

MIT Open Access Articles

Pace of shifts in climate regions increases with global temperature

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Mahlstein, Irina, John S. Daniel, and Susan Solomon. "Pace of Shifts in Climate Regions Increases with Global Temperature." *Nature Climate Change* 3, no. 8 (April 21, 2013): 739–743.

As Published: <http://dx.doi.org/10.1038/nclimate1876>

Publisher: Nature Publishing Group

Persistent URL: <http://hdl.handle.net/1721.1/87693>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



Increasing pace of shifts in climate regions with increasing global temperature

Irina Mahlstein^{1,2*}, John S. Daniel² and Susan Solomon³

¹ Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA

² Chemical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, Colorado, USA

³ Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

*Corresponding author: Irina Mahlstein, NOAA/ESRL Chemistry & Climate Processes, 325 Broadway - R/CSD8, Boulder, CO 80305, USA, irina.mahlstein@noaa.gov
Now at MeteoSwiss: irina.mahlstein@meteoswiss.ch

Human induced climate change causes significant changes in local climates^{1,2}, which in turn lead to changes in regional climate zones. Large shifts in the world distribution of Köppen-Geiger climate classifications by the end of this century have been projected³. However, only a few studies have analyzed the pace of these shifts in climate zones^{4,5}, and none have analyzed whether the pace itself changes with increasing global mean temperature. In this study, pace refers to the rate at which climate zones change as a function of amount of global warming. Here we show that current climate projections suggest that the pace of shifting climate zones increases approximately linearly with increasing global temperature. Using the RCP8.5 emissions pathway, the pace nearly doubles by the end of this century and about 20% of all land area undergoes a change in its original climate. This implies that species will have increasingly less time to adapt to Köppen zone changes in the future, which is expected to increase the risk of extinction⁵.

The questions of the emergence of novel and disappearing climates, and at what velocity these shifts happen have been considered in previous studies^{4,6}. However, earlier studies either only take into account one variable represented by shifting isotherms or a combination of temperature and precipitation indices. These climatological metrics do not necessarily represent biomes. From an impacts perspective, biomes are important, as they represent entirely different types of ecosystems. Among others, Rubel and Kottek³ used the Köppen-Geiger classification to estimate how large the shifts between the different climate classes are based on climate model simulations. The Köppen-Geiger climate classification was first introduced by W. Köppen. Its purpose is to predict biome distribution based not only on monthly temperature and precipitation values but also on the annual cycles of both. This classification also takes into account plant sensitivity to thresholds^{7,8}. Such bioclimatic classification schemes have the advantage that they are easily applied to climate model output, and therefore possible future changes in ecosystem types can be evaluated on a grid cell level as for every grid cell bioclimatic information becomes available.

We use the precipitation and temperature changes calculated from historical and RCP8.5 CMIP5⁹ runs to analyze changes in the Köppen-Geiger climate classification at the grid-point level of the simulations for the time period 1900-2098. The Köppen scheme is very sensitive to thresholds as it distinguishes between different climates based for example upon whether conditions are warmer than some temperature or wetter than a particular precipitation amount. Therefore, model biases are critical to this analysis and models do exhibit quite large discrepancies in their Köppen climates compared to those derived from observations⁷. To help reduce errors in climate classification changes in this work, only anomalies from the model output are used, and these are added to a 20 y observational base period (see Methods). Before determining the climate zone for each year of the time series, a 5 y running mean was applied to each model's temperature and precipitation values in order to reduce the possible impacts of shorter-term climate variability. Results are not highly sensitive to the length of the averaging period. Then, for each model and each time step the percentage of land area that changed to a new climate zone is estimated. In determining the percentage of land area that has changed to a new climate zone in a warming world, a change for a particular grid point is counted when a fully distinct new climate zone appears. To reduce the possibility that climate variability might cause calculated climate zone shifts, for each model and grid cell all 'natural' climate zones that are obtained in linearly detrended 5 y running mean data are evaluated before examining future states (see Methods). Therefore, all changes found are statistically significant, since they are not due to variability. For each model, a quadratic fit to the percentage change in climate zones as a function of globally averaged temperature change was performed and was found to fit the results well (see Methods). The lower panel in Figure 1 illustrates the fitting to the calculated results for two of the models considered. Figure 1a shows the quadratic fit for each model (dashed line), the multi model mean (green line) and the one standard deviation of the models' predictions (shaded in green). Following the RCP 8.5¹⁰ emissions pathway, the mean warming reaches about 4.5°C at the end of this century¹¹, implying that about 20% of the global land area shifts climate zones. Model

uncertainty however is large, and the different models suggest a range from 17% up to 27% that increases with increasing global average temperature. The results are shown as a function of global average temperature so the results can be applied to different RCPs.

