

Future local climate unlike currently observed anywhere

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Fabienne Dahinden¹, Erich M Fischer^{1,2} and Reto Knutti¹¹ Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland² Author to whom any correspondence should be addressed.E-mail: erich.fischer@env.ethz.ch**Keywords:** climate change communication, spatial climate analogs, novel and disappearing climatesSupplementary material for this article is available [online](#)**Abstract**

The concept of spatial climate analogs, that is identifying a place with a present-day climate similar to the projections of a place of interest, is a promising method for visualizing and communicating possible effects of climate change. We show that when accounting for seasonal cycles of both temperature and precipitation, it is impossible to find good analogs for projections at many places across the world. For substantial land fractions, primarily in the tropics and subtropics, there are no analogs anywhere with current seasonal cycles of temperature and precipitation matching their projected future conditions. This implies that these places experience the emergence of novel climates. For 1.5 °C global warming about 15% and for 2 °C warming about 21% of the global land is projected to experience novel climates, whereas for a 4 °C warming the corresponding novel climates may emerge on more than a third of the global land fraction. Similar fractions of today's climates, mainly found in the tropics, subtropics and polar north, are anticipated to disappear in the future. Note that the exact quantification of the land fraction is sensitive to the threshold selection. Novel and disappearing climates may have serious consequences for impacts that are sensitive to the full seasonal cycle of temperature and precipitation. For individual seasons, however, spatial analogs may still be a powerful tool for climate change communication.

1. Introduction

Scientific evidence shows that climate conditions are changing unequivocally (IPCC 2013). But even though climate models have improved over the past, uncertainties about future climate impacts and responses of ecological and human systems remain large (IPCC 2014). The use of spatial climate analogs in order to identify areas whose current climatic conditions are statistically similar to the expected climate at another location can serve as an illustrative method for communicating the effects of climate change. Addressing questions such as, 'Does the future climate projected at some place of interest already exist somewhere today, and where?', or 'Will the current climate experienced at a particular place of interest still exist elsewhere in the future?' may provide valuable information in terms of adaptation and ecological risk assessment.

Previous studies have revealed the potential of the analog approach by linking present and past climates

(Brown and Katz 1995, Beniston 2014) or current and future climates (Hallegatte *et al* 2007, Williams *et al* 2007, Williams and Jackson 2007, Ramírez-Villegas *et al* 2011, CGIAR 2011, CSIRO and Bureau of Meteorology 2015, Dobrowski and Parks 2016). While Brown and Katz (1995) related present-day and historical temperature extremes in order to anticipate the effect of climate change on the frequency of extreme events, Beniston (2014) compared current and past climates of European cities to derive the velocity of northward-moving isotherms. Based on model simulations, other studies used the concept of spatial analogs to estimate future projected economical (Hallegatte *et al* 2007), ecological (Williams *et al* 2007, Williams and Jackson 2007, Dobrowski and Parks 2016) and agricultural (Ramírez-Villegas *et al* 2011) risks. Hallegatte *et al* (2007) and Ramírez-Villegas *et al* (2011) both introduced an approach based on weighted monthly dissimilarities in temperature and precipitation. The same metric has been

further used in a web-based analog tool (CGIAR 2011), which is tailored to identify regions with agricultural practices under current climatic conditions that may be appropriate for other locations in a future climate. A similar tool exists for exploring future climate change in Australia (CSIRO and Bureau of Meteorology 2015). However, here the metric used for identifying analogs relies on comparing annual mean temperatures and precipitation. The analyses conducted by Williams *et al* (2007) and Williams and Jackson (2007) especially focused on identifying regions with future projected novel and disappearing climates, which they defined as areas with June to August (JJA) and December to February (DJF) temperatures and precipitation that do not match any existing biom class.

Many of the studies described above did not evaluate how good the identified analogs are. Only Williams *et al* (2007), Williams and Jackson (2007), Ramírez-Villegas *et al* (2011) and CGIAR (2011) quantified the climatic distance between the reference and analog point. However, their results are sensitive to predefined ecological or agricultural impact factors which are rather complicated to derive and may involve uncertainties. Here we introduce a straightforward distance measure to estimate the accuracy of the identified analogs and globally test the suitability of the spatial analog concept on the basis of 35 models from the Fifth phase of the Coupled Model Intercomparison Project (CMIP5). In contrast to many previous studies, which only consider individual seasons (Williams *et al* 2007, Williams and Jackson 2007) or annual means (Dobrowski and Parks 2016, CSIRO and Bureau of Meteorology 2015), we account for the full seasonal cycle of temperature and/or precipitation when computing the dissimilarities of the analogs. Moreover, we estimate global land fractions with projected seasonal cycles of temperature and/or precipitation for which no analog exists in the present (hereafter referred to as novel climates). The land fractions with current seasonal cycles of temperature and/or precipitation for which no analog exists in the projected future climate (disappearing climate) is quantified likewise.

