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# Stringent mitigation substantially reduces risk of unprecedented near-term warming rates

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## 14 **Abstract**

15 Following the Paris Agreement, many countries are enacting targets to achieve net-zero  
16 greenhouse gas emissions. Stringent mitigation will have clear societal benefits in the second  
17 half of this century by limiting peak warming and stabilizing climate. However, the near-term  
18 benefits of mitigation are generally thought to be less clear because forced surface temperature  
19 trends can be masked by internal variability. Here we use observationally-constrained  
20 projections from the latest comprehensive climate models and a simple climate model emulator,  
21 to show that pursuing stringent mitigation consistent with holding long-term warming below 1.5  
22 °C reduces the risk of unprecedented warming rates in the next 20 years by a factor of 13  
23 compared to a no-mitigation scenario, even after accounting for internal variability. Therefore, in  
24 addition to long-term benefits, stringent mitigation offers substantial near-term benefits by  
25 offering societies and ecosystems a greater chance to adapt to and avoid the worst climate  
26 change impacts.

## 27 **Main text**

28 Near-term warming rates affect how rapidly society and ecosystems must adapt to the worst  
29 impacts of climate change. Recent decades have seen high rates of global average surface  
30 warming; the maximum warming trend for 20-year segments of the observation-based record  
31 since pre-industrial times is  $0.27\text{ }^{\circ}\text{C decade}^{-1}$ , which occurred in the last few decades with the  
32 exact timing dependent on the dataset used (Supplementary Fig. 1). It is clear that to stabilize  
33 climate in the long-term, global net-zero greenhouse gas emissions must be achieved<sup>1</sup>;  
34 however, it is less clear when the benefits of mitigation applied now will become evident<sup>2-6</sup>.

35 Here, we investigate the effect of different levels of mitigation in future emission scenarios on  
36 surface warming rates in the next 20 years (2021-2040), a key period for policymakers at the  
37 forefront of climate change adaptation. For example, crop breeding is unlikely to keep pace with  
38 climate impacts on agriculture over this period under current rates of warming<sup>7</sup>. The next 20  
39 years is also a typical time horizon for initial planning to operation of large-scale structural  
40 responses to support climate change adaptation, such as the design and implementation of  
41 flood defences<sup>8</sup>.

42 The general consensus is that differences in global mean surface temperature between high  
43 and low emission pathways only emerge after roughly the 2050s, with changes not being  
44 detectable beforehand<sup>2-6</sup>. The long atmospheric lifetime of  $\text{CO}_2$  means that substantial emission  
45 reductions are needed to alter the upwards trend in atmospheric concentration and effective  
46 radiative forcing<sup>9</sup>, making it difficult for society to notice the immediate benefits of mitigation  
47 efforts. While the Paris Agreement long-term targets are concerned with addressing the  
48 anthropogenic warming contribution<sup>10-11</sup>, the temperature changes society will experience in the  
49 near-term will come from a combination of a forced response to radiative forcings and internal  
50 climate variability<sup>12-13</sup>. On decadal timescales, internal variability can overwhelm the forced

51 climate response, even for spatially averaged quantities like global temperature<sup>4</sup>, having  
52 profound implications for the public understanding of climate change. For example, the period of  
53 relatively slow surface warming between around 1998 and 2012, which was partly associated  
54 with internal climate variability<sup>14</sup>, was widely misrepresented leading to doubt in the public mind  
55 about how well anthropogenic climate change is understood<sup>15</sup>. It is therefore important to  
56 communicate to what extent strong mitigation efforts will offer benefits in the near-term as well  
57 as in the long-term, and to what extent those benefits may be masked on shorter timescales by  
58 internal variability.

59 Here, we combine two approaches (see Methods) to assess whether mitigation has detectable  
60 benefits for near-term warming rates. The first approach uses projections from the latest  
61 Coupled Model Intercomparison Project Phase 6 (CMIP6) models, driven by Shared  
62 Socioeconomic Pathway (SSP<sup>16</sup>) scenarios and constrained according to their representation of  
63 recent observed warming rates<sup>17</sup>. The second approach uses a simple climate model emulator  
64 (FaIR<sup>18</sup>), with added observation-based estimates of internal variability<sup>19</sup>, also run under SSP  
65 scenarios and, additionally, a scenario consistent with current and projected pledges as of 2019  
66 in the Nationally Determined Contributions (NDCs) under the Paris Agreement<sup>20-22</sup>. Simple  
67 climate models like FaIR are designed to emulate the behavior of more complex climate models  
68 in a computationally inexpensive way, by using simplified representations of the physical  
69 relationships between emissions, atmospheric concentrations of greenhouse gases and other  
70 climate forcers, radiative forcing, and temperature change. The combination of these two  
71 approaches is advantageous because the CMIP6 models - while comprehensive - do not  
72 necessarily accurately represent observed internal variability, and CMIP6 was not designed to  
73 fully sample the range of parameter uncertainties that affect temperature projections. Since  
74 FaIR is inexpensive to run, it can be used to more broadly sample uncertainty in temperature  
75 projections than individual complex climate models (see Methods).

76 We focus on strong mitigation pathways in line with the Paris Agreement 1.5 °C and 2 °C long-  
77 term temperature targets (SSP1-1.9 and SSP1-2.6, respectively), and include the NDC-like  
78 scenario to consider a less ambitious and more plausible mitigation pathway<sup>23</sup>. These are  
79 compared to baseline no mitigation pathways (SSP3-7.0 and SSP5-8.5). SSP5-8.5 is a highly  
80 unlikely “worst case” no mitigation pathway since, for example, it assumes a fivefold increase in  
81 coal use by the late 21st century<sup>23</sup>. Conversely, SSP3-7.0 represents an “average” no mitigation  
82 pathway<sup>23</sup> and, as such, focus will be placed on this as a baseline.

83 Firstly, we ask whether over the next 20 years, mitigation – relative to a baseline of no mitigation  
84 – will reduce: (i) the risk of experiencing unprecedented warming rates (exceeding the highest  
85 warming rate observed to date), and (ii) the potential magnitude of extreme warming rates (i.e.,  
86 low probability 20-year trends in the upper 5th percentile), which could lead to the failure of  
87 adaptation plans.