The quadratic increase of the percentage of land area that changes climate zones leads to two conclusions: First, there does not appear to be a threshold designated by a step function in the shift of climate zones⁶; second, the pace of climate shifts increases with increasing mean global temperature. Figure 1b shows the first derivative of the functions shown in Figure 1a, which can be considered to be the 'pace' of climate zone change. With increasing global mean temperature, the pace at which climate zones are shifting increases. As the pace of climate change induced impacts increases, species will have less time to adapt to the new environment or to migrate to their preferred environment⁵. Based on RCP8.5, the pace will have doubled at the end of this century compared to early 20th century values. Again model uncertainty is significant and covers a range of different changes of the pace. Nonetheless, the models all simulate an increase of the pace of change with increasing global mean temperature. In this study multiple changes are not counted as additional area changed (i.e., if a grid cell moves from one distinct new climate to another distinct new climate, the area is counted only once not twice); therefore, in actual ecosystems the stress might even be larger than shown here.

Figure 1 suggests that if a warming of 2°C were to be reached, about 5% of the land area would be expected to face a new climate zone. However, depending on where these regions are, how much land is used for agriculture, how many endemic species live in this area or how densely populated it is, the impacts could still be quite large. Hansen¹² also shows that this amount of global temperature increase would lead to significant climatic changes. However, it can be seen that at 2°C global mean temperature increase nothing extraordinary happens. There is for example no step function at 2°C that might suggest that many ecosystems would abruptly become unable to cope with that much warming. Therefore, this study does not provide scientific

evidence that 2°C should be a preferred target from a climate zone perspective. Other studies have suggested that the 2°C target does not prevent irreversible changes of the climate^{13,14}.

Novel climates cannot emerge in this study by definition, as all possible combinations of temperature and precipitation will give one of the Köppen climates. Climate zones can disappear, but a large perturbation is required. Whether climate zones disappear is highly dependent on the specific climate model. However, there are some common 21st century changes across all models: Frost climates are largely decreasing, some arid regions are increasing and a large fraction of the land area changes from cool summers to hot summers. Figure 2 shows the changing Köppen climate zones based on the MIROC5 simulations, which is qualitatively representative of most models although the results are somewhat model dependent. However, not every region is equally affected by changes in climate zones. Figure 3 shows at what global mean temperature increase different regions see a shift in climate zone based on the multi model mean. It shows a rather patchy result, probably due to the rather large noise for both of the variables on this small scale plus differences in elevation (see below). Almost all land areas of the northern middle and high latitudes undergo climate shifts, whereas the tropical regions do not see many changes. This seems at first glance to be in contradiction to previous findings where temperature increases show the earliest emerging signals in the tropics¹. However, as the Köppen classes are threshold based, and tropical climates already have hot summers, a further increase in temperature generally will not affect the climate class. Precipitation changes would have an impact, but on a grid cell level, these areas show no significant changes in precipitation².

Nonetheless, the effect of increasing temperatures at low latitudes can clearly be seen at higher elevations. Many low-latitude mountainous regions experience a climate zone shift before low-altitude regions do. As illustrated in Figure 3 by the highlighted areas, a number of tropical mountain regions and their lee sides display changes in climate zones when their surrounding

low-level regions do not see any changes yet. This implies that low latitude high altitude regions are likely affected sooner by climate change from a biome perspective than their surrounding low lands. The reason for these changes is partly due to changes in precipitation. The mountain regions are more strongly affected by changes in precipitation than other regions (see supplemental material). In contrast, the high altitude regions of Greenland and Antarctica show an inverse effect, wherein their low-level coastlines are affected first. This suggests that in high latitude regions, higher elevations remain cold enough to maintain the existing climate zones, while essentially the reverse is true in low latitudes. These findings are based on the multi model mean and do vary when looking at individual models. However, as the topography of mountain regions is simulated in only a smeared fashion in the models, the fact that an effect can nevertheless be seen in the multi model mean suggests that the effect is even greater in reality.

