Heavy Precipitation Events in a Warmer Climate: Results from CMIP5 Models

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ABSTRACT

In this work, the authors investigate possible changes in the distribution of heavy precipitation events under a warmer climate, using the results of a set of 20 climate models taking part in phase 5 of Coupled Model Intercomparison Project (CMIP5). Future changes are evaluated as the difference between the last four decades of the twenty-first century and the twentieth century, assuming the representative concentration pathway 8.5 (RCP8.5) scenario. As a measure of the width of the right tail of the precipitation distribution, the authors use the difference between the 99th and the 90th percentiles. Despite a slight tendency to underestimate the observed heavy precipitation, the considered CMIP5 models well represent the observed patterns in terms of the ensemble average, during both boreal summer and winter seasons for the 1997–2005 period. Future changes in average precipitation are consistent with previous findings based on models from phase 3 of CMIP (CMIP3). CMIP5 models show a projected increase for the end of the twenty-first century of the width of the right tail of the precipitation distribution, particularly pronounced over India, Southeast Asia, Indonesia, and central Africa during boreal summer, as well as over South America and southern Africa during boreal winter.

1. Introduction

Changes in the frequency and intensity of extreme events can affect human health directly through heat waves and cold spells and indirectly through floods or pollution episodes (Zwiers and Kharin 1998; Parry et al. 2007; Peterson et al. 2008). The associated societal implications make an accurate simulation of extremes by climate models a particularly relevant issue. In the past years, many studies have been undertaken to analyze intense precipitation events using coupled and uncoupled general circulation models (GCMs) (Wetherald and Manabe 1999; Kharin and Zwiers 2000; Hegerl et al. 2004; Kharin et al. 2007; Hegerl et al. 2007; Kiktev et al. 2007; Carril et al. 2008; Min et al. 2009; Seager et al. 2012), investigating their capability in detecting changes of extreme precipitation, when analyzing twentieth and twenty-first century climate simulations. Model projections indicate intensification of extreme precipitation in a warming climate leading to wet areas getting wetter and dry areas getting drier (Chou et al. 2009). The availability of a new set of climate simulations for the twenty-first century, carried out with state-of-the-art coupled GCMs produced for phase 5 of the Coupled Model Intercomparison Project (CMIP5; Meehl and Bony 2011), gives us the possibility to investigate future changes in intense precipitation following one of the representative concentration pathways (RCPs) considered as illustrative of potential future scenarios. The present analysis is performed following the RCP8.5 scenario, the one with the highest rate of increase in greenhouse gas concentrations within the new set of RCPs. The main aim of this work is to inspect changes in
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the shape of the right tail of the precipitation events distribution under warmer conditions, comparing the last part of the twenty-first century with the last part of the twentieth century, as simulated by a set of CMIP5 climate models. The paper is organized as follows: Section 2 describes the data and provides an overview of the methodology used, section 3 presents the results of the analyses, and section 4 summarizes the main points of the study and concludes the paper.

2. Data and methodology

a. Reference data

For this analysis we use daily precipitation fields from a subset of the CMIP5 multimodel ensemble, consisting of simulations of the twenty and twenty-first century climate performed with 20 coupled ocean–atmosphere climate models (see Table 1). CMIP5 simulations are conducted in support of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The horizontal resolution of the atmospheric component of the considered models ranges from about 0.75° to about 3.5° with a median of 1.7°. Two periods are analyzed: the period 1966–2005 (labeled PRESENT), corresponding to the last part of the “historical” CMIP5 simulation, and the period 2061–2100 (labeled FUTURE), run under the high-end RCP8.5 scenario (Riahi et al. 2011; Taylor et al. 2012). The historical simulation is performed forcing CMIP5 models with observed concentrations of greenhouse gasses, aerosols, ozone, and solar irradiance, starting from an arbitrary point of a quasi-equilibrium control run. The RCP8.5 scenario follows a rising radiative forcing pathway leading to 8.5 W m$^{-2}$ in 2100.

For this analysis, we make use of daily precipitation fields. The capability of the CMIP5 models to simulate the present climate in terms of heavy precipitation events has been assessed using daily data from the Global Precipitation Climatology Project (GPCP; Bolvin et al.
of the period 1997–2005 (labeled PRES). On the suitability of the use of GPCP data for investigating intense precipitation, see Shiu et al. (2012) and Liu et al. (2009). In the rest of the paper, for the sake of simplicity we will refer to the GPCP data as observations. In this work, we aim to assess potential changes in precipitation extremes that might have a societal impact; thus, we mainly focus on precipitation over land.

b. Methodology

To investigate how CMIP5 models represent intense precipitation compared to observations, we computed the 90th percentile (90p) and 99th percentile (99p) over the distribution of precipitation obtained by aggregating daily precipitation values, belonging to the investigated period, over each single grid point. Furthermore, in our analysis, we want also to assess how heavy rainfall, defined as daily events with a precipitation amount greater than the 90p, might change in intensity. To this aim, we use the difference between the 99p and 90p, where the former is representative of very intense precipitation and the latter is the threshold used to define an event as heavy rainfall. This metric has been defined, separately for PRESENT and FUTURE climates, to quantify the width of the right tail of the precipitation distribution. In the present analysis, the impact of the nonstationarity of precipitation time series associated with the high-end RCP8.5 scenario has been found to be nonsignificant. Percentiles are computed for each model, on the corresponding original spatial grid. Individual model results have been then interpolated onto the GPCP regular grid to allow the multimodel averaging.

