Transient and quasi-equilibrium climate states at 1.5°C and 2°C global warming

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Key points

- Warming patterns at Paris Agreement limits differ substantially between transient and quasi-equilibrium climates
- Summer climate changes over northern land are clearer in a transient climate than a stabilised climate at the same global warming level

- Projections of regional climate designed for the Paris Agreement limits are only useful if the rate of global warming is explicit

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Abstract

Recent climate change is characterised by rapid global warming, but the goal of the Paris Agreement is to achieve a stable climate where global temperatures remain well below 2°C above pre-industrial levels. Inferences about conditions at or below 2°C are usually made based on transient climate projections. To better understand climate change impacts on natural and human systems under the Paris Agreement, we must understand how a stable climate may differ from transient conditions at the same warming level. Here we examine differences between transient and quasi-equilibrium climates based on greenhouse gas-only model simulations at 1.5°C and 2°C global warming. We find substantial local differences between seasonal-average temperatures, with mid-latitude land regions in boreal summer considerably warmer in a transient climate than a quasi-equilibrium state at both 1.5°C and 2°C global warming. Our research demonstrates that the rate of global warming must be considered in regional projections.

Plain language summary

The world has warmed quickly since around 1970, prompting efforts to mitigate climate change and to stabilise global temperatures between 1.5°C and 2°C above pre-industrial levels. We explore the differences between a rapidly-warming climate and one with little change in global temperature over time. We find that a fast-warming climate is characterised by warmer temperatures over Northern Hemisphere mid-latitude land regions than a stable climate at the same level of global warming. The opposite is true in the Southern Ocean where slower warming occurs because of the lag in warming of the deep ocean, so as the global climate stabilises that region continues to warm. As the world continues to warm, some land locations, such as the interior of North America and Eurasia, may experience a temporary emergence of a climate change signal that weakens if the climate stabilises and the

Paris Agreement goals are met. The difference between fast-warming and stable climates can be very large locally, so they must be considered in planning for adapting to future climate change.

Introduction

The planet is warming rapidly and, to date, has already warmed around 1.2°C relative to early-industrial levels due to human influences (Haustein et al., 2017). In an effort to reduce the impacts of climate change, the Paris Agreement was developed with the aim of limiting global warming to well below 2°C and preferably below 1.5°C above pre-industrial levels. Since 2015, when the Paris Agreement was developed, there have been many studies examining climate impacts at different global warming levels (GWLs) to quantify the benefits of limiting global warming. A variety of methods are used to generate quantitative estimates of climate change impacts at different GWLs, including time-slicing of existing model simulations (Schleussner et al., 2016), development of single coupled-model ensembles at GWLs (Sanderson et al., 2017), development of multi-model atmosphere-only ensembles (Mitchell et al., 2017), and pattern scaling (Seneviratne et al., 2016; Tebaldi & Knutti, 2018). These methods are described in James et al. (2017) and Masson-Delmotte et al., (2018). The methods listed above describe worlds at given GWLs with different rates of warming. For example, many studies have used time-slicing from rapid-warming scenarios (Schleussner et al., 2016) or a combination of scenarios (e.g. King et al., 2017) to extract climate information at specified GWLs, while others have used methods based on slower-warming or quasi-equilibriated climates (e.g. Lehner, Coats, et al., 2017; Wehner et al., 2018). While the Paris Agreement is not explicit, it has been argued that the aim is to stabilise global climate at a low GWL (Rogelj et al., 2017; Seneviratne et al., 2018), however, there is value in investigating transient warmer worlds given the current estimated rate of emissions reductions (*NDC Synthesis Report | UNFCCC*, 2021) and high likelihood of continued warming.

It has long been known that transient and equilibriated climates differ in their pattern of warming, with transient climates characterised by greater land-ocean temperature differences (Manabe et al., 1991). Slow warming in high-latitude ocean regions occurs on centennial and even millennial timescales, such that stabilised climates exhibit a different warming pattern to transient climates (Geoffroy & Saint-Martin, 2014; Long et al., 2014). The effects of climate stabilisation have recently been elucidated further in multi-model experiments which highlight evolving patterns of warming over many centuries in simulations under fixed greenhouse gas concentrations (Huang et al., 2020; Rugenstein et al., 2019). Another recent study employed a time-slicing approach with a multi-model ensemble and found substantial differences between transient and quasi-equilibrium climates (King et al., 2020).