2. Data and Methods

We use 35 global climate models from CMIP5, which is coordinated by the World Climate Research Program (WCRP) (Taylor *et al* 2012). One ensemble member is used from each model. We consider 20-year seasonal means of the two climate variables near surface air temperature and precipitation from historical and RCP8.5 simulations for the comparison of the present and the future. All simulations are bilinearly interpolated to a common grid of $2.5^\circ \times 1.875^\circ$ resolution. While the current climate corresponds to the period of 1986–2005, future

climates refer to 20-year time periods centered around the year of a specific global mean temperature change relative to 1986–2005, which implies that results are largely independent of the choice of a model's transient climate response and emission scenario (e.g. Tebaldi and Arblaster 2014, Herger *et al* 2015).

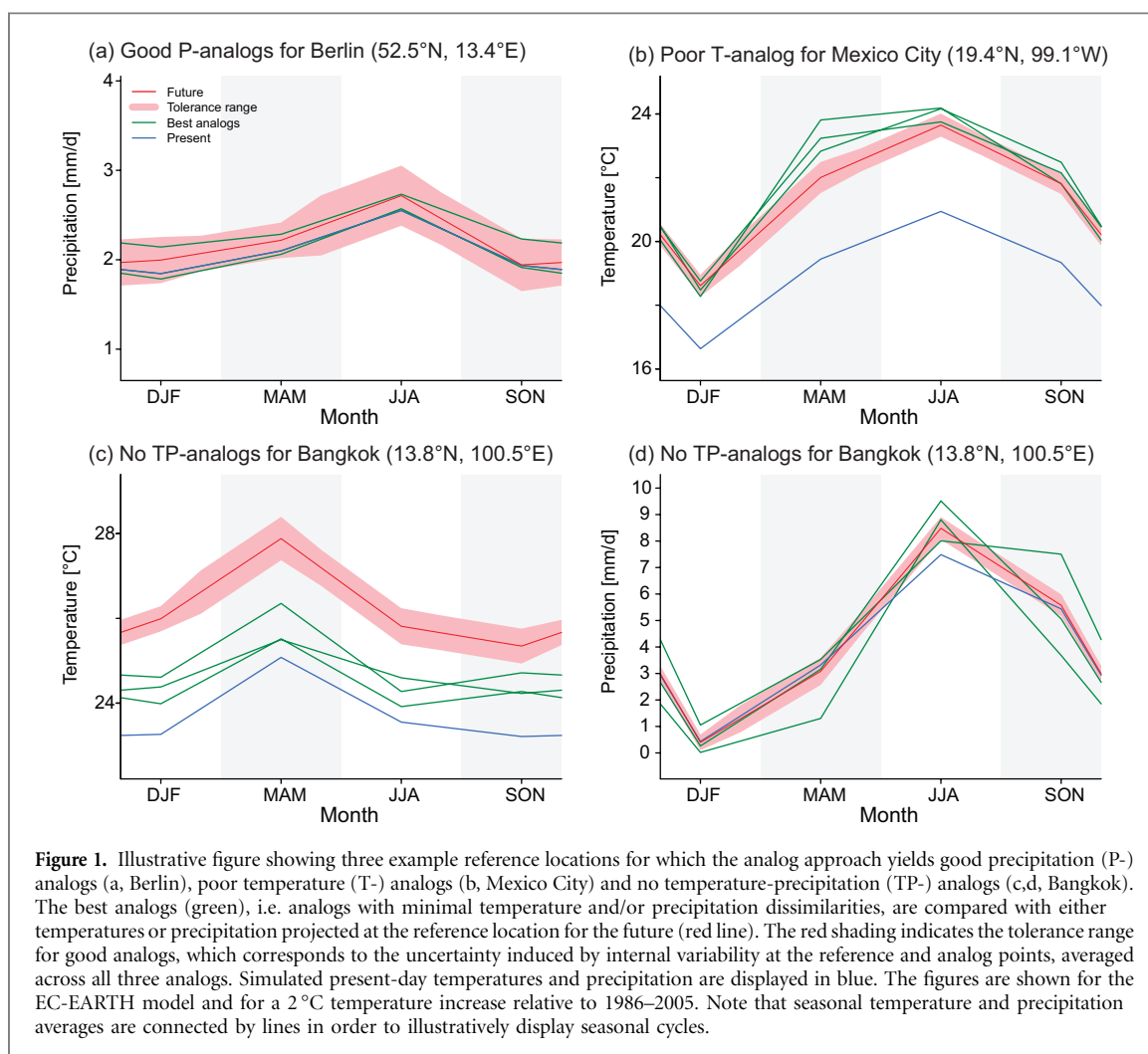
The dissimilarity between the future temperature projected for a specific global warming level at some reference grid point i and the present-day temperature at any land grid point j is quantified as follows

