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<https://doi.org/10.1038/s41558-020-00957-9>

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

Christine M. McKenna^{1,*}, Amanda C. Maycock¹, Piers M. Forster¹,
Christopher J. Smith^{1,2}, and Katarzyna B. Tokarska³

¹ School of Earth and Environment, University of Leeds, Leeds, UK

² International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

³ Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

* Corresponding author: C.McKenna1@leeds.ac.uk

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 achieved¹;
34 however, it is less clear when the benefits of mitigation applied now will become evident²⁻⁶.

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 warming⁷. 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 defences⁸.

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 beforehand²⁻⁶. The long atmospheric lifetime of CO_2 means that substantial emission
45 reductions are needed to alter the upwards trend in atmospheric concentration and effective
46 radiative forcing⁹, 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 contribution¹⁰⁻¹¹, 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 variability¹²⁻¹³. On decadal timescales, internal variability can overwhelm the forced

51 climate response, even for spatially averaged quantities like global temperature⁴, 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 variability¹⁴, was widely misrepresented leading to doubt in the public mind
55 about how well anthropogenic climate change is understood¹⁵. 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 (SSP¹⁶) scenarios and constrained according to their representation of
63 recent observed warming rates¹⁷. The second approach uses a simple climate model emulator
64 (FaIR¹⁸), with added observation-based estimates of internal variability¹⁹, 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 Agreement²⁰⁻²². 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 pathway²³. 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 century²³. Conversely, SSP3-7.0 represents an “average” no mitigation
82 pathway²³ 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 forests²⁴.

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⁻¹ and 0.43-0.79 °C decade⁻¹ respectively, while this extreme range is 0.32-0.50 °C
130 decade⁻¹ for SSP1-2.6 and 0.26-0.43 °C decade⁻¹ for SSP1-1.9 (Fig. 1a; FaIR boxes). For
131 warming rates over 0.4 °C decade⁻¹, evidence suggests that all ecosystems will decline as they
132 will not be able to adapt rapidly enough²⁵. 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⁻¹.
138 ¹. Maher et al. (2020)⁵ 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 α 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 α 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)⁴ – hereafter M19 – is to ask
162 what is the probability that mitigation is both *sufficient* and *necessary* (P_{ns}) for a reduction in the
163 temperature trend over 2021-2040 relative to the trend over the recent past. To calculate P_{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_{ns} is then calculated from $P_{\text{ns}} = P_{\text{mit}} - P_{\text{nomit}}$. This is similar to the approach
171 of M19⁴, 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)²⁶, 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 (CMIP5²⁷) driven by Representative Concentration
195 Pathway (RCP²⁸) 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^{3-6,29-30}. 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^{4,6,29-30} (e.g., M19⁴ consider RCP2.6

201 versus RCP4.5, and Samset et al. (2020)⁶ 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 horizons⁴⁻⁶ (e.g., M19⁴ 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 Report² 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^{1,31} 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 tropics³²⁻³⁴; the
235 hottest days in mid-latitudes becoming up to 3 °C warmer³⁵⁻³⁷; the coldest nights in the Arctic
236 becoming up to 4.5 °C warmer³⁵⁻³⁷; increases in the frequency, intensity, and/or amount of
237 heavy precipitation in several regions globally³⁵⁻³⁷); 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 °C³⁸). 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 Asia³⁹. 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.

References

1. IPCC. Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds Masson-Delmotte, V. et al.). 32pp (World Meteorological Organization, Geneva, Switzerland, 2018).
2. Kirtman, B. et al. Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. et al.). Ch. 11, 953–1028 (Cambridge University Press, Cambridge, 2013).
3. Tebaldi, C. & Friedlingstein, P. Delayed detection of climate mitigation benefits due to climate inertia and variability. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 17229–17234 (2013).
4. Marotzke, J. Quantifying the irreducible uncertainty in near-term climate projections. *WIREs Clim. Change.* **10**, e563 (2019).
5. Maher, N., Lehner, F. & Marotzke, J. Quantifying the role of internal variability in the temperature we expect to observe in the coming decades. *Environ. Res. Lett.* **15**, 054014 (2020).
6. Samset, B. H., Fuglestad, J. S. & Lund, M. T. Delayed emergence of a global temperature response after emission mitigation. *Nat. Commun.* **11**, 3261 (2020).
7. Challinor, A. et al. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nat. Clim. Change* **6**, 954–958 (2016).
8. Gersonius, B. et al. Managing the flooding system's resiliency to climate change. *P. I. Civil. Eng.-Eng. Su* **163**, 15–22 (2010).

9. Allen, M. R. et al. Framing and Context. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds Masson-Delmotte, V. et al). Ch. 1 (2018).
10. Schleussner, C.-F. et al. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change* **6**, 827–835 (2016).
11. Rogelj, J., Schleussner, C.-F. & Hare, W. Getting it right matters: Temperature goal interpretations in geoscience research. *Geophys. Res. Lett.* **44**, 10662–10665 (2017).
12. Hawkins, E. & Sutton, R. The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bull. Amer. Meteor. Soc.* **90**, 1095–1108 (2009).
13. Lehner, F. et al. Partitioning climate projection uncertainty with multiple Large Ensembles and CMIP5/6. *Earth Syst. Dynam.* **11**, 491–508 (2020).
14. Kosaka, Y. & Xie, S.-P. Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* **501**, 403–407 (2013).
15. Medhaug, I., Stolpe, M. B., Fischer, E. M. & Knutti, R. Reconciling controversies about the ‘global warming hiatus’. *Nature* **545**, 41–47 (2017).
16. Meinshausen, M. et al. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2020).
17. Tokarska K. B., et al. Past warming trend constrains future warming in CMIP6 models. *Sci. Adv.* **6**, eaaz9549 (2020).
18. Smith, C. J. et al. FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* **11**, 2273–2297 (2018).
19. Hausteil, K. et al. A Limited Role for Unforced Internal Variability in Twentieth-Century Warming. *J. Climate* **32**, 4893–4917 (2019).