The majority of analyses examining effects of climate stabilisation have used fixed-forcing simulations (i.e. constant greenhouse gas concentrations) so that individual climate models exhibit different amounts of global warming associated with their varying climate sensitivity. To examine the effects of climate stabilisation at the Paris Agreement GWLs with a comparable set of transient model data requires a new approach. Here, we develop a framework for estimating differences in regional temperatures between transient and quasi-equilibrium climate states at the 1.5°C and 2°C GWLs informed by data across a wide range of simulated global temperatures. We use this approach to examine differences in the emergence of a human-caused climate change signal, adapting methods previously employed by Frame et al., (2017) and Hawkins et al., (2020) and applying them to the transient and quasi-equilibrium climates we generate.

The emergence of climate change signals in regional temperature and precipitation (Hawkins & Sutton, 2012; Lehner, Deser, et al., 2017; Mahlstein et al., 2011, 2012; Nguyen et al., 2018), climate extremes (Bador et al., 2016; Diffenbaugh & Scherer, 2011; Harrington et al., 2016; King et al., 2015), and other variables (Lo et al., 2020; Lyu et al., 2014) is useful as an index of how significantly the climate has changed since early-industrial times or is projected to change with future warming. The emergence of a climate change signal is often expressed as a time (i.e. the point when a novel climate has emerged from the variability of past climates) or a signal-to-noise ratio (S/N). Using S/N, we explore whether emergence of climate change signals differs between transient and quasi-equilibrium climates. While the emergence of climate change signals between high and low greenhouse gas emissions scenarios has been evaluated to some extent (e.g. Nguyen et al., 2018), climate stabilisation effects and associated changes in warming patterns have not previously been investigated in the context of climate change emergence.

Data and Methods

We used surface air temperature ("tas") from ten models in the sixth phase of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016) to form transient and quasi-equilibrium warmer climates (Table S1). We use only greenhouse gas-forced simulations to build transient and quasi-equilibrium climates to eliminate regional effects of anthropogenic aerosols, ozone change, and land use/cover change on surface temperature patterns which exist in other simulations. We define transient climates using the 1%CO_2 simulations where carbon dioxide increases by 1% per year from a pre-industrial level resulting in a warming climate (Figure 1a) with generally a greater rate of warming than observed. The quasi-equilibrium climate is defined from pre-industrial control simulations (piControl) and abrupt CO_2 forcing experiments where carbon dioxide is halved (Abrupt-0.5xCO_2), doubled (Abrupt-2xCO_2) or quadrupled (Abrupt-4xCO_2) relative to pre-industrial levels and then simulations are run for typically 150 years. The 1%CO_2, piControl, and Abrupt-4xCO_2 simulations form part of the CMIP6 Diagnostic, Evaluation and Characterization of Klima (DECK), while the Abrupt-0.5xCO_2 and Abrupt-2xCO_2 simulations are run as part of other projects (Good et al., 2016; Webb et al., 2017). The additional abrupt forcing simulations allow sampling from more of the distribution of global temperatures but limits the number of available models. The first 50 years of the abrupt forcing simulations are not used as these include a period of relatively rapid warming or cooling before the global-mean surface temperature (GMST) stabilises to some extent. The annual-average GMST trends from simulations chosen to make up the quasi-equilibrium climate are small, while trends from the 1%CO_2 simulations are considerably larger on average (Figure 1a). We note that the abrupt forcings simulations are not in full equilibrium (which is why we refer to these simulations as *quasi-equilibrium*) as it takes centuries for the simulated climate to reach a new steady state (Charney et al., 1979; Rugenstein et al., 2019).

Model temperature data were interpolated to a common regular 2° grid. Seasonal-average temperatures were calculated for boreal summer (JJA) and winter (DJF). All global-average and local seasonal-average temperatures were calculated as anomalies from the average of piControl data for their respective model. To extract local climates at 1.5°C and 2°C GWLs, a relationship was derived between the 11-year smoothed (running mean) annual-average GMST and the seasonal-average temperature at each gridbox for the transient and quasi-equilibrium data from each model. An example is shown in Figures 1b and 1c for the gridbox over Paris in JJA in the CESM2 model for transient and quasi-equilibrium climates respectively. A fourth-order polynomial statistical fit was applied to the data to enable extraction of local climates at specified GWLs as it has residuals of similar magnitude between the transient and quasi-equilibrium ensembles, despite the clustered nature of the quasi-equilibrium data (Figures S1, S2). Several choices of fitting technique were considered (discussion in Supplementary Information). The fourth-order polynomial is fit to the transient and quasi-equilibrium data separately and the associated equation is used to extract the gridbox seasonal-average temperature associated with the 1.5°C and 2°C GWLs. An analysis of sampling uncertainty effects on differences between transient and quasi-equilibrium climates was performed (Figure S3; discussion in Supplementary Information).