Most changes obtained here seem to be temperature rather than precipitation driven. This finding is supported by doing the same analysis as in Figure 1a for two cases in which either temperature or precipitation is held fixed over time by linearly detrending that variable. In the case in which precipitation is held constant, the fraction of land area that experiences a change is only slightly smaller than that of Figure 1a as shown in Figure 4a. However, when temperature is held constant a much smaller fraction of the land area sees a change, as depicted in Figure 4b. It is interesting to note that when only temperature changes, the increase in area changed seems to be slightly more linear than was found in Figure 1a; however when precipitation is allowed to change and temperature is fixed the changes are quadratic. When added together, the results shown in Figure 4a and b approximately equal the pace shown in Figure 1a. This suggests that the two signals of temperature and precipitation are not counteracting but complement each other. This is not surprising as the Köppen classification is defined such that temperature and precipitation are quantified independently.

There are several reasons why changes in precipitation seem to be less important for the Köppen classification scheme. One factor that should be noted is that the models are known to underestimate the observed precipitation trends¹⁵⁻¹⁷. Further, the nature of the definition of the Köppen scheme should also be considered. Most wet areas become wetter with future changes and dry places drier. The thresholds relevant to the Köppen scheme are often defined as a minimal or maximal amount of precipitation, and most regions are above or below the thresholds to start with. For example, if a region is already rated as wet because its precipitation is more than the required amount, a further increase in precipitation often will not lead to a change of Köppen climate. However, it has been suggested that high heat stress could turn tropical regions into uninhabitable regions for mammals. This could start at a global mean temperature increase of 7°C¹⁸, which is larger than the temperature range analyzed here.

Although the Köppen classification scheme has some disadvantages, such as the lack of wind and sunshine as contributing factors, one advantage is that it is simple to apply to climate model data as a first-order index to characterize climate zones globally and obtain an indication of what climate changes associated with a certain global mean temperature increase means for ecosystems.

We have shown that the more the global mean temperature increases, the faster land areas face a new climate. Furthermore, climate shifts will happen in some locations below 2°C global temperature increase, and the Earth would be committed to significant impacts due to climate change even if we stabilize CO₂ emissions consistent with the 2°C target. Climate zones at middle and higher northern latitudes as well as low-latitude mountainous regions and areas in their lee zones are the ones most sensitive to climate changes. The changes in temperature appear to be more important for the overall changes; while this is dependent upon the thresholds that are used in the definitions of Köppen zones, the precipitation and temperature thresholds are not arbitrary.

However, this does not imply that for specific species the changes in precipitation are not important.

Methods

This study uses the historical and RCP8.5 runs from 13 atmosphere ocean global climate models (AOGCM), which are available from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5)⁹. The RCP8.5 was chosen, because it is the pathway with the largest radiative forcing at the end of this century, about 8.5 W/m^2 , which is equivalent to about 1360 ppm CO_2 concentration¹⁹. This offers the possibility to explore responses over large range of temperature increases. However, as the results are shown as a function of global mean temperature increase, they are not sensitive to the choice of RCP, but allow any RCP to be related to these results. One ensemble member (r1i1p1) from each of the following models is used in this study: CNRM-CM5, CSIRO Mk3.6, CanESM2, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M and bcc-cm1. All model output is regridded to a common T42 grid. As the Köppen-Geiger climate classification is sensitive to thresholds²⁰ and because the models have difficulties in simulating the correct Köppen-Geiger climate zones even for today's conditions⁷ the following method was applied: in each model, anomalies relative to the monthly means for 1980-1999 are calculated, which are then added to the observed 1980-1999 monthly means. For both temperature and precipitation, this results in a total time period of 199 years covering 1900-2098. Comparisons to observed Köppen-Geiger classes show that these time series yield realistic results for the first 30 y and other studies show that models are able to reproduce the past climate change fairly well²¹. Before applying the Köppen-Geiger climate classification algorithm a 5 y running mean is applied to increase the robustness of the results, as a change in a climate zone over a time period of 5 y will more likely result from a climate change, while year-to-year changes would include greater internal variability that may be unrelated to climate trends.