$$\text{dissimilarity}_{i,j,m} = \frac{1}{4} \sum_{s=1}^{S=4} \sqrt{\frac{(T_{i,s} - T_{j,s})^2}{\sigma_{i,s}^2 + \sigma_{j,s}^2}} \bigg|_m \quad (1)$$

where $T_{i,s}$ and $T_{j,s}$ are 20-year seasonal mean temperatures and $\sigma_{i,s}$ and $\sigma_{j,s}$ internal variabilities expressed as standard deviation of 20-year means for individual seasons, all evaluated for a climate model m . Absolute precipitation dissimilarities are computed likewise. The two climate variables are combined by averaging over temperature and precipitation dissimilarities.

The 20-year seasonal internal variabilities are estimated from each model's preindustrial control simulation and defined as one standard deviation of 20-year seasonal running means. We only use models for which the control runs have a length of at least 160 years after having cut the first 50 years for spin-up. This ensures to have eight or more non-overlapping segments for computing the internal variability. Furthermore, we only include climate models that have almost no drift in the control simulation. That is, we require that seasonal 20-year variabilities estimated from a control run's linearly detrended and non-detrended data do not differ by more than 10% over more than half of the total land area. Analyses have shown that if a model's preindustrial control simulation exhibits a trend, then that typically affects less than 20% of the land masses. Moreover, we assume that the internal variability does not change throughout the 21st century. Global warming may lead to a decrease in winter temperature variability over northern mid- to high-latitudes (Screen 2014) and to an increase in summer temperature variability over Europe (Schär *et al* 2004). We tested for changes in the internal variability of 20-year means across the historical and RCP8.5 simulations and found no signs for major systematic temporal changes over larger regions. The changes in variability over the 21st century in one model are generally much smaller than the difference in present-day variability across models.

For each climate model m , we identify the three grid points with the lowest temperature dissimilarities as the best temperature analogs (hereafter T-analogs) to a specific reference point. Likewise, the best precipitation (P-) and temperature-precipitation (TP-) analogs correspond to the three grid points with lowest precipitation and temperature-precipitation dissimilarities. Averaging the T-, P- or TP-dissimilarities over the three best analogs a and all 35



climate models m then yields a standardized metric R to assess the overall performance of the analog approach with respect to T-, P- or TP-analogs at any given grid point i

$$R_i = \frac{1}{M \cdot A} \sum_{m=1}^{M=35} \sum_{a=1}^{A=3} \text{dissimilarity}_{i,a,m}$$

$$= \begin{cases} \text{good analog} & R \leq 2 \\ \text{poor analog} & 2 < R \leq 4. \\ \text{no analog} & R > 4 \end{cases} \quad (2)$$

Given the inherent limitations climate models have, we consider three analog points and not just one. Thus, results are more robust and not sensitive to a single grid point that may for instance have an inaccurate representation of e.g. land surface properties. The threshold selection of two (equation 2) for discerning good analogs is statistically motivated since it corresponds to the 95% confidence interval for an individual season, analog point and climate model. Hence, the value $R=2$ in equation 2 implies that the present climate of the analogs represents the reference point's future projected seasonal cycle of temperature and/or precipitation well, and therefore, the climate already exists somewhere today (figure 1(a)). In contrast, if the R -value is larger than four, then the

current climate of the best analogs differs from the future climate of the reference point by more than twice the range for good analogs on average. In this case, it is not possible to find analogs that match the seasonal cycle of temperature and/or precipitation projected at the reference point for the future (figure 1(c) and (d)). Finally, a R -value between two and four suggests that it is difficult to make a statement whether these poor analogs are still useful representatives for the future climate projected at the reference point (figure 1(b)). In any case, it has to be acknowledged that the specific numbers in the results are sensitive to the criterion for accepting analogs but the patterns of the dissimilarity metric, dependencies on the variables, and general conclusions are not.

Grid points for which no climate analogs exist ($R > 4$) are expected to experience a future seasonal cycle of temperature and/or precipitation that does not exist under current climatic conditions and are thus anticipated to face novel, unprecedented climates in the future. Based on these future climates for which no analogs exist in the present, we further quantify the land fraction with projected novel climates as a function of the increase in global surface temperature. Similarly, there may be present-day climates with no T-, P- or TP-analogs existing in the future, which

implies a disappearing climate. We address this by simply computing the dissimilarities between the present temperature or precipitation simulated at the reference point and the future temperatures or precipitation projected at all land grid points. Climates are expected to disappear with climate change in areas for which the three best analogs have an average dissimilarity $R > 4$.

