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1 ***Latest climate models confirm need for urgent mitigation***

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3
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7
8 **Many recently updated climate models show larger future warming than previously.**

9 **Separate lines of evidence suggest their warming rates may be unrealistically high,**

10 **but the risk of such eventualities only emphasizes the need for rapid and deep**

11 **reductions in emissions.**

12
13
14 To date, one third of the latest-generation climate models from the Coupled Model

15 Intercomparison Project phase 6 (CMIP6) exhibits a higher equilibrium climate sensitivity

16 (ECS) compared to the previous generation (CMIP5). As a result, several CMIP6 models

17 exhibit greater warming over the 21st century ([https://phys.org/news/2019-09-earth-quickly-](https://phys.org/news/2019-09-earth-quickly-climate.html)

18 [climate.html](https://phys.org/news/2019-09-earth-quickly-climate.html)). This might suggest smaller remaining carbon budgets or a need to reach net-

19 zero emissions sooner to limit warming to targets set forth in the Paris Agreement. However,

20 carbon budgets and net-zero emission dates are also sensitive to other factors, including the

21 transient climate response (TCR) and aerosol effects. Here, we argue that the highest-

22 warming CMIP6 models are unlikely to be representative of the real world and that CMIP6

23 projections of global surface temperature should not be exclusively relied on for policy-

24 relevant decisions. Nevertheless, the new generation of results still has scientific value and

25 strengthens the case for urgent mitigation.

26 **High Equilibrium Climate Sensitivity**

27 Equilibrium climate sensitivity (ECS) represents how much warming we can expect for a

28 doubling of the atmospheric CO₂ concentration from its preindustrial state. It has remained a

29 persistent uncertainty in climate science with a likely range (66% probability) of 1.5°C-4.5°C
30 assessed in IPCC reports and elsewhere^{1,2}. Recently, the preliminary ECS range in CMIP6
31 has skewed high relative to CMIP5, with multiple models lying above the upper end of the
32 likely ECS range (Figure 1). This has raised questions in the climate modelling and research
33 community around the plausibility of high ECS values and implications for the projected
34 rates of surface warming over this century³.

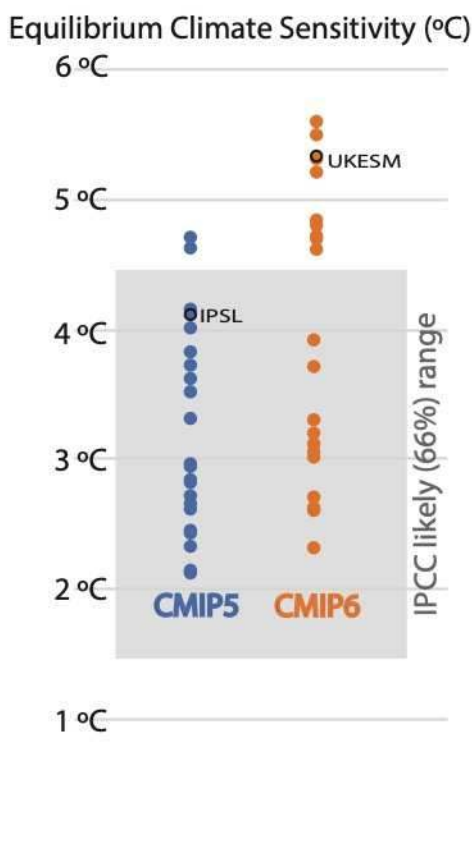
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36 The climate models in CMIP archives are developed by institutes around the world, each
37 with different research and operational foci. Modelling groups generally do not develop their
38 models with a target ECS in mind. Rather, they are built from fundamental physical laws,
39 and each model's ECS is something that emerges from simulations once its development
40 has been finalised. Many of the new-generation models improve on their predecessors in a
41 variety of ways: for example, by more faithfully reproducing observations or by adding
42 missing Earth system process. Many of these improvements do not impact ECS, but some
43 do. One example is the UKESM1-0-LL model, developed by the UK Earth System Modelling
44 project, which shows an improved representation of mid-latitude mixed phase clouds (judged
45 against present-day satellite data)^{4,5}. This leads to a reduced damping effect on temperature
46 from cloud-phase changes⁴. The result of this improvement in the simulation of present
47 climate, all else being equal, is an increase in ECS. This does not mean the resulting higher
48 ECS is more realistic, as other processes may be contributing a high bias.