88 Both the CMIP6 and FaIR simulations show a clear benefit of strong mitigation in terms of  
89 decreasing near-term warming rates (Fig. 1a). The following results are quoted from the FaIR  
90 projections accounting for internal variability, but note that the distributions of trends for the  
91 constrained CMIP6 models are in good agreement with FaIR (Fig. 1a). In the strong mitigation  
92 scenario consistent with warming of below 2.0 °C by 2100 (SSP1-2.6; blue boxes), the median  
93 warming rate is almost half that in the “worst case” no mitigation scenario (SSP5-8.5; brown  
94 boxes), and two thirds that in the “average” no mitigation scenario (SSP3-7.0; orange boxes).  
95 Under the even stronger mitigation scenario consistent with keeping long-term warming below  
96 1.5 °C (SSP1-1.9; green box), the median warming rate is almost one third of that in the “worst  
97 case” no mitigation scenario, and just over half that in the “average” no mitigation scenario.  
98 Even under less ambitious mitigation consistent with current and projected NDCs (grey box),  
99 there is still a reduction in median warming rate by around one third compared to SSP5-8.5 and  
100 one quarter compared to SSP3-7.0. The median effective radiative forcing (ERF) trend in FaIR



101 over this period differs by  $0.63 \text{ W m}^{-2} \text{ decade}^{-1}$  between SSP1-1.9 and SSP5-8.5  
102 (Supplementary Table 1), which comes mainly from carbon dioxide ( $0.42 \text{ W m}^{-2} \text{ decade}^{-1}$ ),  
103 methane ( $0.15 \text{ W m}^{-2} \text{ decade}^{-1}$ ), tropospheric ozone ( $0.13 \text{ W m}^{-2} \text{ decade}^{-1}$ ), and other well-  
104 mixed greenhouse gases ( $0.05 \text{ W m}^{-2} \text{ decade}^{-1}$ ), with a slight offset from anthropogenic aerosols  
105 ( $-0.16 \text{ W m}^{-2} \text{ decade}^{-1}$ ). The difference in near-term total ERF trend is  $0.29 \text{ W m}^{-2} \text{ decade}^{-1}$   
106 between SSP1-2.6 and SSP3-7.0 (Supplementary Table 1). Over the next 20 years, the  
107 difference in median ERF trends between the strong mitigation and no mitigation SSP scenarios  
108 are therefore comparable to, or larger than, the total ERF trend over the recent past (1995-  
109 2014;  $0.40 \text{ W m}^{-2} \text{ decade}^{-1}$ ; Supplementary Table 1).

110 Comparing the distributions of projected warming rates to the maximum trend for 20-year  
111 segments of the observation-based record since the pre-industrial (red ticks on y-axes, Fig. 1a),  
112 we find that strong mitigation has a discernible effect on the risk of experiencing stronger  
113 warming than observed in the past, even after accounting for internal variability. Under SSP1-  
114 1.9 (SSP1-2.6) there is only a 4% (14%) probability of the warming rate in the next 20 years  
115 exceeding the maximum observed trend, while for SSP3-7.0 (SSP5-8.5) this increases  
116 considerably to a 54% (75%) probability. Less ambitious mitigation, in line with current and  
117 projected NDCs, results in a higher probability (21%) of unprecedented near-term warming than  
118 for SSP1-1.9 or SSP1-2.6. Pursuing rapid, stringent mitigation therefore substantially reduces  
119 the risk of experiencing unprecedented warming rates over the next 20 years, giving society and  
120 ecosystems a greater chance to adapt to and avoid the worst impacts of climate change.

121 Indeed, for warming rates of  $0.3 \text{ }^{\circ}\text{C decade}^{-1}$ , which is close to the threshold for unprecedented  
122 warming rates, it has been estimated only 30% of all climate change impacted ecosystems can  
123 adapt and only 17% of impacted forests<sup>24</sup>.

124 Note that very high near-term warming rates, which are substantially larger than the maximum  
125 observed historical 20-year trend, are still possible in all scenarios considered. However, a key

126 point for policymakers to note is that strong mitigation greatly reduces the extremity of these low  
127 probability high impact cases, reducing the risk of ecosystems declining and adaptation plans  
128 failing. Under SSP5-8.5 and SSP3-7.0, the upper 5% of trends are between 0.50-0.83 °C  
129 decade<sup>-1</sup> and 0.43-0.79 °C decade<sup>-1</sup> respectively, while this extreme range is 0.32-0.50 °C  
130 decade<sup>-1</sup> for SSP1-2.6 and 0.26-0.43 °C decade<sup>-1</sup> for SSP1-1.9 (Fig. 1a; FaIR boxes). For  
131 warming rates over 0.4 °C decade<sup>-1</sup>, evidence suggests that all ecosystems will decline as they  
132 will not be able to adapt rapidly enough<sup>25</sup>. These extremes are caused by a combination of  
133 relatively high equilibrium climate sensitivity (ECS), high transient climate response (TCR), high  
134 effective radiative forcing (ERF) trends, and high positive internal variability. Very low near-term  
135 warming rates are also possible in all scenarios considered. However, only under mitigation  
136 would it be possible, but very unlikely, to observe a cooling trend over the next 20 years. Only  
137 2% of trends show near-term cooling in SSP1-1.9, where the minimum trend is -0.13 °C decade<sup>-1</sup>.  
138 <sup>1</sup>. Maher et al. (2020)<sup>5</sup> found that cooling trends could be observed in the near-term even under  
139 a “worse case” emissions scenario, when using a shorter 15-year time horizon and considering  
140 trends at individual locations rather than the global average trend.

141 We now ask what is the probability, over the next 20 years, of the warming trend being lower if a  
142 mitigation pathway is followed rather than a no mitigation pathway. This is important since  
143 internal variability could overwhelm a forced temperature signal from diverging trajectories of  
144 greenhouse gas and aerosol concentrations, masking the near-term benefits of mitigation  
145 efforts. The probability that pursuing a mitigation pathway will result in a lower near-term  
146 temperature trend by a factor  $\alpha$  as compared to following a no mitigation pathway ( $P(\text{trend}_{\text{mit}} <$   
147  $\text{trend}_{\text{nomit}} - \alpha \times \text{trend}_{\text{nomit}})$ ) is shown in Table 1a. Values of  $\alpha$  are chosen to assess whether the  
148 trend is, first, lower by any amount ( $\alpha = 0$ ) and, second, lower by a sizable amount (20% and  
149 40%,  $\alpha = 0.2$  and  $\alpha = 0.4$ ). The probabilities for  $\alpha = 0$  are calculated from the distributions  
150 created by randomly sampling with replacement from each FaIR trend distribution and taking

151 their difference, where this is repeated  $n=10^5$  times (Fig. 2a and 2b). For  $\alpha = 0.2$  and  $\alpha = 0.4$ ,  
152 the probabilities are calculated by shifting the same distributions by amount  $\alpha \times \text{trend}_{\text{nomit}}$ .  
153 Comparing the 1.5 °C and 2 °C scenarios (SSP1-1.9 and SSP1-2.6) to the “average” no  
154 mitigation scenario (SSP3-7.0; Fig. 2a), there is respectively around a 90% and 80% probability  
155 (Table 1a) that the near-term temperature trend would be lower when following the strong  
156 mitigation pathway. Under less ambitious mitigation consistent with current and projected NDCs,  
157 the probability of the warming trend being lower than in the “average” no mitigation pathway is  
158 74%. Even when it is required that the trend under mitigation is at least 20% (40%) lower than  
159 under no mitigation, there is still a 83% (67%) probability of this outcome for SSP1-1.9  
160 compared to SSP3-7.0.