FIG. 2. Box plots of precipitation (%) associated with (left) heavy events (>90p) and (right) very intense events (>99p) with respect to (wrt) the total precipitation amount. The box plots represent the distribution of the 20 CMIP5 models. In each panel, the first two box plots represent DJF and the last two box plots represent JJA under PRESENT and FUTURE periods. The water associated with heavy/very intense events (y axis) is computed over land at global scale. In each box plot, the box represents the interquartile range (IQR) and contains 50% of the data; the upper edge of the box represents the 75th percentile [upper quartile (UQ)], while the lower edge is the 25th percentile [lower quartile (LQ)]. The horizontal lines within the box are the median, and the squares are the mean. The vertical dashed lines indicate the range of the nonoutliers [outliers are either >\((UQ + 1.5 \times IQR)\) or <\((LQ - 1.5 \times IQR)\)]. Circles represent the observed value over the PRES period.
For abbreviation purposes, we will refer to “future changes” to indicate changes between the FUTURE (2061–2100) and the PRESENT (1966–2005) periods.

3. Results

Previous assessments (Kharin et al. 2007; O’Gorman and Schneider 2009) have shown that climate models provide a realistic representation of present-day heavy precipitation in the extratropics, but uncertainties in heavy precipitation in the tropics are very large. The 90p and 99p (Fig. 1 shows the zonal average of the 99th percentile computed at each grid point) are consistently simulated at mid- and high latitudes by CMIP5 models, but they tend to underestimate these indices in the tropics, especially in the northern summer, but also at high latitudes in the Northern Hemisphere during northern winter and in the Southern Hemisphere during northern summer (Fig. 1). This tendency is noticeably less pronounced when only models with a horizontal resolution finer than 1.5° are considered (about 50% of the CMIP5 models used in this analysis; see Table 1), but the dispersion around the mean does not change (not shown). The observed spatially averaged amount of rainfall, associated with heavy precipitation events (>90p; computed for each grid cell) over land during the PRES period, is about 55% of the total precipitation in both boreal winter and summer seasons (circles in Fig. 2, left). The corresponding estimate provided by CMIP5 models amounts to less than 45% (squares in Fig. 2, left) during the PRESENT period in boreal summer and winter. A closer agreement between CMIP5 models and observations is found when we focus on the rainfall associated with very intense precipitation events (>99p): the corresponding amount of water in the observations is about 12% (circles in Fig. 2, right), which is within the uncertainty range of the CMIP5 models. The model results shown in Fig. 2 do not change considering the 1966–2005 or the shorter 1997–2005 period. Very similar results have been found using the globally averaged amount of rainfall including precipitation over the sea (not shown). During the FUTURE period, the CMIP5 box plots are shifted upward by 2%–5%, suggesting a slight increase in the

FIG. 3. Measure of the right tail of the precipitation events distribution (mm day$^{-1}$), represented as 99p – 90p during the period 1997–2005 obtained from (left) observations and (right) CMIP5 (average over the 20 models) for (top) DJF and (bottom) JJA.
amount of rainfall associated with heavy precipitation, over land, in a warmer climate.

The width of the range of values attributable to observed (Fig. 3, left) heavy precipitation events, as represented by the 99p – 90p metric, is reasonably well reproduced by the CMIP5 ensemble average (Fig. 3, right). The model ensemble mean properly captures observed spatial patterns, despite a general tendency to underestimate 99p – 90p over most of the tropics and especially in the Amazon basin, equatorial Africa, Mediterranean basin, and northern Australia in DJF. In JJA, the models appear to overestimate the intense events in the northeastern part of the North American and Asian continents and the Himalayan region. The locations where the intense precipitation appears to be overestimated correspond with the areas where the models precipitation has a positive bias (not shown).