49

50 Climate models have previously informed the likely range of ECS, but over the last decade,
51 increasing evidence has emerged from the paleoclimate record, from historic observations,
52 and from advances in understanding of cloud processes that can be used to constrain
53 ranges of ECS, more or less independently of climate models². Since the CMIP archives are
54 not explicitly designed to sample known uncertainties in ECS, there's no requirement for any
55 one model's value to fall within the canonical range. Nevertheless, they have largely done
56 so, until now (Figure 1). We think that the diversity of ECS across CMIP6 should be

57 celebrated; it means that groups are daring their models to be imperfect, and this will
 58 ultimately aid understanding and drive progress. The IPCC “likely” range implies a 33%
 59 probability that ECS would be outside a 1.5-4.5 °C window, so a higher ECS value is not
 60 unexpected. However, the higher values seen in CMIP6 are not supported by other lines of
 61 evidence² and may eventually be proven wrong.
 62



63
 64 **Figure 1. The Equilibrium Climate Sensitivity (ECS) from CMIP5 and 21 currently**
 65 **available CMIP6 climate models.** Data as of 05.11.2019 from the ESMValTool team as
 66 part of the European Union's Horizon 2020 CRESCENDO project⁶. The ECS from the IPSL-
 67 CM5A-MR model (IPSL) and UKESM1-0-LL (UKESM) models are used in later figures as
 68 they lie around the 95th percentile of the CMIP5 and CMIP6 ECS distributions, respectively.

69 Global warming projections

70 Projections of possible climate futures from complex climate models are strongly affected by
71 their ECS. Complementary simple physical climate modelling approaches that make
72 assumptions on ranges of ECS and radiative forcing can also be used to make projections
73 for a smaller range of physical quantities. For example, the IPCC AR5 Working Group III
74 report employed the MAGICC simple climate model⁷ to make temperature projections for
75 many different scenarios. The IPCC Special Report on 1.5°C (IPCC SR1.5) used both
76 MAGICC and FaIR⁸, another simple climate model, for its projections. These models make
77 gross assumptions but can explore a much broader sampling of uncertainty compared to
78 any complex model. Here we use the FaIR model in its calibration based on IPCC-assessed
79 ranges of input parameters to examine the plausibility of CMIP6 warming trajectories.

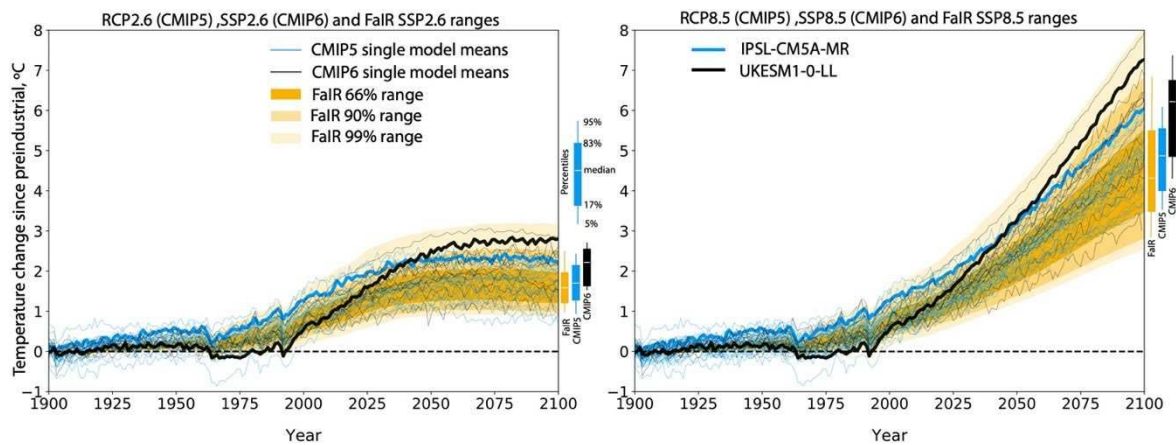
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81 ECS explicitly describes the long-term global surface temperature response to a doubling of
82 atmospheric CO₂ concentration, but it is still a useful measure to interpret temperature
83 projections over the next several decades. The transient climate response (TCR) is also an
84 important measure for projections⁹, as it quantifies the surface temperature response to a
85 1% per year steadily increasing level of CO₂ to the time of doubling. The difference between
86 ECS and TCR relates to the warming of the deep ocean that takes longer to emerge, thus
87 ECS is larger than TCR. Models like MAGICC and FaIR can be used to investigate the effect
88 of ECS and TCR on projections.

