sub>2</sub> emissions reach net-zero, following  
137 each of these SSP scenarios, each run with 6,729 posterior ensemble members (Methods).  
138 Fig. 2a shows  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  relative to the pre-industrial period 1850-1900 as a  
139 function of the year in which emissions cease along a moderate mitigation scenario (SSP2-

140 4.5) (solid black and dashed black lines, respectively). A key result is that the time at  
141 which  $ZEC_{\text{anthro}}^{\text{peak}}$  is reached occurs from four to seven years before that temperature would  
142 be exceeded following SSP2-4.5 (horizontal distance between orange and solid black lines  
143 and shading in Fig. 2a); while there is a 66% probability of *exceeding* 1.5°C by 2035, there  
144 is a 66% probability of being *committed* to at least 1.5°C of warming by 2029 ( $ZEC_{\text{anthro}}^{\text{peak}}$  in  
145 Fig. 2a; Table 1). For 2°C, this becomes 2061 and 2057, respectively ( $ZEC_{\text{anthro}}^{\text{peak}}$  in Fig. 2a;  
146 Table 1). The number of years that  $ZEC_{\text{anthro}}^{\text{peak}}$  is reached before a given warming level is  
147 exceeded depends on the probability threshold considered, with the 17<sup>th</sup> percentile of the  
148 ensemble (corresponding to high aerosol forcing and high climate sensitivity) producing  
149 a larger difference, and the 83<sup>rd</sup> percentile of the ensemble (corresponding to low aerosol  
150 forcing and low climate sensitivity) producing a smaller difference (Table 1).

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

159 Considering the seven other emissions scenarios, results show that committed warm-  
160 ing of 1.5 and 2°C ( $ZEC_{\text{anthro}}^{\text{peak}}$ ) occurs roughly half a decade before those temperatures  
161 would actually be exceeded if emissions were never halted (Figs. 3a,c,e; Table 1). The  
162 choice of emissions pathway becomes increasingly important with time, with high and very

163 high emissions scenarios (SSP3-7.0, SSP5-8.5) generating a  $ZEC_{\text{anthro}}^{\text{peak}}$  of 2°C earlier than  
164 lower emissions scenarios. Conversely, only high mitigation (SSP1-1.9, SSP1-2.6) avoids  
165  $ZEC_{\text{anthro}}^{\text{peak}}$  of 2°C over this century in the 66<sup>th</sup> percentile. A  $ZEC_{\text{anthro}}^{2100}$  exceeding 1.5°C and  
166 2.0°C following a cessation of emissions in this century is avoided in low (SSP1-2.6) and in  
167 low to moderate (SSP4-3.4, SSP2-4.5) emissions scenarios, respectively.

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

## 174 **Committed warming as a function of cumulative emissions**

175 The projected 21<sup>st</sup> century warming following different SSP emissions scenarios (Fig. 3a)  
176 simplifies greatly when cast in terms of the cumulative CO<sub>2</sub> emissions (Fig. 3b; calculated  
177 as cumulative anthropogenic CO<sub>2</sub> emitted since January 2021). Consistent with previous  
178 studies [28, 29, 30], global warming is nearly proportional to cumulative CO<sub>2</sub> emissions,  
179 with small differences between scenarios arising from the assumed rate of emissions and  
180 the fractional contribution of non-CO<sub>2</sub> climate forcing to total forcing. A relevant measure  
181 of this proportionality is the Transient Climate Response to Emissions (TCRE), defined  
182 as the global temperature change per 1000 GtCO<sub>2</sub> emitted. We find that the constrained  
183 FaIR ensemble has  $TCRE = 0.44^\circ\text{C}$  per 1000 GtCO<sub>2</sub> [0.33-0.59°C per 1000 GtCO<sub>2</sub>, 66%  
184 confidence range] when calculated for SSP2-4.5 for the period 2018-2068 (Supplementary

185 Figure S4). These estimates are in line with Matthews et al.’s [31] estimate of 0.44°C per  
186 1000 GtCO<sub>2</sub> [0.32-0.62 °C per 1000 GtCO<sub>2</sub>, 90% range] and the IPCC AR6 [32] estimate  
187 of 0.45°C per 1000 GtCO<sub>2</sub> [0.27-0.63 °C per 1000 GtCO<sub>2</sub>, 66% range].