The change in Köppen-Geiger climate classification is determined on the grid scale level. In order to take into account possible natural fluctuations of climate zones, for each model and each grid cell the naturally occurring climate zones are identified in linearly detrended 5-year running mean temperature and precipitation time series for the full period 1900-2098. In this way, a conservative estimate of a range of climate states that might occur through variability are evaluated first. A change in projected future climate zones is only recorded if a climate zone appears that is not one of the naturally fluctuating climate zones at a specific grid cell. Some regions show quite large natural variability in their climate whereas others are constant. Furthermore, if a change has happened, yet later in time one of the ‘natural’ climate zones reappears in that grid cell, then the grid cell is not deemed to have changed, even if the ‘natural’ zone only reappears for a single 5-year averaging period. The cumulative percentage change of climate zones over all land area is shown as a function of global mean temperature and only shows changes that are significant in the sense that natural variability is not the reason for these changes. By visual inspection, we found that a quadratic function appeared to characterize the changes. Therefore, for each model a quadratic function as following is fitted to the data:

$$P(T)=aT^2+bT+c \quad (1)$$

where P is the change in land area as a function of the global mean temperature (T) and the parameters a,b,c are the fitted values to the model data and therefore different for each model.

The fit proves to be very good, as for all models the R-squared values are larger than 0.98 and are better than for e.g. a linear fit. Only one model has a linear fit that is as good as the quadratic. There is some uncertainty associated with the fits of the model results, but the spread across the models is larger than the uncertainty associated with the fit as illustrated in Figure 1a. The choice of a quadratic over a linear fit is supported by goodness of fit tests. However, it is important to consider whether an equation of higher degrees could yield an even better goodness of fit, as there are more degrees of freedom. Tests showed that the goodness of fit however is only slightly better for a higher order than quadratic. Our choice of a quadratic fit is hence somewhat

conservative. If a higher order of fit had been chosen, the first derivative would change at an even faster rate.

References

- 1 Mahlstein, I., Knutti, R., Solomon, S. & Portmann, R. W. Early onset of significant local warming in low latitude countries. *Environmental Research Letters* **6**, 034009 (2011).
- 2 Mahlstein, I., Portmann, R. W., Daniel, J. S., Solomon, S. & Knutti, R. Perceptible changes in regional precipitation in a future climate. *Geophysical Research Letters* **39**, L05701, Doi 10.1029/2011gl050738 (2012).
- 3 Rubel, F. & Kotteck, M. Observed and projected climate shifts 1901-2100 depicted by world maps of the Koppen-Geiger climate classification. *Meteorol Z* **19**, 135-141, Doi 10.1127/0941-2948/2010/0430 (2010).
- 4 Burrows, M. T. *et al.* The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science* **334**, 652-655, Doi 10.1126/Science.1210288 (2011).
- 5 Sandel, B. *et al.* The Influence of Late Quaternary Climate-Change Velocity on Species Endemism. *Science* **334**, 660-664, Doi 10.1126/Science.1210173 (2011).
- 6 Williams, J. W., Jackson, S. T. & Kutzbach, J. E. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 5738-5742, Doi 10.1073/pnas.0606292104 (2007).
- 7 Gnanadesikan, A. & Stouffer, R. J. Diagnosing atmosphere-ocean general circulation model errors relevant to the terrestrial biosphere using the Koppen climate classification. *Geophysical Research Letters* **33**, L22701, Doi 10.1029/2006gl028098 (2006).
- 8 Koppen, W. The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world. *Meteorol Z* **20**, 351-360, Doi 10.1127/0941-2948/2011/105 (2011).
- 9 Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society* **93**, 485-498, doi:10.1175/bams-d-11-00094.1 (2011).
- 10 van Vuuren, D. P. *et al.* The representative concentration pathways: an overview. *Climatic Change* **109**, 5-31, Doi 10.1007/S10584-011-0148-Z (2011).
- 11 Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim. Change* **2**, 248-253, doi:<http://www.nature.com/nclimate/journal/v2/n4/abs/nclimate1385.html> - supplementary-information (2012).

