Global and regional impacts differ between transient and equilibrium warmer worlds

Andrew D. King^{1,2}, Todd P. Lane^{1,2}, Benjamin J. Henley^{1,2,3}, Josephine R. Brown^{1,2}

1. School of Earth Sciences, University of Melbourne, Parkville, Australia.

2. ARC Centre of Excellence for Climate Extremes, University of Melbourne, Parkville, Australia.

3. School of Earth, Atmosphere and Environment, Monash University, Clayton, Australia

Corresponding author: Andrew King (andrew.king@unimelb.edu.au)

Recently there has been interest in understanding differences between specific levels of global warming, especially the Paris Agreement limits of 1.5°C and 2°C above pre-industrial levels. However, different model experiments^{1–3} have been used in these analyses under varying rates of increase in global-average temperature. Here, we use climate model simulations to show that for a given global temperature, most land is significantly warmer in a rapidly warming (“transient”) case than in a quasi-equilibrium climate. This results in more than 90% of the world’s population experiencing a warmer local climate under transient global warming than equilibrium global warming. Relative to differences between the 1.5°C and 2°C global warming limits, differences between transient and quasi-equilibrium states are substantial. For many land regions the probability of very warm seasons is at least two times greater in a transient climate than in a quasi-equilibrium equivalent. In developing regions, there are sizable differences between transient and quasi-equilibrium climates underlining the importance of explicit framing of projections. Our study highlights the need to better understand differences between future climates under rapid warming and quasi-equilibrium conditions for the development of climate change adaptation policies. Yet, current multi-model experiments^{1,4} are not designed for this purpose.

Main

Since the Paris Agreement of 2015, in which signatories agreed to “Holding the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels”, there have been many analyses examining the implications of 1.5°C and 2°C of global warming, some of which are summarised in the Intergovernmental Panel on Climate Change special report on 1.5°C (IPCC SR1.5⁵). Many different methods⁶ and experiments have been used to better understand the differences between 1.5°C and 2°C of global warming above pre-industrial levels including: timeslice extraction from coupled climate model ensembles^{7,8}, use of single

coupled model ensembles^{3,9}, multi-model atmosphere-only ensembles², and pattern scaling^{10,11}.

It is not explicitly stated in the Paris Agreement text whether the warming levels refer to equilibrium or transient levels of global warming, however, it is generally inferred that these targets refer to stabilised climate¹². Most of the analyses designed to understand the consequences of these global warming targets, especially those focussed on atmospheric variables, use transient model experiments (analyses of sea level rise¹³ and other oceanic variables often use longer coupled-model experiments). For example, timeslice extractions under high greenhouse gas emissions scenarios from the fifth phase of the Coupled Model Intercomparison Project experiment (CMIP5¹) sample a world rapidly warming through the Paris Agreement limits. Specially designed experiments, such as the Community Earth System Model ensemble³, are run to emulate 1.5°C and 2°C warmer worlds with evolving radiative forcings for two centuries to generate climates that are, in a globally averaged sense for surface air temperature, in a quasi-equilibrium state. The atmosphere-only simulations that form the 1.5°C and 2°C climates in the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI²) experiment are forced by warming recent observed sea surface temperatures using transient CMIP5 simulations. These different experiments and methods each have differing degrees of transience and none are in full equilibrium. While they all have value, a robust comparison between transient and equilibrium climates has not been possible due to fundamental differences in model design.

Previous work comparing transient and equilibrium climates has typically used single global climate models^{14,15} or a small ensemble of models, so agreement and consistency between models may be investigated¹⁶. As a result, some differences between transient and equilibrium climates may be inherent to the model, or models, used in these prior analyses. In

addition, many transient simulations of a single model are needed to adequately sample across phases of internal variability to make a robust comparison.

In this study we demonstrate that transient and quasi-equilibrium climates may be compared using extended medium-emissions and short-term high emissions simulations from the CMIP5¹ multi-model ensemble. Our “timeshift technique”¹⁷ allows multiple models to be analysed concurrently, so that large samples of model years are generated for both the transient and quasi-equilibrium climate states. We demonstrate that for projections of mean and extreme temperatures, the use of transient or quasi-equilibrium climate states has a substantial effect on the outcomes.