161 A more stringent test, similar to that described by Marotzke (2019)<sup>4</sup> – hereafter M19 – is to ask  
162 what is the probability that mitigation is both *sufficient* and *necessary* ( $P_{\text{ns}}$ ) for a reduction in the  
163 temperature trend over 2021-2040 relative to the trend over the recent past. To calculate  $P_{\text{ns}}$ ,  
164 the observed 20-year temperature trend for 2000-2019 ( $\text{trend}_{\text{obs}}$ ) is subtracted from each  
165 distribution of FaIR near-term trends for the mitigation and no mitigation scenarios. Since the  
166 recently observed trend differs somewhat in multiple observational datasets (Supplementary  
167 Fig. 1), a dataset is randomly chosen for each comparison with the FaIR projections. The  
168 resulting distributions (Fig. 2c) give the probability of a trend reduction compared to the recent  
169 past under mitigation ( $P_{\text{mit}} = P(\text{trend}_{\text{mit}} < \text{trend}_{\text{obs}})$ ) and no mitigation ( $P_{\text{nomit}} = P(\text{trend}_{\text{nomit}} <$   
170  $\text{trend}_{\text{obs}})$ ) scenarios.  $P_{\text{ns}}$  is then calculated from  $P_{\text{ns}} = P_{\text{mit}} - P_{\text{nomit}}$ . This is similar to the approach  
171 of M19<sup>4</sup>, except that here we use the observed trend, which is known, rather than a distribution  
172 of modelled trends for the recent past. Compared to the first test conducted (Table 1a, Fig. 2a  
173 and 2b), this more stringent test gives, as expected, a lower probability of mitigation causing a  
174 reduction in the near-term temperature trend as compared to no mitigation. However, for the  
175 difference between the 1.5 °C mitigation scenario and the “average” no mitigation scenario, the

176 probability that mitigation is both necessary and sufficient to cause a reduction in the trend as  
177 compared to recent observations is close to a 66% probability (Table 1b).

178 To investigate the extent to which our results depend on the period or trend length considered,  
179 we use the FaIR emulator including estimates of internal variability to calculate warming rates  
180 for temperature trends starting in 2021 and ending in different years (Fig. 3). The 66%  
181 probability range of trends for SSP3-7.0 and SSP1-1.9 become non-overlapping after around 20  
182 years (i.e., by around 2040). This is also around the time at which the SSP5-8.5 and SSP1-2.6  
183 66% probability ranges become separated. For SSP3-7.0 and SSP1-2.6 it takes until around  
184 2047 for the 66% probability distributions to no longer overlap. For periods shorter than 20 years  
185 (i.e., ending before 2040), the distributions of plausible warming trends between the scenarios  
186 are less distinguishable. The black line in Fig. 3 shows the maximum historical observed trend  
187 for different trend lengths based on the mean of the four datasets in Supplementary Fig. 1. The  
188 66% probability range of trends starting from 2021 in SSP1-1.9 always falls below the maximum  
189 observed trend for all periods considered. In contrast, the median trend for SSP3-7.0 lies above  
190 the maximum observed trend for periods longer than around 18 years from present (i.e., ending  
191 after 2038).

192 The results presented here agree with those of Ciavarella et al. (2017)<sup>26</sup>, where it is shown that  
193 strong mitigation markedly reduces the risk of exposure to climate extremes in the near-term in  
194 an earlier generation of climate models (CMIP5<sup>27</sup>) driven by Representative Concentration  
195 Pathway (RCP<sup>28</sup>) scenarios; however, their focus is on regional extremes and local warm  
196 seasons, whereas we take a global and annual mean perspective motivated by the Paris  
197 Agreement targets. Our results do differ somewhat though from the many studies that find little  
198 detectable benefit of mitigation in the near-term<sup>3-6,29-30</sup>. This may reflect that these studies use  
199 model-based rather than observation-based estimates of internal variability (Supplementary Fig.  
200 2), compare pathways with more similar radiative forcings<sup>4,6,29-30</sup> (e.g., M19<sup>4</sup> consider RCP2.6

201 versus RCP4.5, and Samset et al. (2020)<sup>6</sup> focus on idealized mitigation scenarios for individual  
202 forcers rather than the combination of forcing agents in the SSPs), or because they consider  
203 shorter time horizons<sup>4-6</sup> (e.g., M19<sup>4</sup> analyses 15-year temperature trends; Fig. 3).

204 In contrast to our findings for near-term temperature trends, and in agreement with the IPCC's  
205 Fifth Assessment Report<sup>2</sup> where a different set of models and scenarios were compared, our  
206 results show little difference between SSP scenarios for mean temperature anomalies (as  
207 opposed to trends) in the next 20 years (2021-2040) relative to a baseline of 1995-2014 (Fig.  
208 1b). This holds for both the observationally-constrained CMIP6 projections and FaIR projections  
209 with added internal variability. The median 20-year mean temperature anomalies for the  
210 different SSPs all lie within 0.62-0.71 °C for the constrained CMIP6 projections (0.55-0.70 °C for  
211 FaIR), with the range about the median being determined by internal variability, differences in  
212 climate response between models, and differences in effective radiative forcing. Differing  
213 conclusions about the detectability of differences in temperature trends and anomalies between  
214 scenarios in Fig. 1 arise because the anomalies quantify the difference in warming between the  
215 20-year periods centered on 2030 and 2005, while the trends quantify the difference in warming  
216 between the later years of 2040 and 2021, a period for which the different emissions pathways  
217 are more divergent (Supplementary Fig. 3).

218 To conclude, we have shown that rapid mitigation of global greenhouse gas emissions  
219 substantially reduces the risk of experiencing unprecedented rates of surface warming over the  
220 next two decades, even after accounting for internal variability. This is in addition to the longer-  
221 term benefits of stringent mitigation for peak warming and stabilization of climate. While it is  
222 possible that unprecedented warming rates could occur in the near-term even if society pursues  
223 a path towards net-zero emissions around mid-century, the risk of such an outcome is  
224 substantially reduced by around a factor of 13 for the most ambitious mitigation scenario  
225 (SSP1-1.9) as compared to an "average" no mitigation scenario (SSP3-7.0).

226 The rate of warming over the next 20 years will determine the pace at which, and extent to  
227 which, society and ecosystems will need to adapt to evolving climate hazards. Based on our  
228 results, under the strong mitigation scenario SSP1-2.6 the probability of crossing the threshold  
229 of 1.5 °C of anthropogenic warming in the next 20 years is around half that in SSP3-7.0 (42%  
230 compared to 78% probability; Supplementary Table 2). Furthermore, the lower near-term  
231 warming rates under SSP1-1.9 give an estimated 74% probability that the 1.5 °C threshold will  
232 never be crossed (Supplementary Table 2). The IPCC SR1.5 report<sup>1,31</sup> shows that warming  
233 of 1.5 °C is associated with severe and widespread impacts and risks from: extreme weather  
234 events (e.g., projections show extreme heatwaves becoming widespread in the tropics<sup>32-34</sup>; the  
235 hottest days in mid-latitudes becoming up to 3 °C warmer<sup>35-37</sup>; the coldest nights in the Arctic  
236 becoming up to 4.5 °C warmer<sup>35-37</sup>; increases in the frequency, intensity, and/or amount of  
237 heavy precipitation in several regions globally<sup>35-37</sup>); and ocean warming and acidification, which  
238 are expected to impact a range of marine organisms and ecosystems (e.g., 70-90% of warm-  
239 water coral reefs are projected to disappear at a warming of 1.5 °C<sup>38</sup>). The aggregated effect of  
240 these climate impacts and risks is projected to be highest in regions where vulnerable  
241 populations live, particularly in South Asia<sup>39</sup>. The results reported here serve as further  
242 motivation for setting stringent mitigation targets to reach net-zero emissions as soon as  
243 possible on both global and individual-country levels.

