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Accepted Version

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

Following the Paris Agreement, there have been hundreds of studies researching the impacts of 1.5°C and 2°C of global warming above pre-industrial levels. Multiple methods have been developed to address the question of how regional climate change and impacts differ between global warming levels (GWLs) including pattern scaling[1,2], time-slicing of existing climate projections[3], single coupled-model experiments[4], and multi-model atmosphere-only experiments[5]. The problem is that while the Paris Agreement is not explicit, the intention is that of stabilised global temperatures well below the 2°C GWL, or preferably the 1.5°C GWL, rather than continued global warming[6], but the methods described above are based on transient projections in one form or other (Table 1) that do not reflect stabilised climates. This issue has come to the fore in the use of a time-sampling approach of transient simulations for the generation of GWL-based climate projections in Working Group 1 of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WG1).

Warming versus stabilising climate

With respect to a specific GWL, like the 1.5°C Paris Agreement limit, data can be produced showing how a 1.5°C warmer world may look under high greenhouse gas emissions (e.g. Shared Socioeconomic Pathway 5 –8.5; SSP5-8.5) or in a slower warming world (e.g. SSP1-2.6) using a time-slicing method. But it is also known that slow climate processes (such as ice sheet melt and changes in deep ocean circulation) mean that over centuries the climate evolves even as greenhouse gas forcings on the climate stabilise. It has long been understood from abrupt increased CO_2 simulations that global warming under fixed CO_2 concentrations continues for centuries, and that while early in the simulations warming is concentrated over land, as time progresses the focus of warming shifts to high-latitude ocean areas, including the Southern Ocean and North Atlantic[7–9]. While we do not yet have specific model experiments to answer the question of how a 1.5°C warmer world with no warming trend differs from a world warming transiently through 1.5°C, existing evidence points to substantial differences. For around 15% of the world surface, the difference in local seasonal temperatures between rapid warming and quasi-equilibrium climate states at the same GWL exceeds the difference between the 1.5°C and 2°C GWLs[10]. We also know that climate extremes differ depending on the rate of global warming, with hot summers in areas of Europe, Asia and the US, more than twice as common in a fast warming climate than a quasi-equilibrium climate at the same GWL[10]. In bespoke simulations, Sigmond et al.[11] recently showed that the Atlantic Meridional Overturning Circulation and associated surface temperature patterns continue to evolve as the climate stabilises at specified GWLs. There is also evidence that weather and rainfall patterns vary between rapidly-warming and stabilising climate states[12]. Further elucidation of regional climate patterns and impacts in climates undergoing stabilisation at specified levels of global warming is needed to fully understand the implications of the 1.5°C and 2°C GWLs in the Paris Agreement, and of higher GWLs we may yet reach. However, the few existing multi-model studies in this area have been hampered by a lack of suitable experiments to analyse climate stabilisation at specific GWLs. Currently, impacts studies at 1.5 and 2°C GWLs are not based on the stabilising climate states the Paris Agreement refers to. This may lead to ill-informed decision-making, particularly in regions where the rate of global warming has a large effect on local climate.

New experiments needed

Here, we propose that modelling groups consider performing experiments with climate stabilisation at 1.5, 2, 3, and 4°C GWLs that will allow for the required analyses needed to understand climate impacts associated with the Paris Agreement and higher GWLs that may be reached if we fail to meet the Paris targets. This involves a departure from the standard Model Intercomparison Projects (MIPs) which have formed a large part of global climate modelling efforts over the last two and a half decades. In the MIPs, models are run with a given radiative forcing (Fig. 1a) resulting in a range of temperature responses due to model differences (including climate sensitivity) and internal climate variability[13] (Fig. 1b). We propose a new approach whereby carbon dioxide emissions are set to zero at different times in different models depending on the model response (Fig. 1c) to generate specified stabilising climate states at approximately 1.5, 2, 3, and 4°C GWLs beyond 2200 (Fig. 1d). In this approach a model which warms faster under SSP5-8.5 would follow a lower concentration pathway to achieve climate stabilisation at the targeted GWL compared with a model which warms more slowly under SSP5-8.5.

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

The experiments we propose here bear similarities to some existing projects, but fill an important gap not met by previous work. The 21st century scenario simulations exhibit different rates of warming, but none result in climate stabilisation and models warm to different levels in part due to climate sensitivity differences. The Zero Emissions Commitment Model Intercomparison Project[14] is examining climate responses after carbon emissions cease, but while this results in some degree of climate stabilisation, models will stabilise at a range of GWLs depending on their climate sensitivities. The suggested model experiments are also similar to aspects of the community climate simulations developed by Sanderson et al.[4], but differ in that the proposed experiments are longer, thus allowing a greater degree of climate stabilisation, and the design is not based on using an emulator. Also, in the proposed framework multiple models would be considered, and 3 and 4°C GWLs would be included as these align more closely with global climate projections under the current global emissions pathway and something akin to a worst-case scenario respectively. The simulations proposed here would build on those of Sigmond et al.[11] and ongoing experiments in the UK by authors AJD and EH, but as mentioned previously we hope for the participation of multiple modelling centres. While we understand the proposed experiments require significant computational costs and data storage we believe the importance of the problem at hand (i.e. the current deficiency in understanding of climate change impacts in line with the Paris Agreement) necessitates an ambitious plan.

Preparing for a more stable climate

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

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

- exploring changes to weather systems which are sensitive to land-ocean temperature differences, such as monsoons[16], and
- quantifying exposure and understanding vulnerability to climate hazards and how these change as the climate stabilises at different GWLs.

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

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

Acknowledgements

A.D.K. was funded by the Australian Research Council (DE180100638). J.M.K.S. was funded by Australian Research Council grant FL160100028 to Prof. Jon Woodhead. A.J.D. and E.H. were funded by the UK NERC REAL project (NE/N018591/1).

