

Changes in temperature and precipitation extremes in the CMIP5 ensemble

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Abstract Twenty-year temperature and precipitation extremes and their projected future changes are evaluated in an ensemble of climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5), updating a similar study based on the CMIP3 ensemble. The projected changes are documented for three radiative forcing scenarios. The performance of the CMIP5 models in simulating 20-year temperature and precipitation extremes is comparable to that of the CMIP3 ensemble. The models simulate late 20th century warm extremes reasonably well, compared to estimates from reanalyses. The model discrepancies in simulating cold extremes are generally larger than those for warm extremes. Simulated late 20th century precipitation extremes are plausible in the extratropics but uncertainty in extreme precipitation in the tropics and subtropics remains very large, both in the models and the observationally-constrained datasets. Consistent with CMIP3 results,

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CMIP5 cold extremes generally warm faster than warm extremes, mainly in regions where snow and sea-ice retreat with global warming. There are tropical and subtropical regions where warming rates of warm extremes exceed those of cold extremes. Relative changes in the intensity of precipitation extremes generally exceed relative changes in annual mean precipitation. The corresponding waiting times for late 20th century extreme precipitation events are reduced almost everywhere, except for a few subtropical regions. The CMIP5 planetary sensitivity in extreme precipitation is about $6\%/^{\circ}\text{C}$, with generally lower values over extratropical land.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded in its Fourth Assessment Report (AR4, Solomon et al. 2007) that climate change has begun to affect the frequency, intensity, and duration of extreme events such as extreme temperatures, extreme precipitation, droughts, etc. Some of the changes in weather and climate extremes observed in the late 20th century are projected to continue into the future. A subsequent assessment by the IPCC in its special report on Managing the Risks of Extreme Events to Advance Climate Change Adaptation (SREX) confirms these assessments (Seneviratne et al. 2012). The literature assessed by the IPCC AR4 and SREX reports made intensive use of simulations conducted with climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3). The advent of Coupled Model Intercomparison Project Phase 5 (CMIP5), which is based on generally more sophisticated climate models and a new suite of forcing scenarios, indicates that updates to this literature are necessary.

Analyses of temperature and precipitation extremes have focused primarily on two types of descriptions of extreme events (Klein Tank et al. 2009). One is based on various climate extremes indices (e.g., Alexander et al. 2006; Tebaldi et al. 2006) representing moderately extreme meteorological events with re-occurrence times of a year or shorter. An advantage of such indices is that they allow for more robust identification of changes in their characteristics as they are based on events that occur relatively frequently. A second common approach is based on the application of an asymptotic extreme value theory employing the Generalized Extreme Value distribution to approximate the distribution of annual extremes of temperature and precipitation rates. This type of analysis provides insights into the behaviour of extreme events with multi-year to multi-decade re-occurrence times that are of importance to engineering design and planning (e.g., Kharin and Zwiers 2005; Kharin et al. 2007).

The main objective of this paper is to provide an update of the analysis of temperature and precipitation extremes in the CMIP3 multi-model ensemble by Kharin et al. (2007) (in the following referred to as K07) but using the new generation of global climate models participating in CMIP5. In particular, we estimate 20-year return values of annual extremes of temperature and daily precipitation as simulated by the CMIP5 models in the late 20th century in the historical climate experiments, compare them to observationally constrained estimates, and evaluate their projected changes under various radiative forcing scenarios. The comprehensive analysis of a number of climate extreme indices representing more moderate aspects of extreme

climate variability in the CMIP5 ensemble is given in two companion papers by Sillmann et al. (2013a, b).

The remainder of the paper is structured as following. The datasets are described in Section 2. The methodology is briefly reviewed in Section 3. Section 4 compares model simulated extremes with observational evidence. Projected future changes are presented in Section 5 followed by a summary in Section 6. The main body of the paper presents only a small selection of the results on a global scale illustrating the key findings of the study. A more detailed analysis, including some regional aspects, is presented in the accompanying [Supplementary Material](#) (in the following referred to as the SM).