3. Results and Discussion

Figure 1 illustrates the concept of climate analogs by means of three example reference locations with a future projected climate for which we find good precipitation (P-) analogs (figure 1(a)), poor temperature (T-) analogs (figure 1(b)) and no temperature-precipitation (TP-) analogs (figure 1(c) and (d)) in the present climate. The results shown are based on the EC-EARTH model and for a 2 °C global mean temperature increase relative to 1986–2005. All identified P-analogs for Berlin (figure 1(a)) have a seasonal cycle of precipitation that is within the tolerance range for good analogs ($R \leq 2$), which is here displayed as the average uncertainty induced by seasonal 20-year internal variabilities simulated for Berlin and the best three P-analogs. This implies that the future seasonal cycle of precipitation projected for Berlin already exists somewhere today. In fact, the best P-analogs are found in the close neighborhood of Berlin. In contrast, it is not possible to find TP-analogs with a similar seasonal cycle of temperature and precipitation as projected for Bangkok ($R > 4$), which suggests the emergence of a novel climate. The grid points with the most similar climate, found in the close surrounding of Bangkok and at the west coast of Mauritania, clearly underestimate the future projected temperatures for all seasons and are outside the displayed temperature tolerance range (figure 1(c)). The mismatch between the seasonal cycles of precipitation of the TP-analogs and Bangkok is less pronounced (figure 1(d)). Finally, the T-analogs identified for Mexico City, which are located in the south eastern corner of the Arabic Peninsula (Yemen), are referred to as poor analogs ($2 < R \leq 4$). These analogs have a similar seasonal temperature cycle as projected for Mexico City though their climate is not within the tolerance range of two for accepting analogs (figure 1(b)). In particular, the March to May (MAM) temperatures of these poor analogs show a clear mismatch and are outside the shown temperature tolerance range. The tolerance range for accepting analogs is admittedly narrow and sensitive to the threshold selection. However, we point out that the choice of $R \leq 2$ is statistically motivated as for a given individual season it corresponds to the 95% confidence interval.

In general we find it easier to identify good analogs for precipitation due to its high variability, but more

difficult for temperatures or (as a consequence) for both climate variables simultaneously (figure 2). Good spatial analogs to future seasonal cycles of temperature projected for 2 °C global warming (relative to 1986–2005) are primarily found in the mid-, high- and polar-latitudes (green areas in figure 2(a)). Here all T-analogs assigned to some reference location lie on average within the tolerance range representing internal variability and therefore accurately represent the projected temperatures (e.g. Berlin, figure 1(a)). For substantial parts of the tropics and subtropics, however, it is not possible to identify T-analogs in the current climate (red areas in figure 2(a)). The present-day conditions of the grid points with the most similar climate are far outside the tolerance range representing internal variability, which implies the emergence of a novel climate in the future (e.g. Bangkok, figures 1(c) and (d)). Novel climates are mostly found at low-latitudes because they are already hot today and have the lowest internal variability (e.g. Mahlstein *et al* (2011), Hawkins and Sutton (2012)) causing the signal to rapidly emerge and reducing the tolerance range for accepting any spatial analog. The emergence of novel climates is overall robust across models in many regions (stippling indicates where two third of models agree on classification). The yellow areas in figure 2(a) correspond to regions with poor T-analogs that match the projected seasonal cycle of temperature only to some degree (e.g. Mexico City, figure 1(b)). Consequently, a statement whether the future climate projected for these regions already exists somewhere today depends on the location and the criteria for accepting an analog. In contrast, the projected seasonal precipitation cycle can already be found in the present-day climate for most areas across the globe (figure 2(b)) since many places exhibit large internal variabilities in precipitation and a comparatively small climate change signal (e.g. Deser *et al* (2012), Mahlstein *et al* (2012)). Combining both climate variables in the approach yields a larger area to which no analogs can be assigned than temperature alone does, now affecting most of the tropics and in addition also parts of the Tibetan Plateau (figure 2(c)). Differences are also found over the mid- and high-latitudes, where many regions have good T-analogs but only poor TP-analogs. This stems from the fact that the best T-analogs do not necessarily coincide with the best P-analogs, i.e. the locations with the most similar seasonal cycle of temperature are generally not the same as the ones with the most similar seasonal cycle of precipitation. Hence, the seasonal cycles of temperature and precipitation of the identified TP-analogs do not match the projected conditions as well as the individual climate variables do. The comparison of figures 2(a)–(c) further suggests that both climate variables contribute to the emergence of novel climates but temperature is the main driver.

