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Evolution of mean, variance and extremes in 21st century temperatures

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ABSTRACT

Warming of the climate system can result in very large corresponding changes in the occurrence of climate extremes. Temperature extremes may occur due to a shift in the whole distribution, where there is an increase in the entire temperature probability distribution, or to changes in the shape of the distribution, such as an increase in variability causing a widening of the distribution. Understanding the precise characteristics of changes in temperature distributions in response to background warming is an important aspect of fully understanding changes in heat extremes and their associated impacts on human and ecosystem health. This study investigates projected 21st century changes in the characteristics of mean, maximum and minimum temperature on daily- and annual- timescales for various regions (Australia, Asia, Europe and North America) using data from seven models participating in the Coupled Model Intercomparison Phase 5 (CMIP5). Using the RCP8.5 experiment we show that an increase in mean temperature throughout the 21st century is a consistent feature of all models for each region. Changes in the variance of simulated temperatures are equivocal, with the sign and magnitude of variance changes in the 21st century varying in different models and regions. A quantile regression analysis demonstrates differences in upper and lower quantile slopes, relative to the mean, including a consistent skew in daily temperatures towards hot extremes. These potentially complex characteristics of temperature changes should not be overlooked, as temperature extremes are potentially more sensitive to changes in the variance and higher order moments than in the mean. Furthermore, a wider range of extreme temperature behaviour may have important consequences for various stakeholders, due to impacts on public health, agriculture and ecological systems.

1. Introduction

Warming of the climate can result in very large corresponding percentage changes in the occurrence of climate extremes, including an increased probability of observed heat extremes (Alexander et al., 2006; Trenberth and Fasullo, 2012; Coumou and Robinson, 2013). There are various ways that mean climate warming can produce changes in temperature extremes, and the Intergovernmental Panel on Climate Change (IPCC) Special Report on Extremes (IPCC SREX) [IPCC, 2012] identifies three simplified ways that changes in extremes can occur. The identified changes include, 1) a 'Shifted Mean' where there is an increase in the entire temperature probability distribution, 2) an 'Increased Variability' where there is a symmetric widening of the variability of temperature, leading to an increase in extremes in both the cold and warm tails, and 3) a 'Changed Symmetry' where the higher order statistics of the distribution changes. Understanding historical and possible future changes in extreme climate events, and their impacts, requires analysis beyond simply evaluating changes in the mean climate state. Ecological studies, for example, propose that changes in temperature variance may have disproportionately greater effects on species' performance than the impact of mean temperature change (Vasseur et al., 2014). Hence, explicitly exploring how higher statistical moments of temperature distributions change is useful for establishing meaningful predictions of climate change impacts (Mearns et al., 1984).

Various previous studies suggest that a shift in the mean accounts for much the change in observed temperatures extremes (Simolo et al., 2010; Rhines and Huybers, 2013; Tingley and Huybers, 2013; McKinnon et al., 2016), with no further changes in the shape of distributions required. However, potential complexity has been reported in observed temperature extremes. Donat and Alexander (2012) investigated daily maximum and minimum temperatures changes in global gridded observational, comparing the probability density functions (PDFs) of variables in 1951–1980 to 1981–2010. Comparisons showed that both daily maximum (Tmax) and minimum (Tmin) temperatures have shifted towards higher values (equating to an

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increase in mean) in the later 30-year period of observations in all regions. However, the variance and skewness were found to be spatially heterogeneous in this study. Overall, changes in observed extremes result from both a shifting mean and changes in higher order moments, with an overall increase in global daily temperatures in the hot tail of the distribution occurring since the middle of the 20th century.

Observational-based results are equivocal, varying by region, by temperature variable and by timescale investigated. In a further study, Shen et al. (2011) determined that the historical trend in surface air temperature variance over the contiguous United States was decreasing, though the trend calculated was small and not necessarily statistically significant. The trend in the variance of Tmax was larger than Tmin. Data from the United States suggest that the distribution of Tmax was more widely spread compared to Tmin or mean temperatures (Tmean). For Europe, decreasing trends occur in the variance of observed intra-annual daily Tmin, with a lower magnitude trend observed in Tmax (Michaels et al., 1998). However, more recent studies of western Europe calculated variance of daily temperatures had increased by 6% (Della-Marta et al., 2007). While there is little consensus on changes in higher order statistical moments in observed temperature distributions in different regions, such changes must be explicitly explored in order to understand changes in temperature extremes. In a further study, the record-breaking temperatures in Switzerland in the summer of 2003 were explored in terms of both changing mean state and variability (Schär et al., 2004). In this case, a climatic regime described by an increased variability of temperatures, in addition to increases in mean temperature, was necessary to account for the magnitude of temperatures experienced in Europe in summer 2003. This study noted a “tremendous sensitivity of extremes to the width of the statistical distribution,” concluding that variability can indeed be more important than averages for understanding extremes.

