Transitions to new climates (TNCs) in the 21st century

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Abstract
We introduce the concept of transition to a new climate (TNC) based on ensembles of model projections. We consider a variable whose distribution due to interannual variability and inter-model spread of responses within a given time slice is measured by a certain compounded standard deviation, a TNC then occurs when the mean change signal of the variable between a future and a reference period exceeds the sum of the standard deviations for the two periods multiplied by a factor, taken here as 1.6 (see text). We calculate TNCs of regional mean annual surface air temperature from the CMIP6 ensemble of 21st century projections for 31 regions of the globe and four SSP scenarios. For the high-end scenarios, SSP5-8.5 and SSP3-7.0, we find the occurrence of at least one TNC in all regions and a second TNC in 15 and 10 regions, respectively, primarily located in tropical and mid-latitude regions and separated by about 40–45 years. For 30 out of 31 regions there is occurrence of a single TNC in the mid-level SSP2-4.5 scenario, while only 20 out of 31 regions experience a TNC in the low end SSP1-2.6. High latitude and polar regions tend to experience fewer and later occurring TNCs than low latitude ones, due to their larger interannual variability and inter-model response. On the one hand, the occurrence of at least one TNC, and in some scenarios and regions two TNCs, imply severe stress for adaptation of natural ecosystems and different socioeconomic sectors. On the other, the pronounced reduction of TNC occurrence in the low end scenarios point to the urgency of implementing effective mitigation policies to curb global warming.

1. Introduction
The evidence is, by now, unequivocal that human induced global warming is modifying the Earth’s climate at increasing rates, and that this trend would continue in response to foreseen increasing emissions of greenhouse gases (GHG) (IPCC 2021). The possibility that this might induce transitions to entirely new climate regimes has enormous implications for natural ecosystems and many socio-economic sectors, especially if this transition occurs so rapidly that adaptation to the new climate conditions becomes difficult. Assessments of whether such transitions may occur, and how rapidly, can thus be extremely helpful in the design of adaptation policies and in providing impetus towards the implementation of mitigation strategies aimed at containing global warming.

Some studies have addressed this problem, with application to specific issues. For example, an analysis of observations and global model projections suggested that the Arctic region, probably the region undergoing the fastest warming rate of the globe, is already transitioning into a new state for quantities such as sea ice (e.g. Landrum and Holland 2020). As another example, based on an analysis of the CMIP5 global climate model (GCM) ensemble (Taylor et al 2012), Diffenbaugh and Scherer (2011) calculated the time of permanent transition into unprecedented heat stress conditions as the time when the coldest summer of the 21st century becomes permanently warmer than the warmest summer of the 20th century, and found that this transition occurred essentially through all land regions of the globe, and more rapidly in tropical areas. Extending this work, Diffenbaugh and Charland (2016) found that the cumulative emission of...
∼1000 Gtons of CO₂ would trigger a transition of climate regime in the tropics in which the future annual temperatures would be several interannual standard deviations greater than the baseline mean.

As a related issue, using a signal-to-noise approach, several studies have focused on the time of emergence (TOE) of the climate change signal, or of some unprecedented climate characteristics, from the underlying natural variability. As examples of such studies, Giorgi and Bi (2009) and Nguyen et al (2018) found in successive generations of GCM projections that in some high latitude regions, Asian regions and the Mediterranean the mean precipitation change signal emerged in the first half of the 21st century. Focusing on a number of extreme event indicators, studies such as those of Diffenbaugh et al (2017), Giorgi et al (2019), Hawkins et al (2020) and Osso et al (2021) found that global warming can lead to the occurrence of temperature and precipitation extremes of unprecedented intensity, in some cases already in the observed record of the late 20th and early 21st century.

Clearly, given its importance, the issue of climate transitions requires increasing attention in view of both, its relevance for impact and adaptation studies, and the recent availability of a new and more comprehensive generation of GCM projections for different scenarios (CMIP6, Eyring et al 2016). Towards this goal, here we formalize the concept of transition into a new climate (TNC) by defining it as the occurrence of conditions in which the distance between the distribution of the change in a climate variable for a multi-decadal future period and the corresponding distribution for a reference climate period, both obtained from the compounded information from ensembles of climate model projections, exceeds a given threshold (as detailed in section 2). As we will see, an important aspect of our definition, different from previous studies, is that more than one TNC may occur during an analysis period, in our case the 21st century. This would obviously add considerable stress to the adaptive capacity of ecosystems and society.