2 Datasets

Similar to K07, we analyze annual extremes of daily maximum and minimum surface air temperature (T_{\max} and T_{\min}) and of daily precipitation (P) as simulated by CMIP5 models in the historical experiment (years 1850–2005) and experiments for the 21 century (years 2006–2100) employing three different radiative forcing scenarios. The new scenarios, called Representative Concentration Pathways (RCPs, Moss et al. 2010), are designed to accommodate a wide range of possibilities in social and economical development consistent with specific radiative forcing paths. The estimated radiative forcing values by year 2100 are 2.6 Wm^{-2} in the RCP2.6 experiment, peaking at about 3 Wm^{-2} before 2100 and declining afterwards, and 4.5 Wm^{-2} and 8.5 Wm^{-2} in the other two experiments considered here, RCP4.5 and RCP8.5. Compared to the previous Special Report on Emission Scenarios (SRES, Nakicenovic and Swart 2000) used for CMIP3 simulations and analyzed in K07, the RCP8.5 forcing exceeds that in SRES A2, RCP4.5 is comparable to SRES B1, and the SRES A1B scenario falls between RCP8.5 and RCP4.5.

CMIP5 daily model output was available for 32 models for the historical experiment, 22 models for the RCP2.6 experiment, 31 models for the RCP4.5 experiment, and 29 models for the RCP8.5 experiment (SM Tables S1 and S2). Some modelling groups submitted more than one simulation for the same forcing scenario; we use these runs to estimate the sampling uncertainty of the derived extreme value statistics due to natural climate variability. The CMIP5 models generally have higher spatial resolution with a median horizontal grid resolution of about 160×96 and a median number of vertical levels of 38 compared to a 128×64 median grid and 26 levels in the CMIP3 ensemble. The CMIP5 global climate models are also generally more comprehensive compared to CMIP3 models. Most models now include ocean and terrestrial carbon cycle components, dynamic vegetation, interactive atmospheric chemistry, and direct and indirect effects of aerosols, and most now also employ time-evolving volcanic and solar forcing.

Several observationally-constrained datasets are used to evaluate simulated climate extremes in the late 20th century climate over the globe. In addition to the reanalyses used in K07, the recent European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis (Dee et al. 2011) is also used. The main advantages of using reanalyses is that they are available on the global scale and that their output is gridded and thus more comparable to model output representing spatial scales of a grid box size and larger, as opposed to station data which are by their nature

local point measurements. However, our confidence in precipitation from reanalyses is generally much lower than that in surface temperature because precipitation observations are not assimilated in the current global reanalysis systems. Alternatives to daily precipitation from reanalyses are global gridded precipitation products of non-overlapping 5-day precipitation rates (pentads) that are obtained by merging various sources such as rain gauge observations, satellite estimates and, optionally, reanalyses in the regions where neither rain gauge nor satellite measurements are available. Two such products are considered in the SM (Table S3).

3 Methodology

We follow the approach of K07 and references therein for analysis of climate extremes of near surface air temperature and daily precipitation amounts in terms of return values of their annual extremes. A return value for a specified T -year return period is the value that is exceeded by an annual extreme with probability $p = 1/T$. Most of the analysis presented here is performed for the 20-year return period, or equivalently, for an annual exceedance probability of $p = 5\%$. Following K07, the 20-year return period is chosen as a compromise between the rareness of the event of interest and uncertainty in the estimated return values.

Return values are determined as the quantiles of a Generalized Extreme Value (GEV) distribution that is fitted at every grid point to samples of annual temperature and precipitation extremes. Two methods are used to estimate the three GEV distribution parameters, location, scale and shape. First, as in K07, the robust method of L-moments (Hosking 1990) with the feasibility modification of Dupuis and Tsao (1998) is used to estimate return values in several 20-year time slices such as years 1986–2005 to represent the late 20th century climate, and years 2016–2035, 2046–2065 and 2081–2100 to estimate projected future changes in climate extremes. Alternatively, we employ the method of maximum-likelihood for estimating the parameters of a GEV distribution that depend on time as a covariate, as in Kharin and Zwiers (2005) (referred to as K05 below). The parameters are estimated for each year from overlapping 51-year time windows. The location and scale parameters are assumed to depend linearly on time while the shape parameter is assumed to be time-invariant. Both methods result in very similar estimates of return values (SM Figs. S3 and S6). An advantage of the maximum likelihood method is that time covariates can be included, which potentially allows extreme value statistics to be estimated more accurately for each individual year, particularly near the ends of available time records, for example, in year 2100. In contrast, L-moment estimates are representative of a whole 20-year time slice and thus can be slightly biased in opposite directions at the ends of these time slices when a secular trend is present. In the following, we use L-moment estimates when presenting results for 20-year time slices to be consistent with K07, but employ the method of maximum likelihood with time covariates as in K05 when presenting the time evolution of spatially averaged extreme value statistics.