244 Lastly, it is important to communicate what can be reasonably expected from stringent  
245 mitigation in the near-term, so as to manage expectations and avoid causing doubt in the public  
246 mind about how well anthropogenic climate change is understood. In particular, while we have  
247 shown there is a high probability that stringent mitigation would result in lower near-term  
248 warming rates as compared to an “average” no mitigation scenario, there is a lower probability  
249 that stringent mitigation is necessary and sufficient to cause a slow-down in the warming rate in  
250 the near-term as compared to the recent past.

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## 251 **Methods**

252 The global mean surface air temperature projections used in this study come from two different  
253 approaches: the Finite amplitude Impulse Response (FaIR) simple climate model emulator<sup>18</sup>,

254 with added observation-based estimates of internal variability<sup>19</sup> described below, and the latest-  
255 generation comprehensive climate models from CMIP6<sup>40</sup> constrained by observations<sup>17</sup>. In the  
256 main text, the main results regarding temperature trends are quantified using the distributions  
257 from FaIR rather than CMIP6, since FaIR is computationally inexpensive and can therefore  
258 more broadly sample parameter uncertainty than the more complex models used in CMIP6.  
259 FaIR can also be used to explore a wider range of emission scenarios, including an NDC-like  
260 scenario (not available for CMIP6) and the most ambitious mitigation scenario, SSP1-1.9 (too  
261 few CMIP6 models were available at the time of writing to generate adequate statistics). Note  
262 the temperature trend distributions for the constrained CMIP6 models are very similar to FaIR,  
263 however, so both approaches are in good agreement. All trends were calculated using least-  
264 squares linear regression.

#### 265 **Finite Amplitude Impulse Response (FaIR) model**

266 FaIR was used in the IPCC SR1.5 report<sup>41</sup> and uses values for equilibrium climate sensitivity  
267 (ECS), transient climate response (TCR), and a time-series of effective radiative forcing (ERF)  
268 to make projections of surface temperature. Here, distributions of near-term temperature  
269 projections for FaIR were calculated using 500 simulations for each SSP and the NDC-like  
270 scenario, using distributions of ECS, TCR, and ERF that reflect our latest understanding since  
271 SR1.5.

272 The ECS can be defined as  $-F_{2x}/\lambda$ , where  $F_{2x}$  is the effective radiative forcing from a doubling of  
273 CO<sub>2</sub> and  $\lambda$  is the global climate feedback parameter. To construct a distribution of ECS we use  
274 this relationship, sampling  $\lambda$  from a normal distribution with mean  $-1.34 \text{ W m}^{-2} \text{ K}^{-1}$  and standard  
275 deviation  $0.28 \text{ W m}^{-2} \text{ K}^{-1}$ , and  $F_{2x}$  equal to  $4.01 \text{ W m}^{-2}$ . This reproduces a distribution of ECS that  
276 is right-skewed (long tail which does not exclude very high ECS values) and a 5-95% range of  
277 2-5 °C with a best estimate near 3 °C (cf. ref. 42). The higher value of  $F_{2x}$  compared to the

278 IPCC's Fifth Assessment Report results from an updated spectroscopic relationship for  
279 stratospherically-adjusted CO<sub>2</sub> radiative forcing of 3.81 W m<sup>-2</sup> for a doubling of CO<sub>2</sub> (ref. 43) plus  
280 tropospheric radiative adjustments that sum to 0.20 W m<sup>-2</sup> (ref. 44), calculated using radiative  
281 kernels in ten climate models, and subtracting the land-surface warming component. The TCR  
282 is sampled to maintain a strong correlation with ECS<sup>45</sup>, with a marginal distribution of TCR of 1.7  
283 °C (1.2-2.4 °C, 5-95% range) that is broadly consistent with observational constraints<sup>17</sup>. Our  
284 sampling method allows the possibility of high ECS for modest TCR<sup>46</sup>.

285 Emissions of greenhouse gases and short-lived climate forcers are taken from the Reduced  
286 Complexity Model Intercomparison Project dataset<sup>47</sup>, which assimilate anthropogenic and  
287 natural short-lived climate forcers<sup>48-49</sup> and inversions of greenhouse gas concentrations  
288 observed historically as well as those projected in SSP scenarios<sup>16,50</sup>. The emissions used for  
289 the NDC-like pathway are representative of the scenarios described in the UNEP Emissions  
290 Gap Report 2019<sup>21</sup> and also of the pathways for the NDC-like projections in ref. 22. The  
291 emissions pathways used for each SSP scenario considered and the NDC-like scenario are  
292 shown in Supplementary Fig. 3. The most ambitious (strong) mitigation scenario SSP1-1.9  
293 (SSP1-2.6) is associated with a mitigation rate of -0.3 GtC year<sup>-1</sup> (-0.2 GtC year<sup>-1</sup>) in global net  
294 CO<sub>2</sub> emissions from 2021 to reach net-zero emissions in 2056 (2076). This is consistent with  
295 keeping anthropogenic warming below 1.5 °C (2 °C) with a probability of 74% (92%)  
296 (Supplementary Fig. 4). These pathways are therefore equivalent to the "Below-1.5 °C" and  
297 "Lower-2 °C" pathways considered in the IPCC SR1.5 report (i.e., pathways with no or limited  
298 overshoot; see Table 2.1 in ref. 51).

299 Emissions of CO<sub>2</sub> are converted to concentrations through a simple carbon cycle representation  
300 that is temperature and carbon-uptake dependent<sup>52</sup>. The carbon cycle parameters that govern  
301 the atmospheric lifetime of CO<sub>2</sub> (pre-industrial airborne fraction, and sensitivity of airborne  
302 fraction to increasing global mean surface air temperature (GSAT) and total atmospheric carbon

303 burden) are sampled from Gaussian distributions<sup>16</sup> that reproduce the observed CO<sub>2</sub>  
304 concentration of 407 ppm in 2018 in the ensemble median. Concentrations of non-CO<sub>2</sub> gases  
305 are calculated from a simple one-box model based on atmospheric lifetimes from ref. 53.  
306 Greenhouse gas ERFs are calculated from concentrations from ref. 43 for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O,  
307 and ref. 54 for other species. To account for tropospheric rapid adjustments, CO<sub>2</sub> forcing is  
308 increased by 5% and CH<sub>4</sub> forcing reduced by 14%<sup>18</sup>, the latter case based on the behavior of  
309 tropospheric water vapor in climate models that include shortwave forcing of methane. Simple  
310 relationships that convert aerosol and ozone precursors to forcings are also employed<sup>55-57</sup> as  
311 described in ref. 18. Noting that the default CMIP6 aerosol forcing may have resulted in too little  
312 warming over the later 20th century in some models<sup>47,58</sup> with a strong warming rebound in more  
313 recent years, we repeat the analysis but substituting in the aerosol ERF time series from AR5<sup>59</sup>.  
314 However, this makes little difference to future near-term warming rates (Supplementary Fig. 5).  
315 Volcanic forcing is determined from the CMIP6 stratospheric sulphate optical depth time-series  
316 (REF) converted to ERF at -18τ with an additive offset applied such that the mean volcanic ERF  
317 over the historical period is zero. Solar forcing is taken from the CMIP6 extraterrestrial solar flux  
318 dataset<sup>60</sup> using a reference time frame of 1850-1873 as recommended for CMIP6 pre-industrial  
319 control simulations. To convert solar flux anomaly to annual ERF, it is multiplied by ¼  
320 (geometric factor) x 0.7 (planetary co-albedo).

