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Estimating changes of temperatures and precipitation extremes in India using the Generalized Extreme Value (GEV) distribution

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Abstract

Changes in extreme temperature and precipitation may give some of the largest significant societal and ecological impacts. For changes in the magnitude of extreme temperature and precipitation over India, we used a statistical model of generalized extreme value (GEV) distribution. The GEV statistical distribution is a time-dependent distribution with different time scales of variability bounded by a precipitation, maximum (T_{max}), and minimum (T_{min}) temperature extremes and also assessed their possibility changes are evaluated and quantified over India is presented. The GEV-based method is applied on both precipitation and temperature extremes over India during the 20th and 21st centuries using multiple coupled climate models taking an interest in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and observational datasets. The regional means of historical warm extreme temperatures are 34.89, 36.42, and 38.14 ^{o}C for three different (10, 20, and 50-year) periods, respectively; whereas the cold extreme mean temperatures are 7.75, 4.19, and -1.57 ^{o}C. It indicates that 20th century cold extreme temperatures have relatively larger variations than the warm extremes. As for the future, the CMIP5 models of warm extreme regional mean values increase from 0.33 to 0.75 ^{o}C in all return periods (10-, 20-, and 50-year periods), while in the case of cold extreme means values vary between 0.58 and 2.29 ^{o}C. In the future, cold extreme values have a larger increasing rate over the northwest, northeast, some parts of north central, and Inter Peninsula regions. The CRU precipitation extremes are larger than the historical extreme precipitation in all three (10, 20, and 50-year) return-periods.

Keywords: Precipitation, surface temperature, GEV, Historical, and CMIP5.

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1. Introduction

Extreme weather events, amplified by climate change, can lead to major environmental issues affecting human society. Precipitation and temperature are two major components of a changing climate that have been analyzed extensively over the past two decades (Trenberth and Shea 2005; Li et al., 2009; Kharin et al., 2013). According to the United Nations Office for Disaster Risk Reduction UNISDR (2015), India is the third most influenced nation by weather related by disasters, which can largely be attributed to both higher occurrences of extreme temperatures and precipitation. Recently, Trenberth (2005) showed that climate change due to increased greenhouse gas emissions leads to changes in extreme event behavior in terms of precipitation and temperature all over the world. Generalized Extreme Value (GEV) statistical distribution has long been used to examine time-series of climate extremes with different return levels using three extreme value distributions that were proposed by Fisher and Tippet (1928). The three distributions are referred to as Gumbel, Frechet, and negative Weibull, which are discussed in Section 2. Jaruskova and Rencova (2008) studied the extreme changes in annual maxima and minima temperature series using five meteorological sites, implementing extreme value theory and hypothesis testing within the framework of the GEV-based method.

Jenkinson (1955) used GEV distribution for extreme precipitation events, which offered extensive adaptability of the three extreme value distributions. Later, several researchers used GEV statistical distribution to study extreme precipitation for many regions and different countries around the world (Fowler and Kilsby 2003; Nadarajah 2005; and Gilleland and Katz 2006). In China, a warming trend has been confirmed in both annual minimum and maximum temperature in the twentieth century (Choi et al. 2009; You et al. 2011). Later studies also showed notable extreme temperature increases in northeastern China, and the smallest increase in the southern region (Liu et al. 2004). The frequency of extreme temperature events in China is expected to increase at an accelerating rate based on Coupled Model Inter-comparison Project (CMIP) historical projections (Wang and Chen 2014; Yang et al. 2014). Utilization of GEV distribution on temperature and precipitation over China has been extensively studied in several investigations (Wang and Zhou 2005; Zhang et al. 2011; Yang et al. 2014). As for India, Shashikanth et al. (2017) applied a GEV distribution to GCM summer monsoon precipitation in India during 1961-1990 and 2081-2100. They found a slight increase in the future extreme spatial mean in the later period. However, the statistical GEV distributions of extreme minimum and maximum temperatures in India have not been examined in any previous studies. We utilize this method over India to address this issue. CMIP models and observations are discussed in Section 2. The GEV statistical distribution methodology is described in Section 3. Section 4 presents the results of the GEV distribution in three different periods and occurrences over India, and finally the conclusions are discussed in Section 5.