89

90 Figure 2 shows that some CMIP6 models exhibit more mid- and late-century warming
91 compared to their CMIP5 counterparts. This is true for both the strong mitigation (Figure 2,
92 left) and high-emissions scenarios (Figure 2, right). The higher warming models in both
93 cases tend to be the ones with high ECS. Similar to Figure 1 for ECS, several CMIP6
94 models have temperature projections outside the likely range produced by the uncertainty
95 analysis from FaIR as employed in IPCC SR1.5. This is illustrated by the shading in Figure 2

96 based on assessed ranges of ECS, TCR and radiative forcing. However, the CMIP6 models
 97 still fall within the broader 99% range plume from the FaIR analysis. This indicates that these
 98 high-end CMIP6 projections are not outside the assessed range of possible futures, but they
 99 are unlikely futures. These larger warming models also overestimate the current warming
 100 trend, again suggesting that their future warming could be too strong. Even if this is the
 101 case, such models are still useful for understanding the very low-probability, high-risk
 102 outcomes, which has been a gap in previous IPCC assessments¹⁰.
 103



104
 105 **Figure 2. Temperature response to low- and high-end emissions scenarios.** Modelled
 106 global average surface air temperature change over 1900-2100 is shown in a strong
 107 mitigation scenario (left) and a high emissions scenario (right). CMIP5 and CMIP6 model
 108 projections are shown as individual curves superimposed on FaIR simple model projections
 109 (shading) from a broader uncertainty analysis of possible futures, based on lines of evidence
 110 for ECS, TCR, and radiative forcing updated from those used in similar analysis for IPCC
 111 SR1.5. Note that CMIP5 and CMIP6 employed slightly different emission scenarios but FaIR
 112 simulations available from the GitHub repository below suggest this has a minimal effect on
 113 the projected CMIP6 and CMIP5 differences. UKESM1-0-LL and IPSL-CM5A-MR
 114 projections are highlighted in the figures. The CMIP5 and CMIP6 percentile ranges for 2100
 115 are shown on the figure to aid the reader in identifying the differences of the CMIP models
 116 compared with the FaIR ranges. However, as stated in the main text, the CMIP ensemble

117 *does not represent a broad statistical sample, so differences in percentiles are not*
118 *necessarily meaningful. Data and additional figures comparing SSPs and RCPs are*
119 *available from https://github.com/Priestley-Centre/CMIP5_CMIP6_FaIR_gsata_data.*

120

121 Implications for net-zero dates

122

123

124 Targets for mitigation action are often framed around the remaining carbon budget and/or
125 dates to reach net-zero greenhouse gas emissions. Higher ECS models might be expected
126 to mean smaller remaining carbon budgets and earlier net-zero dates. However, the
127 relationship between ECS and the remaining carbon budget is not straightforward¹¹. Net-
128 zero dates and carbon budgets are in fact more sensitive to the TCR and to changes in the
129 natural sink of CO₂, as well as non-CO₂ forcing agents such as aerosols¹².