We use the extended mid-range greenhouse gas emissions simulations to 2300 (ECP4.5) from the CMIP5 ensemble¹ (Table S1) to generate a quasi-equilibrium ensemble that may be directly compared to transient warming through the equivalent model’s level of global warming under a high emissions scenario (RCP8.5). The model-simulated global mean warming is subtracted from each models’ distribution of global-average temperatures to generate ensembles for the comparison of transient and quasi-equilibrium climate states (Fig. 1) with regional average and extreme temperatures subsequently investigated. The robustness of this method, particularly the efficacy of comparing transient and quasi-equilibrium climates derived from a selection of models across global warming levels, and associated sensitivity tests are discussed in the Methods and Supplementary Information. Specifically, we demonstrate that the difference between transient and quasi-equilibrium warming patterns shows little dependence on the level of global warming itself (Supplementary Information) which differs by almost 2°C across the models analysed here (Table S1). We use this result to allow for the difference between transient and quasi-equilibrium climates to be compared with the 0.5°C increment of warming between the Paris Agreement warming levels.

From the ensembles of transient and equivalent quasi-equilibrium climates we may infer differences between these climate states. For most land areas of the world the average boreal summer (June-August, JJA) and winter (December-February, DJF) temperatures are substantially higher in the transient climate relative to the equivalent quasi-equilibrium climate with strong model agreement. This is especially true in boreal summer over continental climate zones in the northern hemisphere (Fig. 2a, b). In contrast, over the Southern Ocean and the North Atlantic there are large areas where a quasi-equilibrium climate is on average at least 0.5°C warmer than the equivalent transient climate. In the quasi-equilibrium world, the passage of time has resulted in heat redistribution such that the land regions are cooler and the extratropical oceans are warmer^{14,18}. This result aligns with previous work showing that ocean warming lags that over the land surface¹⁹. The quantification of these differences is important, especially given the recent focus on inferring differences in future warmer climates. As land regions are warmer in the transient climate state, most of the world's people would experience higher average local temperatures than in a quasi-equilibrium world. In boreal summer, 91% of the world's population²⁰ (90% confidence interval of 76-97%) would experience warmer average temperatures in the transient climate state. Many people in North America and Eurasia would experience at least a 0.5°C warmer local climate in a transient climate than in the quasi-equilibrium equivalent state. In boreal winter, 85% of the global population (90% CI: 70-92%) are in locations where the transient climate is warmer than the quasi-equilibrium climate. In total, over 600 million people in boreal summer and over 200 million in boreal winter live in locations where a rapidly warming climate is at least 0.5°C warmer than the equivalent equilibrium climate. In comparison, fewer than 20 million people live in locations where an equilibrium climate is on average more than 0.5°C warmer than the transient equivalent for either boreal summer or winter.

The difference between transient and quasi-equilibrium climate states is substantial relative to the difference between the projected 1.5°C and 2°C warmer worlds^{8,11} (Fig. 3). Over the Southern Ocean and North Atlantic, where the regional projected warming from 1.5°C to 2°C of global warming is lower than elsewhere, the difference between transient and quasi-equilibrium climates exceeds the difference in regional temperatures between the Paris Agreement levels. Both these regions play major roles in the uptake and transport of carbon and heat²¹ as they warm at much slower rates relative to other parts of the world.

Overall, around 15% of the world's surface area has a bigger difference between the transient and quasi-equilibrium climates than between the Paris Agreement warming levels. This includes both slow-warming ocean areas, where the quasi-equilibrium 1.5°C world is warmer than a transient 2°C world, and continental land regions, where the transient 1.5°C world is warmer than a quasi-equilibrium 2°C world. For a typical location on the world's surface, the absolute difference between transient and quasi-equilibrium climates amounts to around 40% of the absolute difference between the Paris warming limits.

The difference between transient and equilibrium climates extends to temperature extremes. The probability ratio of moderate heat extremes²², such as one-in-ten hot seasons (Fig. 4a,b), shows broad regions where in the transient climate a heat event is twice as likely (i.e. a one-in-five year event instead) compared to a quasi-equilibrium climate state. This is particularly true in boreal summer where, for almost all land regions of the world the likelihood of a hot season is significantly higher in a transient climate than the equivalent quasi-equilibrium state. Regions with at least a doubling in the probability of hot summers in a transient climate compared to a quasi-equilibrium world of equivalent global warming encompass major cities including New York City, Istanbul, Baghdad, Seoul, and Tokyo. While this is a global-scale analysis, one could infer that for these densely populated locations, the heat-related impacts

of human-induced climate change would be lessened in a stabilised climate relative to a rapidly warming climate at the same level of global warming.

A similar pattern of results is found when examining cold extremes, with far fewer cold seasons (below the 10th percentile extracted from the quasi-equilibrium climate) in the transient climate state in northern hemisphere land areas (Fig. S5). Overlaying gross domestic product (GDP) per capita estimates²⁰ shows that poorer areas of the world tend to experience greater probability of hot seasons in a transient climate than a quasi-equilibrium equivalent (in DJF the correlation is -0.39, although in JJA it is negligible). There is a large benefit of climate stabilisation in terms of reduced frequency of hot extremes, relative to a rapidly warming climate at the same global warming level, and this is particularly true for the developing world where the likelihood of hot seasons is reduced year-round.