2. Data and Method

The observational dataset of gridded monthly precipitation (P), minimum and maximum surface temperatures (T_{min} and T_{max}) are taken from the study of the Climate Research Unit (CRU TS3.1) described by Harris et al. (2014). The datasets are collected from 1901 to 2005 over land areas, based on daily values from rain gauge measurements provided by more than 4,000 weather stations distributed around the world (New et al.,

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1999, 2000). The precipitation and surface temperatures are collected from different sources, with rigorous quality checking procedures before gridding (Mitchell and Jones, 2005; Harish et al., 2014). Figure 1 shows the Indian map with seven regions.

The monthly precipitation, and the minimum and maximum surface temperatures (T_{min} and T_{max}) are simulated by CMIP5 (Coupled Intercomparison Project Phase 5) models for a historical (hereafter referred to as "Historical") period from 1850 to 2005 (Smith et al., 2013; Lamarque et al., 2010) as well as the 21st century (years 2006-2100) employing four different representative concentration pathways (RCPs) (Moss et al., 2010, Taylor et al., 2012). The Historical and different scenarios of CMIP5 models are listed in Table 1. Further details on the models and their configuration are described in the references, online at http://www-pcmdi.llnl.gov/. We have considered only models for which the same ensemble member i.e. 'r1i1p1' is available both in the historical and four (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) scenarios considered here. According to the IPCC Fifth Assessment Report, the CMIP5 models exhibit improvements in the simulations especially surface temperature and precipitation compared to the previous climate models (Flato et al. 2013). The outputs for both historic and different RCPs outputs are available on different spatial scales, which are consequently regridded to a common spatial scale of 1^{o} in latitude and 1^{o} in longitude resolution.

Out of the monthly CMIP5 model outputs (listed in Table 1), Historical experiments, RCP (2.6, 4.5, 6.0, and 8.5) experiments of T_{min}, T_{max}, and Precipitation (P) are utilized for our analysis.

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Three types of extreme distributions compose a GEV distribution: Gumbel, Frèchet, and Weibull, also known as type I, II, and III respectively (Martins and Stedinger 2000; Feng et al., 2007). These can generally be described by

$$G((z;\mu,\sigma,\xi)=\begin{cases} exp\left\{-exp\left[-\left(\frac{z-\mu}{\sigma}\right)\right]\right\},\ \xi=0 \\ exp\left\{-\left[1+\xi\frac{z-\mu}{\sigma}\right]^{-\xi^{-1}}\right\}, \xi\neq 0,\ 1+\xi\frac{x-\mu}{\sigma}>0 \end{cases} \quad (1)$$

where μ, σ and ξ are the location, scale, and shape parameters, respectively. Particular cases of Eq. (1) with $\xi\rightarrow 0, \xi>0, and\ \xi<0$ correspond to the Gumbel, Frèchet, and the negative Weibull distributions, respectively. Generally, the value of ξ is greater than zero for precipitation data, although the distribution of Gumbel is sometimes adequate.

Several methods have been developed for the estimation of the parameters of GEV distributions. These include the method of moments by Christopeit (1994), the less influenced method of L-moments (Hosking, 1990; Hosking and Wallis, 1997); the Bayesian method by Smith and Naylor (1987), Coles and Tawn (2005). The most popular method is the maximum likelihood method (Smith and Naylor, 1987; Unkašerić and Tošić, 2009), which has the advantage of allowing the addition of fitting co-variables (such as trends, cycles or physical variables) (Katz et al., 2002). The detailed procedure of these methods summarized by the El Adlouni et al. (2007), Kioutsioukis et al. (2010), and Kharin et al. (2013). In this study, the maximum likelihood method is used to estimate the parameters of the GEV distribution. The regression parameters of $\mu(t), \sigma(t), and\ \xi(t)$ are the location, scale, and shape respectively. The parameters of the likelihood function, given n observations $\{(t_1,z_1), (t_2,z_2),......,(t_n,z_n)\}$ at period t_i at which the greatest z_i is acquired, is provided by

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$$L(\theta|t_{t,}z_t) \;=\; \prod_{i=1}^{m} g[z_i;\; \mu(t_i), \sigma(t_i), \xi(t_i)] \qquad (2)$$

where

$$g(z;\, \mu, \sigma, \xi) \;=\; \frac{1}{\sigma}\left\{[1 + \xi\left(\frac{z-\mu}{\sigma}\right)]^{-(1+1/\xi)}\right\}\; exp\left\{-\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \qquad (3)$$