The sampling uncertainty of the return values estimated by the L-moment method from 20-year time slices is derived from ensemble simulations for the models with multi-member ensembles. The resulting standard sampling errors are averaged

across models to represent typical sampling errors for all the models, and are compared to the inter-model ensemble spread.

The projected changes in temperature and precipitation extremes are determined relative to the 1986–2005 reference period and are also expressed in terms of the corresponding changes in return periods for climate extremes simulated in the reference period. When more than one simulation for the same forcing scenario is available for a model, all simulations are used to derive extreme value statistics to represent that model in the multi-model ensemble. The projected multi-model median changes are assessed with the Wilcoxon signed-rank test. Tests results help to guide interpretation, although it should be noted that the significance of the projected changes is difficult to interpret formally (von Storch and Zwiers 2012).

Here we also estimate the dependence of local changes in extreme precipitation on mean temperature changes at the same location as simulated in the CMIP5 ensemble. This is done by fitting a GEV distribution to annual precipitation extremes at each grid point in the historical and all available RCP experiments for each model with the three GEV parameters linearly depending on mean temperature change at the same grid point. Since we are primarily interested in the dependence of precipitation extremes on prevailing time-averaged temperature conditions, interannual variability in the annual temperature time series is suppressed by applying a 21-year moving average when computing mean temperature changes. The resulting six parameters are estimated by the method of maximum likelihood. Once the parameters are estimated, the return values and their changes per unit of warming are obtained by computing the corresponding quantiles of the GEV distribution. More flexible statistical models with additional quadratic terms in the dependence of the GEV parameters on the time-mean temperature change were also tested but proved to be of little additional benefit for goodness of fit as judged by standard likelihood ratio tests.

4 Simulated late 20th century climate extremes

The performance of the CMIP5 models in simulating temperature and precipitation extremes is generally comparable to that in the CMIP3 ensemble reported in K07. Here we present some of the main findings, and refer the reader to the SM for a more detailed analysis.

Figure 1 displays the CMIP5 multi-model median of 20-year return values of 1986–2005 annual maximum temperature ($T_{\max,20}$), annual minimum temperature ($T_{\min,20}$) and annual extremes of daily precipitation amounts (P_{20}), as well as the corresponding differences compared to the ERA-Interim estimates. There is fairly good correspondence between the CMIP5 multi-model estimate of the magnitude of warm and cold extremes and that in the ERA-Interim reanalysis with differences typically within a few degrees C over most of the globe. There is a modest warm bias (about 0.5 °C, on average) for warm extremes, particularly over central South America, and a cold bias (about –0.5 °C, on average) for cold extremes, particularly in northern high latitudes, as compared to ERA-Interim. However this model bias depends on the choice of the verification dataset. For example, warm extremes in NCEP2 are about 0.8 °C warmer (globally averaged) than in ERA-Interim, and NCEP2 cold extremes are about 2.9 °C colder than those in ERA-Interim (SM

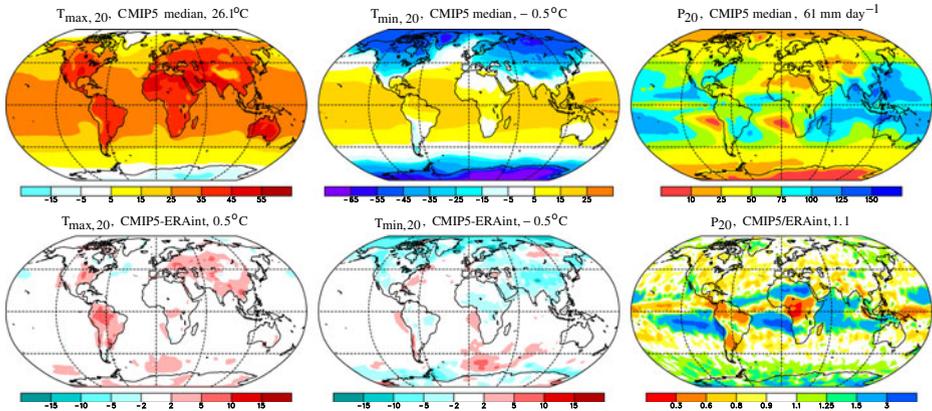


Fig. 1 *Top:* The CMIP5 multi-model ensemble median of 20-year return values of 1986–2005 annual maximum temperature $T_{\max,20}$ ($^{\circ}\text{C}$, left), annual minimum temperature $T_{\min,20}$ ($^{\circ}\text{C}$, center), and annual maximum of daily precipitation P_{20} (mm day^{-1} , right). *Bottom:* The difference between the CMIP5 multi-model median of $T_{\max,20}$ (left) and $T_{\min,20}$ (center) and the corresponding temperature extremes estimated from ERA-Interim in 1986–2005, and the ratio of the CMIP5 median of P_{20} over ERA-Interim P_{20} (right)

Fig. S3 and Table S5). Local differences between the ERA-Interim and NCEP2 estimates of the magnitude of cold extremes over land and sea-ice are as large as 15°C , or more, in some places.