321 Twelve categories of anthropogenic and natural radiative forcings are simulated using input  
322 emissions, with best estimate and uncertainties in the pre-industrial to present-day ERF taken  
323 from the IPCC's Fifth Assessment Report<sup>53</sup>, with the exception being for aerosols for which the  
324 review of ref. 61 is used for the 5-95% distribution of aerosol forcing of -2.0 to -0.4 W m<sup>-2</sup> based  
325 on a comprehensive assessment (this range of present-day aerosol ERF is also applied to the  
326 AR5 time series in Supplementary Fig. 5). Uncertainties are applied as a fraction of the present-  
327 day forcing (see Table 3 in ref. 18). Historical (1995-2014) and projected near-term (2021-2040)

328 trends in the median total ERF, and its twelve components, are shown in Supplementary Table  
329 1.

330 FaIR does not include internal climate variability and, therefore, the simulations described above  
331 only give the distribution of externally-forced temperature trends (Supplementary Fig. 6).

332 However, near-term warming trends will be significantly affected by internal variability (e.g., ref.  
333 4). To account for this, we add an observation-based estimate of internal variability to the forced  
334 temperature trends from FaIR. To estimate internal variability from the observed record, we use  
335 the approach of a recent study<sup>19</sup>. In this approach, a two-box impulse response model (IRM) is  
336 used to calculate forced temperature changes since 1850, and this estimate is subtracted from  
337 the observational record to estimate temperature changes due to internal variability alone  
338 (Supplementary Fig. 7a and 7b). The resulting histogram of rolling trends for 20-year segments  
339 of the temperature residuals (Supplementary Fig. 7c and 7d) is then added to each of the 500  
340 simulated temperature trends in FaIR (Supplementary Fig. 6), and a boxplot is calculated (Fig.  
341 1a). Here we use HadOST as the observational dataset because its sea surface temperatures  
342 (SSTs) are less biased than other datasets (e.g., Berkeley Earth Land-Ocean and Cowtan-Way  
343 version 2 updated with HadSST3)<sup>19</sup>. However, the dataset used has little effect on the  
344 distributions of 20-year temperature trends due to internal variability (Supplementary Fig. 8a).

345 An alternative for estimating the range of temperature trends due to internal variability is to use  
346 the CMIP6 pre-industrial control simulations. Histograms of rolling temperature trends for 20-  
347 year segments of the control simulation for each of the 48 currently available CMIP6 models are  
348 shown in Supplementary Fig. 2 (see Supplementary Table 3 for a list of the models used).

349 Before calculating these trends, any drift in each simulation was removed by subtracting the  
350 linear trend across the whole simulation. Clearly, there are noticeable differences in the  
351 magnitude of low frequency temperature variability between models, where MIROC-ES2L is an  
352 example of a “low” variability model and BCC-CSM2-MR a “high” variability model. Adding the

353 histogram for MIROC-ES2L to each of the 500 FaIR temperature trends gives similar  
354 distributions to using an observation-based estimate of variability (compare Supplementary Fig.  
355 8a with 8bi). The range of resulting trends is larger when using the “high” variability model BCC-  
356 CSM2-MR (Supplementary Fig. 8bii), but even with this high estimate of variability strong  
357 mitigation still substantially reduces the risk of unprecedented warming. Under SSP1-1.9  
358 (SSP1-2.6), 13% (26%) of trends are above the maximum observed historical trend, while for  
359 SSP3-7.0 (SSP5-8.5) this increases to 55% (69%).

360 Observation-based estimates of internal variability are also added to the distributions of  
361 temperature anomalies for FaIR in Fig. 1b. To do this, we first calculate the rolling mean for 20-  
362 year segments of the temperature residuals in Supplementary Fig. 7b. We then calculate rolling  
363 differences in these 20-year means, where – to preserve autocorrelation – the temporal  
364 separation between each pair of 20-year means is consistent with the separation between 2021-  
365 2040 and 1995-2014. The resulting histogram of differences in 20-year means of residuals is  
366 then added to the forced temperature anomalies from FaIR.

367 Note that the residuals in Supplementary Fig. 7b do not include natural variability due to  
368 volcanic and solar forcing, since ref. 19 includes volcanic and solar forcing in the IRM  
369 simulations of historical temperatures. Estimated future solar variability is included in the ERF  
370 time-series used to make the FaIR GSAT projections, but forcing from possible future volcanic  
371 eruptions is not. It is therefore acknowledged that if, in the near-term, solar variability is different  
372 from estimated or a large volcanic eruption occurs, near-term temperature trends will be  
373 different from those reported here.

#### 374 **Coupled Model Intercomparison Project Phase 6 (CMIP6) models**

375 We now describe the estimates of near-term warming trends derived from the CMIP6 models. It  
376 has been reported that some CMIP6 models simulate higher ECS values than previous versions

377 in CMIP5, with some models simulating an ECS of up to around 5.7 °C (e.g., ref. 62). Projected  
378 raw warming rates in those models may be higher than in the past<sup>62</sup> and inconsistent with recent  
379 observed warming rates<sup>17</sup>. Additional information can be used to constrain a multi-model  
380 ensemble using so-called emergent constraints. Several studies have recently applied  
381 constraints to the CMIP6 multi-model ensemble global temperature projections using observed  
382 warming rates over the past few decades as compared to the models' "historical"  
383 simulations<sup>17,58,63-64</sup>. Here, we use the approach of ref. 17, which applies an emergent constraint  
384 on the CMIP6 model spread based on the relationship between the surface warming rate over  
385 1981-2017 and projected future warming levels (R = 0.92 and R = 0.86 for mid- and end-of-  
386 century, respectively, for SSP5-8.5). This justifies using the present-day observational trend  
387 estimates to constrain future projections. The observationally-constrained CMIP6 median  
388 warming is over 10% lower by 2050 compared to the raw CMIP6 median, and over 17% lower  
389 by 2100<sup>17</sup>. Constrained CMIP6 projections were not provided for SSP1-1.9 because at the time  
390 of writing not enough models were available to apply the emergent constraint based on past  
391 warming rates.