130

131 Figure 3 compares the response to idealised net-zero greenhouse emission dates emulated
132 with FaIR using inputs for ECS, TCR, and effective radiative forcing that come from either
133 assessed ranges (Figure 3b) or are chosen to match the IPSL-CM5A-MR and UKESM1-0-
134 LL models (Figures 3c and 3d). These bottom panels show how the response might differ if
135 the Earth behaved like the models sitting around the 95th percentile of the ECS distribution
136 from CMIP5 and CMIP6, respectively.

137

138 IPCC SR1.5 concluded that net-zero greenhouse gas emission dates around 2070 or earlier
139 are needed for a 50% chance to limit global warming in 2100 to 1.5 °C. Probabilistic chances
140 of meeting the target are made as the physical climate response remains uncertain. The
141 median FaIR analysis and the IPSL-CM5A-MR model, even with its relatively high ECS, both
142 manage to stay close to 1.5 °C with a 2070 net-zero date, supporting the IPCC SR1.5
143 assessment. The IPSL-CM5A-MR model has a relatively modest TCR and aerosol cooling,
144 which limits the amount of near-term warming in rapid mitigation pathways. In contrast, the
145 UKESM1-0-LL model has a high ECS accompanied by a high TCR and strong aerosol

146 cooling. This would lead to an unavoidable additional 0.5 °C of rapid warming from the
147 mitigation scenarios, which would make staying below even 2 °C challenging.

148

149 But does the real world behave the same way as UKESM1-0-LL? The answer is probably
150 not. The simulations of the UKESM model shown in Figure 2 indicate that current warming
151 rates are biased high. This, coupled with an overestimated ECS when considering other
152 lines of evidence², would suggest the model results should be downplayed.

153

154 IPCC has tended to rely on ensembles of available complex models for surface temperature
155 projections and give each model equal weight in its analysis. This has long been known to
156 be imperfect but it has been difficult to reach a community consensus on alternative
157 choices¹³. As we have shown that raw projections of surface temperature from CMIP6
158 should not be used directly in creating policy involving temperature targets, a way of
159 translating the model results to improve their policy relevance is needed. Well-tested and
160 calibrated simple models can be used both to translate evidence from the more complex
161 models and to make more policy relevant projections of global surface temperature that
162 draw on multiple lines of evidence, including process evidence from the complex models.
163 We recommend that such simple modelling approaches become central tools in future
164 assessments.

165

166 In spite of the issues discussed in this commentary, the high-end warming outcomes seen in
167 some CMIP6 models cannot be ruled out at the 1% level. The best way to avoid the
168 potentially devastating impacts of a high ECS (even if low probability) is to mitigate towards
169 net-zero emissions as urgently as possible. As such, CMIP6 model results reinforce the
170 IPCC SR1.5 conclusion that urgent mitigation towards net-zero emissions is needed to limit
171 future climate change risk. They also reinforce that we need to develop adaptation strategies
172 to cope with global temperatures in excess of 2°C above pre-industrial levels. To echo the