For each model, we further quantify the land fraction with novel climates that do not exist under

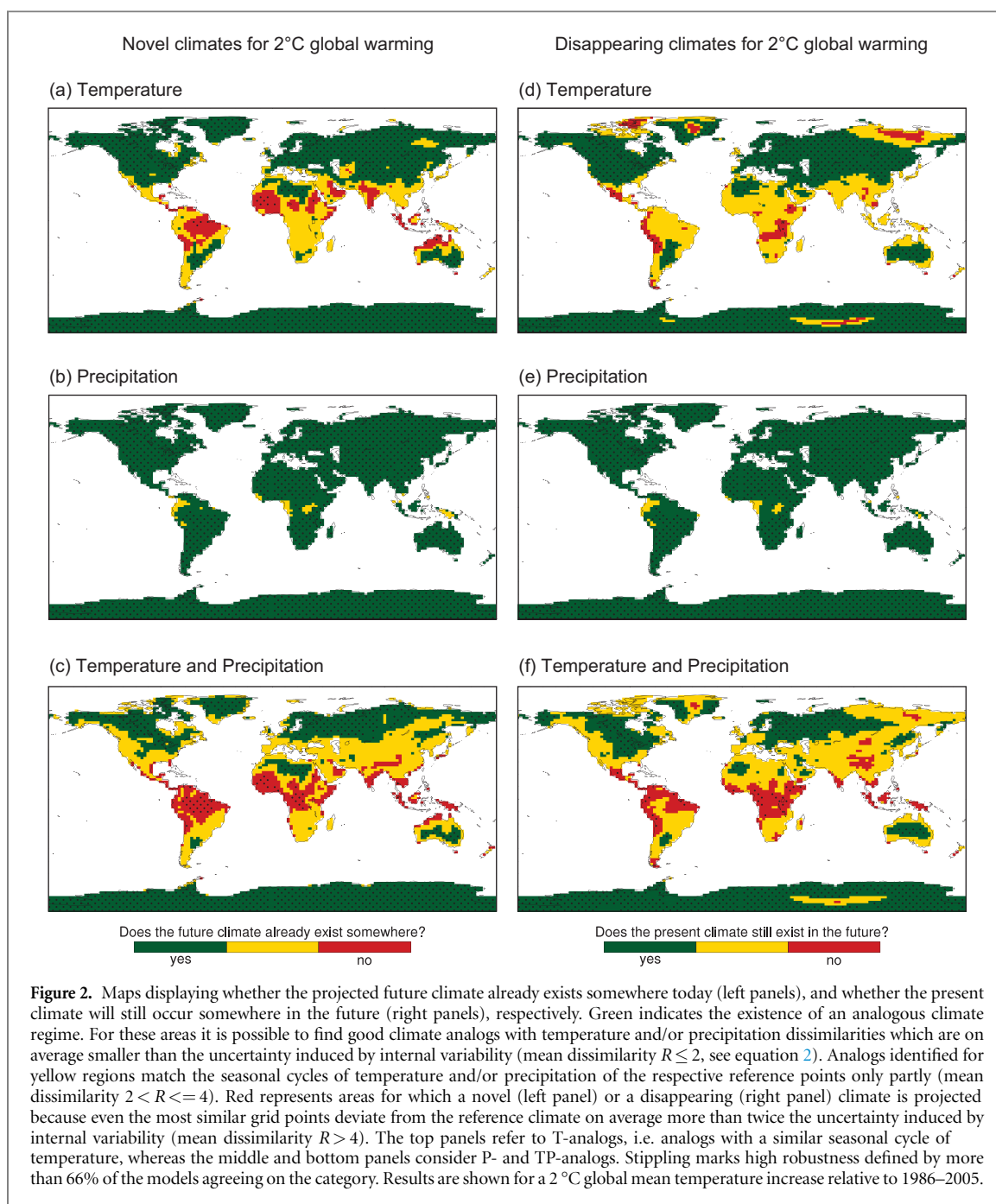
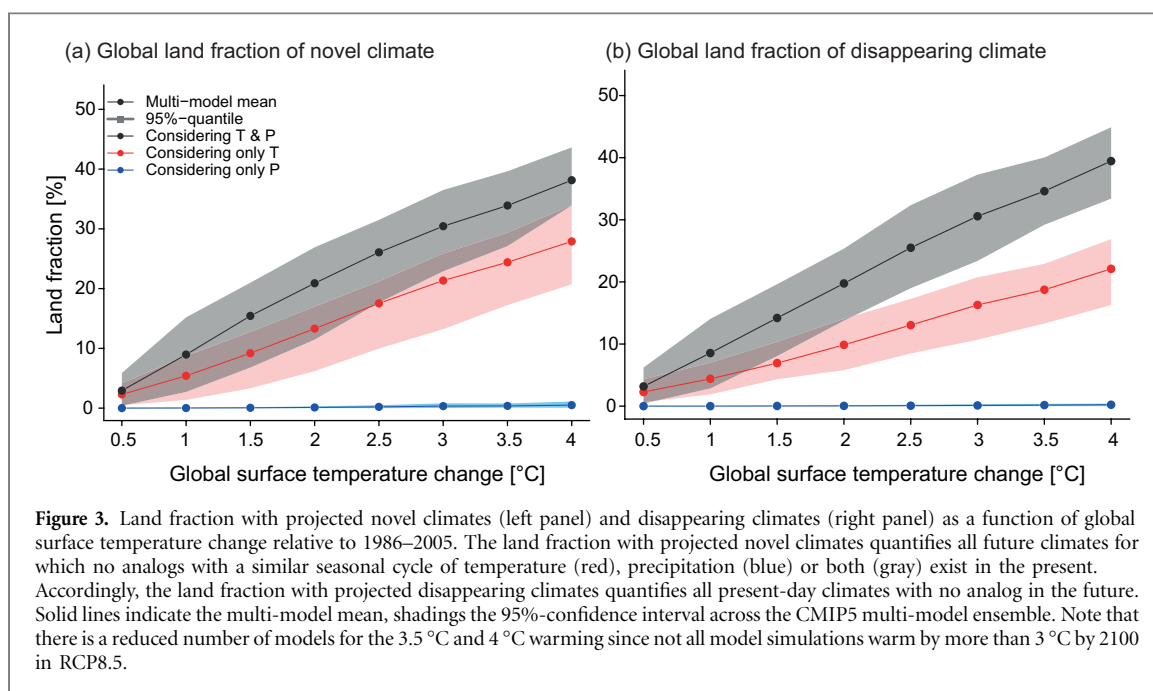


