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Article

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Studying climate stabilisation at Paris Agreement levels

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11 **Since the Paris Agreement, emphasis has been on impacts at 1.5°C and 2°C of global**
12 **warming, but the rate of warming also has regional effects. A new framework of model**
13 **experiments is needed to increase understanding of climate stabilisation and its impacts.**

14 Following the Paris Agreement, there have been hundreds of studies researching the impacts
15 of 1.5°C and 2°C of global warming above pre-industrial levels. Multiple methods have been
16 developed to address the question of how regional climate change and impacts differ between
17 global warming levels (GWLs) including pattern scaling^{1,2}, time-slicing of existing climate
18 projections³, single coupled-model experiments⁴, and multi-model atmosphere-only
19 experiments⁵. The problem is that while the Paris Agreement is not explicit, the intention is
20 that of stabilised global temperatures well below the 2°C GWL, or preferably the 1.5°C
21 GWL, rather than continued global warming⁶, but the methods described above are based on
22 transient projections in one form or other (Table 1) that do not reflect stabilised climates. This
23 issue has come to the fore in the use of a time-sampling approach of transient simulations for
24 the generation of GWL-based climate projections in Working Group 1 of the Sixth
25 Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WG1).

26 **Warming versus stabilising climate**

27 With respect to a specific GWL, like the 1.5°C Paris Agreement limit, data can be produced
28 showing how a 1.5°C warmer world may look under high greenhouse gas emissions (e.g.
29 Shared Socioeconomic Pathway 5 –8.5; SSP5-8.5) or in a slower warming world (e.g. SSP1-
30 2.6) using a time-slicing method. But it is also known that slow climate processes (such as ice
31 sheet melt and changes in deep ocean circulation) mean that over centuries the climate
32 evolves even as greenhouse gas forcings on the climate stabilise. It has long been understood
33 from abrupt increased CO₂ simulations that global warming under fixed CO₂ concentrations
34 continues for centuries, and that while early in the simulations warming is concentrated over

35 land, as time progresses the focus of warming shifts to high-latitude ocean areas, including
36 the Southern Ocean and North Atlantic⁷⁻⁹. While we do not yet have specific model
37 experiments to answer the question of how a 1.5°C warmer world with no warming trend
38 differs from a world warming transiently through 1.5°C, existing evidence points to
39 substantial differences. For around 15% of the world surface, the difference in local seasonal
40 temperatures between rapid warming and quasi-equilibrium climate states at the same GWL
41 exceeds the difference between the 1.5°C and 2°C GWLs¹⁰. We also know that climate
42 extremes differ depending on the rate of global warming, with hot summers in areas of
43 Europe, Asia and the US, more than twice as common in a fast warming climate than a quasi-
44 equilibrium climate at the same GWL¹⁰. In bespoke simulations, Sigmond et al.¹¹ recently
45 showed that the Atlantic Meridional Overturning Circulation and associated surface
46 temperature patterns continue to evolve as the climate stabilises at specified GWLs. There is
47 also evidence that weather and rainfall patterns vary between rapidly-warming and stabilising
48 climate states¹². Further elucidation of regional climate patterns and impacts in climates
49 undergoing stabilisation at specified levels of global warming is needed to fully understand
50 the implications of the 1.5°C and 2°C GWLs in the Paris Agreement, and of higher GWLs we
51 may yet reach. However, the few existing multi-model studies in this area have been
52 hampered by a lack of suitable experiments to analyse climate stabilisation at specific GWLs.
53 Currently, impacts studies at 1.5 and 2°C GWLs are not based on the stabilising climate
54 states the Paris Agreement refers to. This may lead to ill-informed decision-making,
55 particularly in regions where the rate of global warming has a large effect on local climate.