An attempt at evaluation of this process for generating transient and quasi-equilibrium climates is made by comparing recent observed warming, using the Berkeley Earth Surface Temperature dataset (Rohde et al., 2013; Rohde & Hausfather, 2020), with the statistical estimation of transient warming simulated by the climate models from 0.5°C to 1°C global warming (Figure S4; discussion in Supplementary Information).

The different emergent climate change signals between transient and quasi-equilibrium climates at 1.5°C and 2°C GWLs were explored as a way of elucidating the effects of the rate of global warming on local climates. The emergence of a climate change signal can be measured in different ways, such as Kolmogorov-Smirnov tests (Mahlstein et al., 2011) or probability ratios (Harrington et al., 2016), but the most commonly used method is S/N (Frame et al., 2017; Hawkins et al., 2020; Hawkins & Sutton, 2012; Nguyen et al., 2018). Signal and noise are calculated differently between studies; here the signal is simply the warming from the transient 1°C climate to the GWL in question as inferred from the fourth-order polynomial fit (similar to Frame et al. (2017)). The noise is the standard deviation of residuals from the fourth-order polynomial fit in the transient climate for values between 0.5°C and 1°C global warming. This gives estimates of interannual climate variability that are relevant to recent climate. The S/N is then calculated for each model, and the ensemble-median for each location. The difference between S/N under transient and quasi-equilibrium climates at the same GWL is also computed. Smaller gridboxes at high latitudes likely inflate noise relative to low latitudes (e.g. Fischer et al., 2013), but mapped differences in S/N between climate states are less affected by this property.

Results

The multi-model ensemble-median warming pattern is broadly similar between transient and quasi-equilibrium climates at 1.5°C and 2°C global warming (Figure 2) with pattern correlations exceeding 0.9 in both seasons. Warmer climates under both transient and quasi-equilibrium states exhibit greater warming over land than ocean (Joshi et al., 2008), and Arctic amplification is evident in DJF (Kim et al., 2016; Screen & Simmonds, 2010). There are, however, substantial and consistent differences between transient and quasi-equilibrium climates, especially in JJA (Figure 2i,j). Differences between transient and stabilised climates may arise from a number of sources, including the land-sea contrast evident in equilibrium vs transient runs in other settings (Dong et al., 2009; Joshi et al., 2008; Lambert et al., 2011). Land-sea contrasts arise from differences in effective heat capacity and slow heat transport in the ocean (e.g. Long et al., 2014, 2020), atmospheric lapse rate and relative humidity over land and ocean (Joshi et al., 2008), biological responses including stomatal resistance (Dong et al., 2009; Joshi & Gregory, 2008), and also differences over polar oceans (Collins et al., 2013). Here, the constraint of the same global warming level in transient and quasi-equilibrium states necessitates local differences in one region to be offset by differences of the opposite sign elsewhere. Consistent with previous literature, differences are evident over continental mid-latitude regions in the Northern Hemisphere where the model ensemble-median JJA-average temperature is at least 0.5°C greater in a transient climate than a quasi-equilibrium climate over large areas; this is the case at both 1.5°C and 2°C GWLs. In contrast, in the Southern Ocean, in particular, a quasi-equilibrium climate is warmer than a transient climate at the same GWL. In DJF (Figure 2k,l), differences between transient and quasi-equilibrium climates are less striking but remain substantial in some regions. The overall pattern of differences shows strong seasonality. The strongest model agreement in the sign of the differences in transient and quasi-equilibrium temperatures tends to be in similar regions to where the largest differences in the ensemble-median are found. In at least nine of the ten climate models, in JJA there are large swathes of Northern Hemisphere land regions that are locally warmer in transient climates than quasi-equilibrium climates for the same GWL.

The differences between transient and quasi-equilibrium climates can also be contextualised against the current climate and the long-term goals of the Paris Agreement. Figure 3 shows the ensemble-median difference between transient and quasi-equilibrium climate states as a percentage of the difference between the transient 1°C climate (analogous to the recent climate) and the quasi-equilibrium climate at the 1.5°C and 2°C GWLs (the long-term Paris Agreement goals). Over much of North America and Eurasia differences exceed 100% meaning that the local difference in JJA-average temperatures between transient and quasi-equilibrium climates exceeds the local warming anticipated between the recent climate and the Paris Agreement 1.5°C GWL (Figure 3a). Over the Southern Ocean there are large areas where differences are below -50%, which indicates that the difference in both JJA- and DJF-average temperatures between quasi-equilibrium and transient climates locally accounts for more than half of the local warming associated with global warming from the recent climate to the long-term 1.5°C GWL (Figure 3a,b). These results highlight how large the difference between transient and quasi-equilibrium climate states can be relative to projected warming associated with low global warming targets. This effect weakens when applied to higher GWLs, but even relative to projected warming to the 2°C GWL, local differences between transient and quasi-equilibrium climates at the 2°C GWL remain substantial. Areas where the warming between the transient 1°C GWL and the quasi-equilibrium 1.5°C and 2°C GWLs is very small, such as the North Atlantic, exhibit large percentage differences which are less meaningful.