20. Rogelj, J. et al. Understanding the origin of Paris Agreement emission uncertainties. *Nat. Commun.* **8**, 15748 (2017).
21. Rogelj, J., den Elzen, M., Huppmann, D. & Luderer, G. The Emissions Gap. In: Emissions Gap Report 2019. Ch. 3 (United Nations Environment Programme, Nairobi, Kenya, 2019).
22. Vrontisi, Z. et al. Enhancing global climate policy ambition towards a 1.5°C stabilization: a short-term multi-model assessment. *Environ. Res. Lett.* **13**, 044039 (2018).
23. Hausfather, Z. & Peters, G. P. Emissions – the ‘business as usual’ story is misleading. *Nature* **577**, 618–620 (2020).
24. Leemans, R. & Eickhout, B. Another reason for concern: regional and global impacts on ecosystems for different levels of climate change. *Global Environ. Change* **14**, 219–228 (2004).
25. Neilson, R. P. Transient ecotone response to climatic change: some conceptual and modelling approaches. *Ecol. Appl.* **3**, 385–395 (1993).
26. Ciavarella, A., Stott, P. & Lowe, J. Early benefits of mitigation in risk of regional climate extremes. *Nat. Clim. Change* **7**, 326–330 (2017).
27. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the Experiment Design. *Bull. Amer. Meteor. Soc.* **93**, 485–498 (2012).
28. Meinshausen, M. et al. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change* **109**, 213–241 (2011).
29. Lehner, F., Deser, C. & Sanderson, B. M. Future risk of record-breaking summer temperatures and its mitigation. *Clim. Change* **146**, 363–375 (2018).
30. Tebaldi, C. & Wehner, M. F. Benefits of mitigation for future heat extremes under RCP4.5 compared to RCP8.5. *Clim. Change* **146**, 349–361 (2018).
31. Hoegh-Guldberg, O. et al. Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission*

pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (eds Masson-Delmotte, V. et al.). Ch. 3 (2018).

32. Mahlstein, I., Knutti, R., Solomon, S. & Portmann, R. W. Early onset of significant local warming in low latitude countries. *Environ. Res. Lett.* **6**, 034009 (2011).
33. Coumou, D. & Robinson, A. Historic and future increase in the global land area affected by monthly heat extremes. *Environ. Res. Lett.* **8**, 034018 (2013).
34. Dosio, A., Mentaschi, L., Fischer, E. M. & Wyser, K. Extreme heat waves under 1.5 °C and 2 °C global warming. *Environ. Res. Lett.* **13**, 054006 (2018).
35. Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R. & Wilby, R. L. Allowable CO₂ emissions based on regional and impact-related climate targets. *Nature* **529**, 477–483 (2016).
36. Wartenburger, R. et al. Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geosci. Model Dev.* **10**, 3609–3634 (2017).
37. Seneviratne, S. I et al. Climate extremes, land–climate feedbacks and land-use forcing at 1.5°C. *Phil. Trans. R. Soc. A.* **376**, 20160450 (2018).
38. Schleussner, C.-F. et al. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dynam.* **7**, 327–351 (2016).
39. Byers, E. Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environ. Res. Lett.* **13**, 055012 (2018).

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 emulator¹⁸,

254 with added observation-based estimates of internal variability¹⁹ described below, and the latest-
255 generation comprehensive climate models from CMIP6⁴⁰ constrained by observations¹⁷. 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 report⁴¹ 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 CO₂ and λ is the global climate feedback parameter. To construct a distribution of ECS we use
274 this relationship, sampling λ 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 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 CO₂ radiative forcing of 3.81 W m⁻² for a doubling of CO₂ (ref. 43) plus
280 tropospheric radiative adjustments that sum to 0.20 W m⁻² (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 ECS⁴⁵, 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 constraints¹⁷. Our
284 sampling method allows the possibility of high ECS for modest TCR⁴⁶.

285 Emissions of greenhouse gases and short-lived climate forcers are taken from the Reduced
286 Complexity Model Intercomparison Project dataset⁴⁷, which assimilate anthropogenic and
287 natural short-lived climate forcers⁴⁸⁻⁴⁹ and inversions of greenhouse gas concentrations
288 observed historically as well as those projected in SSP scenarios^{16,50}. The emissions used for
289 the NDC-like pathway are representative of the scenarios described in the UNEP Emissions
290 Gap Report 2019²¹ 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⁻¹ (-0.2 GtC year⁻¹) in global net
294 CO₂ 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 CO₂ are converted to concentrations through a simple carbon cycle representation
300 that is temperature and carbon-uptake dependent⁵². The carbon cycle parameters that govern
301 the atmospheric lifetime of CO₂ (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 distributions¹⁶ that reproduce the observed CO₂
304 concentration of 407 ppm in 2018 in the ensemble median. Concentrations of non-CO₂ 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 CO₂, CH₄, and N₂O,
307 and ref. 54 for other species. To account for tropospheric rapid adjustments, CO₂ forcing is
308 increased by 5% and CH₄ forcing reduced by 14%¹⁸, 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 employed⁵⁵⁻⁵⁷ 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^{47,58} with a strong warming rebound in more
313 recent years, we repeat the analysis but substituting in the aerosol ERF time series from AR5⁵⁹.
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 dataset⁶⁰ 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 Report⁵³, 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⁻² 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 study¹⁹. 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)¹⁹. 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 past⁶² and inconsistent with recent
379 observed warming rates¹⁷. 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^{17,58,63-64}. 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 2100¹⁷. 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 (HadCRUT4.6⁶⁵); Berkeley Earth Land-Ocean (BE⁶⁶);
398 Cowtan-Way version 2 updated with HadSST3 (CWv2⁶⁷⁻⁷⁰); and GISTEMP version 4
399 (GISTEMPv4⁷¹⁻⁷²).