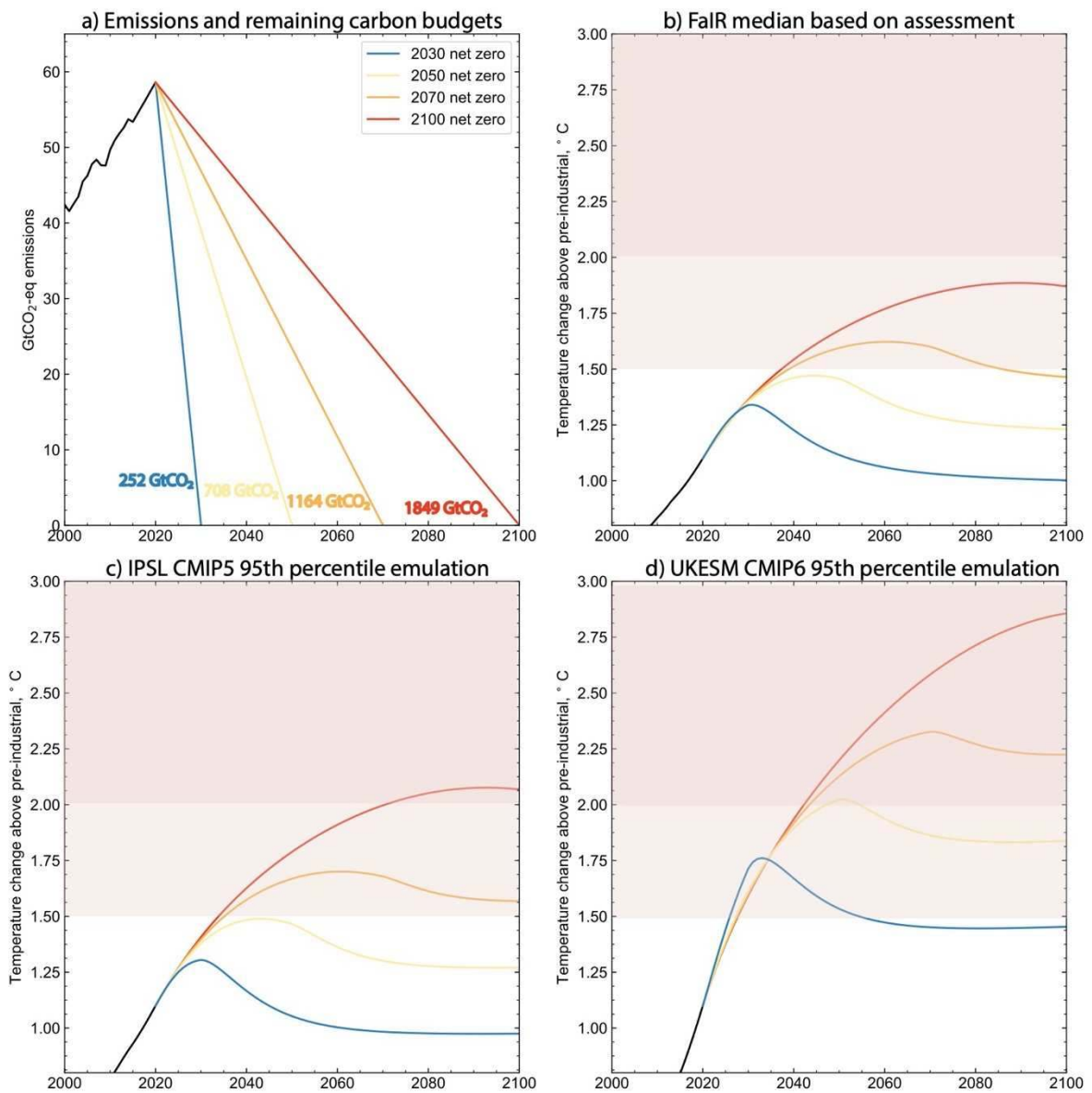
173 words from the IPCC SR1.5 press conference in October 2018, “Every bit of warming
 174 matters, every year matters, every choice matters”.

175

176

177

178



179

180 **Figure 3. Idealised emissions scenarios with different net-zero dates and associated**
 181 **surface temperature change.** These simple scenarios assume that CO₂ and non-CO₂
 182 emissions (including aerosol precursor emissions) are phased out at the same rate to zero

183 *by a specified year. The remaining carbon budget associated with each pathway is*
184 *displayed. Using these scenarios, temperature changes are emulated with the FaIR simple*
185 *model, using inputs based assessed ranges and on CMIP: (a) shows global emissions and*
186 *carbon budgets; (b) shows the expected response computed with the FaIR median; (c) and*
187 *(d) show how the response if the Earth behaved similarly to the CMIP5 IPSL-CM5A-MR*
188 *model and CMIP6 UKESM1-0-LL model respectively. Note that unlike in Figure 2, the*
189 *warming in both models has been scaled to match 1.1°C in 2020.*

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201 **Author Contributions**

202 PMF conceived of the work and wrote the comment, with extensive contributions to both
203 writing and ideas from ACM. CMM provided the analysis of CMIP6 projections, made Figure
204 2 and commented on the paper. CJS provided the FaIR analysis and made Figure 3.

205 Competing Interests

206 The authors declare no competing interests

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