Many analyses written for the IPCC SR1.5 have focussed on understanding changes in hot and cold extremes between the Paris Agreement global warming limits^{8,23,24}. The results presented in this study demonstrate that the difference in the frequency of hot and cold extremes between a transient and quasi-equilibrium climate state at a given level of global warming is also large for many populated regions of the world. The frequency of hot summers for global-average temperature passing through a global warming level relative to equilibrating at that level is starkly different in the Middle East, much of Eurasia and northern Africa, and North America. Results from some studies of future extremes, such as ref.²³, may apply to transient 1.5°C and 2°C warmer worlds, but would likely represent substantial overestimates for changes in the frequency of heat extremes for equilibrium 1.5°C and 2°C climates relative to the present.

The comparison of RCP8.5 and ECP4.5 simulations from a multi-model ensemble allows us to isolate the effects of the transient and quasi-equilibrium nature of the different model

experiments. This allows us to address a fundamental question about the nature of the Earth's climate system: what differences in climate would we expect between transient and equilibrium warmer worlds for a given level of global warming? This is a vitally important question in the context of international agreements such as the Paris Agreement, where analyses using transient and equilibrium climate model experiments may yield different results and lead to the formation of different conclusions and policy pathways. It is worth noting that some of the largest differences between transient and quasi-equilibrium climate states are identified for regions which are poorly observed and where model biases exist, such as the Southern Ocean²⁵. As a result, projections for the Southern Ocean should be treated with caution, although they generally align with our understanding of the climate system¹⁹. For further discussion of the results over the Southern Ocean see Supplementary Material.

The differences between transient and equilibrium climate states have important implications in impacts modelling. For example, some empirical impacts models, such as damage functions²⁶, are based on global-average warming, but in reality one would expect different economic costs to occur between transient and equilibrium warmer worlds for both the globe as a whole²⁶ and individual countries,²⁷ especially developing countries in the tropics, due to the different patterns of regional warming. Differences in methods used to simulate future climates and their impacts have the potential to lead to decision-makers receiving inadequate information about the nature of possible future climates for their region of interest. This may result in the development of ineffective policy, especially in building resilience for future extreme heat events, which is already more challenging in the developing world²⁸.

Many of our results suggest that the differences between transient and quasi-equilibrium climates are substantial. A future 1.5°C or 2°C quasi-equilibrium warmer climate reached after overshoot (where global warming has exceeded these limits but then fallen) would likely look very different to the equivalent transient 1.5°C or 2°C climate that the world is

likely to experience in the coming decades^{29,30}. Indeed, a transient warmer world represents a poor predictor for an equivalent equilibrium world in many populated land regions where the difference in average seasonal temperatures is at least 0.5°C and the likelihood of hot extremes is at least twice as high in some places under the transient state. Studies of the implications of future global warming must be very clear in their framing of results with respect to the transience of the experiments used for their conclusions to be relevant for policy development.

Current multi-model projection efforts, such as CMIP5¹ and the subsequent CMIP6⁴ projects, do not incorporate experiments that explicitly address the needs of policy-makers following the Paris Agreement. Multi-model experiments that may be used to examine climate change at stabilised 1.5°C and 2°C warmer climates would be invaluable in meeting the needs of decision-makers given that the Paris Agreement is implicitly targeting stabilised global warming levels¹² and we have demonstrated here that the rate of global warming has a large effect on the warming pattern across the globe. While single-model experiments have been performed³, these are not a substitute for multi-model projections that can more comprehensively examine the impacts of the Paris Agreement global warming levels.

Our study highlights the striking differences in model-simulated transient and quasi-equilibrium climate states. We find that these differences are significant and substantial across many regions of the world, such that they must be considered in the design of both model studies on the implications of future global warming, and in the design of future multi-model experiments following CMIP5 and CMIP6. Studies must be clear in the precise definition of temperature targets and the framework given the differing implications of a given level of global warming depending on the transience of the climate state.