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, GBST¹⁷). Over land, HadCRUT4.6 and CWv2 use
403 CRUTEM4⁷³; BE uses the Berkeley Earth land-surface temperature field; and GISTEMPv4 uses
404 NOAA GHCN v4⁷⁴. Over ocean, HadSST is used for HadCRUT4.6, CWv2, and BE; and
405 GISTEMPv4 uses ERSSTv5⁷⁵. 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 assessments⁷⁶. Since the observation-based GBST metric has been warming slower on
412 average than GSAT⁷⁷, 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 HadSST4⁸⁰ here), BE, and HadOST¹⁹. HadOST combines CWv2 over land with HadISST2⁸¹
423 and OSTIA⁸² 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>]⁸³. 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>]⁸⁴. 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>]⁸³.
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.

References

40. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
41. IPCC. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds Masson-Delmotte, V. et al.). (2018).
42. Dessler, A. E. & Forster, P. M. An estimate of equilibrium climate sensitivity from interannual variability. *J. Geophys. Res. Atmos.* **123**, 8634–8645 (2018).
43. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **43**, 12614–12623 (2016).
44. Smith, C. J. et al. Understanding rapid adjustments to diverse forcing agents. *Geophys. Res. Lett.* **45**, 12023–12031 (2018).
45. Flato, G. et al. Evaluation of Climate Models. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. et al.). Ch. 9 (Cambridge University Press, 2013).
46. Pfister, P. L. & Stocker, T. F. The realized warming fraction: a multi-model sensitivity study. *Environ. Res. Lett.* **13**, 124024 (2018).

47. Nicholls, Z. R. et al. Reduced complexity model intercomparison project phase 1: Protocol, results and initial observations. *Geosci. Model Dev. Discuss.*, <https://doi.org/10.5194/gmd-2019-375>, in press (2020).
48. van Marle, M. J. E. et al. Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015). *Geosci. Model Dev.* **10**, 3329–3357 (2017).
49. Hoesly, R. M. et al. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **11**, 369–408 (2018).
50. Meinshausen, M. et al. Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geosci. Model Dev.* **10**, 2057–2116 (2017).
51. Rogelj, J. et al. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds. Masson-Delmotte, V. et al.). Ch. 2 (2018).
52. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* **17**, 7213–7228 (2017).
53. Myhre, G. et al. Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. et al.). Ch. 8 (Cambridge University Press, Cambridge, 2013).
54. Hodnebrog, Ø. et al. Global warming potentials and radiative efficiencies of halocarbons and related compounds: A comprehensive review. *Rev. Geophys.* **51**, 300–378, (2013).

55. Stevenson, D. S. et al. Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos. Chem. Phys.* **13**, 3063–3085 (2013).
56. Myhre, G. et al. Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos. Chem. Phys.* **13**, 1853–1877 (2013).
57. Ghan, S. J. et al. A simple model of global aerosol indirect effects. *J. Geophys. Res. Atmos.* **118**, 6688–6707 (2013).
58. Flynn, C. M. & Mauritsen, T. On the Climate Sensitivity and Historical Warming Evolution in Recent Coupled Model Ensembles. *Atmos. Chem. Phys. Discuss.* **20**, 7829–7842 (2020).
59. IPCC. Annex II: Climate System Scenario Tables (eds Prather, M. et al.). In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. et al.). (Cambridge University Press, Cambridge, 2013).
60. Matthes, K. et al. Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev.* **10**, 2247–2302 (2017).
61. Bellouin, N. et al. Bounding global aerosol radiative forcing of climate change. *Reviews of Geophysics* **57**, e2019RG000660 (2019).
62. Forster, P. M., Maycock, A. C., McKenna, C. M. & Smith, C. J. Latest climate models confirm need for urgent mitigation, *Nat. Clim. Change* **10**, 7–10 (2020).
63. Jiménez-de-la-Cuesta, D. & Mauritsen, T. Emergent constraints on Earth’s transient and equilibrium response to doubled CO₂ from post-1970s global warming. *Nat. Geosci.* **12**, 902–905 (2019).
64. Nijse, F. J. M. M., Cox, P. M. & Williamson, M. S. Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. *Earth Syst. Dynam.* **11**, 737–750 (2020).

65. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset. *J. Geophys. Res.* **117**, D08101 (2012).
66. Rohde, R. et al. A new estimate of the average Earth surface land temperature spanning 1753 to 2011. *Geoinfo. Geostat. Overview* **1** (2013).
67. Kennedy, J. J., Rayner, N. A., Smith, R. O., Saunby, M. & Parker, D. E. Reassessing biases and other uncertainties in sea-surface temperature observations since 1850: 1. Measurement and sampling errors. *J. Geophys. Res.* **116**, D14103 (2011).
68. Kennedy J. J., Rayner, N. A., Smith, R. O., Saunby, M. & Parker, D. E. Reassessing biases and other uncertainties in sea-surface temperature observations since 1850: 2. Biases and homogenisation. *J. Geophys. Res.* **116**, D14104 (2011).
69. Cowtan, K. & Way, R. G. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.* **140**, 1935–1944 (2014).
70. Cowtan, K. D. & Way, R. G. *Global temperature reconstructions version 2 (Cowtan and Way)*. Dataset accessed at: <https://doi.org/10.15124/20ee85c3-f53c-4ab6-8e50-270b0ddd3686> (2020-02-07).
71. Lenssen, N. et al. Improvements in the GISTEMP uncertainty model. *J. Geophys. Res. Atmos.* **124**, 6307–6326 (2019).
72. GISTEMP Team. *GISS Surface Temperature Analysis (GISTEMP), version 4*. NASA Goddard Institute for Space Studies. Dataset accessed at: <https://data.giss.nasa.gov/gistemp/> (2020-01-28).
73. Jones, P. D. et al. Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010. *J. Geophys. Res.* **117** (2012).
74. Menne, M. J., Williams, C. N., Gleason, B. E., Rennie, J. J. & Lawrimore, J. H. The Global Historical Climatology Network Monthly Temperature Dataset, Version 4. *J. Climate* **31**, 9835–9854 (2018).