392 A list of the CMIP6 models used to derive the constrained temperature trends can be found in  
393 Supplementary Table 3 (see Supplementary Table S1 in ref. 17 for a more detailed list of  
394 models used in each SSP scenario).

### 395 **Observation-based surface temperature datasets**

396 To calculate observation-based temperature trends over the historical period we use four  
397 different datasets: HadCRUT4.6.0.0 (HadCRUT4.6<sup>65</sup>); Berkeley Earth Land-Ocean (BE<sup>66</sup>);  
398 Cowtan-Way version 2 updated with HadSST3 (CWv2<sup>67-70</sup>); and GISTEMP version 4  
399 (GISTEMPv4<sup>71-72</sup>).



400 The observation-based datasets report global mean historical surface temperature anomalies,  
401 calculated using a blend of land near-surface air temperatures and SSTs (referred to here as  
402 global blended surface temperature, GBST<sup>17</sup>). Over land, HadCRUT4.6 and CWv2 use  
403 CRUTEM4<sup>73</sup>; BE uses the Berkeley Earth land-surface temperature field; and GISTEMPv4 uses  
404 NOAA GHCN v4<sup>74</sup>. Over ocean, HadSST is used for HadCRUT4.6, CWv2, and BE; and  
405 GISTEMPv4 uses ERSSTv5<sup>75</sup>. BE, CWv2, and GISTEMPv4 are interpolated to near-full  
406 coverage, while HadCRUT4.6 is left un-interpolated and therefore has incomplete coverage. By  
407 using several datasets, we aim to ensure the results are not biased towards any one  
408 combination of land and ocean data.

409 We report CMIP6 and FaIR model results in terms of the global mean near-surface air  
410 temperature (GSAT), since this is most relevant for future climate projections and impact  
411 assessments<sup>76</sup>. Since the observation-based GBST metric has been warming slower on  
412 average than GSAT<sup>77</sup>, we apply a scaling factor to GBST that accounts for the blending bias  
413 and converts it to a GSAT equivalent, therefore allowing a like-for-like comparison between the  
414 observations and models. We use  $GSAT = 1.087 \times GBST$  for BE, CWv2, and GISTEMPv4; and  
415  $GSAT = 1.19 \times GBST$  for HadCRUT4.6. These scaling factors are based on estimates derived  
416 from the CMIP5 models for fully-blended GBST (applicable to BE, CWv2, and GISTEMPv4) and  
417 blended-masked GBST (applicable to HadCRUT4.6); see Table 1 in ref. 78, and Supplementary  
418 Fig. 1 in ref. 79. Note that the results reported in this study are, however, relatively insensitive to  
419 the exact scaling factor applied.

420 To calculate the observation-based estimates of internal variability in 20-year temperature  
421 trends (Supplementary Fig. 7), we use the same datasets as in ref. 19: CWv2 (updated with  
422 HadSST4<sup>80</sup> here), BE, and HadOST<sup>19</sup>. HadOST combines CWv2 over land with HadISST2<sup>81</sup>  
423 and OSTIA<sup>82</sup> data over ocean, and is interpolated to near-full coverage. To convert HadOST to  
424 a GSAT equivalent, we use the scaling factor for fully-blended GBST (1.087). To account for a

425 warm bias in SSTs around 1942-1945 due to changing SST sampling methods, correction  
426 factors have been applied over these years to the observation-based datasets in Supplementary  
427 Fig. 7 as in ref. 19.

## 428 **Data availability**

429 The data that support the findings of this study are available at [[https://github.com/Priestley-](https://github.com/Priestley-Centre/Near_term_warming)  
430 [Centre/Near\\_term\\_warming](https://github.com/Priestley-Centre/Near_term_warming)] with the identifier [<https://doi.org/10.5281/zenodo.3762042>]<sup>83</sup>. This  
431 repository includes the FaIR simulation data, the constrained CMIP6 projections, the  
432 observation-based data, and the observation-based estimates of internal variability (in fully  
433 processed form only). The SSP emissions datasets used in the FaIR simulations were  
434 downloaded from [<https://www.rcmip.org/>], and the NDCs emissions dataset was provided by  
435 Joeri Rogelj. The constrained CMIP6 projections are based on ref. 17 and used surface air  
436 temperature data downloaded from ESGF (Dec 4 2019). The raw data used to calculate the  
437 observation-based estimates of internal variability are based on ref. 19, and were provided by  
438 Karsten Haustein. Surface air temperature data for the CMIP6 pre-industrial control simulations  
439 were obtained from the JASMIN/CEDA archive (Jul 29 2020).

## 440 **Code availability**

441 The FaIR model is available from [<https://doi.org/10.5281/zenodo.3588880>]<sup>84</sup>. FaIR version 1.5  
442 is used for all simulations in this paper. The code used to setup the FaIR simulations, analyze  
443 data, and produce figures is available at [[https://github.com/Priestley-](https://github.com/Priestley-Centre/Near_term_warming)  
444 [Centre/Near\\_term\\_warming](https://github.com/Priestley-Centre/Near_term_warming)] with the identifier [<https://doi.org/10.5281/zenodo.3762042>]<sup>83</sup>.  
445 Python/Matplotlib was used for all coding and data visualization, and for some figures the vector

446 graphics editor Inkscape (available at [<https://inkscape.org/>]) was used to combine different  
447 figure parts into one file.

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663



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665

## 666 Author Contributions

667 PMF and ACM designed the study. CMM performed the analysis and produced the figures. CJS  
668 performed the FaIR simulations. KBT provided the constrained CMIP6 projections. All authors  
669 contributed to writing the manuscript.

670

## 671 Competing Interests statement

672 The authors declare no competing interests.

## 673 Figure Legends

674 **Figure 1: Near-term (2021-2040) global mean surface air temperature trends and**  
675 **anomalies relative to near present day (1995-2014) baseline. a,** trends in [ $^{\circ}\text{C decade}^{-1}$ ]; **b,**  
676 anomalies in [ $^{\circ}\text{C}$ ]. Data are shown for pathways consistent with: current and projected  
677 Nationally Determined Contributions (NDCs, grey box); highest ambition mitigation in line with  
678 the Paris Agreement target to pursue efforts to keep warming to below 1.5  $^{\circ}\text{C}$  (SSP1-1.9, green  
679 box); strong mitigation in line with the Paris Agreement target to keep warming below 2  $^{\circ}\text{C}$   
680 (SSP1-2.6, blue boxes); “average” no policy baseline scenario (SSP3-7.0, orange boxes); and  
681 unlikely “worst case” no mitigation scenario (SSP5-8.5, brown boxes). Lighter shading shows  
682 CMIP6 projections with a historical constraint applied, and darker shading shows FaIR  
683 projections plus an observation-based estimate of internal variability (see Methods). Boxes  
684 denote the 17-83% range (66% probability) and whiskers denote the 5-95% range (90%

685 probability) of projections. Maximum and minimum values are shown as crosses. The maximum  
686 trend for 20-year segments of the observation-based record is  $0.27\text{ }^{\circ}\text{C decade}^{-1}$  (red ticks on y-  
687 axes) based on the mean of four datasets, with a range across datasets of  $0.25 - 0.29\text{ }^{\circ}\text{C}$   
688  $\text{decade}^{-1}$  (grey horizontal bar;  $0.25\text{ }^{\circ}\text{C decade}^{-1}$  for 2000-2019 in GISTEMPv4,  $0.26\text{ }^{\circ}\text{C decade}^{-1}$   
689 for 1984-2003 in CWv2 and BE, and  $0.29\text{ }^{\circ}\text{C decade}^{-1}$  for 1984-2003 in HadCRUT4.6; see  
690 Supplementary Fig. 1). To compare with the model simulated GSAT projections, the observation  
691 data have been converted from GBST to GSAT using a scaling factor of 1.087 for BE, CWv2,  
692 and GISTEMPv4, and 1.19 for HadCRUT4.6 (see Methods).