Figure 2. Maps displaying whether the projected future climate already exists somewhere today (left panels), and whether the present climate will still occur somewhere in the future (right panels), respectively. Green indicates the existence of an analogous climate regime. For these areas it is possible to find good climate analogs with temperature and/or precipitation dissimilarities which are on average smaller than the uncertainty induced by internal variability (mean dissimilarity $R \leq 2$, see equation 2). Analog identified for yellow regions match the seasonal cycles of temperature and/or precipitation of the respective reference points only partly (mean dissimilarity $2 < R \leq 4$). Red represents areas for which a novel (left panel) or a disappearing (right panel) climate is projected because even the most similar grid points deviate from the reference climate on average more than twice the uncertainty induced by internal variability (mean dissimilarity $R > 4$). The top panels refer to T-analogs, i.e. analogs with a similar seasonal cycle of temperature, whereas the middle and bottom panels consider P- and TP-analogs. Stippling marks high robustness defined by more than 66% of the models agreeing on the category. Results are shown for a 2 °C global mean temperature increase relative to 1986–2005.

current conditions (corresponds to red category in figure 2) as a function of global warming relative to 1986–2005 (figure 3(a)). The land fraction with projected novel seasonal cycles of temperature increases approximately linearly as the globe warms. A similar characteristic is found when accounting for seasonal cycles of both temperature and precipitation, which reemphasizes the dominant role of temperature as a driver for novel climates. In fact, precipitation changes alone rarely lead to novel climates, and the land fraction is close to zero for all warming levels. The model uncertainty range (colored shading two-sided 95% confidence) is relatively low. This follows from the fact that results are shown as a function of global temperature increase rather than time, eliminating the uncertainty in how strongly each model responds to

greenhouse gases. Note that when models agree on the fraction of land with novel climate, they may still not agree on where those are. The multi-model means (solid lines) at 2 °C global warming correspond to the red areas in figures 2(a)–(c). Accordingly, at 2 °C warming about 21% (95% confidence interval: 11%–27%) and for 1.5 °C warming about 15% (7%–21%) of the total land is predicted to face a novel climate regarding the seasonal cycle of temperature and precipitation. For a 4 °C warming level, the respective percentage of novel climates increases to more than third (34%–44%) of the global land fraction. Note that the fraction with poor analogs is substantially larger. With further warming also the regions with good climate analogs (green areas) decrease in the mid- to high-latitudes for temperatures and combined climate



variables, as well as in the tropics and subtropics for precipitation. Note that the warming here is quantified relative to the present-day period 1986–2005 and thereby not necessarily equivalent to changes due to the policy-relevant warming targets relative to pre-industrial conditions. Nevertheless, we expect the numbers to be very similar for warming targets relative to pre-industrial conditions, since the tolerance range due to internal variability used here is based on pre-industrial control simulations and we do not identify strong non-linearities in response to the warming.