56 **New experiments needed**

57 Here, we propose that modelling groups consider performing experiments with climate
58 stabilisation at 1.5, 2, 3, and 4°C GWLs that will allow for the required analyses needed to
59 understand climate impacts associated with the Paris Agreement and higher GWLs that may

60 be reached if we fail to meet the Paris targets. This involves a departure from the standard
61 Model Intercomparison Projects (MIPs) which have formed a large part of global climate
62 modelling efforts over the last two and a half decades. In the MIPs, models are run with a
63 given radiative forcing (Fig. 1a) resulting in a range of temperature responses due to model
64 differences (including climate sensitivity) and internal climate variability¹³ (Fig. 1b). We
65 propose a new approach whereby carbon dioxide emissions are set to zero at different times
66 in different models depending on the model response (Fig. 1c) to generate specified
67 stabilising climate states at approximately 1.5, 2, 3, and 4°C GWLs beyond 2200 (Fig. 1d). In
68 this approach a model which warms faster under SSP5-8.5 would follow a lower
69 concentration pathway to achieve climate stabilisation at the targeted GWL compared with a
70 model which warms more slowly under SSP5-8.5.

71 The proposed model experiments would run to at least 2500 CE (preferably 3000 CE) to
72 achieve some stabilisation of the climate^{8,9}, albeit with continuing sea level rise and local
73 changes occurring beyond the timeframe of the simulations. This is suggested as a pragmatic
74 timeframe that helps policymakers understand the consequences of the Paris Agreement for
75 the coming generations and beyond, and gives time for regional climate to evolve under
76 stable global temperatures as many land regions cool and ocean areas warm over centuries^{8,10}.
77 A climate approaching full equilibrium would require simulations to run for many thousands
78 of years which would be of less policy relevance. Box 1 provides details of the model
79 framework we are putting forward.

80 The experiments we propose here bear similarities to some existing projects, but fill an
81 important gap not met by previous work. The 21st century scenario simulations exhibit
82 different rates of warming, but none result in climate stabilisation and models warm to
83 different levels in part due to climate sensitivity differences. The Zero Emissions
84 Commitment Model Intercomparison Project¹⁴ is examining climate responses after carbon

85 emissions cease, but while this results in some degree of climate stabilisation, models will
86 stabilise at a range of GWLs depending on their climate sensitivities. The suggested model
87 experiments are also similar to aspects of the community climate simulations developed by
88 Sanderson et al.⁴, but differ in that the proposed experiments are longer, thus allowing a
89 greater degree of climate stabilisation, and the design is not based on using an emulator. Also,
90 in the proposed framework multiple models would be considered, and 3 and 4°C GWLs
91 would be included as these align more closely with global climate projections under the
92 current global emissions pathway and something akin to a worst-case scenario respectively.
93 The simulations proposed here would build on those of Sigmond et al.¹¹ and ongoing
94 experiments in the UK by authors AJD and EH, but as mentioned previously we hope for the
95 participation of multiple modelling centres. While we understand the proposed experiments
96 require significant computational costs and data storage we believe the importance of the
97 problem at hand (i.e. the current deficiency in understanding of climate change impacts in
98 line with the Paris Agreement) necessitates an ambitious plan.

99 **Preparing for a more stable climate**

100 The proposed model experiments will allow better understanding of the climate implications
101 of the Paris Agreement. We envisage many exciting research avenues that may be explored
102 using these simulations. These include, but are not limited to:

- 103 • Multi-model analyses of regional climate means and extremes under stabilising 1.5
104 and 2°C GWLs associated with the Paris Agreement,
- 105 • examining if the El Niño-Southern Oscillation and other prominent modes of climate
106 variability respond differently under transient warming than in a stabilising world at
107 the same GWL (building on the work of Callahan et al.¹⁵),

- 108 • exploring changes to weather systems which are sensitive to land-ocean temperature
109 differences, such as monsoons¹⁶, and
110 • quantifying exposure and understanding vulnerability to climate hazards and how
111 these change as the climate stabilises at different GWLs.

112 Comparisons with rapid climate warming under simulations with increasing carbon dioxide at
113 the same GWLs would provide greater understanding of the influence of rate of global
114 warming on climate changes and associated impacts. Regional high-resolution simulations
115 could also be embedded in the proposed experiments to enable localised projections and more
116 detailed impacts analyses at the Paris Agreement GWLs and 3 and 4°C global warming.