Note that the concepts of TOE and TNC, although naturally related, are indeed different: while the TOE measures the time when, for a given region or location, the climate change signal starts to emerge from the underlying natural variability, the TNC occurs when the climate regime of the region (as defined by a given variable and statistics) changes to an entirely new state. Therefore, the region might reach a TOE but not a TNC. From the application point of view, the TOE has more relevance for detection and attribution studies, while the TNC for impact and adaptation studies.

As an illustration of our TNC identification methodology, we here use as climatic metric a single variable which is most representative of the climate state of a region, i.e. the region-average annual surface air temperature (SAT), but we stress that the method can be applied to any variable, either individually or in a multi-variable approach, as required for specific applications. We apply the method to calculate occurrences of TNCs in the CMIP6 ensemble using SAT projections for four GHG concentration pathways averaged over 31 land regions covering all continental areas of the globe (with the addition of the Arctic Ocean Region). Our paper starts with a description of the method (section 2), followed by a presentation of the results (section 3) and a final discussion (section 4).

2. Methods

Our analysis is based on the regionally averaged SAT (hereafter SAT refers to the regional and annual average SAT) for the 31 land regions shown in figure 1 (with the addition of the Arctic Ocean, ARO), in the CMIP6 ensemble of GCM projections for four Shared Socio-economic Pathways (IPCC 2021), SSP5-8.5, SSP3-7.0, SSP2-4.5, SSP1-2.6, from the high to low end, respectively. We did not include the SSP1-1.9 scenario because the number of available simulations is smaller than for the other scenarios, and because the results are probably similar to those for the SSP1-2.6 (IPCC 2021). The 31 regions selected are adapted from those used in IPCC (2021) and described by Iturbi et al (2020), by simply joining some relatively small regions in the original regional subdivision. The number of model simulations available for each scenario is reported in table 1, where we use only one realization per model, so as not to have the results dominated by models with multiple realizations. About 30 models are available for each scenario, but note that some models are different variants of the same modeling system, and therefore the models in the ensembles cannot be considered as entirely independent of each other.

The procedure used to calculate the time of occurrence of a TNC is as follows. Our calculations are based on 30 year periods in order to filter out decadal variability. Let $T_{m,i}$ denote the SAT over a given region for model $m$ and year $i$ within the selected time period of $N_Y$ years (where in our case $N_Y = 30$). Then the $N_Y$ year mean of $T_{m,i}$, or $T_M$, and its interannual standard deviation, $\sigma_{(TM)}$, are defined by

$$ T_M = 1/N_Y \times (\Sigma_{i=1}^{N_Y} T_{m,i}) $$

$$ \sigma_{(TM)} = [1/N_Y \times \Sigma_{i=1}^{N_Y} (T_{m,i} - T_M)^2]^{0.5}. $$

Therefore, given a 30 year reference period and a 30 year future period, for a given region and a single model projection $m$ we first calculate the interannual standard deviation of the SAT for the two periods, $\sigma_{(TMref)}$ and $\sigma_{(TMsg)}$, respectively. Then we assume that a TNC occurs if

$$ DT_M > a \times (\sigma_{(TMref)} + \sigma_{(TMsg)}). $$
Figure 1. Set of 31 regions used in this work. For all regions, except for the Arctic Ocean one (ARO) only land points are used in the averaging. The regions are adapted from those of Iturbide et al (2020).

Table 1. List of CMIP6 GCMs used for each scenario. An ✗ means that that model was not available for the corresponding scenario.