- 12 Hansen, J. E. A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? *Climatic Change* **68**, 269-279 (2005).
- 13 Randalls, S. History of the 2°C climate target. *Wiley Interdisciplinary Reviews: Climate Change* **1**, 598-605, doi:10.1002/wcc.62 (2010).
- 14 Richard, S. J. T. Europe'S Long Term Climate Target: A Critical Evaluation. *Energy Policy* **35**, 424-434 (2005).
- 15 Noake, K., Polson, D., Hegerl, G. & Zhang, X. Changes in seasonal land precipitation during the latter twentieth-century. *Geophys. Res. Lett.*, doi:10.1029/2011GL050405 (2012).
- 16 Zhang, X. B. *et al.* Detection of human influence on twentieth-century precipitation trends. *Nature* **448**, 461-464, Doi 10.1038/Nature06025 (2007).
- 17 Liu, C., Allan, R. P. & Huffman, G. J. Co-variation of temperature and precipitation in CMIP5 models and satellite observations. *Geophys. Res. Lett.* **39**, L13803, doi:10.1029/2012GL052093 (2012).
- 18 Sherwood, S. C. & Huber, M. An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 9552-9555, Doi 10.1073/Pnas.0913352107 (2010).
- 19 Meinshausen, M. *et al.* The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**, 213-241, Doi 10.1007/S10584-011-0156-Z (2011).
- 20 Kottek, M., Grieser, J., Beck, C., Rudolf, B. & Rubel, F. World map of the Koppen-Geiger climate classification updated. *Meteorol Z* **15**, 259-263, Doi 10.1127/0941-2948/2006/0130 (2006).
- 21 IPCC. Climate change 2007: The physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, 996pp. (2007).

Correspondence and requests for materials should be addressed to Irina Mahlstein.

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with

the Global Organization for Earth System Science Portals. We also thank Urs Beyerle, Jan Sedlacek and Thierry Corti for downloading and regridding the model data.

Irina Mahlstein, John S. Daniel and Susan Solomon designed the study; Irina Mahlstein did all the analysis shown in the study; Irina Mahlstein, John S. Daniel and Susan Solomon wrote the paper.

There are no competing financial interests.

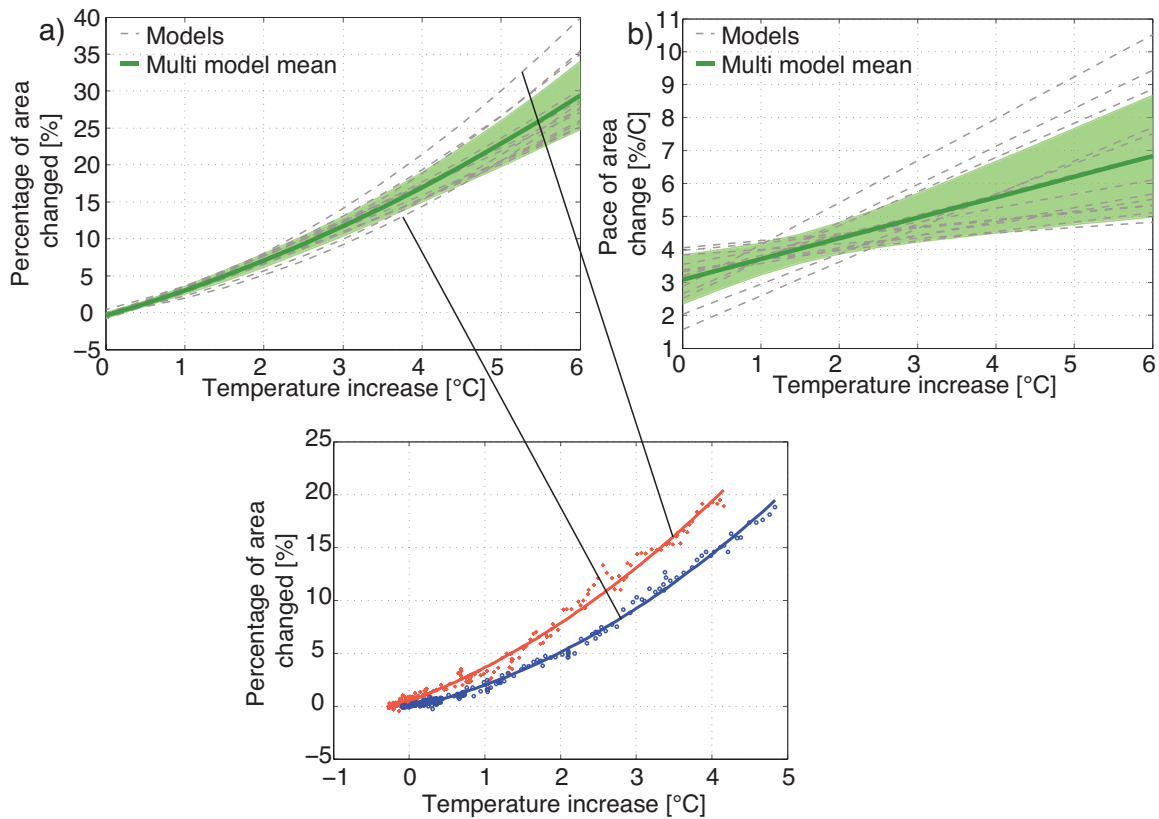


Figure 1: Amount of land area affected by climatic shifts and its pace. a) Fitted cumulative percentage of land area changed for each model (dashed lines) shown as a function of global mean temperature. The multi model mean (green line) and one standard deviation (shaded green) are shown. The lower panel shows the fitted curve to the model results for two models