693

694 **Figure 2: The effect of mitigation versus no mitigation on near-term (2021-2040) global**  
695 **mean surface air temperature trend distributions from FaIR [ $^{\circ}\text{C decade}^{-1}$ ].** Distributions for:  
696 **a**, mitigation pathways minus an “average” no mitigation pathway; **b**, mitigation pathways minus  
697 a “worst case” no mitigation pathway; **c**, mitigation and no mitigation pathways, minus the  
698 observed trend for the past 20 years (2000-2019; observational datasets used are those in  
699 Supplementary Fig. 1). Trends are calculated from FaIR projections plus an observation-based  
700 estimate of internal variability (see Methods). See the main text for details on how the  
701 distributions were calculated.

702

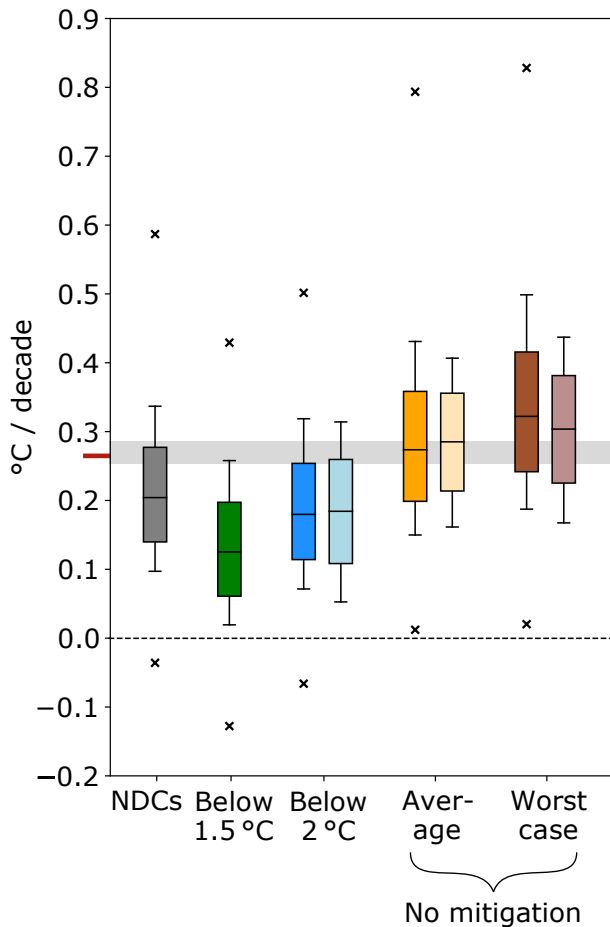
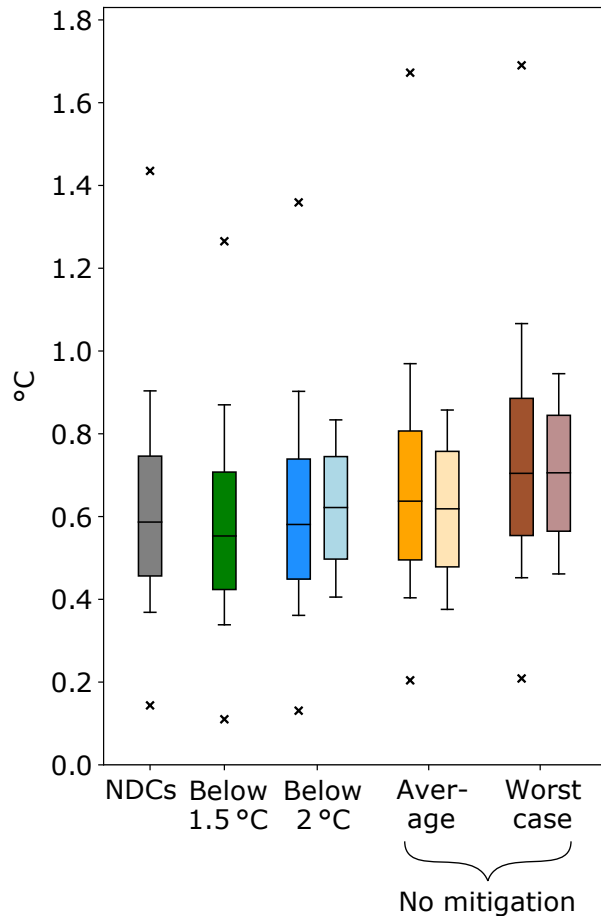
703 **Figure 3: Global mean surface air temperature trends from FaIR starting in 2021, for**  
704 **different end years or trend lengths [ $^{\circ}\text{C decade}^{-1}$ ].** Median trends are shown by colored solid  
705 lines, and the 17-83% (66% probability) range in trends is shown by colored shading. Trends  
706 are calculated from FaIR projections plus an observation-based estimate of internal variability  
707 (see Methods). Data are shown for emissions pathways consistent with: very strong mitigation  
708 in line with limiting warming to below  $1.5\text{ }^{\circ}\text{C}$  (SSP1-1.9, green); strong mitigation in line with  
709 limiting warming to below  $2\text{ }^{\circ}\text{C}$  (SSP1-2.6, blue); “average” no policy baseline scenario (SSP3-  
710 7.0, orange); and “worst case” no mitigation scenario (SSP5-8.5, brown). Black shading/line

711 shows the range/mean of maximum historical trends for different trend lengths from four  
712 different observation-based records (GISTEMPv4, CWv2 updated with HadSST3,  
713 HadCRUT4.6, and BE; see Supplementary Fig. 1). To compare with the model simulated GSAT  
714 projections, the observation data have been converted from GBST to GSAT using a scaling  
715 factor of 1.087 for BE, CWv2, and GISTEMPv4, and 1.19 for HadCRUT4.6 (see Methods). The  
716 gray vertical line highlights the year 2040, or a trend length of 20 years, which corresponds to  
717 the trend distributions for 2021-2040 shown in Fig. 1a.