Similar to our previous studies Kharin et al. (2005, 2007), discrepancies between the models (and between the reanalyses) are generally larger for cold extremes than for warm extremes (SM Fig. S4). The globally averaged inter-model standard deviation is about 2.4°C for warm extremes but 3.3°C for cold extremes. Inter-model disagreements are generally small over ice-free oceans but are greater over land and sea-ice covered regions. Sampling errors constitute only a small fraction of the total uncertainty in local estimates of temperature extremes with standard sampling errors being about a factor of four smaller than the total inter-model standard deviation.

The CMIP5 multi-model estimate of the magnitude of extratropical precipitation extremes in the extratropics compares reasonably well to ERA-Interim, with typical discrepancies lying within about $\pm 20\%$. However, there is much less agreement between the models and between the reanalyses in the tropics and subtropical regions where the details of the parametrization of deep convection seem to be a dominant factor. The coefficient of variation of CMIP5 P_{20} (bottom right panel in Fig. 1), which is a measure of inter-model dispersion normalized by the multi-model median, is about 0.2 in the extratropics but in excess of 0.6 or more in tropical regions, indicating that the inter-model discrepancies in tropical precipitation extremes are comparable to the magnitude of the simulated extremes themselves. Again, sampling variance generally plays only a minor role in the total inter-model variability (SM Fig. S7).

5 Projected future changes in climate extremes

The general evolution of the magnitude of temperature and precipitation extremes over global land in the CMIP5 ensemble for the period 1900–2100 is displayed in

Fig. 2. The extreme value statistics in this figure are estimated for each year in the running 51-year time slices using the maximum-likelihood method with time as a covariate following K05. Changes in temperature extremes are in °C while changes in precipitation extremes are expressed as percentage change from the reference period. The latter are also expressed in terms of waiting times, in years, for 1986–2005 20-year events P_{20} .

Results in Fig. 2 are generally consistent with previous studies. In particular, cold extremes generally warm faster than warm extremes. The land-averaged multi-model median change in $T_{\max,20}$ by the end of the 21st century is 1.2 °C, 2.4 °C and 5.4 °C in the RCP2.6, RCP4.5 and RCP8.5 experiments, respectively, compared to the corresponding changes of 1.7 °C, 3.2 °C, and 6.2 °C for $T_{\min,20}$. The magnitude of the precipitation extremes over land increases appreciably with global warming, with the multi-model median increasing by about 6%, 12% and 30% in the RCP2.6, RCP4.5 and RCP8.5 experiments respectively by the year 2100. Correspondingly, return periods for 1986–2005 20-year events are reduced to about 14, 11 and 6 years, respectively. There is appreciable inter-model uncertainty in the magnitude of the projected future changes over global land for a particular forcing scenario as indicated by the dotted lines for individual models and the associated inter-quartile range. Inter-scenario differences in the multi-model response become the dominant component in the overall uncertainty of the projected changes of temperature and precipitation extremes by about 2050.