(CNRM-CM5 and CSIRO Mk3.6) b) Pace of land area changed [%/°C] shown as a function of global mean temperature for each model (dashed lines) and the multi model mean (green line). The green shading shows the one standard deviation. Temperature increases up to 6°C are shown in panel a) and b).

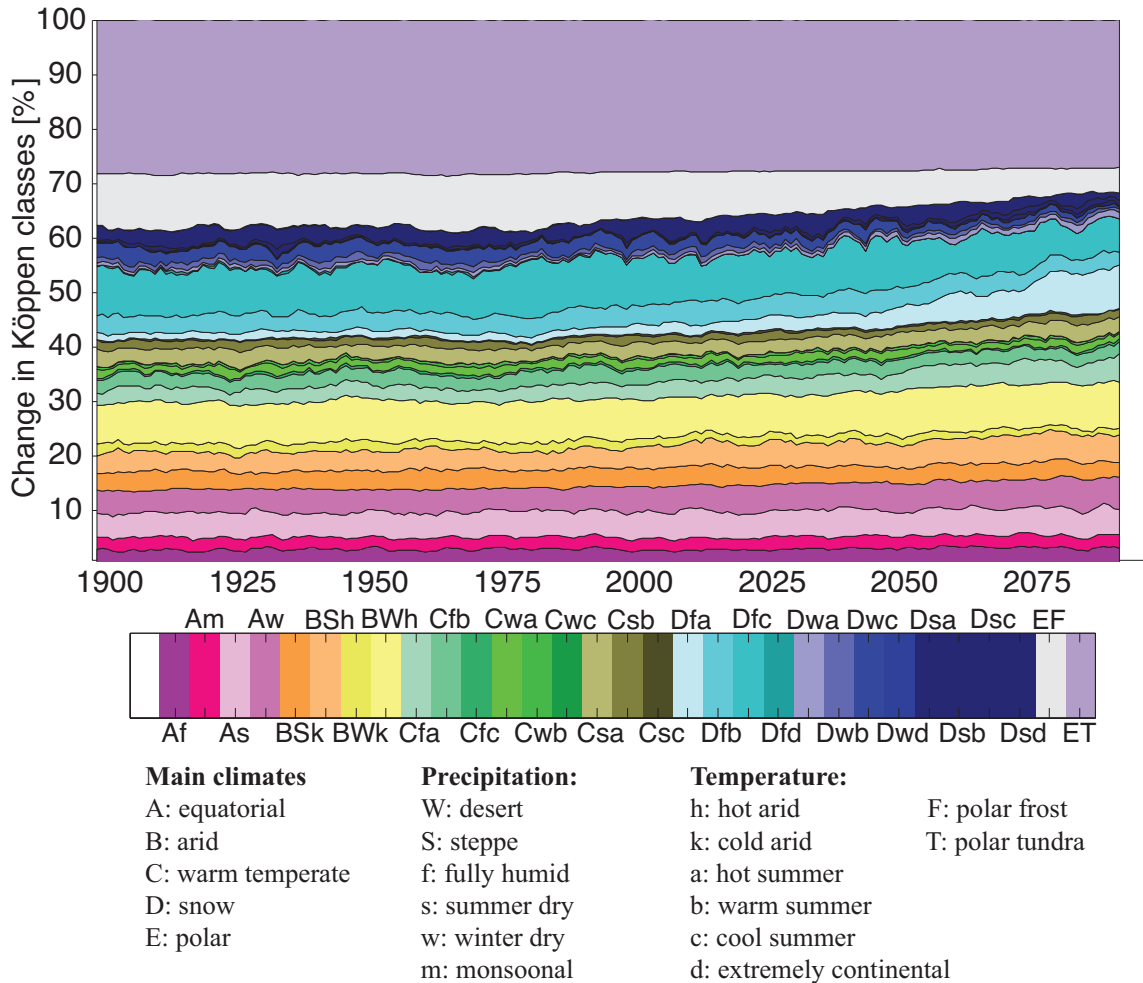


Figure 2: Percentage change in Köppen zones. The changes based on a 5 y running mean for the historical and RCP8.5 run of the MIROC5 model. Some climates show larger changes; some climates such as the polar tundra climate (ET) seem to show no change. This does not necessarily mean that no changes happen. It is possible that the fraction of land experiencing an ET climate is constant, but not necessarily that it has not shifted geographically.