Climates that are likely to disappear with increasing warming are predominantly found in the northern high-latitudes, Andes, Central America, sub-Saharan Africa and south-east Asia when considering temperature and precipitation simultaneously (red areas in figure 2(f)). For parts of these regions it is impossible to find TP-analogs with simulated present-day conditions that match the future projected seasonal cycles of both climate variables. As the globe warms, one would expect to observe the climate of today's warmest regions just more towards the poles. However, as we move polewards the solar irradiation changes, and consequently also the seasonal cycle of temperature. Hence, these warmest present-day climates do not occur elsewhere in the future. On the other hand, today's coldest areas naturally move outside the current temperature range as global mean temperatures increase. It has to be acknowledged that some regions with a disappearing climate have extremely low internal variability (e.g. Central America) or steep but unresolved topography (e.g. Andes), in which case grid resolution might be a limiting factor. For such grid points it is already difficult to find perfectly matching analogs in the same climate. A more detailed discussion about limitations of the approach and the grid resolution is presented in

the subsequent paragraph. Good TP-analogs can mainly be found over Eurasia, North America and Antarctica (green area in figure 2(f)). For large parts of the globe, a statement whether the simulated present climate will still exist somewhere in the future depends on the location and the criteria for accepting an analog (yellow areas in figure 2(f)). Regions for which good T-analogs exist occur more frequently over the mid- to high-latitudes (green area in figure 2(d)). In return, the area to which no T-analogs can be assigned, i.e. the area of disappearing climates, is smaller than for TP-analogs (red regions in figure 2(d)). Finally, if climates are only defined based on the seasonal cycle of precipitation, present climates still exist for most areas across the world as global warming continues (figure 2(e), and figure 3(b)). Figure 3(b) displays the fraction of land with disappearing climates as a function of global warming, which is akin to the findings presented in figure 3(a) (novel climates). For a warming of 1.5 °C about 14% (95% confidence interval: 8%–20%), for 2 °C about 20% (14%–25%) and for 4 °C almost 40% (33%–45%) of the land fraction is projected to experience disappearing climates. Temperature is the main driver for the disappearance of present-day climates though precipitation changes also have a reasonable influence.

The results of our analysis are in broad agreement with the findings of Williams *et al* (2007) and Williams and Jackson (2007), who conducted similar studies on novel and disappearing climates. They also projected the emergence of novel climates for regions over the tropics and subtropics. Likewise, disappearing climates are predominantly identified in the Andes, tropical mountains and poleward sides of continents. However, the land fraction of novel and disappearing climates is somewhat smaller than in our analysis (figures 2(c) and (f) and figure 3). Recall that Williams

et al (2007) and Williams and Jackson (2007) quantify dissimilarities by the Euclidean distance of DJF and JJA temperatures and precipitation normalized by the interannual variability. On this account, we tested our method using only DJF and JJA temperatures and precipitation instead of the full seasonal cycle and considered only one climate analog, which explains part of the differences. Further differences are mainly due to different normalization factors and thresholds for identifying novel and disappearing climates. While in the presented method seasonal temperature and precipitation differences are normalized with multi-decadal variabilities (standard deviation of 20-year means), Williams *et al* (2007) and Williams and Jackson (2007) use the interannual internal variability for normalization. The internal variability of 20-year means is comparatively small and we are thus more restrictive in accepting analogs. However, we argue that normalizing 20-year means with the corresponding 20-year variabilities is more appropriate for the comparison of different climatologies, and consistent with the treatment of variability in IPCC AR5 (Collins *et al* (2013), box. 12.1, footnote 3).