188 We next evaluate how  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  scale with the cumulative CO<sub>2</sub> emit-  
189 ted until the year emissions cease. The evolution of  $ZEC_{\text{anthro}}^{\text{peak}}$  is nearly proportional to  
190 cumulative CO<sub>2</sub> emissions (Fig. 3b), despite its dependence on aerosol forcing at the time  
191 emissions cease. This is likely due to the approximately constant fraction of aerosol forcing  
192 relative to total forcing over time for most individual SSP pathways. Exceptions are SSP1-  
193 2.6 and SSP1-1.9, wherein aerosols decrease rapidly during the first half of the 21<sup>st</sup> century  
194 and decline more slowly thereafter (Fig. E6), resulting in a non-linear response in peak  
195 warming as a function of emissions cessation year. The proportionality with cumulative  
196 CO<sub>2</sub> emissions is more evident for  $ZEC_{\text{anthro}}^{2100}$ , which is independent of the emissions sce-  
197 nario (Fig. 3c) because the residual CO<sub>2</sub> forcing dominates total forcing by 2100 following  
198 a cessation of emissions.

199 The proportionality of committed warming to cumulative CO<sub>2</sub> emissions permits the  
200 quantification of a remaining carbon budget for committed warming of 1.5, 1.7, and 2°C  
201 (Table 2). Total cumulative carbon emitted between 1850 and 2019 is approximately 2,290  
202 GtCO<sub>2</sub>, within the IPCC AR6 estimate of 2,390 +/- 240 GtCO<sub>2</sub> for the same period [32]. A  
203 median  $ZEC_{\text{anthro}}^{\text{peak}}$  of 1.5°C is reached after the emission of 120 GtCO<sub>2</sub> [0-340 GtCO<sub>2</sub>, 66%  
204 confidence] relative to the beginning of 2021 (Fig. 2b); for 2°C the remaining carbon budget  
205 is 1,120 GtCO<sub>2</sub> [470-1,550 GtCO<sub>2</sub>]. At the end-of-century ( $ZEC_{\text{anthro}}^{2100}$ ), 1.5°C is reached  
206 after the emission of 1,080 GtCO<sub>2</sub> [420-1,470 GtCO<sub>2</sub>]; for 2°C this remaining carbon budget  
207 is 1,980 GtCO<sub>2</sub> [1,170-not reached within the experiments]. Uncertainty in the remaining

208 carbon budgets stems mainly from uncertainties in aerosol forcing and climate sensitivity.  
209 However, the results are consistent across the emissions scenarios (Table S2) – a key to  
210 maintaining consistency in the calculation of carbon budgets [31].

211 Remaining carbon budgets estimated using the ZEC can be contrasted to those esti-  
212 mated following emissions pathways without a cessation of emissions (Table 2). 1.5°C is  
213 exceeded with 66% probability when cumulative emissions since 2021 reach 600 GtCO<sub>2</sub>  
214 following SSP2-4.5 (orange line in Fig. 2b), a measure of the ‘threshold exceedance bud-  
215 get’ [32]. This is substantially larger than the 66<sup>th</sup> percentile estimate of 340 GtCO<sub>2</sub> using  
216  $ZEC_{\text{anthro}}^{\text{peak}}$  because it does not account for the additional warming that would occur as  
217 aerosol forcing is reduced upon abrupt cessation of emissions. The smaller carbon bud-  
218 gets obtained using  $ZEC_{\text{anthro}}^{\text{peak}}$  would provide an underestimate for emissions pathways that  
219 achieve net-zero CO<sub>2</sub> through the implementation of carbon dioxide removal technologies  
220 while maintaining some level of anthropogenic aerosol emissions. However, compared to  
221 scenarios that phase out emissions more slowly and without net-negative CO<sub>2</sub>,  $ZEC_{\text{anthro}}^{\text{peak}}$   
222 provides the smallest estimate of peak warming over the 21<sup>st</sup> century, and therefore can be  
223 considered a lower bound on committed warming (Fig. E7).