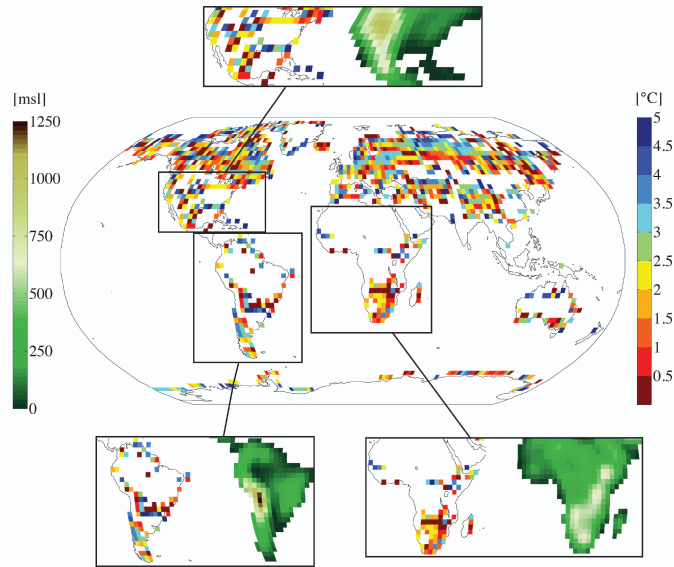


Figure 3: Map of changes in Köppen zones. The map shows at what global mean temperature increase a specific grid cell undergoes a shift in climate (colorbar on the right), white areas represent no change for global mean temperature increases $< 5^{\circ}\text{C}$ (the multi model mean has a maximum global mean temperature increase of about 5°C). The highlighted regions illustrate the dependence of climate shifts with altitude by showing the topography of the T42 grid of climate models (on the right in the box). The green-to-brown color bar indicates the elevation. Only land areas are considered (the areas close or in the Southern Ocean near Antarctica stem from the coarser T42 land-sea map).

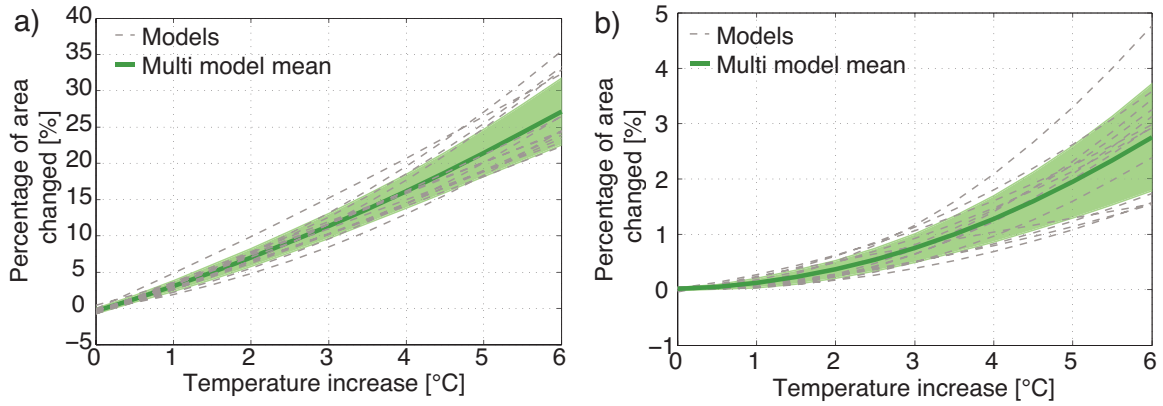


Figure 4: Analysis of the driving factor. a) The same as Figure 1a but precipitation is not allowed to change. b) The same as Figure 1a but temperature is not allowed to change. The green shading represents one standard deviation. Note the different scales on the ordinates.