Future changes in climatological precipitation patterns (Fig. 4, left) are overall coherent with previous findings (Giorgi and Bi 2009) obtained using models from the previous phase of the Coupled Model Intercomparison Project (CMIP3). During boreal winter a general increase in precipitation over land is found, except for Central and South America. During boreal summer, a general increase of precipitation over land at latitudes higher than 55°N is found and a strong decrease over southern Europe, up to 60%, is made apparent (red pattern in Fig. 4, bottom left). A less intense decrease in the total precipitation appears also over western North America, Central America, equatorial South America, and western Africa around 15°N (Fig. 4, left panels). Future changes in 90p (Fig. 4, center) follow the described changes in total precipitation. The usage of 99p – 90p gives the possibility to better investigate changes in the right tail of the distribution of precipitation events, especially over regions where both 90p and 99p increase/decrease. In fact,
despite the very similar patterns found in future changes of climatological precipitation and 90p (Fig. 4, left and center, respectively), the 99p – 90p changes, pertaining to heavy precipitation events (Fig. 4, right), look different: in the FUTURE period the 99p – 90p metric increases worldwide, even over regions where total precipitation and 90p values show a decrease (red patterns in Fig. 4). This is the case for southeastern Europe during boreal summer, where the width of the right tail of the distribution increases, even if nearly the entire precipitation distribution becomes dryer (i.e., decreases in total, 90p, and 99p precipitation). Over some regions the 99p – 90p increase reaches 180% of the PRESENT period precipitation value (blue patterns in Fig. 4, right), amounting to about 8 mm day$^{-1}$ over land between 30°S and the equator, during boreal winter and involving all continents. These intense positive patterns move northward between 5°S and 15°N during boreal summer, covering Africa and South America, reaching maximum values of 10 mm day$^{-1}$ over India, southern China, and Indochina. A future increase in the width of the right tail of the precipitation events distribution, greater than 5 mm day$^{-1}$, is also evident along the eastern coast of Asia, up to Siberia, during the boreal summer. The largest increases in 99p – 90p, of greater than 12 mm day$^{-1}$, are found in the Indonesian region in both seasons. The described long-term tendencies for the 99p – 90p metric were also found in a separate analysis performed by grouping
rainfall data over 26 regions (Fig. 5) selected following the IPCC special report on extreme events (Field et al. 2012). We separately assessed the 99p – 90p changes for the entire domain and for land points only. It is found (not shown) that, for both DJF and JJA, the vast majority of the selected regions shows a positive increment of the 99p – 90p index. No significant differences are found with or without the inclusion of the ocean portion of each regional domain. This positive tendency is more pronounced for the rightmost part of the rainfall distribution, compared with the leftmost part, as highlighted in Fig. 6 where changes in moderate, heavy, very intense, and extreme events (75th, 90th, 99th, and 99.9th percentiles, respectively) in the FUTURE period with respect to the PRESENT period are shown.

4. Discussion and conclusions

In this paper we apply the difference between the 99th and 90th percentile of the daily precipitation resulting from a set of twenty CMIP5 simulations, with the aim of quantifying potential changes in the width of the right tail of precipitation distribution and, thus, to the range of values attributable to a heavy (greater than 90p) precipitation event.

Precipitation intensity seems to increase more than mean precipitation under a warmer climate, confirming previous findings (Trenberth et al. 2003; Meehl et al. 2005; Chou et al. 2009). These changes are consistent with a greater moisture-holding capacity of the warmer air contributing to greater moisture convergence (Tebaldi et al. 2006) and with the Clausius–Clapeyron dependence, relevant for heavy precipitation events (Giorgi et al. 2011), which are able to empty the atmospheric moisture column (Allen and Ingram 2002; Allan and Soden 2008). It is, in fact, well known that increases in atmospheric water vapor content are generally associated with increases in heavy precipitation in a warmer climate (e.g., Pall et al. 2007; O’Gorman and Schneider 2009). The width of the right tail of the precipitation event distribution increases almost everywhere (Fig. 4, right), independently of the direction in which the distribution evolves in a warmer climate, suggesting more heavy precipitation events especially over the tropics during boreal summer. The increased availability of water in a warmer climate, is confirmed by the water...
vapor content (WCONT), vertically integrated through the atmospheric column. The regions affected by strong stretching of the right tail of precipitation event distribution in the future (blue patterns in Fig. 4, right) correspond to strong increased availability of water vapor content in the atmospheric column (blue patterns in Fig. 7, right).

To a first approximation, if one considers no changes in precipitation efficiency (here defined as the ratio of total precipitation to total available moisture), we would link the increased width of the right tail of FUTURE precipitation distribution to the increased availability of WCONT. Regional changes in the atmospheric circulation patterns (Hertig et al. 2013) might also alter the statistics of the heavy rain events. However, a conclusive disentangling of the causes underlying the detected changes in the precipitation distribution is beyond the purpose of this work. In summary, despite the fact that model projections of future changes in heavy precipitation events in response to global warming might be underpredicted (Allan and Soden 2008), a picture of a world with intensifying heavy precipitation events over the majority of land seems confirmed by CMIP5 model projections for the end of the twenty-first century, at least following a future scenario with a continuous rise in radiative forcing during the twenty-first century. This implies increasing risks for natural and human systems that are sensitive to wet extremes (Kunkel et al. 1999; Giorgi et al. 2011).

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