75. Huang, B. et al. Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5): Upgrades, Validations, and Intercomparisons. *J. Climate* **30**, 8179–8205 (2017).
76. Tokarska, K. B. et al. Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy. *Nat. Geosci.* **12**, 964–971 (2019).
77. Cowtan, K. et al. Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures, *Geophys. Res. Lett.* **42**, 6526–6534 (2015).
78. Richardson, M., Cowtan, K. & Millar, R. J. Global temperature definition affects achievement of long-term climate goals. *Environ. Res. Lett.* **13**, 054004 (2018).
79. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342 (2019).
80. Kennedy, J. J., Rayner, N. A., Atkinson, C. P. & Killick, R. E. An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set. *J. Geophys. Res. Atmos.* **124** (2019).
81. Titchner, H. & Rayner, N. The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations. *J. Geophys. Res.* **119**, 2864–2889 (2014).
82. Donlon, C. J. et al. The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. *Remote Sens. Environ.* **116**, 140–158 (2012).
83. McKenna, C. M., Forster, P. M., Maycock, A. C., Smith, C. J. & Tokarska, K. B.. Priestley-Centre/Near_term_warming (Version v1.1). <https://doi.org/10.5281/zenodo.3762042> (Zenodo, 2020).
84. chrisroadmap, Gieseke, R. & Nicholls, Z. OMS-NetZero/FAIR: RCMIP phase 1 (Version v1.5). <https://doi.org/10.5281/zenodo.3588880> (Zenodo, 2019).
85. Haustein, K. et al. A real-time Global Warming Index. *Sci. Rep.* **7**, 15417 (2017).

86. Smith, T. M., Reynolds, R. W., Peterson, T. C. & Lawrimore, J. Improvements to NOAA's Historical Merged Land–Ocean Surface Temperatures Analysis (1880–2006). *J. Climate* **21**, 2283–2296 (2008).
87. Vose, R. S. et al. NOAA's merged land-ocean surface temperature analysis. *Bull. Amer. Meteor. Soc.* **93**, 1677–1685 (2012).
- 448 88. Dix, M. et al. *CSIRO-ARCCSS ACCESS-CM2 model output prepared for CMIP6 CMIP*
449 *piControl*. Version 20200729. Earth System Grid Federation.
450 <https://doi.org/10.22033/ESGF/CMIP6.4311> (2019).
- 451 89. Ziehn, T. et al. *CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 CMIP*
452 *piControl*. Version 20200729. Earth System Grid Federation.
453 <https://doi.org/10.22033/ESGF/CMIP6.4312> (2019).
- 454 90. Semmler, T. et al. *AWI AWI-CM1.1MR model output prepared for CMIP6 CMIP piControl*.
455 Version 20200729. Earth System Grid Federation.
456 <https://doi.org/10.22033/ESGF/CMIP6.2777> (2018).
- 457 91. Danek, C. et al. *AWI AWI-ESM1.1LR model output prepared for CMIP6 CMIP piControl*.
458 Version 20200729. Earth System Grid Federation.
459 <https://doi.org/10.22033/ESGF/CMIP6.9335> (2020).
- 460 92. Wu, T. et al. *BCC BCC-CSM2MR model output prepared for CMIP6 CMIP piControl*.
461 Version 20200729. Earth System Grid Federation.
462 <https://doi.org/10.22033/ESGF/CMIP6.3016> (2018).
- 463 93. Xin, X. et al. *BCC BCC-CSM2MR model output prepared for CMIP6 ScenarioMIP*.
464 Version 20191204. Earth System Grid Federation.
465 <https://doi.org/10.22033/ESGF/CMIP6.1732> (2019).
- 466 94. Zhang, J. et al. *BCC BCC-ESM1 model output prepared for CMIP6 CMIP piControl*.
467 Version 20200729. Earth System Grid Federation.
468 <https://doi.org/10.22033/ESGF/CMIP6.3017> (2018).

- 469 95. Rong, X. *CAMS CAMS_CSM1.0 model output prepared for CMIP6 CMIP piControl*.
470 Version 20200729. Earth System Grid Federation.
471 <https://doi.org/10.22033/ESGF/CMIP6.9797> (2019).
- 472 96. Rong, X. *CAMS CAMS-CSM1.0 model output prepared for CMIP6 ScenarioMIP*. Version
473 20191204. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.11004>
474 (2019).
- 475 97. Swart, N. C. et al. *CCCma CanESM5 model output prepared for CMIP6 CMIP piControl*.
476 Version 20200729. Earth System Grid Federation.
477 <https://doi.org/10.22033/ESGF/CMIP6.3673> (2019).
- 478 98. Swart, N. C. et al. *CCCma CanESM5 model output prepared for CMIP6 ScenarioMIP*.
479 Version 20191204. Earth System Grid Federation.
480 <https://doi.org/10.22033/ESGF/CMIP6.1317> (2019).
- 481 99. Danabasoglu, G., Lawrence, D., Lindsay, K., Lipscomb, W. & Strand, G. *NCAR CESM2*
482 *model output prepared for CMIP6 CMIP piControl*. Version 20200729. Earth System Grid
483 Federation. <https://doi.org/10.22033/ESGF/CMIP6.7733> (2019).
- 484 100. Danabasoglu, G. *NCAR CESM2 model output prepared for CMIP6 ScenarioMIP*. Version
485 20191204. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.2201>
486 (2019).
- 487 101. Danabasoglu, G. *NCAR CESM2-FV2 model output prepared for CMIP6 CMIP piControl*.
488 Version 20200729. Earth System Grid Federation.
489 <https://doi.org/10.22033/ESGF/CMIP6.11301> (2019).
- 490 102. Danabasoglu, G. *NCAR CESM2-WACCM model output prepared for CMIP6 CMIP*
491 *piControl*. Version 20200729. Earth System Grid Federation.
492 <https://doi.org/10.22033/ESGF/CMIP6.10094> (2019).