| Model             | SSP126 | SSP245 | SSP370 | SSP585 |
|-------------------|--------|--------|--------|--------|
| ACCESS-CM2        | ✔      | ✔      | ✔      | ✔      |
| ACCESS-ESM1-5     | ✔      | ✔      | ✔      | ✔      |
| AWI-CM-1-1-MR     | ✔      | ✔      | ✔      | ✔      |
| BCC-CSM2-MR       | ✔      | ✔      | ✔      | ✔      |
| CAMS-CSM1-0       | ✔      | ✔      | ✔      | ✔      |
| CanESM5           | ✔      | ✔      | ✔      | ✔      |
| CESM2             | ✔      | ✔     | ✗      | ✔      |
| CESM2-WACCM       | ✔      | ✔     | ✔      | ✔      |
| CIESM             | ✔      | ✗     | ✗      | ✔      |
| CMCC-CM2-SR5      | ✔      | ✔     | ✗      | ✔      |
| CNRM-CM6-1        | ✔      | ✔     | ✔      | ✔      |
| CNRM-ESM2-1       | ✔      | ✔     | ✔      | ✔      |
| EC-Earth3-Veg     | ✔      | ✔     | ✔      | ✔      |
| EC-Earth3         | ✔      | ✗     | ✔      | ✔      |
| FGOALS-f3-L       | ✔      | ✗     | ✗      | ✔      |
| FGOALS-g3         | ✗      | ✔     | ✗      | ✔      |
| FIO-ESM2-1        | ✔      | ✔     | ✗      | ✔      |
| GFDL-ESM4         | ✗      | ✔     | ✗      | ✔      |
| GISS-E2-1-G       | ✔      | ✔     | ✔      | ✔      |
| HadGEM3-GC31-LL   | ✔      | ✔      | ✗      | ✔      |
| IITM-ESM          | ✔      | ✔      | ✔      | ✔      |
| INM-CM4-8         | ✔      | ✔      | ✔      | ✔      |
| IPSL-CM6A-LR      | ✔      | ✔      | ✗      | ✔      |
| KACE-1-0-G        | ✔      | ✔      | ✔      | ✔      |
| MCM-UA-1-0        | ✔      | ✔      | ✔      | ✔      |
| MIROC6            | ✔      | ✔      | ✗      | ✔      |
| MIROC-ES2L        | ✔      | ✔      | ✔      | ✔      |
| MPI-ESM1-2-HR     | ✔      | ✔      | ✔      | ✔      |
| MRI-ESM2-0        | ✔      | ✔      | ✗      | ✔      |
| NESM3             | ✔      | ✔      | ✗      | ✔      |
| TaiESM1           | ✔      | ✔      | ✔      | ✔      |
| UKESM1-0-LL       | ✔      | ✗     | ✔      | ✔      |
where $DT_M$ is the mean change of the SAT between the two periods for the model $m$, and the parameter $a$ determines the stringency of the TNC requirement. Here we adopt a value of $a = 1.6$, which implies that, if the distributions are considered approximately Gaussian (see later), only about 5% of each distribution can potentially overlap with the other. For example, a value of $a = 2$ (or 1), would yield a potential overlap of $\sim 2.1\%$ (or $\sim 16\%$) of the distributions.

Equation (3) can be more conveniently expressed in terms of the SAT changes rather than the future values as

$$DT_M > a \times (\sigma(T_{M\text{ref}}) + \sigma(DTM))$$

(4)

where now, for the model $m$, $\sigma(DTM)$ is the standard deviation of the changes in SAT between individual years of the future period and the SAT mean for the reference period, i.e.

$$\sigma(DTM) = [1/N_Y \times \sum_i (DT_{m,i} - DT_M)]^{0.5}. (5)$$

Note that we do not de-trend the SAT series within the 30 year periods because we want to consider all actual SAT values during the periods. Detrending the data would lead to a spurious underestimation of the actual standard deviations, since the presence of trends essentially results in a broadening of the distributions.

Now, if we have $N_M$ projections, each with a different model for a given scenario, the actual projected change is given by the ensemble mean of the model changes. In this case, another element of uncertainty is the difference in the projected DT across models, which in general depends on the models’ global climate sensitivity (e.g. Hawkins and Sutton 2009). Thus, the standard deviations of the SAT distribution in the reference period and of the changes in SAT have to reflect both the interannual variability within the different models and the inter-model spread of responses. Therefore, the TNC criterion of equation (4) for the model ensemble becomes

$$DT_{M\text{mean}} > a \times (\sigma(T_{\text{refmean}}) + \sigma(DTM))$$

(6)

where $DT_{M\text{mean}}$ is the multimodel mean change in SAT, $\sigma(T_{\text{refmean}})$ is the root mean square of the multimodel mean of the variances of the SAT for the reference period, i.e.

$$\sigma(T_{\text{refmean}}) = [\sum_{m=1}^{N_M} (DT_{m,i} - DT_{M,i})^2]^{0.5}. (7)$$

Here we can see the advantage of using a definition based on changes, as we effectively remove the dependency of the SAT distributions of each model on the mean SAT bias for the reference period. In this process, we thus assume that the model biases in the reference period are carried over to the future one, and are removed if the change is taken, as is usually done when assessing changes in climate variables. In other words, for each model, the change is calculated with respect to a reference mean value.

Having identified the TNC criterion of equation (6), we start the process by using as reference the end of century 30 year period, 1970–1999, and as initial future an early 21st century slice, the 30 year period centered around 2000, i.e., 1985–2014. We verify whether the criterion of equation (6) is satisfied for these two time slices, and if it is not we move forward to a second future 30 year period shifted by 5 years forward compared to the previous one, i.e. 1990–2019, end eventually repeat the procedure at 5 year intervals throughout the 21st century, until the TNC criterion of equation (6) is finally satisfied. If this happens, say for the 30 year period centered around 2050, i.e. 2035–2064, then we assume that there has been a TNC at that time and we take this TNC period as the new reference and the multi-model mean SAT for this period as reference for the SAT. We then repeat the procedure to identify time slices satisfying the TNC criterion at 5 year intervals forward in the future, and if another TNC is found, say for the decades centered around 2070, i.e. 2055–2085, we assume this as new reference and proceed with the TNC test until the last 30 year slice of the 21st century (2070–2099) is reached. In this way, more than one TNC can be found, which is important information relevant for ecosystem and societal adaptation.