The pattern of climate change emergence, as measured by the signal-to-noise, is also broadly similar between transient and quasi-equilibrium climate states with many low-latitude regions projected to experience S/N values greater than two (also known as “unfamiliar” climates relative to the recent climate; Frame et al. 2017) at 2°C global warming in either transient or quasi-equilibrium states (Figure 4). Higher S/N in low-latitude areas is a common feature in climate change emergence studies (Hawkins & Sutton, 2012; Mahlstein et al., 2011) and is primarily due to reduced interannual variability relative to higher latitudes.

Differences in S/N between transient and quasi-equilibrium climates are substantial due to differences in signal (S). Generally, land regions are projected to exhibit clearer emergence of local climate change signals under transient warming while oceans have higher S/N estimates in quasi-equilibrium climates for the same GWL. In boreal summer, S/N is greater by at least 0.5 over large swathes of the Northern Hemisphere mid-latitudes. This represents a substantial effect of the rate of global warming on the projected detectability of changes in local climates up to the Paris Agreement GWLs. Over large areas of North America and Eurasia, summer-average temperatures would shift to becoming “unusual” (S/N between one and two; Frame et al. 2017) under a transient warming climate at the 1.5°C GWL, but under a quasi-equilibrium 1.5°C climate summer temperatures in these areas would remain similar to the recent climate (S/N less than one). The opposite is true for the Southern Ocean where climate change signals would continue to emerge as global climate stabilises at a given GWL. These S/N estimates illustrate that there will be perceptible differences in local climate for many parts of the world between transient and quasi-equilibrium climates.

Discussion

In this study we described a statistical framework for deriving comparable transient and quasi-equilibrium climate states at specified levels of global warming and under greenhouse gas-only forcings for the first time. We used this method to estimate differences between local temperatures in transient and quasi-equilibrium climates at the Paris Agreement GWLs of 1.5°C and 2°C above pre-industrial levels. We find substantial local differences between transient and quasi-equilibrium climates over some areas, particularly Northern Hemisphere mid-latitude land regions (warmer in a transient climate than a quasi-equilibrium state) and the Southern Ocean (cooler in a transient climate than a quasi-equilibrium state).

This study adds to others which show differences in temperature patterns between rapid-warming and steady-state climates (Armour et al., 2013; Geoffroy & Saint-Martin, 2014; Huang et al., 2020; King et al., 2020; Manabe et al., 1991; Rugenstein et al., 2019). Indeed, it is encouraging that differences between transient and quasi-equilibrium climates found in this study broadly resemble those seen in previous analyses despite being generated using a different method and dataset. This adds further weight to the need for decision-making based on climate projections to consider the path of global temperatures and rate of warming, as well as the amount of global warming. In particular, in heavily populated regions such as central Europe, parts of the Middle East, and east Asia, there is a strong indication that transient warming through a GWL is associated with much more local warming in boreal summer (broadly greater than 0.4°C) relative to a quasi-equilibrium climate at the same GWL. This results in very different possible local climates at the same amounts of global warming, so adaptation and mitigation planning informed by quantitative climate change information will need to account for the rate of global warming as well as the amount. Similarly, we find that the emergence of local climate changes differs between transient and quasi-equilibrium global climates. Stabilising the climate at the 1.5°C GWL would result in substantially less perceptible temperature change in summer over North America and Eurasia than transient warming through the 1.5°C GWL.

While we believe this study to be helpful there are a number of caveats. As discussed in Supplementary Information, the choice of fitting method was a compromise, with no ideal technique identified, and evaluation of the method was challenging. The use of ten CMIP6 models gives an estimate of model differences and uncertainty, but the sample size is constrained by the limited set of models with Abrupt-0.5xCO_2 and Abrupt-2xCO_2 simulations.