- 493 103. Danabasoglu, G. *NCAR CESM2-WACCM model output prepared for CMIP6*
494 *ScenarioMIP*. Version 20191204. Earth System Grid Federation.
495 <https://doi.org/10.22033/ESGF/CMIP6.10026> (2019).
- 496 104. Danabasoglu, G. *NCAR CESM2-WACCM-FV2 model output prepared for CMIP6 CMIP*
497 *piControl*. Version 20200729. Earth System Grid Federation.
498 <https://doi.org/10.22033/ESGF/CMIP6.11302> (2019).
- 499 105. Voltaire, A. *CMIP6 simulations of the CNRM-CERFACS based on CNRM-CM6-1 model*
500 *for CMIP experiment piControl*. Version 20200729. Earth System Grid Federation.
501 <https://doi.org/10.22033/ESGF/CMIP6.4163> (2018).
- 502 106. Voltaire, A. *CNRM-CERFACS CNRM-CM6-1 model output prepared for CMIP6*
503 *ScenarioMIP*. Version 20191204. Earth System Grid Federation.
504 <https://doi.org/10.22033/ESGF/CMIP6.1384> (2019).
- 505 107. Voltaire, A. *CNRM-CERFACS CNRM-CM6-1-HR model output prepared for CMIP6*
506 *CMIP piControl*. Version 20200729. Earth System Grid Federation.
507 <https://doi.org/10.22033/ESGF/CMIP6.4164> (2019).
- 508 108. Seferian, R. *CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6 CMIP*
509 *piControl*. Version 20200729. Earth System Grid Federation.
510 <https://doi.org/10.22033/ESGF/CMIP6.4165> (2018).
- 511 109. Seferian, R. *CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6*
512 *ScenarioMIP*. Version 20191204. Earth System Grid Federation.
513 <https://doi.org/10.22033/ESGF/CMIP6.1395> (2019).
- 514 110. Bader, D. C., Leung, R., Taylor, M. & McCoy, R. B. *E3SM-Project E3SM1.0 model output*
515 *prepared for CMIP6 CMIP piControl*. Version 20200729. Earth System Grid Federation.
516 <https://doi.org/10.22033/ESGF/CMIP6.4499> (2018).

- 517 111. Bader, D. C., Leung, R., Taylor, M. & McCoy, R. B. *E3SM-Project E3SM1.1 model output*
518 *prepared for CMIP6 CMIP piControl*. Version 20200729. Earth System Grid Federation.
519 <https://doi.org/10.22033/ESGF/CMIP6.11489> (2019).
- 520 112. Bader, D. C., Leung, R., Taylor, M. & McCoy, R. B. *E3SM-Project E3SM1.1ECA model*
521 *output prepared for CMIP6 CMIP piControl*. Version 20200729. Earth System Grid
522 Federation. <https://doi.org/10.22033/ESGF/CMIP6.11490> (2019).
- 523 113. EC-Earth Consortium (EC-Earth). *EC-Earth-Consortium EC-Earth3 model output*
524 *prepared for CMIP6 ScenarioMIP*. Version 20191204. Earth System Grid Federation.
525 <https://doi.org/10.22033/ESGF/CMIP6.251> (2019).
- 526 114. EC-Earth Consortium (EC-Earth). *EC-Earth-Consortium EC-Earth3-Veg model output*
527 *prepared for CMIP6 ScenarioMIP*. Version 20191204. Earth System Grid Federation.
528 <https://doi.org/10.22033/ESGF/CMIP6.727> (2019).
- 529 115. YU, Y. *CAS FGOALS-f3-L model output prepared for CMIP6 CMIP piControl*. Version
530 20200729. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.3447>
531 (2019).
- 532 116. YU, Y. *CAS FGOALS-f3-L model output prepared for CMIP6 ScenarioMIP*. Version
533 20191204. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.2046>
534 (2019).
- 535 117. Li, L. *CAS FGOALS-g3 model output prepared for CMIP6 CMIP piControl*. Version
536 20200729. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.3448>
537 (2019).
- 538 118. Song, Z. et al. *FIO-QLNM FIO-ESM2.0 model output prepared for CMIP6 CMIP piControl*.
539 Version 20200729. Earth System Grid Federation.
540 <https://doi.org/10.22033/ESGF/CMIP6.9205> (2019).
- 541 119. Guo, H. et al. *NOAA-GFDL GFDL-CM4 model output piControl*. Version 20200729. Earth
542 System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.8666> (2018).

- 543 120. Guo, H. et al. *NOAA-GFDL GFDL-CM4 model output prepared for CMIP6 ScenarioMIP*.
544 *Version 20191204*. Earth System Grid Federation.
545 <https://doi.org/10.22033/ESGF/CMIP6.9242> (2018).
- 546 121. Krasting, J. P. et al. *NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 CMIP*
547 *piControl*. *Version 20200729*. Earth System Grid Federation.
548 <https://doi.org/10.22033/ESGF/CMIP6.8669> (2018).
- 549 122. John, J. G. et al. *NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6*
550 *ScenarioMIP*. *Version 20191204*. Earth System Grid Federation.
551 <https://doi.org/10.22033/ESGF/CMIP6.1414> (2018).
- 552 123. NASA Goddard Institute for Space Studies (NASA/GISS). *NASA-GISS GISS-E2.1G*
553 *model output prepared for CMIP6 CMIP piControl*. *Version 20200729*. Earth System Grid
554 Federation. <https://doi.org/10.22033/ESGF/CMIP6.7380> (2018).
- 555 124. NASA Goddard Institute for Space Studies (NASA/GISS). *NASA-GISS GISS-E2-1-G-CC*
556 *model output prepared for CMIP6 CMIP piControl*. *Version 20200729*. Earth System Grid
557 Federation. <https://doi.org/10.22033/ESGF/CMIP6.11856> (2019).
- 558 125. NASA Goddard Institute for Space Studies (NASA/GISS). *NASA-GISS GISS-E2.1H*
559 *model output prepared for CMIP6 CMIP piControl*. *Version 20200729*. Earth System Grid
560 Federation. <https://doi.org/10.22033/ESGF/CMIP6.7381> (2018).
- 561 126. NASA Goddard Institute for Space Studies (NASA/GISS). *NASA-GISS GISS-E2-2-G*
562 *model output prepared for CMIP6 CMIP piControl*. *Version 20200729*. Earth System Grid
563 Federation. <https://doi.org/10.22033/ESGF/CMIP6.7382> (2019).
- 564 127. Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M. & Andrews, T. *MOHC HadGEM3-*
565 *GC31-LL model output prepared for CMIP6 CMIP piControl*. *Version 20200729*. Earth
566 System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.6294> (2018).