Note that this methodology is quite flexible in that it can be applied to different climate variables and can be modified for example in the length of time slices, say 20 or 40 years, and in the stringency of the criterion in equation (6) through the parameter $a$. As mentioned, we apply this procedure to all 31 regions of figure 1 and four CMIP6 SSP scenarios to calculate whether, how many and at what times TNC events occur for each regional case. Note that, before we carry out these calculations, we interpolate all model temperatures to a common 1 degree grid and only use land points of this common grid (except for the Arctic Ocean region), so that some uncertainty related to
model resolution in areas of complex coastlines may be present.

As suggested by one reviewer, since our calculation of TNC is solely based on model data, there is an inherent uncertainty associated with possible biases in the model simulation of interannual variability. To assess this problem for our specific application, we compared our \( \sigma_{\text{Trefmean}} \) values with the SAT standard deviations obtained from the observation dataset of the Climatic Research Unit (CRU) of the University of East Anglia (Harris et al. 2020) for the (1970–1999) reference period and all regions except for the polar ones (for which observed data may not be realistic). The results are reported in table 2. It can be seen that there are both positive and negative biases, but with a prevailing tendency for the models to overestimate the SAT interannual variability compared to the CRU data, with errors mostly lower than 25%. The CMIP6 ensemble thus appears to be reasonably accurate for this metric, and the prevailing variability overestimate possibly implies that our estimates of TNC occurrence are relatively conservative.

**Table 2.** Values of SAT interannual standard deviation \( \sigma \) calculated for the observation dataset CRU (\( \sigma_{\text{Tobs}} \)) and for the model ensemble (\( \sigma_{\text{Trefmean}} \)) over our analysis regions except for the polar ones.

| Region | \( \sigma_{\text{Tobs}} \) | \( \sigma_{\text{Trefmean}} \) |
|-------|----------------|----------------|
| WSA   | 0.351          | 0.325          |
| ARP   | 0.355          | 0.398          |
| CNA   | 0.633          | 0.736          |
| EAF   | 0.235          | 0.301          |
| ENA   | 0.335          | 0.653          |
| NAS   | 0.663          | 0.694          |
| NAU   | 0.378          | 0.480          |
| NEN   | 0.931          | 0.799          |
| NES   | 0.346          | 0.412          |
| NWN   | 0.877          | 0.873          |
| RAR   | 0.763          | 0.856          |
| SAF   | 0.323          | 0.369          |
| SAH   | 0.318          | 0.419          |
| SAU   | 0.289          | 0.389          |
| SCA   | 0.255          | 0.330          |
| SEA   | 0.213          | 0.250          |
| SSA   | 0.263          | 0.334          |
| TIB   | 0.338          | 0.423          |
| WCA   | 0.515          | 0.532          |
| WNA   | 0.516          | 0.601          |
| MED   | 0.390          | 0.423          |
| NEU   | 0.742          | 0.837          |
| WCE   | 0.672          | 0.763          |
| CSA   | 0.256          | 0.449          |
| WAF   | 0.277          | 0.319          |
| SAS   | 0.259          | 0.359          |
| EAS   | 0.373          | 0.378          |

3. Results

3.1. Illustrative cases

In order to illustrate our methodology, we first discuss in some detail the results for some individual regional cases, whose data are reported in table 3. We begin with the Mediterranean region, which has been identified as one of the most prominent climate change hot spots of the planet (Giorgi 2006). Table 3(a) reports the values of \( \sigma_{\text{Tfutmean}} \), \( \sigma_{\text{Trefmean}} \) and \( 1.6 \times (\sigma_{\text{Trefmean}} + \sigma_{\text{Tfutmean}}) \) for the SSP5-8.5 scenario. For this region, we find the occurrence of two TNCs, one early in the 21st century, centered at 2035 (2020–2049), and the second centered at 2075 (2060–2089). Both the intermodel and interannual standard deviations increase going towards the end of the 21st century, and the contribution of the intermodel spread to the overall future standard deviation increases with time. This latter result is due to the well known increase of intermodel divergence of warming with increasing GHG radiative forcing (e.g. Hawkins and Sutton 2009). Conversely, the increase in interannual variability has two components, one from the warming trend within the 30 year periods, which tends to increase towards the end of the century in the SSP5-8.5 scenario (IPCC 2021), and one from an increase in de-trended interannual variability, which has been found to prevail over most warm climate regions of the world (e.g. Giorgi and Bi 2005). Also note that the \( \sigma_{\text{Tfutmean}} \) values are relatively low after the first TNC is reached because they refer to this new reference slice rather than the original one.