References

- 223 1. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the
224 Experiment Design. *Bull. Am. Meteorol. Soc.* **93**, 485–498 (2012).
- 225 2. Mitchell, D. *et al.* Half a degree additional warming, prognosis and projected impacts
226 (HAPPI): background and experimental design. *Geosci. Model Dev* **10**, 571–583
227 (2017).
- 228 3. Sanderson, B. M. *et al.* Community Climate Simulations to assess avoided impacts in
229 1.5°C and 2°C futures. *Earth Syst. Dyn. Discuss.* (2017). doi:10.5194/esd-2017-42
- 230 4. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6
231 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958
232 (2016).
- 233 5. Masson-Delmotte, V. *et al.* *Global warming of 1.5°C. An IPCC Special Report on the*
234 *impacts of global warming of 1.5°C above pre-industrial levels and related global*
235 *greenhouse gas emission pathways, in the context of strengthening the global response*
236 *to the threat of climate change.*, (2018).
- 237 6. James, R., Washington, R., Schleussner, C.-F., Rogelj, J. & Conway, D.
238 Characterizing half-a-degree difference: a review of methods for identifying regional
239 climate responses to global warming targets. *Wiley Interdiscip. Rev. Clim. Chang.* **8**,
240 e457 (2017).
- 241 7. Schleussner, C.-F. *et al.* Differential climate impacts for policy-relevant limits to
242 global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dyn.* **7**,
243 327–351 (2016).
- 244 8. King, A. D., Karoly, D. J. & Henley, B. J. Australian climate extremes at 1.5 °C and 2
245 °C of global warming. *Nat. Clim. Chang.* **7**, (2017).

- 246 9. Lehner, F. *et al.* Projected drought risk in 1.5°C and 2°C warmer climates. *Geophys.*
247 *Res. Lett.* **44**, 7419–7428 (2017).
- 248 10. Tebaldi, C. & Knutti, R. Evaluating the accuracy of climate change pattern emulation
249 for low warming targets. *Environ. Res. Lett.* **13**, 055006 (2018).
- 250 11. King, A. D. *et al.* On the linearity of local and regional temperature changes from
251 1.5°C to 2°C of global warming. *J. Clim.* JCLI-D-17-0649.1 (2018).
252 doi:10.1175/JCLI-D-17-0649.1
- 253 12. Rogelj, J., Schleussner, C.-F. & Hare, W. Getting It Right Matters: Temperature Goal
254 Interpretations in Geoscience Research. *Geophys. Res. Lett.* **44**, 10,662–10,665 (2017).
- 255 13. Mengel, M., Nauels, A., Rogelj, J. & Schleussner, C.-F. Committed sea-level rise
256 under the Paris Agreement and the legacy of delayed mitigation action. *Nat. Commun.*
257 **9**, 601 (2018).
- 258 14. Manabe, S., Stouffer, R. J., Spelman, M. J. & Bryan, K. Transient Responses of a
259 Coupled Ocean–Atmosphere Model to Gradual Changes of Atmospheric CO₂. Part I.
260 Annual Mean Response. *J. Clim.* **4**, 785–818 (1991).
- 261 15. Blackport, R. & Kushner, P. J. The Transient and Equilibrium Climate Response to
262 Rapid Summertime Sea Ice Loss in CCSM4. *J. Clim.* **29**, 401–417 (2016).
- 263 16. Boulange, J., Hanasaki, N., Veldkamp, T., Schewe, J. & Shiogama, H. Magnitude and
264 robustness associated with the climate change impacts on global hydrological variables
265 for transient and stabilized climate states. *Environ. Res. Lett.* **13**, 064017 (2018).
- 266 17. Herger, N., Sanderson, B. M. & Knutti, R. Improved pattern scaling approaches for the
267 use in climate impact studies. *Geophys. Res. Lett.* **42**, 3486–3494 (2015).
- 268 18. Held, I. M. *et al.* Probing the Fast and Slow Components of Global Warming by

- 269 Returning Abruptly to Preindustrial Forcing. *J. Clim.* **23**, 2418–2427 (2010).
- 270 19. Long, S.-M., Xie, S.-P., Zheng, X.-T. & Liu, Q. Fast and Slow Responses to Global
271 Warming: Sea Surface Temperature and Precipitation Patterns. *J. Clim.* **27**, 285–299
272 (2014).
- 273 20. Murakami, D. & Yamagata, Y. Estimation of gridded population and GDP scenarios
274 with spatially explicit statistical downscaling. (2016).
- 275 21. Frölicher, T. L. *et al.* Dominance of the Southern Ocean in Anthropogenic Carbon and
276 Heat Uptake in CMIP5 Models. *J. Clim.* **28**, 862–886 (2015).
- 277 22. Fischer, E. M. & Knutti, R. Anthropogenic contribution to global occurrence of heavy-
278 precipitation and high-temperature extremes. *Nat. Clim. Chang.* **5**, 560–564 (2015).
- 279 23. King, A. D. & Karoly, D. J. Climate extremes in Europe at 1.5 and 2 degrees of global
280 warming. *Environ. Res. Lett.* **12**, (2017).
- 281 24. Dosio, A., Mentaschi, L., Fischer, E. M. & Wyser, K. Extreme heat waves under
282 1.5 °C and 2 °C global warming. *Environ. Res. Lett.* **13**, 054006 (2018).
- 283 25. Grise, K. M. & Polvani, L. M. Southern Hemisphere Cloud–Dynamics Biases in
284 CMIP5 Models and Their Implications for Climate Projections. *J. Clim.* **27**, 6074–
285 6092 (2014).
- 286 26. Nordhaus, W. D. To Slow or Not to Slow: The Economics of The Greenhouse Effect.
287 *Econ. J.* **101**, 920 (1991).
- 288 27. Roson, R. & Sartori, M. *Estimation of Climate Change Damage Functions for 140*
289 *Regions in the GTAP9 Database. Ssrn* (2016). doi:10.2139/ssrn.2742053
- 290 28. Mertz, O., Halsnæs, K., Olesen, J. E. & Rasmussen, K. Adaptation to Climate Change