## 718 **Tables**

719 **Table 1: The probability of experiencing different near-term (2021-2040) global mean**  
720 **surface air temperature trends, as a result of following a mitigation pathway rather than a**  
721 **no mitigation pathway. a,** The probability of the near-term temperature trend in a mitigation  
722 scenario ( $\text{trend}_{\text{mit}}$ ) being lower than in a no mitigation scenario ( $\text{trend}_{\text{nomit}}$ ) by a factor  $\alpha$   
723 ( $P(\text{trend}_{\text{mit}} < \text{trend}_{\text{nomit}} - \alpha \times \text{trend}_{\text{nomit}})$ ). For  $\alpha = 0$ , the probabilities are calculated from the  
724 distributions in Fig. 2a and 2b; for  $\alpha = 0.2$  and  $\alpha = 0.4$ , they are calculated by shifting the same  
725 distributions by amount  $\alpha \times \text{trend}_{\text{nomit}}$ . **b,** The probability,  $P_{\text{ns}}$ , that mitigation is both necessary  
726 and sufficient to experience a near-term temperature trend that is smaller than the trend  
727 observed,  $\text{trend}_{\text{obs}}$ , over the past 20 years (2000-2019).  $P_{\text{ns}}$  is given by  $P_{\text{mit}} - P_{\text{nomit}}$ , where  $P_{\text{mit}} =$   
728  $P(\text{trend}_{\text{mit}} < \text{trend}_{\text{obs}})$  and  $P_{\text{nomit}} = P(\text{trend}_{\text{nomit}} < \text{trend}_{\text{obs}})$ .  $P_{\text{mit}}$  and  $P_{\text{nomit}}$  are calculated from the  
729 distributions in Fig. 2c. Probabilities are shown for mitigation pathways consistent with current  
730 and projected Nationally Determined Contributions (NDCs), very strong mitigation in line with  
731 limiting warming to below 1.5 °C (SSP1-1.9), and strong mitigation in line with limiting warming  
732 to below 2 °C (SSP1-2.6); and no mitigation pathways consistent with an “average” no policy  
733 baseline scenario (SSP3-7.0), and a “worst case” no mitigation scenario (SSP5-8.5).

Scenario comparison	<b>a</b> $P(\text{trend}_{\text{mit}} < \text{trend}_{\text{nomit}} - \alpha \times \text{trend}_{\text{nomit}})$			<b>b</b> $P_{\text{ns}} = P_{\text{mit}} - P_{\text{nomit}}$		
	$\alpha = 0$	$\alpha = 0.2$	$\alpha = 0.4$	$P_{\text{mit}}$	$P_{\text{nomit}}$	$P_{\text{ns}}$
Below 1.5 °C versus “average” no mitigation	0.91	0.83	0.67	0.88	0.25	0.63
Below 2 °C versus “average” no mitigation	0.80	0.65	0.43	0.69	0.25	0.43
NDCs versus “average” no mitigation	0.74	0.56	0.32	0.57	0.25	0.32
Below 1.5 °C versus “worst case” no mitigation	0.96	0.90	0.77	0.88	0.12	0.76
Below 2 °C versus “worst case” no mitigation	0.89	0.77	0.56	0.69	0.12	0.57
NDCs versus “worst case” no mitigation	0.85	0.70	0.46	0.57	0.12	0.46

**a** 2021-2040 GSAT trend**b** 2021-2040 GSAT anomaly

x max

95%

83%

median

17%

5%

x min

FaIR

+ IV



CMIP6

with

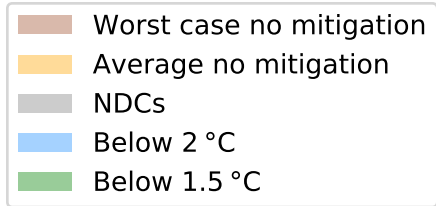
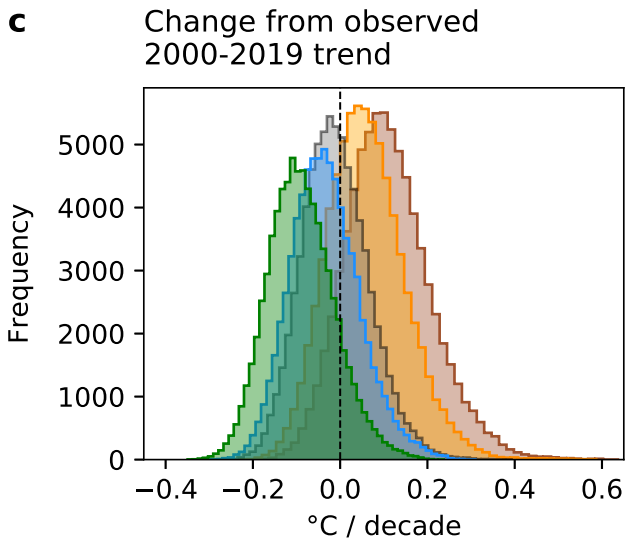
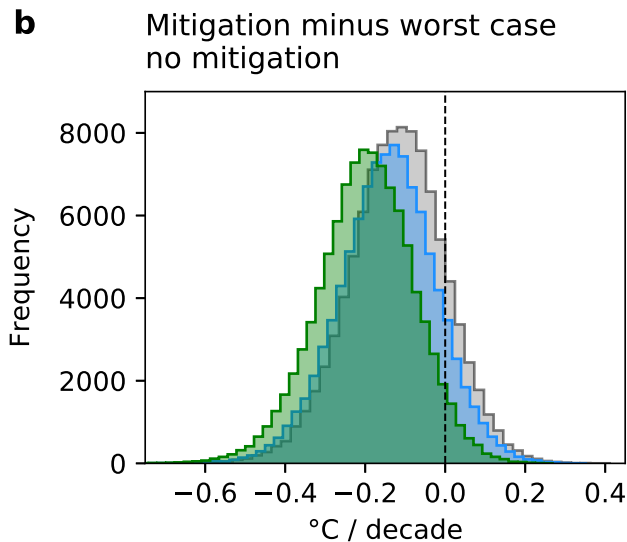
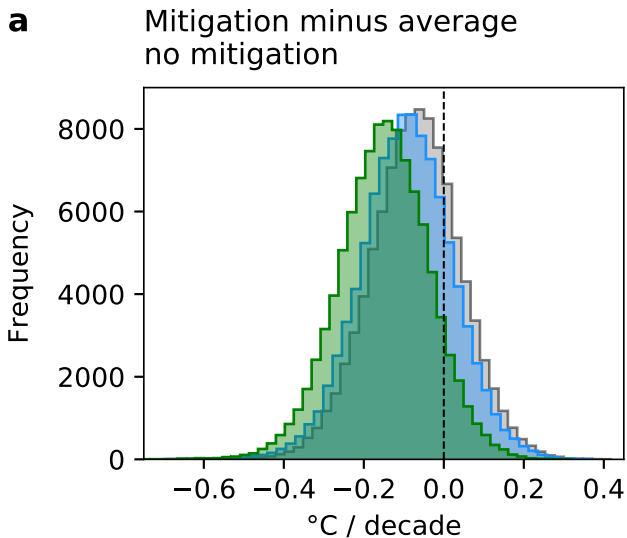
constraint



mean

Max trend for  
20-year segments  
of observational  
record

# 2021-2040 GSAT trend distributions from FaIR plus IV



GSAT trends from FaIR starting in 2021 for different end years or trend lengths