The use of a multi-model ensemble-median reduces effects of diverse model responses and internal variability in individual models affecting the results. Indeed, while most models produce broadly similar patterns of differences between transient and quasi-equilibrium worlds, there are rather different patterns in a minority of models (Figures S5,S6). No models can be justifiably removed from the ensemble due to difficulties with evaluation discussed previously. It is possible that outlier models with unusual patterns of temperature difference may have passed climate "tipping points" that are physically realistic and important to consider in projections (Lenton et al., 2019; Steffen et al., 2018).

There is a clear gap in our model experiments that necessitates methods such as the one applied here for developing analyses highlighting substantial differences between transient and quasi-equilibrium climate states at policy-relevant GWLs. New experiments would be beneficial if they involved participation of multiple modelling groups (given the large model differences shown in Figures S5, S6) and could follow the framework of Sigmond et al., (2020), who ran multi-century simulations with some climate stabilisation.

In this study we discuss comparisons between *transient* and a *quasi-equilibrium* climate states. These terms can take on a host of different meanings. The transient climate analysed here includes simulations mostly with slightly faster warming than the recent real-world trend (marked by cross in Figure 1a). By applying statistical fits on models separately, the effect of different models' transient climate responses on the pattern of differences between transient and quasi-equilibrium climate states may be examined, but no significant effect is identified (not shown). We refer to *quasi-equilibrium* climates rather than equilibrium climates as the simulations used are not run for long enough to reach a full equilibrium. Even after hundreds of years there are changes occurring in temperature patterns (Rugenstein et al., 2019) as some aspects of the earth system are particularly slow to respond to climate forcings. Indeed, ocean regions with detectable differences between transient and quasi-equilibrium states in this study (e.g. the Southern Ocean) experience larger local temperature changes as the planet moves towards full equilibrium (Rugenstein et al., 2019). Other aspects of the climate system are expected to differ between transient and quasi-equilibrium climate states, such as rainfall patterns (Burls & Fedorov, 2017; Sniderman et al., 2019), deep ocean temperatures (Gillett et al., 2011), vegetation (Heinze et al., 2019), and ice sheets and sea ice (Blackport & Kushner, 2016; Hansen et al., 2013).

Conclusions

In this study we have developed a framework for the comparison of transient and quasi-equilibrium climates at a prescribed level of global warming under greenhouse-gas forcings. We have shown that there are substantial differences in local-, seasonal-average temperatures between transient and quasi-equilibrium climate states at the Paris Agreement GWLs and that these differences are large compared to the projected warming to the 1.5°C and 2°C GWLs. The emergence of local climate change signals in seasonal temperature also differs between transient and quasi-equilibrium climates pointing to a return to weaker local climate change impacts in Northern Hemisphere mid-latitude land regions if society achieves a steady-state climate at 1.5°C global warming as compared to a continued rapidly warming climate. Our study demonstrates the need for regional climate projections at GWLs to account for the substantial influence of the rate of global warming to prevent misinformed decision-making.

Data Availability statement

All data used in this study are available to access in public repositories. The CMIP6 data are published here: https://esgf-node.llnl.gov/projects/cmip6/ and data in this study were accessed through this ESGF and the National Computing Infrastructure ESGF in Australia (https://esgf.nci.org.au/projects/esgf-nci/). The BEST dataset is available publicly here: http://berkeleyearth.org/data/.