The log-likelihood function is

$$l(\theta|t_{t,}z_t) \;=\; -\sum_{i=1}^{m}\left\{log\sigma(t_i) + \left(1 + \frac{1}{\xi(t_i)}\right)\, log\left[1 + \xi(t_i)\left(\frac{z_i-\mu(t_i)}{\sigma(t_i)}\right)\right] + [1 + \xi(t_i)\left(\frac{z_i-\mu(t_i)}{\sigma(t_i)}\right)]^{-\frac{1}{\xi(t_i)}}\right\} \qquad (4)$$

$\sigma(t_i) > 0$ and $\{1 + \xi(t_i)(z_i - \mu(t_i))/\sigma(t_i) > 0\}$ for i=1, …., n. For every value of $\xi(t_i)$ that equals to zero, it is important to utilize the suitable limiting form, replacing the GEV by the Gumbel ($Eq.(1)\; for\; \xi = 0$) log-likelihood function,

$$l(\theta|t_j, z_j) = -log\sigma(t_i) - \frac{z_j-\mu(t_j)}{\sigma(t_j)} - exp\left[-\frac{z_j-\mu(t_j)}{\sigma(t_j)}\right] \qquad (5)$$

The maximum likelihood estimate of θ yields the maximization of Eq. (4) and/or Eq. (5). Rao (1973) estimated the confidence intervals for the selected return periods using the delta method. Figure 1 shows the regression, model fits and estimated the return values of monthly maximum temperatures.

We implement this GEV analysis to study the minimum and maximum surface temperatures and precipitation as simulated by CMIP5 models in the historical experiments (years 1901-2005), CRU observations, and experiments for the 21st century (years 2006-2100) with four different radiative forcing scenarios.

3. Results

3.1 CMIP Historical and CRU temperature extremes

The spatial distribution of extremes for the Historical runs in India during 1901-2005 is presented by showing maximum and minimum temperature extremes with different return time periods are shown in Figure 2. The top and bottom panels show maximum and minimum extremes respectively with return periods of 10, 20 and 50 years, denoted as $T_{(max,10)}$, $T_{(max,20)}$, and $T_{(max,50)}$ for maximum temperatures and $T_{(min,10)}$, $T_{(min,20)}$, $T_{(min,50)}$, for minimum temperatures respectively. The regional mean value for each return time period is mentioned at the top of each plot. The mean values indicate high warm extreme temperature conditions in India with average values of 34.89, 36.42, and 38.14^{o}C for $T_{(max,10)}$, $T_{(max,20)}$, and $T_{(max,50)}$ respectively. The mean CRU extreme regional values are 34.80, 36.46, and 38.42^{o}C for the 10, 20, and 50 year periods (Figure not shown). $T_{(max,10)}$ and $T_{(max,20)}$ show the most evident warm extremes over Northwest and North-central regions. These extreme regions extend to the Interior peninsula at $T_{(max,50)}$. Similar extreme warm surface temperatures are observed over the northwestern part of India (Gadgil, 2018). These three regions show maximum extremes with return values all above 40^{o}C, while the Western Himalaya region exhibits the lowest maximum temperature extremes at about 10^{o}C. At $T_{(max,10)}$ large cold extremes cover most parts of the Western Himalaya region and slowly turn to warming extremes at $T_{(max,50)}$. The minimum temperature extremes show large variations over India except for the Western Himalaya region. The mean value of minimum temperature extreme over the entire region in India is 7.75, 4.19, and -1.57^{o}C for three (10, 20 and 50-year) return periods, respectively. More extreme cold changes are observed in Figure 2 over the northeastern and western regions of India, and cold temperature extremes drop from 7^{o}C to -20^{o}C for

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10 and 50 years period. The warmer and colder extremes of the minimum temperature are observed over southern and northern parts of India respectively.

3.2 CMIP Historical and CRU changes in temperature extremes

The spatial differences between CMIP and CRU warm and cold temperature extremes for the three return estimates of 10, 20, and 50 year periods are shown in Figure 3. The upper and lower panels display the changes in warm and cold temperature extremes for three time periods respectively. The positive (red color) and negative (blue color) values in these diagrams indicate the warmest and coldest Historical extremes for the three different periods.