117 We believe that the climate model experiments we have proposed here would help piece
118 together a clearer picture of how the future of Earth's climate will look if we are to keep
119 global warming below the Paris Agreement levels, or indeed exceed the agreed levels but
120 stabilise global temperatures at a higher level. This would enable humanity to better prepare
121 for the climate of the coming centuries. We call on modelling groups around the world to
122 build the simulations needed for understanding the implications of the Paris Agreement for
123 the coming centuries.

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128 **Competing Interests**

129 The authors declare no competing interests.

130 **Author contributions**

131 A.D.K. conceived the comment and led the writing. All authors contributed to the writing and
132 revision of the manuscript.

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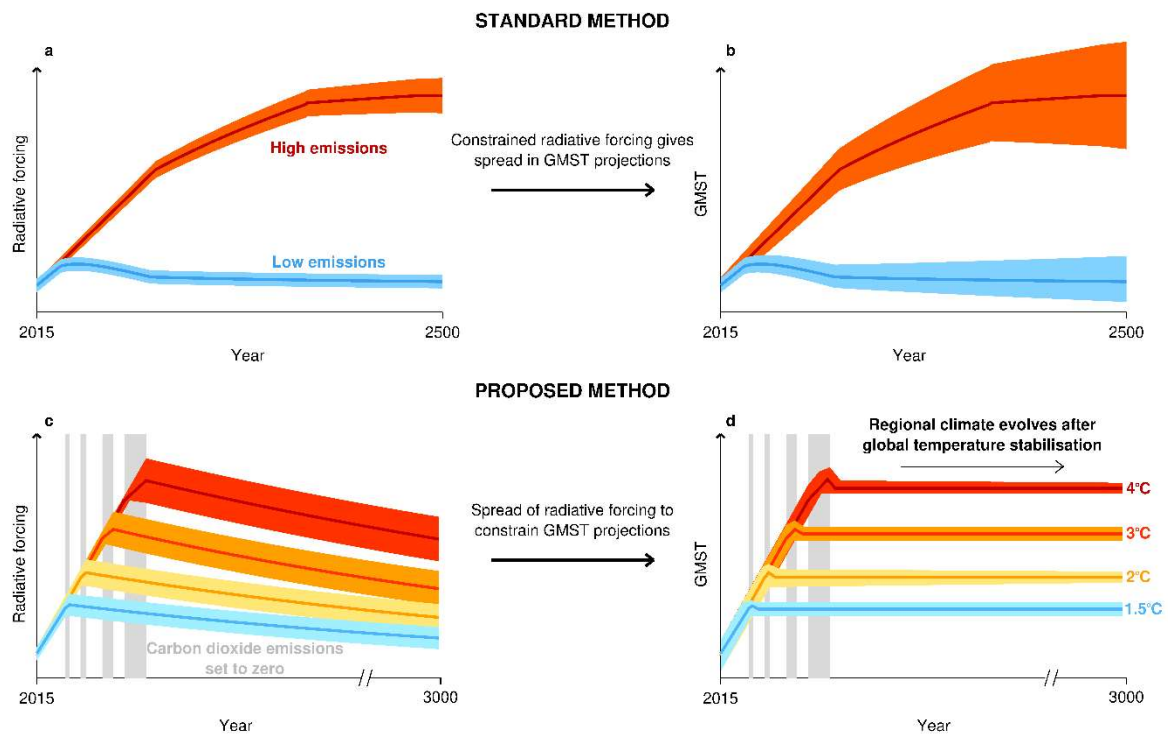
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Method	Details of transient climate state
Pattern scaling	Tebaldi and Knutti ² focussed on periods and scenarios with little to no global warming (2081-2100 Representative Concentration Pathway (RCP)2.6 and RCP4.5) following more rapid warming earlier in the 21 st century.
	Seneviratne et al. ¹ investigated pattern scaling with different emissions scenarios encompassing the whole range of CMIP5 2006-2100 global warming rates.
Time sampling	Schleussner et al. ³ used rapid warming projections (RCP8.5 predominantly sampled from the early-to-mid 21 st century), but other studies have used a combination of scenarios and this was also the approach of IPCC AR6 WG1.
Single coupled model experiments	The Community Climate simulations ⁴ are characterised by weak global warming trends in the second half of the 21 st century, but this follows from a period of rapid global warming in the early 21 st century. The emulator used is also trained on transient warming climates.