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Figures and Tables

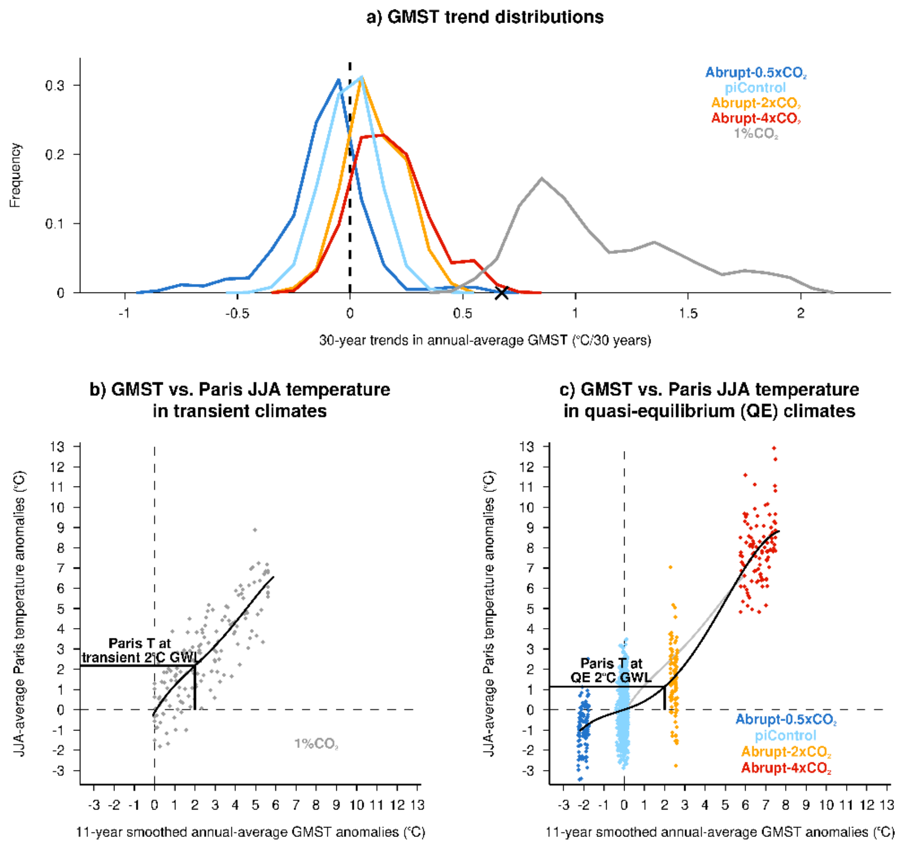

Figure 1. GMST trends in greenhouse gas-forced simulations and examples of GMST against Paris gridbox temperatures in transient and quasi-equilibrium warmer worlds. a) Statistical distributions of 30-year trends in annual-average GMST extracted from the CMIP6 models in Table 1 for Abrupt-0.5xCO_2 (dark blue), piControl (light blue), Abrupt-2xCO_2 (orange), Abrupt-4xCO_2 (red), and 1%CO_2 (grey) simulations. The black cross marks the recent observed GMST trend from 1990-2020 in the BEST dataset. Scatter plots of 11-year smoothed GMST against the Paris JJA-average gridbox temperatures in b) the transient climate simulation and c) the ensemble of quasi-equilibrium simulations for the CESM2 model. In each graph the fourth-order polynomial fit is shown which is used to extract GWLs, such as the 2°C GWL example shown. In c) the fourth-order polynomial fit for the transient climate is shown in light grey for easier visual comparison with the quasi-equilibrium fit.