in Developing Countries. *Environ. Manage.* **43**, 743–752 (2009).

29. Henley, B. J. & King, A. D. Trajectories toward the 1.5°C Paris target: Modulation by the Interdecadal Pacific Oscillation. *Geophys. Res. Lett.* **44**, 4256–4262 (2017).

30. Smith, D. M. *et al.* Predicted Chance That Global Warming Will Temporarily Exceed 1.5 °C. *Geophys. Res. Lett.* (2018). doi:10.1029/2018GL079362

Acknowledgements

We thank Reto Knutti for useful discussions. We acknowledge the support of the NCI facility in Australia and we acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the US Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. A.D.K. is funded through an Australian Research Council Discovery Early Career Researcher Award (DE180100638). T.P.L. is funded through the Australian Research Council Centre of Excellence for Climate Extremes (CE170100023). B.J.H. is funded through an Australian Research Council Linkage project (LP150100062).

Author contributions

A.D.K. conceived the study, developed the methodology, and performed the analysis. All authors discussed the results and contributed to the preparation of the manuscript.

Supplementary Information

Supplementary Text, Figs. 1-13, Tables 1-2 and references.

Methods

Model simulations and population data

Simulations from 13 CMIP5¹ models were used in this analysis (see Table S1). Simulations from the historicalNat experiment were used to calculate a natural climate reference, while ECP4.5 simulations to 2300 were used to construct an approximation for an equilibrium climate and RCP8.5 simulations to 2100 were used to construct a transient ensemble. The surface air temperature ‘tas’ variable was used for all calculations. All model data were interpolated onto a regular 2° grid to allow for comparative analysis between models.

Population and GDP estimates for 2010 were downloaded from the Global Carbon Project (<http://www.cger.nies.go.jp/gcp/population-and-gdp.html>)²⁰ and also interpolated onto a 2° grid. Estimates for 2010 were used as uncertainties are lower than for projections, although we note that the pattern of projected population and wealth does not change greatly up until the mid-21st century and previous work shows low dependence on use of different population and GDP projections for global analyses³¹.

Construction of transient and quasi-equilibrium ensembles

Firstly, a natural climate reference point was constructed for each model by taking the average global-average temperature in historicalNat simulations for 1901-2005. There are many ways of defining a pre-industrial or counterfactual natural climate^{32,33}. In the case of this analysis, it is of more use to have a model-based reference point rather than one constrained by observation-based data as all subsequent analysis is only model-based. Also, the use of a century-long window in the historicalNat simulations provides a well-constrained baseline from a period of relatively few major volcanic eruptions (compared to the often-used late 19th century). This definition for a natural climate reference point has been used previously^{8,11,23}.

The quasi-equilibrium climate is constructed using the extended RCP4.5 simulations to 2300 and is calculated as the 2200-2299 average global-average temperature in each model. The level of global warming in each model from its own natural reference climate to its quasi-equilibrium state is shown (Fig. S1, Table S2). In the 23rd century of the ECP4.5 simulations the climate is not in full equilibrium with changes still evident in the oceans. However, the atmosphere is relatively close to equilibrium and the global-average temperature exhibits relatively weak trends in the 23rd century compared to the transient RCP8.5 simulations (Fig. 1). Model drift is commonly accounted for in analysis of multi-century pre-industrial control simulations³⁴, however, removal of model drift was not adopted here as substantial trends are possible over the course of a single century due to internal variability and we would not desire this effect to be removed. Note that a range of changes, in addition to those studied here, would have occurred in a warmer equilibrium climate of the 23rd century. These include, but are not limited to, higher sea level and reduced ice sheets^{13,35}. Many of these additional changes, and their associated feedbacks on the climate system, are represented with a wide range of uncertainty in the extended CMIP5 simulations¹³.