- 567 128. Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M. & Andrews, T. *MOHC HadGEM3-*
568 *GC31-MM model output prepared for CMIP6 CMIP piControl*. Version 20200729. Earth
569 System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.6297> (2019).
- 570 129. Raghavan, K. & Panickal, S. *CCCR-IITM IITM-ESM model output prepared for CMIP6*
571 *CMIP piControl*. Version 20200729. Earth System Grid Federation.
572 <https://doi.org/10.22033/ESGF/CMIP6.3710> (2019).
- 573 130. Volodin, E. et al. *INM INM-CM4-8 model output prepared for CMIP6 CMIP piControl*.
574 Version 20200729. Earth System Grid Federation.
575 <https://doi.org/10.22033/ESGF/CMIP6.5080> (2019).
- 576 131. Volodin, E. et al. *INM INM-CM4-8 model output prepared for CMIP6 ScenarioMIP*.
577 Version 20191204. Earth System Grid Federation.
578 <https://doi.org/10.22033/ESGF/CMIP6.12321> (2019).
- 579 132. Volodin, E. et al. *INM INM-CM5-0 model output prepared for CMIP6 CMIP piControl*.
580 Version 20200729. Earth System Grid Federation.
581 <https://doi.org/10.22033/ESGF/CMIP6.5081> (2019).
- 582 133. Volodin, E. et al. *INM INM-CM5-0 model output prepared for CMIP6 ScenarioMIP*.
583 Version 20191204. Earth System Grid Federation.
584 <https://doi.org/10.22033/ESGF/CMIP6.12322> (2019).
- 585 134. Boucher, O., Denvil, S., Caubel, A. & Foujols, M. A. *IPSL IPSL-CM6A-LR model output*
586 *prepared for CMIP6 CMIP piControl*. Version 20200729. Earth System Grid Federation.
587 <https://doi.org/10.22033/ESGF/CMIP6.5251> (2018).
- 588 135. Boucher, O., Denvil, S., Caubel, A. & Foujols, M. A. *IPSL IPSL-CM6A-LR model output*
589 *prepared for CMIP6 ScenarioMIP*. Version 20191204. Earth System Grid Federation.
590 <https://doi.org/10.22033/ESGF/CMIP6.1532> (2019).
- 591 136. Stouffer, R. *UA MCM-UA-1-0 model output prepared for CMIP6 CMIP piControl*. Earth
592 System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.8890> (2019).

- 593 137. Hajima, T. et al. *MIROC MIROC-ES2L model output prepared for CMIP6 CMIP piControl*.
594 Version 20200729. Earth System Grid Federation.
595 <https://doi.org/10.22033/ESGF/CMIP6.5710> (2019).
- 596 138. Tachiiri, K. et al. *MIROC MIROC-ES2L model output prepared for CMIP6 ScenarioMIP*.
597 Version 20191204. Earth System Grid Federation.
598 <https://doi.org/10.22033/ESGF/CMIP6.936> (2019).
- 599 139. Tatebe, H. & Watanabe, M. *MIROC MIROC6 model output prepared for CMIP6 CMIP*
600 *piControl*. Version 20200729. Earth System Grid Federation.
601 <https://doi.org/10.22033/ESGF/CMIP6.5711> (2018).
- 602 140. Shiogama, H., Abe, M. & Tatebe, H. *MIROC MIROC6 model output prepared for CMIP6*
603 *ScenarioMIP*. Version 20191204. Earth System Grid Federation.
604 <https://doi.org/10.22033/ESGF/CMIP6.898> (2019).
- 605 141. Neubauer, D. et al. *HAMMOZ-Consortium MPI-ESM1.2-HAM model output prepared for*
606 *CMIP6 CMIP piControl*. Version 20200729. Earth System Grid Federation.
607 <https://doi.org/10.22033/ESGF/CMIP6.5037> (2019).
- 608 142. Jungclaus, J. et al. *MPI-M MPI-ESM1.2-HR model output prepared for CMIP6 CMIP*
609 *piControl*. Version 20200729. Earth System Grid Federation.
610 <https://doi.org/10.22033/ESGF/CMIP6.6674> (2019).
- 611 143. Schupfner, M. et al. *DKRZ MPI-ESM1.2-HR model output prepared for CMIP6*
612 *ScenarioMIP*. Version 20191204. Earth System Grid Federation.
613 <https://doi.org/10.22033/ESGF/CMIP6.2450> (2019).
- 614 144. Wieners, K.-H. et al. *MPI-M MPI-ESM1.2-LR model output prepared for CMIP6 CMIP*
615 *piControl*. Version 20200729. Earth System Grid Federation.
616 <https://doi.org/10.22033/ESGF/CMIP6.6675> (2019).

- 617 145. Yukimoto, S. et al. *MRI MRI-ESM2.0 model output prepared for CMIP6 CMIP piControl*.
618 Version 20200729. Earth System Grid Federation.
619 <https://doi.org/10.22033/ESGF/CMIP6.6900> (2019).
- 620 146. Yukimoto, S. et al. *MRI MRI-ESM2.0 model output prepared for CMIP6 ScenarioMIP*.
621 Version 20191204. Earth System Grid Federation.
622 <https://doi.org/10.22033/ESGF/CMIP6.638> (2019).
- 623 147. Cao, J. & Wang, B. *NUIST NESMv3 model output prepared for CMIP6 CMIP piControl*.
624 Version 20200729. Earth System Grid Federation.
625 <https://doi.org/10.22033/ESGF/CMIP6.8776> (2019).
- 626 148. Cao, J. *NUIST NESMv3 model output prepared for CMIP6 ScenarioMIP*. Version
627 20191204. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.2027>
628 (2019).
- 629 149. Bethke, I. et al. *NCC NorCPM1 model output prepared for CMIP6 CMIP piControl*.
630 Version 20200729. Earth System Grid Federation.
631 <https://doi.org/10.22033/ESGF/CMIP6.10896> (2019).
- 632 150. Guo, C. et al. *NCC NorESM1-F model output prepared for CMIP6 CMIP piControl*.
633 Version 20200729. Earth System Grid Federation.
634 <https://doi.org/10.22033/ESGF/CMIP6.11595> (2019).
- 635 151. Seland, Ø. et al. *NCC NorESM2-LM model output prepared for CMIP6 CMIP piControl*.
636 Version 20200729. Earth System Grid Federation.
637 <https://doi.org/10.22033/ESGF/CMIP6.8217> (2019).
- 638 152. Bentsen, M. et al. *NCC NorESM2-MM model output prepared for CMIP6 CMIP piControl*.
639 Version 20200729. Earth System Grid Federation.
640 <https://doi.org/10.22033/ESGF/CMIP6.8221> (2019).