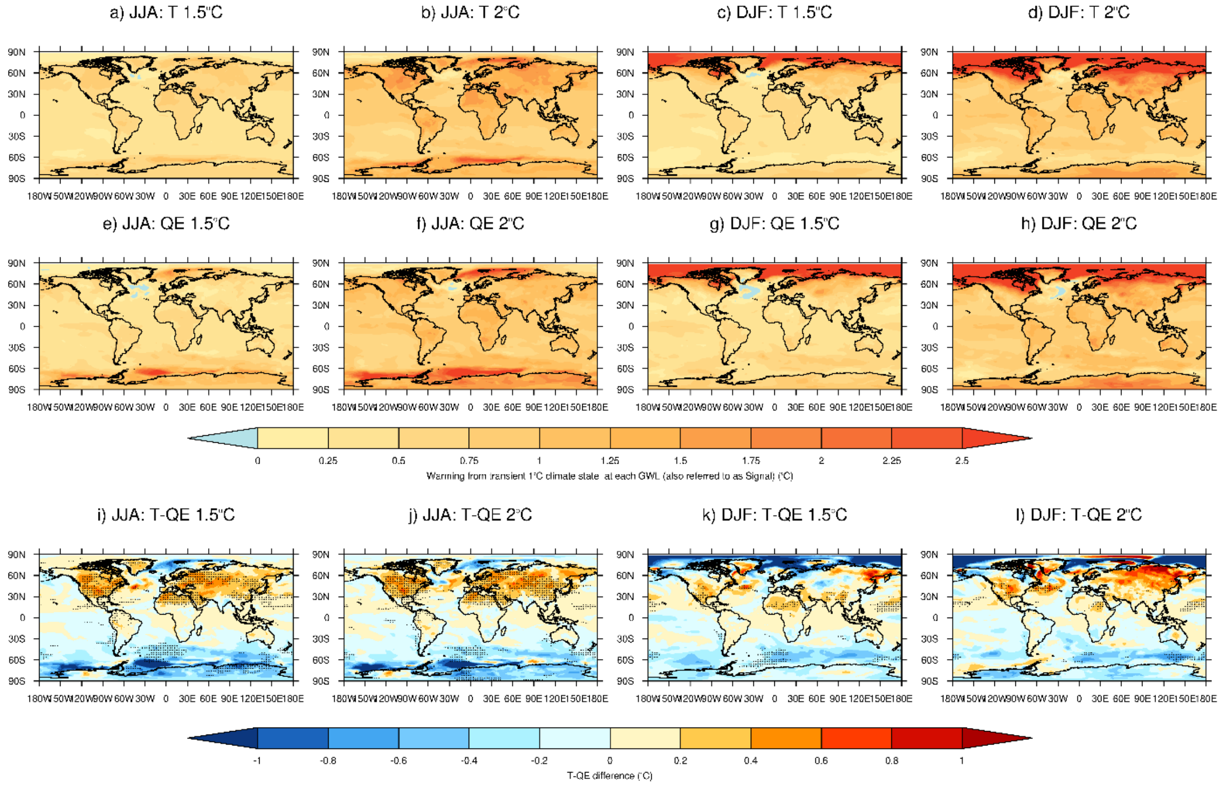

Figure 2. Constructed transient and quasi-equilibrium climates at Paris Agreement GWLs and their differences. Multi-model median warming pattern relative to transient 1°C GWL extracted for a)-d) transient warmer worlds at a),c) 1.5°C global warming and b),d) 2°C global warming for JJA and DJF respectively. Multi-model median warming pattern relative to transient 1°C GWL extracted for e)-h) quasi-equilibrium warmer worlds at e),g) 1.5°C global warming and f),h) 2°C global warming for JJA and DJF respectively. Maps of the multi-model median gridbox differences between transient and quasi-equilibrium climates at i),k) 1.5°C GWL and j),l) 2°C GWL in JJA and DJF respectively. Stippling in i)-l) indicates at least nine out of ten model differences are of the same sign.