The results of table 3 for the MED region are better illustrated by figure 2, which presents the frequency distributions of the annual SAT anomalies in the initial reference period, the new reference period after the first TNC occurs, and the corresponding yearly anomalies in SAT changes during the periods when the TNCs are found. We can see that the SAT anomaly distribution for the initial reference period, to which only the interannual variability of the models contribute, resembles rather closely a Gaussian, with most values in the range of \( \pm 1 \) °C (top left panel). The distribution of the individual yearly changes when the first TNC is reached (bottom left panel) is considerably broader and flatter than the reference one due to the additional contribution of the intermodel spread and the presence of substantial SAT trends within the period. Note that, in this case the distribution somewhat deviates from the Gaussian shape, especially towards the high change tail, indicating an amplification of hot events due to very dry conditions and associated feedbacks (e.g. Giorgi and Lionello 2008). The second reference distribution is broader than the original one (top right panel), but is narrower than the distribution of the first TNC changes. This is because the intermodel spread is no longer present in the calculation of \( \sigma_{\text{Trefmean}} \), since future changes are calculated with respect to this new reference. On the other hand, the presence of more pronounced trends and possible increases in interannual variability within each model makes this distribution wider
Table 3. Values of DT\(\text{mean}\), \(\sigma(T\text{refmean})\), \(\sigma(T\text{futmean})\), \(1.6 \times (\sigma(T\text{refmean}) + \sigma(T\text{futmean}))\), and period of occurrence of TNC (in bold italics), for the Mediterranean (MED), Eastern North America (ENA), Arctic Ocean (ARO) and West Africa (WAF) (see figure 1). Calculations are for the scenario SSP5-8.5.

|       | \(\text{MED}\) | \(\text{ENA}\) | \(\text{ARO}\) | \(\text{WAF}\) |
|-------|----------------|----------------|----------------|----------------|
| \(\text{DT mean}\) | 0.531 | 0.277 | 1.082 | 6.251 |
| \(\sigma(T\text{refmean})\) | 0.423 | 0.578 | 0.653 | 0.906 |
| \(\sigma(T\text{futmean})\) | 0.559 | 0.608 | 0.726 | 1.258 |
| \(1.6 \times (\sigma(T\text{refmean}) + \sigma(T\text{futmean}))\) | 1.572 | 1.897 | 2.208 | 3.462 |
| Period | 1985–2014 | 2025–2054 | 2025–2059 | 2030–2059 |
|       | 0.740 | 0.560 | 1.509 | 5.548 |
|       | 0.423 | 0.578 | 0.653 | 0.906 |
|       | 0.590 | 0.642 | 1.402 | 2.801 |
|       | 1.621 | 1.951 | 3.693 | 5.931 |
|       | 1990–2019 | 2025–2059 | 1990–2019 | 2025–2054 |
|       | 0.969 | 1.065 | 2.480 | 3.542 |
|       | 0.423 | 0.653 | 0.906 | 0.906 |
|       | 0.580 | 0.793 | 1.722 | 1.976 |
|       | 1.605 | 2.315 | 4.205 | 4.611 |
|       | 2019–2024 | 2025–2044 | 2020–2034 | 2025–2034 |
|       | 1.193 | 1.308 | 1.545 | 2.398 |
|       | 0.423 | 0.653 | 0.653 | 0.906 |
|       | 0.594 | 0.818 | 0.859 | 1.283 |
|       | 1.627 | 2.354 | 2.419 | 4.942 |
|       | 2000–2029 | 2005–2034 | 2005–2034 | 2010–2020 |
|       | 1.396 | 1.545 | 1.822 | 2.748 |
|       | 0.423 | 0.653 | 0.653 | 0.906 |
|       | 0.638 | 0.818 | 0.859 | 1.283 |
|       | 1.698 | 2.354 | 2.419 | 4.942 |
|       | 2005–2024 | 2010–2020 | 2005–2034 | 2010–2020 |
|       | 1.863 | 2.223 | 2.572 | 2.992 |
|       | 0.423 | 0.578 | 0.797 | 1.013 |
|       | 0.744 | 0.853 | 1.066 | 1.103 |
|       | 1.867 | 2.201 | 2.982 | 3.041 |
|       | 2015–2044 | 2005–2034 | 2020–2040 | 2025–2040 |
|       | 2.119 | 0.578 | 2.748 | 3.404 |
|       | 0.423 | 0.853 | 0.915 | 0.797 |
|       | 0.789 | 0.906 | 2.388 | 1.157 |
|       | 1.939 | 2.515 | 2.586 | 3.128 |
|       | 2020–2049 | 2010–2020 | 2015–2044 | 2025–2049 |
|       | 0.277 | 0.560 | 0.863 | 0.277 |
|       | 0.578 | 0.578 | 0.578 | 0.764 |
|       | 0.608 | 0.642 | 0.831 | 0.831 |
|       | 1.897 | 1.951 | 2.552 | 2.552 |
|       | 2025–2044 | 2019–2029 | 2020–2040 | 2025–2049 |
|       | 0.277 | 0.560 | 0.863 | 0.277 |
|       | 0.578 | 0.578 | 0.578 | 0.764 |
|       | 0.608 | 0.642 | 0.831 | 0.831 |
|       | 1.897 | 1.951 | 2.552 | 2.552 |
|       | 2025–2044 | 2019–2029 | 2020–2040 | 2025–2049 |
|       | 0.277 | 0.560 | 0.863 | 0.277 |
|       | 0.578 | 0.578 | 0.578 | 0.764 |
|       | 0.608 | 0.642 | 0.831 | 0.831 |
|       | 1.897 | 1.951 | 2.552 | 2.552 |
|       | 2025–2044 | 2019–2029 | 2020–2040 | 2025–2049 |
|       | 0.277 | 0.560 | 0.863 | 0.277 |
|       | 0.578 | 0.578 | 0.578 | 0.764 |
|       | 0.608 | 0.642 | 0.831 | 0.831 |
|       | 1.897 | 1.951 | 2.552 | 2.552 |
|       | 2025–2044 | 2019–2029 | 2020–2040 | 2025–2049 |