The transient climate is constructed using the high greenhouse gas emissions RCP8.5 simulations to 2100 (Table S1). Decadal-average global-average temperatures are calculated in moving windows for 2006-2100. All the years within decades where the global-average temperature is within 0.05°C of the same model's quasi-equilibrium level of global warming are extracted.

The transient and quasi-equilibrium ensembles are then constructed by subtracting the level of global warming in each model (Fig. 1). This generates ensembles of 1300 model years in the quasi-equilibrium climate and 369 model years in the transient climate.

There are numerous choices made in the definition of the transient climate state including the length of the moving window for which the global-average temperature is computed (in the main analysis this is ten years) and the leeway given to annual global-average temperature for which years are included in the ensemble (in the main analysis this is $\pm 0.05^{\circ}\text{C}$). Sensitivity of results to these choices is discussed in Supplementary Material.

Analysis of transient and quasi-equilibrium ensembles

The transient and quasi-equilibrium climates were first compared for seasonal-average temperatures (Fig. 2). The median-average seasonal-average temperature difference was computed in each model at each gridbox. The ensemble-median was then calculated at each gridbox as the median of each modelled average difference (so as to evenly weight models and account for the different numbers of transient years in each model). The number of models where the average difference between transient and quasi-equilibrium climates was positive or negative was also computed (Fig. 2, Fig. S6). The population as a function of the average difference between transient and quasi-equilibrium climate states was computed by overlaying the population data onto the ensemble-average difference between the climate states and then aggregating the population. Confidence intervals were calculated through bootstrapping sub-ensembles of the models and re-computing the median average difference between transient and quasi-equilibrium climates across each sub-ensemble at each gridbox 1000 times. The population was again aggregated for each difference between transient and quasi-equilibrium sub-ensembles and the 5th and 95th percentile estimates were extracted. The population was also aggregated for the level of model-agreement in the sign of the transient and quasi-equilibrium temperature difference (Fig. S6c,d).

Comparison with 1.5°C and 2°C warmer worlds

To relate the difference between the transient and quasi-equilibrium climates to policy-relevant global warming levels, the ratio of the difference between transient and quasi-equilibrium seasonal-average temperatures and the difference between seasonal-average temperatures at the Paris Agreement 1.5°C and 2°C global warming limits was computed at each location. The 1.5°C and 2°C climates were constructed following the method described in ref⁸ and the difference in seasonal-average temperatures is shown in Figure 1f,i of ref¹¹. The method for constructing the 1.5°C and 2°C climates uses timeslices, much like the transient ensemble described previously, but using simulations under all available greenhouse gas emissions scenarios and a larger leeway for global decadal-average temperatures. The ratio of the absolute difference in seasonal-average temperatures between transient and quasi-equilibrium climates and the absolute difference in seasonal-average temperatures between 1.5°C and 2°C warmer worlds was computed at each location. The statistical distribution of this ratio as a function of global area coverage was then computed by area-weighting each gridbox and aggregating the areas. We note that the 1.5°C warmer world tends to sample earlier periods in the 21st century compared with the 2°C warmer worlds. This results in a different balance of forcings with reduced anthropogenic aerosol concentrations in the 2°C world relative to the 1.5°C world in locations such as East Asia^{11,36}. This means that the difference between the 1.5°C and 2°C warmer worlds is not entirely related to anthropogenic greenhouse gas concentrations as there is a small aerosol component to the difference also.

Analysis of extremes

The difference in hot and cold extremes between the transient and quasi-equilibrium climates was also investigated by examining hot and cold seasonal-average temperatures above the 90th and below the 10th percentile respectively at each location. The percentiles were

extracted from the quasi-equilibrium climate ensemble as it is larger than the transient equivalent such that the tails of the distributions are better constrained. Only these moderate extremes were examined due to the sample sizes involved.

The probability ratios of extremes in the transient climate above and below the 90th and 10th percentiles derived from the quasi-equilibrium climate were calculated. Probability ratios (sometimes known as risk ratios) are widely used in the analysis of changing extremes^{22,37} and are a useful tool in comparing extremes between two climate states (often current and pre-industrial climates, but in this case transient and quasi-equilibrium climates).