Climate models have also been used to explore changes in temperature extremes (Kharin et al., 2013; Sillmann et al., 2013; Wuebbles et al., 2014). For example, global climate models project a several-fold increase in the frequency of monthly to seasonal scale heat extremes over the decades to 2040, irrespective of the emissions scenario (Coumou and Robinson, 2013). However, these particular studies did not comprehensively examine the characteristics of mean, variance and the evolution of extremes in simulated historical temperatures or changes under future greenhouse gas warming. A 2014 study focused specifically on differences in the cold and warm tails of seasonal extremes projected a wider range of seasonal extreme temperatures in the 21st century due to asymmetry in cold and hot tails (Kodra and Ganguly, 2014). As these results are based on a normalisation of temperatures relative to a reference period, a large overestimation of changes in extremes and asymmetry between cold and hot events may have been reported (Sippel et al., 2015). Hence, it remains unclear whether projected changes in extremes under future mean climate warming will correspond to simply a result of a shifting mean, or whether further changes in variance and higher order moments are expected. An increasing variance in future summer temperatures is indicated in distributions derived from Representative Concentration Pathway (RCP) experiments (Taylor et al., 2012) in certain extreme event attribution studies (Lewis and Karoly, 2013; Christidis et al., 2014), However, it is not clear whether this is an artefact of the specific methods of analysis, such as using varying sample size, or rather is rather a genuine feature associated with mean warming. Furthermore, it is unclear whether such simulated changes are model-dependent.

Understanding the characteristics of changes in temperature distributions in response to background warming remains an important aspect of fully understanding potential future changes in heat extremes and their impacts. In this present study, specific characteristics of temperature distributions are investigated for Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) model experiments. We focus on model data in various regions (Australia, North America, Europe and Asia) and on various timescales (daily, seasonal and annual averages). The analysis uses historical and 21st century simulations with combined anthropogenic and natural forcings to investigate the statistical characteristics (mean, variance and evolution of extremes) of the daily and seasonal temperature timeseries throughout the historical period and the 21st century. Do projected extreme temperatures change throughout the 21st century, and if so, in which ways?

2. Data

Temperatures were investigated in two CMIP5 experiments. These were the standard historical experiment simulating the climate of 1850–2005 with anthropogenic (greenhouse gases, aerosols and ozone) and natural forcings (volcanic and solar) and the RCP8.5 experiment of the 21st century. We focus on temperatures in the RCP8.5 experiment for two reasons. First, this emissions scenario is most representative of global CO_2 emissions occurring from the termination of the historical experiment in 2005 to the present (Peters et al., 2012). Second, this strong forcing leads to the highest temperature projections amongst the CMIP5 scenarios (Peters et al., 2012) and hence provides an opportunity to explore possible changes in the statistical characteristics of simulated temperatures due to the higher signal to noise ratios. Models were included in the analysis where data were available for each experiment at the daily and monthly timescales for mean (tas), maximum (tasmax) and minimum (tasmin) temperatures (ACCESS1-3, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-ES, MRI-CGCM3, GFDL-CM3).

Model data were re-gridded onto a common 1.5° latitude by 1.5° longitude horizontal grid using first-order conservative mapping. Only model gridboxes comprising of at least 75% surface land fraction were used for calculation of area-mean temperatures for each region (Australia 50–10°S, 110–155°E; Asia 10–70°N, 60–170°E; Europe 30–70°N, 10°W–60°E; North America 20–70°N, 160°-50W). These regions were selected due to the relative availability of observational data (Dittus et al., 2015). Area-weighted mean values were calculated for each region and temperature variables were considered in detail on annual and daily timescales. Comparable observational temperature distributions were calculated from the Berkeley Earth Surface Temperature product, which merges temperature observations from 12 sources to provide daily and monthly gridded land surface data for Tmean, Tmax and Tmin variables (Rohde et al., 2013).

Temperature anomalies were calculated relative to the 1961–1990 average for observations and used to assess whether simulated multi-model distributions were statistically indistinguishable from observations using a Kolmogorov-Smirnov (K-S) test (Fig. 1). The K-S test is useful for such determinations as it makes few assumptions about the distribution of data and is nonparametric. However, as the K-S test is not specialised towards departures in the tails of distributions, we next checked these results using an Anderson-Darling (A-D) test. The A-D test does make assumptions about the specifics of the underlying distribution, but is a particularly useful test for determining the significance of changes in distributions and is sensitive to departures in the tails. First, we compared annual, DJF and JJA Tmean, Tmax and Tmin distributions for the historical$_{1976–2005}$ to the observations (Fig. 1 and Supplementary Fig. 1 and 2) using a K-S test we determined that distributions for Australia, Asia, Europe and N. America are statistically indistinguishable from observations using both K-S and A-D testing. However, the equivalent daily historical curves have an increased variance compared to observations and are statistically distinct from observations. We note that the Berkeley temperature dataset is not yet fully documented and hence data should be used cautiously, although model-observational differences can result from both model biases and observational errors.