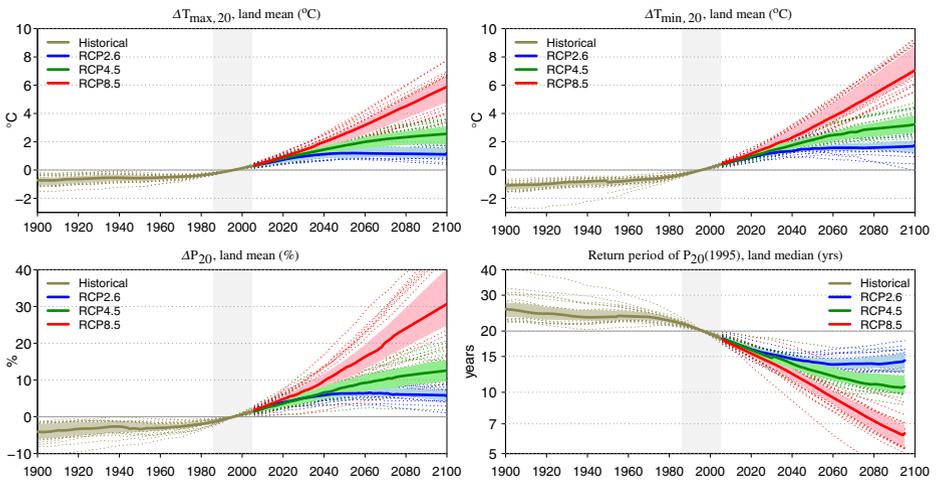


Fig. 2 The CMIP5 multi-model ensemble change in 20-year return values of annual maximum temperature $\Delta T_{\max,20}$ (°C, *top left*), annual minimum temperature $\Delta T_{\min,20}$ (°C, *top right*), and annual extremes of daily precipitation ΔP_{20} (% *bottom left*) averaged over global land relative to 1986–2005 in the historical, RCP2.6, RCP4.5 and RCP8.5 experiments. The corresponding spatial median over land of return periods of 1986–2005 P_{20} (years) is displayed in the *bottom right* panel. *Thick solid lines* are multi-model ensemble medians. *Shading* indicates the multi-model ensemble inter-quartile (25–75%) range. *Dotted lines* indicate individual model simulations. Small discontinuities in the multi-model median near years 1950 and 2035 are a consequence of the different multi-model ensemble sizes before and after years 1950 and 2035 (SM Table S2)

5.1 Changes in temperature extremes

Figure 3 displays multi-model median changes in 20-year return values of annual warm and cold extremes projected for 2081–2100 relative to 1986–2005 as simulated by the CMIP5 models in the RCP2.6, RCP4.5 and RCP8.5 experiments. The asymmetry in the magnitude of the changes in warm extremes versus cold extremes reported in the previous studies is also evident in the CMIP5 ensemble.

Changes in warm and cold extremes are comparable over ice free oceans. Cold extremes warm considerably faster over extratropical land masses and over high latitude oceans, likely due to snow and sea-ice albedo feedbacks in these and adjacent regions. The models tend to simulate larger increases in warm extremes than in cold extremes over subtropical land regions, most notably over the Iberian Peninsula, northern and southern Africa, southern Asia, central and south America, and south Australia. These are regions that become generally drier, and the larger increases in warm extremes are presumably at least partially due to reduced moderation by evaporative cooling from the land surface (e.g., Mueller and Seneviratne 2012).

Changes in warm extremes generally follow changes in the mean summertime temperature. Changes in cold extremes substantially exceed changes in the mean wintertime temperature in regions where snow and sea-ice retreat with global warming (SM Fig. S9).