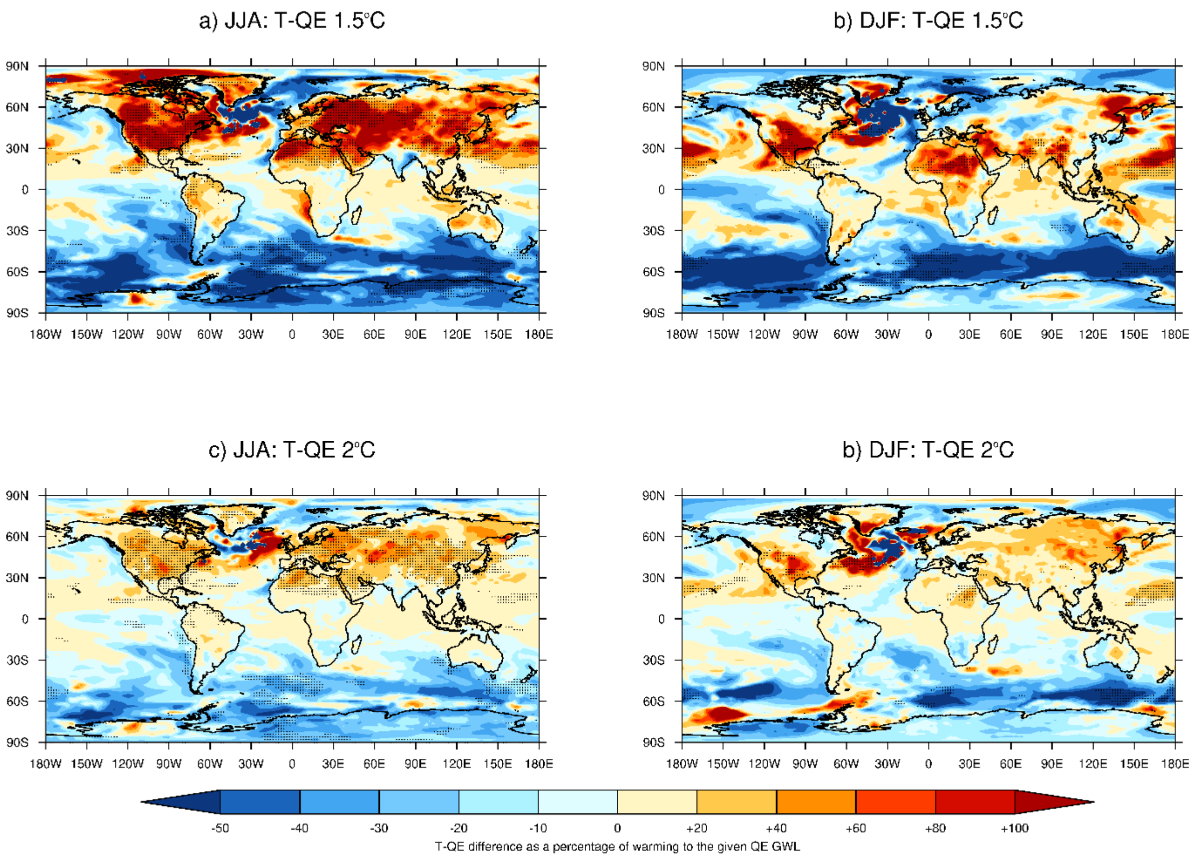

Figure 3. Difference between transient and quasi-equilibrium climate states as a percentage of projected warming. Multi-model median maps of the difference between transient and quasi-equilibrium seasonal-average temperatures at a),b) 1.5°C global warming and c),d) 2°C global warming as a percentage of the projected warming from a transient 1°C climate to a quasi-equilibrium climate at the same GWL. These maps are for a),c) JJA- and b),d) DJF-average temperatures. Stippling indicates at least nine out of ten model differences are of the same sign.

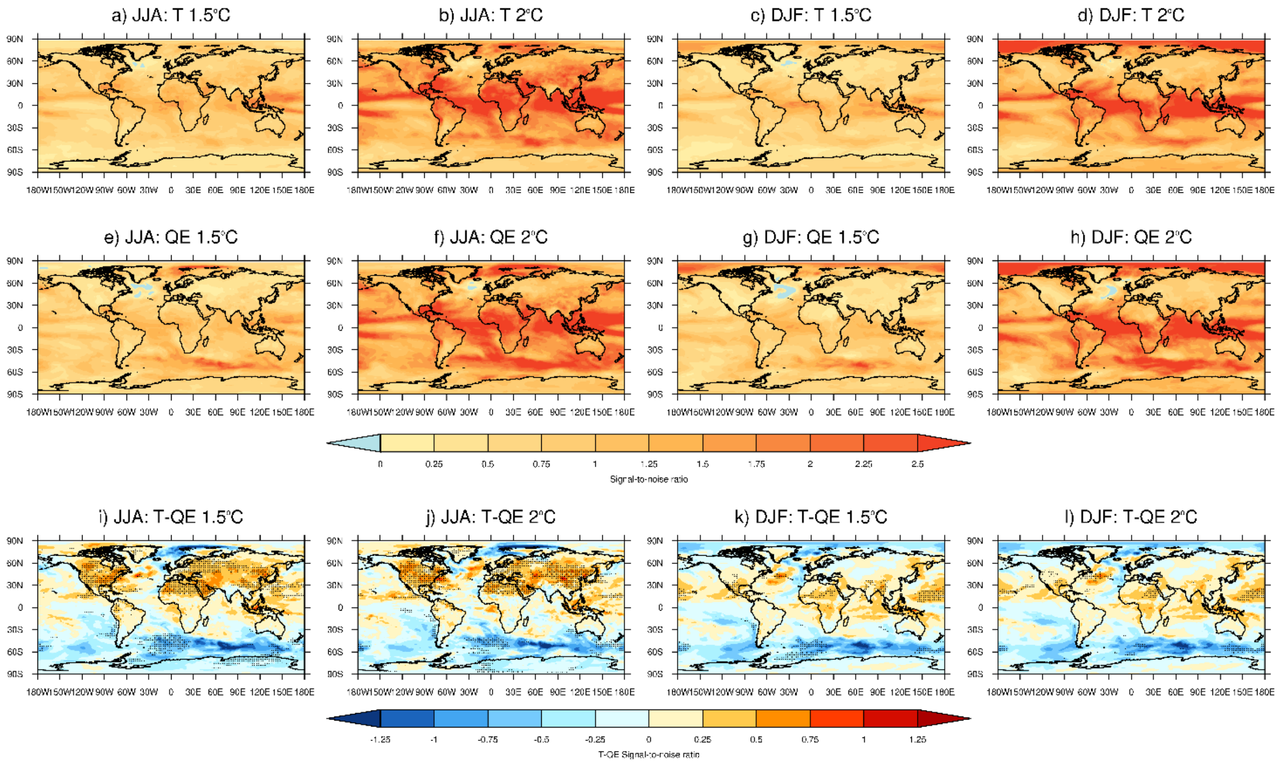

Figure 4. Emergence of local climate change signals under different levels of global warming for transient and quasi-equilibrium climate states. The signal-to-noise of local seasonal-average temperature changes in JJA and DJF at 1.5°C and 2°C global warming for transient and quasi-equilibrium climate states. Differences in signal-to-noise ratios between transient and quasi-equilibrium states are shown for g), h) JJA and i), j) DJF at 1.5°C and 2°C global warming respectively. Stippling in i)-l) indicates at least nine out of ten model differences are of the same sign (identical to Figure 3).