<p>Multi-model atmosphere only simulations</p>	<p>The Half a degree additional warming, prognosis and projected impacts simulations⁵ sample RCP2.6 and RCP4.5 with little to no global warming to generate data at Paris GWLs. Sea surface temperature fields forcing atmospheric models are derived from periods with warming trends.</p>
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161 **Figure 1. A framework for delivering climate projections consistent with the Paris**
 162 **Agreement.** Instead of the traditional method of Model Intercomparison Projects where (a)
 163 prescribed radiative forcings give rise to (b) large spread in global temperature projections,
 164 we propose that modelling centres adopt (c) differing radiative forcing pathways for each
 165 model to enable (d) stabilised climate projections at 1.5, 2, 3, and 4°C global warming. In (c)
 166 and (d) the grey bars indicate when carbon dioxide emissions are set to zero to achieve the
 167 desired GWLs, which will vary across the ensemble of models. Models which warm faster

168 will have carbon dioxide emissions turned off earlier than models which warm more slowly.

169 GMST= Global Mean Surface Temperature. This schematic is for illustrative purposes only.

170 **Box 1. An experimental framework for simulating climate stabilisation**

171 There are several different ways in which the desired 1.5, 2, 3 and 4°C GWL simulations
172 could be configured. We recommend a technique that builds on the methods used in Jones et
173 al.¹⁴, Rugenstein et al.⁸, and Sigmond et al.¹¹ and may be applied to Earth System Models.

174 The proposed simulations branch from pre-existing simulations and should be run in
175 emissions mode with carbon dioxide emissions set to zero. Models with pre-existing “esm-
176 ssp585” simulations are already run in emissions mode, but for models without these runs
177 they may branch from “ssp585” simulations with a switch from concentration mode to
178 emissions mode.

179 Shortly after global mean warming has surpassed the desired GWL in the pre-existing SSP5-
180 8.5 simulation (either “esm-ssp585” or “ssp585”) the new simulation is initialised with no
181 further anthropogenic carbon dioxide or aerosol emissions. The choice of forcing these
182 simulations with zero emissions rather than fixed concentrations should result in global-
183 average temperature stabilisation occurring earlier in the model simulations, although some
184 drift remains possible¹⁷. Any drift in GMST would be at a much slower rate than recent
185 climate change and near-term climate projections.

186 A five-year global mean surface temperature may be used to smooth out interannual
187 variability when selecting the branch year from SSP5-8.5. The 1850-1900 period from the
188 historical simulation of the corresponding model should be used as a proxy for a pre-
189 industrial climate baseline for consistency with IPCC AR6 WG1, despite there being some
190 small anthropogenic influence by this time. The exact timing of when the new simulation
191 branches from the corresponding SSP5-8.5 simulation will require testing and likely be
192 model-dependent as the spread in Zero Emissions Commitment Model Intercomparison
193 Project¹⁴ (ZECMIP) results for GMST following cessation of carbon dioxide emissions

194 suggests¹⁷. This may require an iterative process where a simulation branches from a different
195 point from initially selected, so we suggest running the simulation for ten years and checking
196 that the five-year average GMST for years 6-10 is within 0.1°C of the target GWL. If the
197 simulation is warmer than the target GWL then an earlier branch time is required and *vice*
198 *versa*. In ZECMIP, which differs from this framework in several respects, there are weak
199 relationships between Transient Climate Response (and related model characteristics) and
200 GMST change after carbon dioxide emissions have ceased¹⁷. These may be used to guide the
201 initial selection of when the new simulation branches from SSP5-8.5 for a given model.

202 Land use and ozone emissions remain fixed at the levels seen in the year branching from the
203 SSP5-8.5 simulation while other anthropogenic greenhouse gas emissions return to 1850
204 levels. Following Sigmond et al.¹¹, models with an interactive carbon cycle that are run
205 following the method above should simulate a climate with GMST stabilisation close to the
206 target GWLs.

207 These simulations are run to at least 2500 CE, and preferably 3000 CE, to capture changes as
208 stabilisation occurs. The SSP5-8.5 simulations for some models may not warm fast enough
209 for 4°C simulations to be viable for those models.