(Continued.)
than in the original reference. Finally, the distribution of the changes for the second TNC (bottom right panel) is the broadest due to the strongest contributions of all effects (interannual variability, trends within the period and inter-model spread). In this latter case the deviation from Gaussian, with a strong extension of the right end tail (extreme hot events) is also quite pronounced. Because the distributions somewhat deviate from Gaussian the assumption of 5% potential overlap between distributions implied by the factor $a = 1.6$ is to be considered only as indicative.

A second illustrative case is that of Eastern North America (ENA, table 3(b)), which lies at mid latitudes

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### Table 3. (Continued.)

| Period   | DT\(_{\text{mean}}\) | $\sigma_{(T_{\text{refmean}})}$ | $\sigma_{(T_{\text{futmean}})}$ | $1.6 \times (\sigma_{(T_{\text{refmean}})} + \sigma_{(T_{\text{futmean}})})$ |
|----------|----------------------|------------------------------|----------------------|----------------------------------------------------------------------------------|
| 1985–2014 | 0.300                | 0.319                        | 0.405                | 1.159                                                                             |
| 1990–2019 | 0.427                | 0.319                        | 0.469                | 1.261                                                                             |
| 1995–2024 | 0.584                | 0.319                        | 0.491                | 1.297                                                                             |
| 2000–2029 | 0.745                | 0.319                        | 0.528                | 1.355                                                                             |
| 2005–2034 | 0.885                | 0.319                        | 0.573                | 1.427                                                                             |
| 2010–2039 | 1.066                | 0.319                        | 0.610                | 1.487                                                                             |
| 2015–2044 | 1.251                | 0.319                        | 0.673                | 1.588                                                                             |
| 2020–2049 | 1.455                | 0.319                        | 0.713                | 1.651                                                                             |
| 2025–2054 | 1.676                | 0.319                        | 0.761                | 1.728                                                                             |
| 2030–2059 | 1.916                | 0.319                        | 0.829                | 1.837                                                                             |
| 2035–2064 | 0.266                | 0.587                        | 0.618                | 1.928                                                                             |
| 2040–2069 | 0.538                | 0.587                        | 0.656                | 1.990                                                                             |
| 2045–2074 | 0.826                | 0.587                        | 0.711                | 2.078                                                                             |
| 2050–2079 | 1.121                | 0.587                        | 0.762                | 2.158                                                                             |
| 2055–2084 | 1.441                | 0.587                        | 0.829                | 2.266                                                                             |
| 2060–2089 | 1.764                | 0.587                        | 0.894                | 2.371                                                                             |
| 2065–2094 | 2.107                | 0.587                        | 0.966                | 2.486                                                                             |
| 2070–2099 | 2.471                | 0.587                        | 1.043                | 2.609                                                                             |