- 641 153. Park, S. & Shin, J. *SNU SAM0-UNICON model output prepared for CMIP6 CMIP*
642 *piControl*. Version 20200729. Earth System Grid Federation.
643 <https://doi.org/10.22033/ESGF/CMIP6.7791> (2019).
- 644 154. Lee, W.-L. & Liang, H.-C. *AS-RCEC TaiESM1.0 model output prepared for CMIP6 CMIP*
645 *piControl*. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.9798>
646 (2020).
- 647 155. Tang, Y. et al. *MOHC UKESM1.0-LL model output prepared for CMIP6 CMIP piControl*.
648 Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.6298> (2019).
- 649 156. Good, P. et al. *MOHC UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP*.
650 Version 20191204. Earth System Grid Federation.
651 <https://doi.org/10.22033/ESGF/CMIP6.1567> (2019).

Acknowledgements

652 We are grateful to Joeri Rogelj for providing the NDC scenario data and to Karsten Haustein for
653 providing the data used to calculate the observation-based estimates of internal variability.

654 CMM, ACM, PMF, CJS and KBT were supported by the European Union's Horizon 2020
655 research and innovation programme under grant agreement No 820829 (CONSTRAIN project).

656 ACM was supported by the Natural Environment Research Council (NE/M018199/1) and
657 Leverhulme Trust. CJS was supported by a NERC/IIASA Collaborative Research Fellowship
658 (NE/T009381/1). We acknowledge the World Climate Research Programme, which, through its
659 Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate
660 modelling groups for producing and making available their model output, the Earth System Grid
661 Federation (ESGF) for archiving the data and providing access, and the multiple funding
662 agencies who support CMIP6 and ESGF.

663

Correspondence statement

664 Correspondence and requests for materials should be addressed to CMM.

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 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

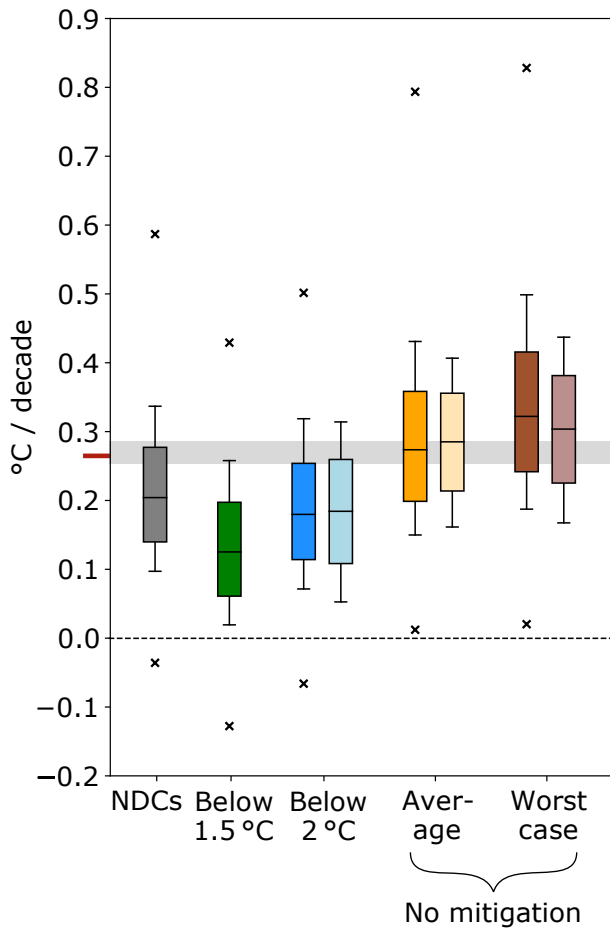
711 shows the range/mean of maximum historical trends for different trend lengths from four
712 different observation-based records (GISTEMPv4, CWv2 updated with HadSST3,
713 HadCRUT4.6, and BE; see Supplementary Fig. 1). To compare with the model simulated GSAT
714 projections, the observation data 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**