224 These calculations are relatively pathway-independent across priority SSPs, and are  
225 therefore robust to choice of emissions trajectory. As such, they do not require an exam-  
226 ination of only a subset of emissions trajectories that are calibrated to avoid 1.5 or 2°C  
227 (such as those presented in IPCC AR6), or that are constrained by socioeconomic feasibility  
228 [14, 33]. This methodology is appropriate when considering the possibility of a tempera-  
229 ture overshoot that may persist for over a decade, with subsequent impacts on human and  
230 natural systems that respond quickly, and perhaps irreversibly, to global warming.

231 Two important insights are that: (i) the world will have a greater than 66% probability  
232 of being committed to peak warming above 1.5°C by 2027-2032 in all emissions scenarios,  
233 and 2°C by 2043-2057 in medium to high emissions scenarios (SSP2-4.5 to SSP5-8.5), and  
234 (ii) these temperature commitments will occur 4 to 6 years before the 1.5 and 2°C warming  
235 levels will actually be exceeded, assuming emissions follow SSP2-4.5. We find that the 1.5  
236 and 2.0°C peak warming commitments ( $ZEC_{\text{anthro}}^{\text{peak}}$ ) correspond to median carbon budgets of  
237 approximately 120 and 1,120 Gt CO<sub>2</sub> relative to the beginning of 2021, respectively. Given  
238 that FaIR does not capture the possibility of future destabilizing climate feedbacks such  
239 as decreased ice sheet cover [34], thawing permafrost and methane hydrate dissociation  
240 due to ocean warming [35, 36], or a sea-surface temperature pattern effect that allows for  
241 a more substantial shift toward destabilizing cloud feedbacks in the future than modeled  
242 here [37, 38, 39, 40, 10], these estimates of the timing of geophysical warming commitments  
243 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  $ZEC_{anthro}^{peak}$  and  $ZEC_{anthro}^{2100}$  of 1.5, 1.7 and 2°C following SSP2-4.5 at the 17<sup>th</sup>, 50<sup>th</sup>, 66<sup>th</sup>, and 83<sup>rd</sup> 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			
		17 <sup>th</sup>	50 <sup>th</sup>	66 <sup>th</sup>	83 <sup>rd</sup>
1.5	$ZEC_{anthro}^{peak}$	A/R	2024	2029	2037
	$ZEC_{anthro}^{2100}$	2031	2046	2055	2065
	No cessation	2024	2031	2035	2040
1.7	$ZEC_{anthro}^{peak}$	A/R	2032	2040	2050
	$ZEC_{anthro}^{2100}$	2038	2055	2064	2076
	No cessation	2031	2039	2044	2052
2.0	$ZEC_{anthro}^{peak}$	2032	2047	2057	2074
	$ZEC_{anthro}^{2100}$	2048	2068	N/R	N/R
	No cessation	2040	2052	2061	2077

Table 2. Estimated remaining carbon budget (GtCO<sub>2</sub>) relative to the beginning of 2021

for  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  of 1.5, 1.7 and 2°C following SSP2-4.5 at the 17<sup>th</sup>, 50<sup>th</sup>, 66<sup>th</sup>, and 83<sup>rd</sup> 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			
		17 <sup>th</sup>	50 <sup>th</sup>	66 <sup>th</sup>	83 <sup>rd</sup>
1.5	$ZEC_{\text{anthro}}^{\text{peak}}$	0	120	340	680
	$ZEC_{\text{anthro}}^{2100}$	420	1080	1470	1870
	No cessation	120	420	600	820
1.7	$ZEC_{\text{anthro}}^{\text{peak}}$	0	470	820	1260
	$ZEC_{\text{anthro}}^{2100}$	730	1470	1830	2250
	No cessation	420	770	990	1340
2.0	$ZEC_{\text{anthro}}^{\text{peak}}$	470	1120	1550	2190
	$ZEC_{\text{anthro}}^{2100}$	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<sub>2</sub> emissions (dotted line,  $ZEC_{\text{CO}_2}$ ) and of all anthropogenic emissions (dashed line,  $ZEC_{\text{anthro}}$ ) 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,  $ZEC_{\text{anthro}}^{\text{peak}}$  (solid black line) and  $ZEC_{\text{anthro}}^{2100}$  (dashed black line), as functions of emissions cessation year (a) and cumulative anthropogenic CO<sub>2</sub> 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);  $ZEC_{\text{anthro}}^{\text{peak}}$  (b) and  $ZEC_{\text{anthro}}^{2100}$  (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<sub>2</sub> emissions reach net zero; CO<sub>2</sub> 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<sub>2</sub>O and CH<sub>4</sub> 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:

$$C \frac{dT}{dt} = F + \lambda T - \epsilon \gamma (T - T_0)$$

$$C_0 \frac{dT_0}{dt} = \gamma (T - T_0)$$

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);  $\gamma$  is the coefficient of heat exchange between the two layers, representing a measure of the ocean heat uptake efficiency;  $\lambda$  is the radiative feedback parameter; and  $\epsilon$  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<sub>2</sub> 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  $\gamma$ ,  $C$  and  $C_0$  are generated using distributions from GCMs (Global Climate Models) (Geoffroy et al.) [25], but with standard deviations ( $\sigma$ ) expanded by 50%; the distribution in  $\gamma$  is truncated to avoid values less than 0.1, while  $C_0$  is truncated to avoid sampling deep ocean heat capacities less than 10  $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1} \text{ yr}$  ( $\gamma$ : mean = 0.67  $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$ ,  $\sigma = 0.225 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ ;  $C$ : mean = 8.2  $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1} \text{ yr}$ ,  $\sigma = 1.4 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1} \text{ yr}$ ;  $C_0$ : mean = 124.7  $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1} \text{ yr}$ ,  $\sigma = 65.8 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1} \text{ yr}$ ). A lognormal prior distribution for  $\epsilon$  is generated using distributions from GCMs [25] (mean = 1.28,  $\sigma = 0.375$ ), with values of  $\epsilon$  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  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  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;  $\text{CO}_2$ : mean = 2.15  $\text{W m}^{-2}$ ,  $\sigma = 0.16 \text{ W m}^{-2}$ ;  $\text{CH}_4$ : mean = 0.54  $\text{W m}^{-2}$ ,  $\sigma = 0.07 \text{ W m}^{-2}$ ;  $\text{N}_2\text{O}$ : mean = 0.19  $\text{W m}^{-2}$ ,  $\sigma = 0.02 \text{ W m}^{-2}$ ). Aerosol forcing is also scaled by a constant amount by values drawn from a uniform distribution ranging from -2.2 to -0.1  $\text{W m}^{-2}$  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 variability,  $ZEC_{\text{anthro}}^{\text{peak}}$  and  $ZEC_{\text{anthro}}^{2100}$  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  $\delta T$ ,  $\delta Q$  and  $\delta F$  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  $\sigma_T$ ,  $\sigma_Q$  and  $\sigma_N$  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:  $\Delta T_{\text{obs}} = 1.03 \pm 0.2^\circ\text{C}$ ,  $\Delta Q_{\text{obs}} = 0.59 \pm 0.35 \text{ W m}^{-2}$  and  $\Delta N_{\text{obs}} = 2.20 \pm 0.7 \text{ W m}^{-2}$  [18]. Modeled  $\text{CO}_2$  concentrations are additionally constrained to be within  $\pm 2$  ppm of the 2006-2018 mean (395.98 ppm) [47].

This method produces a posterior estimate on the equilibrium climate sensitivity of  $2.9^\circ\text{C}$  [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 ( $\gamma$ ,  $\epsilon$ ,  $C$  and  $C_0$ ) are shown in Figs. E1-E4). However, the observational record is not long enough to adequately constrain  $\epsilon$  owing to the slow adjustment of the deep ocean (the timescale on which the value of  $\epsilon$  becomes relevant for surface warming). The posterior distribution of  $\epsilon$  used in this study is thus the same as the prior (Fig. E2c); however, sensitivity tests show that the choice of prior distribution in  $\epsilon$  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 set up model simulations, analyze model output and create figures, are available to view and download from GitHub [49].