As the transient ensemble has more spread in global-average annual-average temperatures than the quasi-equilibrium ensemble (Fig. 1), there is a risk of over-estimating the likelihood of local-scale extremes in the transient climate relative to the quasi-equilibrium climate. To account for this a scaling factor was applied to the probability ratios based on the global-average temperature at the 10th and 90th percentiles in the transient ensemble relative to the quasi-equilibrium ensemble.

$$\text{Scaling Factor (cold)} = \frac{100 - P_{10}}{90},$$

$$\text{Scaling Factor (hot)} = \frac{P_{90}}{90}$$

where P_{10} and P_{90} are the percentiles of the transient distribution of global annual temperatures equivalent to the temperatures at the 10th and 90th percentiles in the quasi-equilibrium distribution of global annual temperatures respectively. The scaling factors are subsequently applied to the probability ratios computed at every location. Note that the weight of the tails of the distributions may have a higher-order effect on the probability ratios that is not accounted for with this scaling factor, but that this effect is small as demonstrated by the subsequent analysis on the effect of using a scaling factor.

Note, a sensitivity test on the use of a scaling factor was conducted using a smaller ensemble of transient model years with shorter 6-year timeslices. This alternate transient ensemble produces a much narrower distribution of global annual average temperatures (Fig. S7) which is statistically indistinguishable from the distribution of global annual average temperatures from the quasi-equilibrium ensemble (Kolmogorov-Smirnov test with $p > 0.1$). This allows for the extremes analysis to be repeated, without any scaling factor required, using the smaller transient ensemble. The resulting maps of probability ratios are very similar between the use of the larger ensemble with scaling and smaller ensemble with no scaling (pattern correlations in excess of 0.89 for JJA and DJF hot and cold extremes; Fig. S10).

The multi-model ensemble median probability ratio for hot and cold was computed at each location (Fig. 4a,b, Fig. S5). Sample uncertainty estimates were computed by bootstrapping 50% of the model ensemble 1000 times and recalculating the probability ratio at each gridbox. If at least 90% of the probability ratios were above or below one then there is at least 90% confidence in the probability of a hot or cold extreme being higher in either the transient or quasi-equilibrium ensemble. This commonly used method provides an estimate of the influence of sampling uncertainty on the best-estimate results. We note that a range of methods are available for this purpose in addition to the “bootstrap percentile” used here and that the use of moderate thresholds, and the methodological design which prevents extreme probability ratios, avoids the largest limitations associated with this method³⁸.

The GDP per capita estimates for 2010 were derived by simply dividing the gridded GDP estimates by the population estimates. The GDP per capita estimates at each location were plotted against the median probability ratio for that location (Fig. 4c,d). Four large sub-continental regions³⁹ primarily composed of locations in the developing world were highlighted (Central America [116°W-83°W, 10°N-30°N]. West Africa [20°W-22°E, 12°S-18°N], Sahara [20°W-65°E, 18°N-30°N], and Southeast Asia [95°E-155°E, 11°S-20°N]).

Note that Central America and Sahara in particular include a few locations in the developed world.

The relationship between the gridbox median probability ratio and the corresponding gridbox GDP per capita was examined using a Spearman rank correlation coefficient. A non-parametric test was required due to the highly non-Gaussian nature of the statistical distribution of GDP per capita.

A sensitivity test using future population and GDP estimates (under Shared Socioeconomic Pathway 1⁴⁰) was performed, but, as the global distribution of wealth does not exhibit a major change, the results are very similar³¹ (not shown).

Data availability

The model data used in this study are available in public repositories, for example at <https://esgf-node.llnl.gov/projects/esgf-llnl/>. The model data used here were stored on the Australian node of the Earth System Grid (the National Computational Infrastructure). Population and GDP data were downloaded from the Global Carbon Project (<http://www.cger.nies.go.jp/gcp/population-and-gdp.html>). The figures and the IDL code used in this analysis is available: <https://zenodo.org/record/3471030#.XaVve-gzbIU> (doi:10.5281/zenodo.3471029). Raw figure data are available here: https://melbourne.figshare.com/articles/Source_figures_for_publication_on_transient_and_eq_uilibrium_climate_change/10250954. For assistance using the code or figures contact the authors.

References

31. King, A. D. & Harrington, L. J. The Inequality of Climate Change From 1.5 to 2°C of Global Warming. *Geophys. Res. Lett.* (2018). doi:10.1029/2018GL078430