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Figure 2. Mediterranean region (MED) frequency distributions of multi-model SAT anomalies for the initial reference period (1970–1999, top left panel) and the new reference after the first TNC is reached (2020–2049, top right panel). Distribution of the individual SAT changes compared to the reference multi-model mean SAT for the first TNC (2020–2049, bottom left panel) and the second TNC (2060–2085, bottom right panel).
higher than for the Mediterranean. Also in this case we find the occurrence of two TNCs, which however occur later than for the Mediterranean, i.e. the first in (2025–2054) and the second at the very end of the century (2070–2099). The main reason for this delay is that this mid-latitude continental region is characterized by greater interannual variability (e.g. see the $\sigma_{\text{Trefmean}}$ values) than the Mediterranean, which overcomes a greater mean annual warming trend (for the Mediterranean the warming is largest in summer and much reduced in winter, e.g. Giorgi and Lionello 2008, resulting in a lower mean annual warming).

Table 3(c) reports the results for another hot-spot region, the Arctic Ocean region (ARO), where warming is maximum compared to any other region of the World, especially in winter, due to melting of sea ice and reduced ice cover (e.g. IPCC 2021). Table 3(c) shows that in this case there is only one TNC occurring at (2030–2059), while the end of 21st century period remains only slightly below the threshold for a second TNC. This result, which might seem counterintuitive given the large DT$_{\text{mean}}$ over this region, is essentially due to the fact that the ARO region is characterized by high interannual variability and especially high inter-model spread of warming, mostly as a result of cross-model differences in the description of ice-atmosphere interactions. For example, compared to the MED region, the ARO exhibits more than doubled warming, but more than three times higher values of $\sigma_{\text{Tfutmean}}$.

This is better illustrated by figure 3. The top panel shows the multimodel distribution of annual SAT anomalies in the first reference period, which rather closely follows a Gaussian distribution, and is substantially wider than for the Mediterranean region (note the much wider temperature anomaly scale in the x-axis of figure 3 compared to that of figure 2). When the TNC period is reached (bottom panel), the distribution of the SAT change values is even wider, order of several degrees, and this effectively counterbalances the large DT$_{\text{mean}}$ values in determining the TNC occurrence. Also note that in the SAT change anomaly distribution there is a hint of a double peak, maybe because of clustering of sea ice parameterizations across models.

A yet different case is illustrated by the tropical region WAF (table 3(d)), which is characterized by very low interannual variability (e.g. $\sigma_{\text{Trefmean}}$) but high inter-model spread (large difference between $\sigma_{\text{Tfutmean}}$ and $\sigma_{\text{Trefmean}}$). As a result, even if the change and variability characteristics are very different form the ARO region, also in this case we find a relatively late occurring single TNC (2030–2059).

From these illustrative cases it is thus evident that the occurrence of a TNC is related not so much to the magnitude of the warming, as on how this magnitude compares with the interannual variability and inter-model spread. As a result, regions characterized by widely different changes and variabilities may result in similar TNC occurrences.

### 3.2. Overall TNC occurrence for all regions and scenarios

Figure 4 summarizes the calculations of the TNC for all regions and scenarios considered. Starting with the SSP5-8.5, i.e. the most extreme scenario, we find the occurrence of at least one TNC in all regions and two TNCs in 15 out of 31 of them. Double TNC regions are mostly concentrated in tropical and mid-latitude areas, such as the Mediterranean, Africa and the Middle East (except of west Africa, WAF), most of Asia (except for South Asia, SAS), western and eastern North America (WNA and ENA), central America (CAM), Western and Southern South America (WSA, SSA). In these cases the first TNC occurs in periods with centers from 2030 to 2040 and the second in periods centered from 2075 to 2085, i.e. the two successive TNCs are about 40–45 years apart. Conversely, most high latitude regions of both hemispheres (except North Asia, NAS, and Southern South America, SSA), including the Arctic and Antarctic ones, exhibit only one TNC, even though the SAT change is relatively large there. As already discussed in the illustrative examples, this is because of...
the relatively large uncertainty, and thus wide distributions, associated with interannual and inter model variability. Both Australian regions only show one TNC, perhaps because of the mitigating effect of the surrounding oceans. In general, when only one TNC is found, this mostly occurs in periods centered around the mid of the 21st century, but we should stress that in several cases of single TNC occurrence the threshold for the second TNC was almost reached by the last 30 year slice of the century, so would presumably take place early in the 22nd century.