It is important to acknowledge different limitations of the analog approach presented above. First of all, results are sensitive to the threshold selection in order to discern good, poor or no analogs. Ultimately, there is no single correct way of defining the threshold. On this account, we additionally provide the underlying values of the analysis in the supplementary material available at stacks.iop.org/ERL/12/084004/mmedia (figure S1). The choice of the threshold $R \leq 2$ based on seasonal 20-year means is arguably a narrow criterion for accepting analogs, but it is statistically motivated. Due to this sensitivity of the results towards the threshold selection, a rather conservative threshold of $R > 4$ is chosen for quantifying novel and disappearing climates. In general, it has to be noted that grid cell based variability is lower than point based which implies that we are more restrictive in accepting analogs. Independent of the exact threshold used to define novel and disappearing climates, the general patterns across space, and their dependence on individual variables is robust. The conclusion about a large fraction of novel and disappearing climates also likely holds for a variety of definitions. Second, the relatively low grid resolution of the global climate models entails the risk of missing accurate, yet unresolved analogs. In other words there is the possibility that better analogs were found if a data set was available at higher resolution. If this was a limiting factor we would expect that many of today's local climates have no analog in space even under present-day conditions. We tested this by quantifying the dissimilarities between the current climate at some reference point and the present climate at all other grid points (see figure S2 in the supplementary material). The results indicated near perfectly matching analogs for most parts across the world for all three types of input variables (T, P, TP). Only in areas of extremely low internal variability

(e.g. Central America, south east Asia) or steep but unresolved topography (e.g. Andes, Himalaya) grid resolution seems to be a limiting factor regarding temperature and both climate variables combined. In mountainous regions analogs are often expected at a different altitude, yet the resolution available here would miss those. Third, the whole analysis is done in a model world. Although our findings are robust across models, one has to be aware that those climate models have known limitations in simulating the current climate, and uncertainties in projecting climate (e.g. Tebaldi and Knutti (2007), Knutti (2008), Hawkins and Sutton (2009)). Fourth, even if analogs are found and have identical seasonal cycles, they may still have different year-to-year or day-to-day variability or different extremes. Note also that variability is assumed to be Gaussian. Furthermore, the same mean annual cycle of temperature and precipitation does not necessarily imply the same climate. Other important parameters such as topography, vegetation, soil properties or winds that define the climate of a given grid point have been entirely ignored in the analysis. If a more comprehensive definition of climate was used the fraction of novel and disappearing would be larger. Fifth, we assume that the models represent temperature and precipitation differences between grid points correctly, i.e. the spatial temperature and precipitation differences simulated for today correspond to the observed differences. Sixth, due to the distinct seasonal cycle of temperature, the distance metric naturally excludes all grid points on the other hemisphere. Hence, there is the possibility of missing out on good analogs with a seasonal cycle of temperature shifted by half a year. Finally, the construction of the distance metric matters. Some systems (e.g. plant species) or impacts are more sensitive to changes in one season than to another, or may depend only on conditions in some seasons, in which case more or fewer analogs will exist, and they will be in different places. Another quantity that may be relevant for impacts (e.g. biomes or species that need to migrate) is how far these analogs are away (Williams *et al* 2007, Williams and Jackson 2007), and how quickly the Earth warms (LoPresti *et al* 2015). Nevertheless, despite all those limitations, we argue that the main results are robust: for warming of 2 °C or more, a substantial fraction of the locations will experience a future climate that is different from anything observed anywhere today, particularly in the tropics, and many climates today will no longer exist anywhere.

4. Conclusion

Here we globally assess the potential of the climate analog approach by means of a 35-member ensemble of global climate models from the CMIP5. While most earlier studies used the concept of climate analogs without testing how well the analogs represent the climate of the reference location, we demonstrate that

the performance of the approach highly depends on the input climate variable and the geographical region. Overall good analogs are found for precipitation, whereas identifying analogs for the seasonal cycle of temperature or both variables is often not possible. This implies that many places, particularly in the subtropics and tropics, will experience novel climates that do not exist under current conditions. Similarly, disappearing climates, i.e. places with present-day climates for which no future analog exists, are projected for large fractions of the tropics, subtropics and Northern polar regions. The global land fraction of novel climates regarding the seasonal cycle of temperature and precipitation is around 21% for 2 °C global warming relative to 1986–2005 and approximately linearly increases with further warming. The results found for disappearing climates are similar. When we include only individual seasons (e.g. DJF or JJA) in the analog approach instead of the full seasonal cycle, identifying good analogs is much easier. In fact, the land fraction of novel and disappearing climates is drastically reduced for all three types of input variables if only one season matters.

We argue that the concept of climate analogs still has unrecognized potential for visualization, awareness raising and impact appraisal, as far as it is enough to consider only individual seasons. Depending on the context in which the concept of climate analogs is applied, it might be sufficient to solely look at independent seasons. Ski resorts, for example, probably just use winter and maybe spring analogs for planning the future, whereas those concerned with agriculture may be exclusively interested in future spring and summer conditions. If the full seasonal cycle of temperature and precipitation is important, the approach is less suitable to find analogs, but is a powerful demonstration of the serious consequences for climate change impacts, including species, natural habitats and the existence of the climate zones (or lack thereof) as we experience them today (Leemans and Eickhout 2004).

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