- 478 32. Hawkins, E. *et al.* Estimating changes in global temperature since the pre-industrial
479 period. *Bull. Am. Meteorol. Soc.* BAMS-D-16-0007.1 (2017). doi:10.1175/BAMS-D-
480 16-0007.1
- 481 33. Schurer, A. P., Mann, M. E., Hawkins, E., Tett, S. F. B. & Hegerl, G. C. Importance of
482 the pre-industrial baseline for likelihood of exceeding Paris goals. *Nat. Clim. Chang.* **7**,
483 563–567 (2017).
- 484 34. Sen Gupta, A., Jourdain, N. C., Brown, J. N. & Monselesan, D. Climate Drift in the
485 CMIP5 Models*. *J. Clim.* **26**, 8597–8615 (2013).
- 486 35. Nicholls, R. J. *et al.* Stabilization of global temperature at 1.5°C and 2.0°C:
487 implications for coastal areas. *Philos. Trans. A. Math. Phys. Eng. Sci.* **376**, 20160448
488 (2018).
- 489 36. Lamarque, J.-F. *et al.* Global and regional evolution of short-lived radiatively-active
490 gases and aerosols in the Representative Concentration Pathways. *Clim. Change* **109**,
491 191–212 (2011).
- 492 37. Kharin, V. V. *et al.* Risks from Climate Extremes Change Differently from 1.5°C to
493 2.0°C Depending on Rarity. *Earth's Futur.* **6**, 704–715 (2018).
- 494 38. Paciorek, C. J., Stone, D. A. & Wehner, M. F. Quantifying statistical uncertainty in the
495 attribution of human influence on severe weather. *Weather Clim. Extrem.* **20**, 69–80
496 (2018).
- 497 39. Giorgi, F. & Francisco, R. Uncertainties in regional climate change prediction: a
498 regional analysis of ensemble simulations with the HADCM2 coupled AOGCM. *Clim.*
499 *Dyn.* **16**, 169–182 (2000).
- 500 40. Leimbach, M., Kriegler, E., Roming, N. & Schwanitz, J. Future growth patterns of

501 world regions – A GDP scenario approach. *Glob. Environ. Chang.* **42**, 215–225
502 (2017).

503

505

506 **Figure 1. Illustration of our technique for the comparison of transient and quasi-**

507 **equilibrium climates.** The transient and quasi-equilibrium warmer worlds are compared

508 through time-slicing the transient RCP8.5 simulations at the equivalent level of global

509 warming as the same model average warming in the quasi-equilibrium ECP4.5 simulations

510 for the 23rd century (left panel). Each model’s own 23rd century average global warming is

511 subtracted from both the quasi-equilibrium and transient climates to extract annual global

512 temperature anomalies (shown as probability density graphs in the right panel). The grey bars

513 show the years extracted with the depth of grey indicative of the number of models for which

514 that year was extracted. For details on which years are extracted from which models see

515 Figure S1.

516

517

Figure 2. Transient climates are warmer over land regions resulting in human populations experiencing more local warming. a, b The difference in local-average JJA and DJF temperatures respectively between the multi-model median transient and equilibrium climates. Stippling indicates at least three-quarters of models agree on the sign of the difference. **c, d** Distributions of the population experiencing differences between transient and quasi-equilibrium climates. The grey shading indicates a 90% confidence interval (derived from bootstrapping model simulations only) and the black line represents a best estimate.

Figure 3. The difference between transient and quasi-equilibrium climates is substantial relative to the difference between the Paris Agreement warming limits. a, b The ratio of the absolute difference between transient and quasi-equilibrium climates relative to the absolute difference in climates between 1.5°C and 2°C global warming for JJA and DJF respectively. **c** Distribution of the area of the world by the ratio of the absolute difference between transient and quasi-equilibrium climates and the Paris Agreement warming limits for JJA (red) and DJF (black). The red and black dashed lines show the median differences in JJA and DJF respectively.

Figure 4. Greater probability of very warm seasons over land and especially less developed regions under transient warming relative to quasi-equilibrium warming. a, b The probability ratio of JJA and DJF seasons above the 90th percentile between the transient and quasi-equilibrium climates. The maps show the best estimates while stippling indicates at least 90% confidence in the ratio being above or below one derived from a bootstrap percentile method. **c, d** Scatter plots of local probability ratio and GDP per capita (2010 PPP USD) for JJA and DJF respectively. Points lying within four large regions (boxes shown in **a**) are highlighted: Central America (black), West Africa (blue), Sahara (orange), and Southeast Asia (red) with all other points shown in grey. The black dashed line represents PR of one (i.e. no difference in frequency of extremes between transient and quasi-equilibrium climates).

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

King, AD;Lane, TP;Henley, BJ;Brown, JR

Title:

Global and regional impacts differ between transient and equilibrium warmer worlds

Date:

2020-01-01

Citation:

King, A. D., Lane, T. P., Henley, B. J. & Brown, J. R. (2020). Global and regional impacts differ between transient and equilibrium warmer worlds. NATURE CLIMATE CHANGE, 10 (1), pp.42-+. <https://doi.org/10.1038/s41558-019-0658-7>.

Persistent Link:

<http://hdl.handle.net/11343/241666>