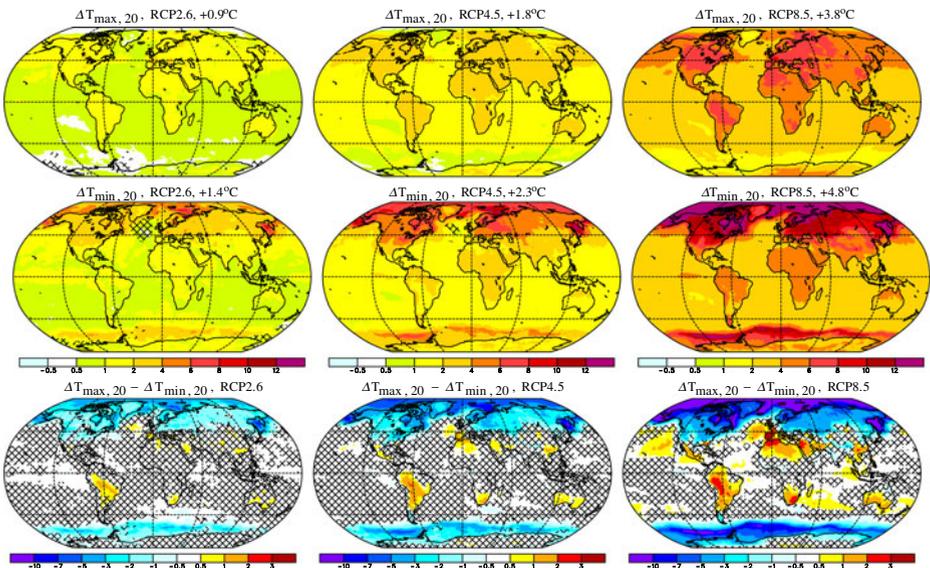


Fig. 3 Top row: The CMIP5 multi-model median change in 20-year return values of annual warm temperature extremes $T_{\max,20}$ simulated in 2081–2100 relative to 1986–2005 in the RCP2.6 (left), RCP4.5 (middle), and RCP8.5 (right) experiments. Global averages of changes are indicated in the titles. Middle row: The same as above but for 20-year return values of annual cold temperature extremes $T_{\min,20}$. Bottom row: The corresponding difference between the CMIP5 multi-model median changes in $T_{\max,20}$ and $T_{\min,20}$. Changes that are not significant at the 5% level are indicated by cross-hatching

5.2 Changes in precipitation extremes

The CMIP5 multi-model ensemble median changes in annual mean and extreme precipitation are displayed in Fig. 4 as simulated in 2046–2065 and 2081–2100 relative to 1986–2005 in the RCP4.5 experiment. As in CMIP3, global relative changes in 20-year return values of annual maximum daily precipitation exceed changes in annual mean precipitation. For example, the global multi-model median change in extreme precipitation is about 10% by the end of the 21st century in the RCP4.5 scenario compared to about 5% for mean precipitation. Similarly amplified changes in extreme precipitation are also reported by Sillmann et al. (2013b) for precipitation-based indices that represent more moderate and more frequent extremes. There are regions where annual mean precipitation is projected to decrease (e.g., Central America, parts of Africa, Australia) but the intensity of precipitation extremes increases. The corresponding return periods for late 20th century 20-year extreme precipitation events are reduced almost everywhere over the globe, except for drying subtropical regions. The approximate relationship of a factor of two in return period reduction with a 10% increase in the amplitude of P_{20} reported by K07 for CMIP3 also holds in the CMIP5 ensemble.

It has been argued that changes in extreme precipitation may follow changes in temperature according to the Clausius–Clapeyron relationship that predicts an increase in moisture availability of about 6–7% per °C (e.g., Boer 1993; Allen and Ingram 2002). Figure 5 displays the percentage changes in globally averaged P_{20} as a function of global annual mean temperature changes as simulated by the CMIP5 models in 2046–2065 and 2081–2100 in the three emission scenarios. The linear regression fit is indicated by the dashed line with the slope of about 6%/°C. This value

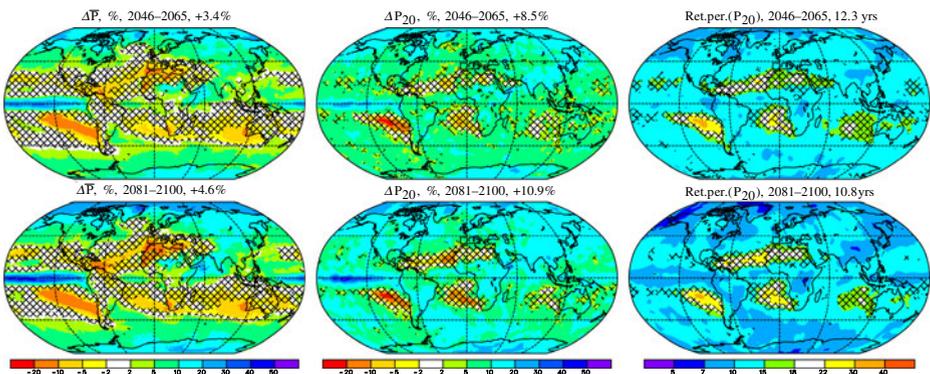


Fig. 4 *Top row:* The CMIP5 multi-model median relative change (%) in the annual mean precipitation rate (*left*) and in 20-year return values of annual extremes of daily precipitation (*middle*) simulated in 2046–2065 relative to 1986–2005 in the RCP4.5 experiment. The corresponding median of return periods, in years, for 1986–2005 20-year events is shown in the *right* panel. *Bottom row:* The same as above but for the 2081–2100 period. Global averages, or global medians for the return periods, are indicated in the titles. Changes that are not significant at the 5% level are indicated by cross-hatching

is comparable to that reported by K07 for the CMIP3 ensemble. A histogram of the “hydrological sensitivities” for extreme precipitation, $\Delta P_{20}(\%)/\Delta \bar{T}(\text{°C})$, indicates considerable inter-model uncertainty in this statistic in the CMIP5 ensemble, with the majority of the models simulating values in the 4–10%/°C range. For comparison, the lower diagrams in Fig. 5 show similar statistics for annual mean precipitation with the bulk of models simulating values in the 1.5–2.5%/°C range.