Competing Interests

The authors declare no competing interests.

Author contributions

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

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Figures and Tables

Table 1. Existing tools and techniques for analysing climates at the Paris Agreement global warming levels based on publicly available data.

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 21st 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 21st 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 21st century, but this follows from a period of rapid global warming in the early 21st century. The emulator used is also trained on transient warming climates.

Multi-model atmosphere only simulations	The Half a degree additional warming, prognosis and projected impacts simulations[5] 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.

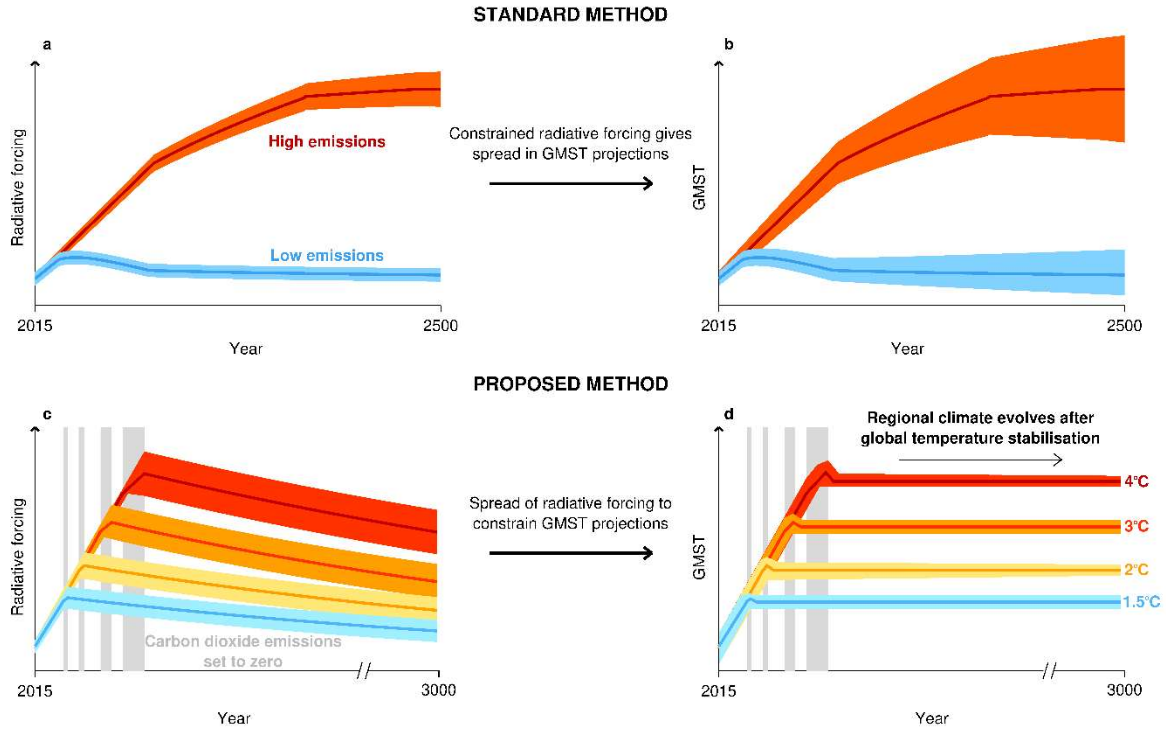

Figure 1. A framework for delivering climate projections consistent with the Paris Agreement. Instead of the traditional method of Model Intercomparison Projects where (**a**) prescribed radiative forcings give rise to (**b**) large spread in global temperature projections, we propose that modelling centres adopt (**c**) differing radiative forcing pathways for each model to enable (**d**) stabilised climate projections at 1.5, 2, 3, and 4°C global warming. In (**c**) and (**d**) the grey bars indicate when carbon dioxide emissions are set to zero to achieve the desired GWLs, which will vary across the ensemble of models. Models which warm faster

will have carbon dioxide emissions turned off earlier than models which warm more slowly. GMST= Global Mean Surface Temperature. This schematic is for illustrative purposes only.

Box 1. An experimental framework for simulating climate stabilisation

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

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

Shortly after global mean warming has surpassed the desired GWL in the pre-existing SSP5-8.5 simulation (either "esm-ssp585" or "ssp585") the new simulation is initialised with no further anthropogenic carbon dioxide or aerosol emissions. The choice of forcing these simulations with zero emissions rather than fixed concentrations should result in global-average temperature stabilisation occurring earlier in the model simulations, although some drift remains possible[17]. Any drift in GMST would be at a much slower rate than recent climate change and near-term climate projections.

A five-year global mean surface temperature may be used to smooth out interannual variability when selecting the branch year from SSP5-8.5. The 1850-1900 period from the historical simulation of the corresponding model should be used as a proxy for a pre-industrial climate baseline for consistency with IPCC AR6 WG1, despite there being some small anthropogenic influence by this time. The exact timing of when the new simulation branches from the corresponding SSP5-8.5 simulation will require testing and likely be model-dependent as the spread in Zero Emissions Commitment Model Intercomparison Project[14] (ZECMIP) results for GMST following cessation of carbon dioxide emissions suggests[17]. This may require an iterative process where a simulation branches from a different point from initially selected, so we suggest running the simulation for ten years and checking that the five-year average GMST for years 6-10 is within 0.1°C of the target GWL. If the simulation is warmer than the target GWL then an earlier branch time is required and *vice versa*. In ZECMIP, which differs from this framework in several respects, there are weak relationships between Transient Climate Response (and related model characteristics) and GMST change after carbon dioxide emissions have ceased[17]. These may be used to guide the initial selection of when the new simulation branches from SSP5-8.5 for a given model.

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

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