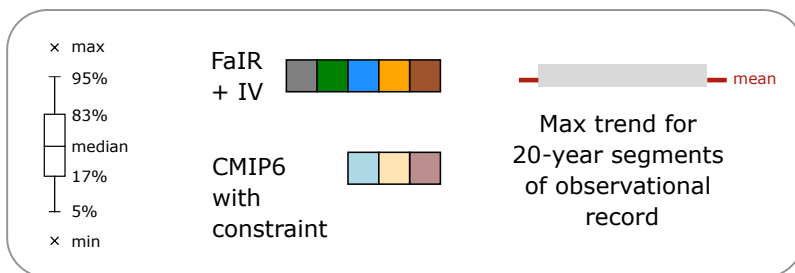
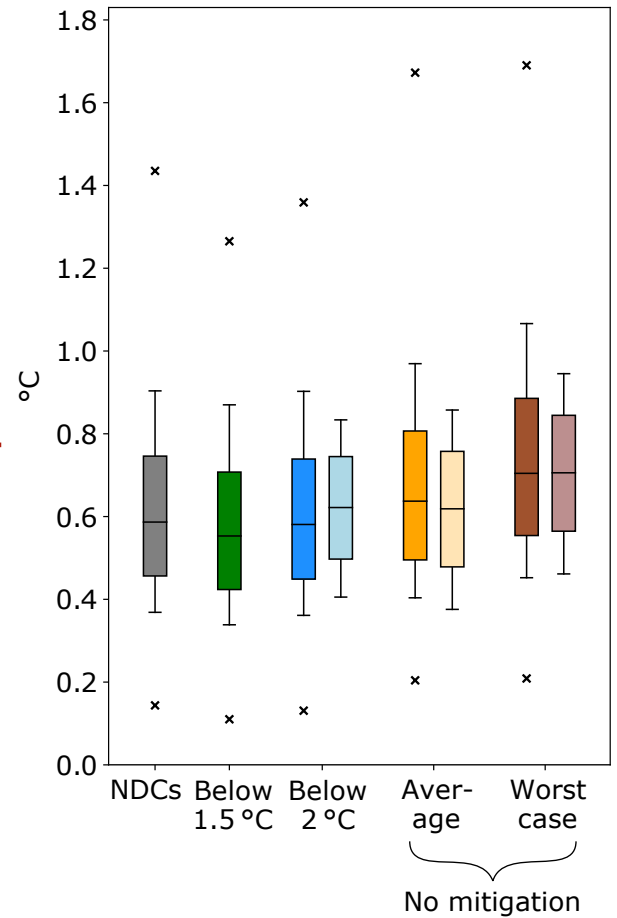
719 **Table 1: The probability of experiencing different near-term (2021-2040) global mean**
720 **surface air temperature trends, as a result of following a mitigation pathway rather than a**
721 **no mitigation pathway. a**, The probability of the near-term temperature trend in a mitigation
722 scenario ($\text{trend}_{\text{mit}}$) being lower than in a no mitigation scenario ($\text{trend}_{\text{nomit}}$) by a factor α
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_{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_{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_{mit} and P_{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	a $P(\text{trend}_{\text{mit}} < \text{trend}_{\text{nomit}} - \alpha \times \text{trend}_{\text{nomit}})$			b $P_{\text{ns}} = P_{\text{mit}} - P_{\text{nomit}}$		
	$\alpha = 0$	$\alpha = 0.2$	$\alpha = 0.4$	P_{mit}	P_{nomit}	P_{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

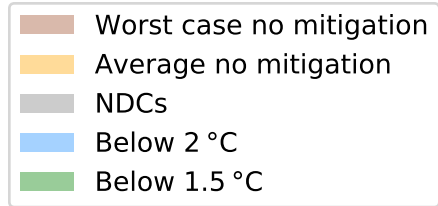
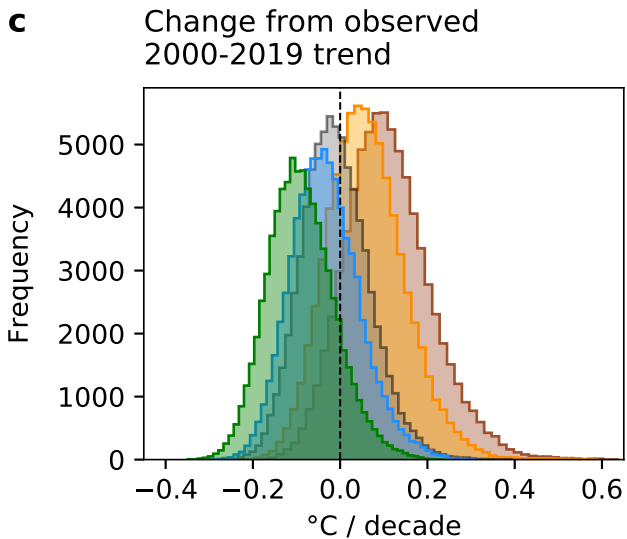
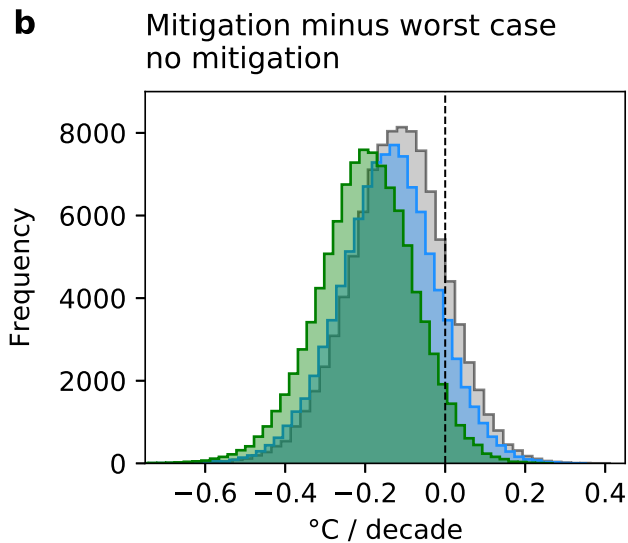
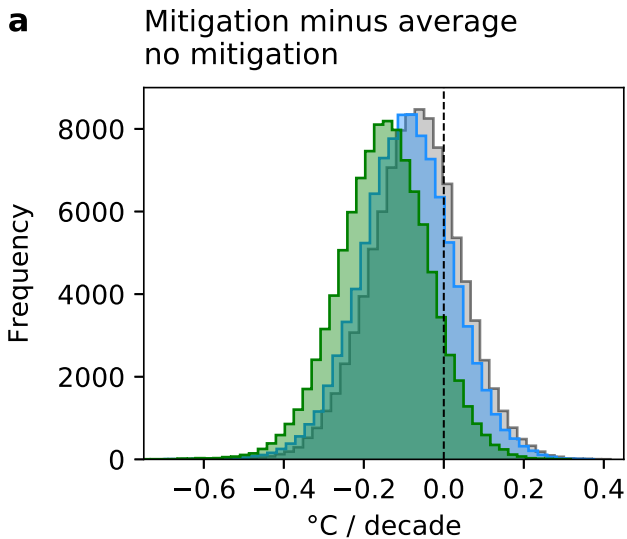
a 2021-2040 GSAT trend



b 2021-2040 GSAT anomaly



2021-2040 GSAT trend distributions from FaIR plus IV



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