Relative changes in extreme precipitation per unit of warming are not uniformly distributed over the globe (Fig. 6, left panel). Over global land or land in the Northern extratropics, the CMIP5 multi-model median estimate of ΔP_{20} is about 4%/°C which is close to the value reported by Min et al. (2011) for a small subset of CMIP3 models. The global multi-model median sensitivity of 5.3%/°C derived from local sensitivities is somewhat lower than the planetary sensitivity derived from globally averaged statistics as in Fig. 5. The corresponding CMIP5 multi-model median of return periods of late 20th century 20-year events P_{20} associated with a local warming of +1 °C is displayed in the right panel of Fig. 6. The resulting return periods mirror the corresponding changes in return values. Return periods are reduced by about 10–20% per 1 °C of local warming over Northern Hemisphere land masses. Changes in generally wetter tropical land regions are comparatively larger with reductions by up to 50% or more.

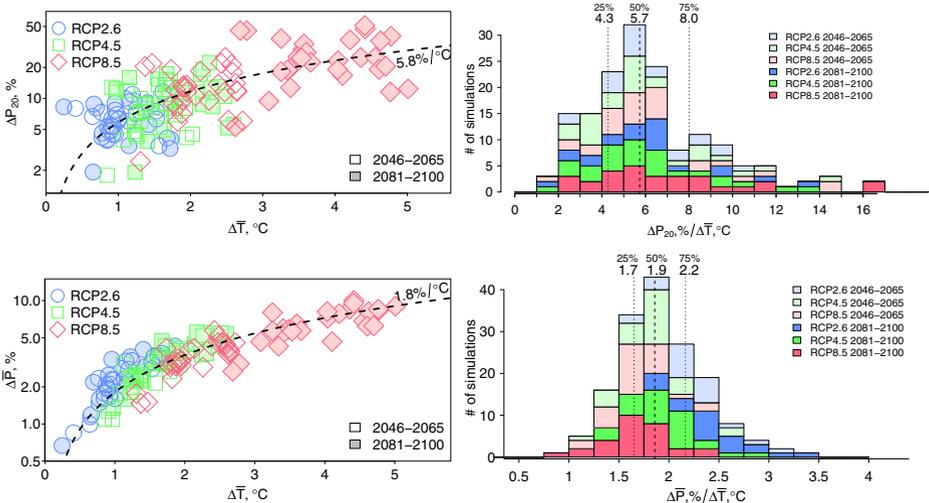


Fig. 5 *Top left panel:* Relative changes (%) in globally averaged 20-year return values of annual daily precipitation extremes (ΔP_{20}) plotted on a log scale as a function of globally averaged changes in annual mean near surface temperature ($\Delta \bar{T}$, °C) simulated by the CMIP5 models in the RCP2.6, RCP4.5 and RCP8.5 experiments in 2046–2065 and 2081–2100. The linear regression fit is indicated by the dashed line. *Top right panel:* Histogram of extreme precipitation sensitivities $\Delta P_{20}/\Delta \bar{T}$, %/°C, simulated by the CMIP5 models in the three scenarios and two time periods. The median value (50%) and inter-quartile range (25–75%) is indicated by the vertical dashed and dotted lines respectively. *Bottom panels:* the same as above but for changes in global annual mean precipitation ($\Delta \bar{P}$) instead of ΔP_{20}

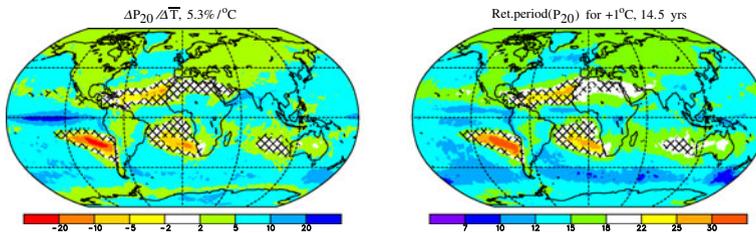


Fig. 6 *Left:* The CMIP5 multi-model ensemble median relative change (%) in 20-year return values of annual extremes of daily precipitation (ΔP_{20} , %) per 1°C of local warming. *Right:* The CMIP5 multi-model ensemble median of the return periods (years) of late 20th century 20-year return values of precipitation corresponding to $+1^\circ\text{C}$ of local warming. Changes that are not significant at the 5% level are indicated by cross-hatching

6 Summary

The present study documents the performance of CMIP5 models in simulating annual extremes of surface temperature and daily precipitation rates and their projected changes for three climate change scenarios, RCP2.6, RCP4.5, and RCP8.5. This is an update of the analysis of the CMIP3 ensemble in K07 but for the latest generation of global climate models and a different set of forcing scenarios. Most of the K07 findings continue to hold for the recent CMIP5 ensemble, and are summarized as follows.