In the second high end scenario SSP3-7.0, the number of regions experiencing two TNCs decreases to 10, and includes mostly Mediterranean, middle East, central America, African and Asian regions. Compared to the SSP5-8.5, mostly mid and high latitude regions disappear from the ensemble with double TNCs. In general, in most cases the time of occurrence of TNC for this scenario is shifted forward by 5–15 years with respect to the SSP5-8.5. All regions, however, still experience at least one TNC, mostly occurring in time slices centered around 2040–2050. This is because the warming associated with this scenario increases in a manner similar to the other SSPs in the first half of the 21st century, but only very slowly after mid century (IPCC 2021). Finally, in the low end scenario SSP1-2.6, in which the warming remains essentially constant, or slightly decreases, after 2050 (IPCC 2021) only 20 out of 31 regions experience a TNC, mostly occurring in periods centered around mid-century, 2040–2060. Note that all the regions experiencing two TNCs in the SSP5-8.5 also see one TNC occurrence in the SSP1-2.6, confirming that the climate transition signal over these regions is relatively high.

4. Discussion

In this paper we have formalized the concept of TNC as occurring when the change signal obtained from a model ensemble for a given variable exceeds a threshold calculated as the sum of the standard deviations of the variable for a reference period and that of the change for a future period, multiplied by a factor 1.6. The variable analyzed in this work is regionally averaged mean annual SAT and the factor 1.6 is such that only about 5% of the reference and change SAT distributions overlap (assuming approximately Gaussian distributions). This definition includes the compounded contributions of interannual variability (and within it the contribution of trends during the period) and inter-model variations of responses, and an important property of it is that it allows the calculation of multiple TNCs within the same time series.

We applied this method to the calculation of 21st century TNCs over 31 sub-continental size regions...
from the CMIP6 ensembles of projections (about 30 models) for four scenarios: SSP5-8.5, SSP3-7.0, SSP2-4.5 and SSP1-2.6 (from the highest GHG emissions to the lowest, respectively). Also, we used in the calculation of the TNC periods of 30 year length, with 1970–1999 being the initial reference.

For the two high end scenarios, we found the occurrence of two TNCs in 15 and 10 regions out of 31, for the SSP-8.5 and SSP3-7.0, respectively. These regions mostly lie in the tropics and mid-latitudes, and the two TNCs are separated by about 40–45 years. We should also mention that, for some regions, in the last 21st century slice the second TNC was almost reached. In the two high end scenarios, for a number of regions, mostly those with a double TNC, the first TNC occurs early in the century, i.e. for time slices centered around 2030 and 2035.

In the mid-level scenario, SSP2-4.5 30 out of 31 regions experience one TNC, but none reach the second TNC. However, still some early century TNC occurrence is found in eight regions. Finally, the situation is much less severe in the SSP1-2.6 scenario, although still 20 out of 31 regions experience one TNC, mostly occurring around mid to late century.

In terms of spatial distribution of TNC occurrence, we find that high latitude regions exhibit lower numbers and later occurring TNCs, even though they are characterized by a more pronounced warming. This is because of the relatively high contribution of both interannual and inter-model variability, which makes it more difficult for TNCs to emerge. This result is for example in agreement with the analysis of Diffenbaugh and Charland (2016).

Note that, as shown in table 3, our method allows one to estimate the relative contributions of interannual variability and intermodel spread to the TNC occurrence by comparing the values of $\sigma(T_{\text{ref mean}})$ and $\sigma(T_{\text{mean}})$. However, it does not allow a direct inter-comparison of the TNCs occurring in the individual models. The main reason behind our approach is that we consider the climate change information for a region as compounded over the ensemble of models as a whole, and not by the comparison of the behavior of individual models.

Here we applied our methodology to a single, albeit highly representative, climate variable, i.e. mean annual temperature. However the method can be readily extended to different or multiple variables which might be of more direct interest for different applications. In addition, a more or less stringent TNC criterion can be easily adopted by using different values of the parameter $a$ in equation (6).

Regardless of the choice of variable and parameter, our study shows that most of the planet’s surface is going to face relatively rapid transitions to entirely different climatic regimes under most scenarios envisioned in the IPCC process, even the lower GHG ones, and this has strong implications concerning adaptation and mitigation policies. The occurrence of early 21st century TNCs highlights the urgency of implementing adaptation measures in socio-economic systems that might be affected; the occurrence of double TNCs in the high end scenarios implies considerable added stress to both natural and anthropic systems, and thus highlights the need of mitigation measures aimed at reducing global warming. In particular, natural ecosystems and ecosystem services might be particularly vulnerable to rapid and multiple climate transitions, so that how to limit effectively the occurrence of these transitions should be a high priority within the global change debate.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

There is no conflict of interest in any element of the manuscript.

Data access statement

The CMIP6 data used in this work can be found at the following web site: https://esgf-node.llnl.gov/search/cmip6/.

Ethics statement

The article does not contain any studies involving human or animal participants.

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