- Warm temperature extremes in the late 20th century climate are plausibly simulated by the CMIP5 models. The CMIP5 multi-model median estimate of the 20-year return values of annual warm extremes $T_{\max,20}$ is typically within the uncertainty in the observationally-constrained reanalyses (ERA-Interim, NCEP2 and others) of about 1°C on a global scale. The discrepancies on the local scale usually do not exceed $\pm 5^\circ\text{C}$. Inter-model differences are generally larger over land; the inter-model standard deviation is about 4°C over land, on average, while it is about 1.5°C over oceans.
- Uncertainties in CMIP5-simulated cold extremes in the late 20th century and in the reanalyses are greater than those for warm extremes, especially over sea-ice. The inter-model standard deviation for cold extremes is about 50% larger than that for warm extremes. Nevertheless the multi-model median estimate of 20-year return values of annual cold extremes $T_{\min,20}$ is well within the range of estimates obtained from the different reanalyses.
- There remain large uncertainties in simulated extreme precipitation, especially in tropical and subtropical regions. Overall, the performance of the CMIP5 ensemble is comparable to that of the older CMIP3 ensemble. The models agree better in the extratropics where they also compare reasonably well with the observational evidence. The typical discrepancies in the magnitude of extratropical 20-year precipitation events (P_{20}) in the models and reanalyses are within about $\pm 20\%$. But there are very large differences in the tropical regions.
- Cold extremes generally warm faster than warm extremes. The CMIP5 multi-model median warming of cold extremes over the globe by the end of the

21st century is 1.5 °C, 2.4 °C, and 4.9 °C in the RCP2.6, RCP4.5 and RCP8.5 experiments, respectively, as compared to the corresponding changes of 0.8 °C, 1.7 °C and 3.8 °C for warm extremes. The enhanced warming is generally confined to regions influenced by retreating cryosphere under global warming and is therefore amplified in high latitudes.

- There are tropical and subtropical land regions, most notably North and South Africa, the Mediterranean region, Central and South America, and south Australia where warming rates of warm extremes exceed those of cold extremes. These are regions that become generally drier and where evaporative cooling from the land surface is therefore likely to be reduced.
- Relative (%) increases in the intensity of precipitation extremes generally exceed those for annual mean precipitation under global warming. Globally averaged, the CMIP5 multi-model P_{20} increase is about 6% in the RCP2.6 experiment, 10% in the RCP4.5 experiment and more than 20% in the RCP8.5 experiment by the end of the 21-st century. This is 2–3 times faster than the corresponding multi-model change in annual global mean precipitation. Confidence in the projected changes in extreme precipitation is diminished by the very large inter-model disagreements in the tropics which indicate that some physical processes associated with extreme precipitation are not well represented in the current generation of models. This uncertainty is also evident in observationally constrained analyses.
- Return periods of late 20th century extreme precipitation events are projected to become shorter, except for a few drying regions in subtropics. Return periods for 1986–2005 20-year extreme precipitation events over land are projected to shorten to about 14, 11 and 6 years (median values) by the end of the 21st century in the RCP2.6, RCP4.5 and RCP8.5 experiments, respectively.
- **The CMIP5 multi-model estimate of the planetary sensitivity in extreme precipitation (P_{20}) is about 6%/°C** which is comparable to the CMIP3 estimate reported in K07. Relative changes in extreme precipitation per unit of warming are not evenly distributed over the globe, with generally lower rates of about 4%/°C over land relative to the local warming. However, in view of the large inter-model uncertainty of these estimates, especially in the tropics, our confidence in the diagnosed relationships is reduced.

Overall, the performance of the CMIP5 multi-model ensemble in simulating temperature and precipitation climate extremes is comparable to that in the CMIP3 ensemble. Apart from the different forcing scenarios in the CMIP5 protocol, most of the conclusions of the analysis by K07 still hold in the present study.

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