The difference between the warm extremes decreases slightly from the 10 to 50-year period over central and northern parts of India. Warm and cold bands are clearly observed over the southern regions of the warm extreme difference map. Looking at the cold extreme differences, a cold band (with a magnitude of ~4.5^{o}C) is observed in the northwest region of India for the 50-year period, indicating that the CRU cold extremes are warmer than those of CMIP5 historical runs. The regional mean value decreases from 0.14 to -0.20^{o}C for warm extremes and decreases from -0.55 to -0.95^{o}C for cold extremes from 10 to 50 year periods. From Figure 3, the magnitude of the difference of cold extremes is little larger than those of the warm extremes for all three return periods over India. The mean value of warm and cold extreme differences are less than a degree indicating a fairly good agreement between the Historical and CRU temperatures for the three different return periods. Kharin et al. (2005, 2007) observed that the temperature differences between CMIP5 multi-model and ERA-Interim are generally larger for cold extremes than for warm extremes during the period from 1986 to 2005. Table 2

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summarizes the warm and cold extreme temperature mean values for the 10, 20, and 50-year periods of each region for the CRU, Historical, as well as the differences between the two. It is evident from the table that the maximum warm extreme mean temperature is observed in the Interior Peninsula over the Historical ensemble and CRU temperatures for the 20- and 50-year return periods.

3.4 Future climate extreme changes in CMIP5 projections

The spatial GEV distribution for three different return values of 10, 20, and 50 years estimated from CMIP5 maximum temperatures of different RCP scenarios (RCP 2.6, 4.5, 6.0, and 8.5) for the period 2006-2099 are shown in Figure 4. All RCPs suggests comparable spatial distributions of maximum temperatures over the three different periods. The spatial distributions of warm extremes for all RCPs look similar in the 50-year period. Moderately warm regional mean temperature changes are observed in RCP2.6 and RCP8.5 scenarios at about 1.15, 1.28, and 1.28^{o}C for the three (10, 20 and 50 year) periods, respectively. In RCP2.6, the warm temperature extremes are observed in northwest (NW) and north central (NC) regions in the 10-year period, while warm extremes cover three regions (NW, NC, and IP) in the 20-year period, and most of the regions in India in the 50 year period. In RCP8.5 the maximum temperatures are observed in most of the Indian regions with regional means of 39.96, 39.99, and 41.18^{o}C for the three (10, 20, and 50-year) return periods, respectively. Maximum extreme temperatures of about ~44^{o}C are observed in several grids throughout India under (RCP 2.6 and 8.5) CMIP5 experiments in the 20 and 50 year return periods. Similar extreme temperatures reach values of around 46^{o}C in large areas of northwest and Interior peninsula regions over equatorward of 25^{o}. All simulations demonstrate an ascent of

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more than ~3.5°C over three regions (NW, NC, and IP), and a warming of more than 2°C over the western Himalayan region in the 50 year period.

The spatial distribution of cold temperature extremes during the 21st century under the RCP scenarios (RCP 2.6, 4.5, 6.0, and 8.5) for the three different time periods over India are shown in Figure 5. The regional mean values of cold extremes have consistently decreasing trends in all RCP scenarios. The northwest, western Himalayas, and northeast are the main regions exhibiting diminishing trends in all three return periods. The mean value of cold extremes for the 50-year period is ~7°C higher than the 20-year period for RCP2.6. For the other concentration pathways (RCP 4.5, 6.0 and 8.5), the projected increase in cold temperature extremes ranges from 2.5°C to 2.8°C, and 3.3° C to 3.9° C over the period 10 to 20 and 20 to 50-year return periods, respectively. Note that the positive changes of about ~5° C in temperature are observed in the RCP8.5 experiment in 21st century relative to the 1901-1960 historic period (Basha et al., 2017). The cold temperature extreme slowly decreases with latitude from south to north of India in all RCP scenarios. The magnitude at the southern tip of India is about 20°C, which decreases to -23°C over the northern tip. The maximum regional cold extreme value at about 12.73°C is observed in RCP8.5 for a 10-year period, while the minimum at about -0.99°C is observed in RCP2.6 for 50-year return period.

3.5 Temperature extremes inter-model uncertainty in CMIP5 projections:

The variability of the warm and cold temperature extremes over India can be shown by standard deviations as shown in Figures 6 and 7, which depict the spatial distributions of standard deviations for three different time periods (10, 20, and 50-year) of warm (T_{max}) and cold (T_{min}) extremes projected in the four different scenarios (RCP2.6,

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4.5, 6.0, and 8.5), respectively. The spatial map in Figure 6 indicates the maximum to be in the southern part of Interior Peninsula (IP), while the second maximum (relatively weak) is at the Western Himalaya (WH) region in RCP2.6 at the 50-year period. The standard deviation of warm extremes is larger in the 50-year period compared to the 10- and 20-year periods especially in the southern part of India in all RCP scenarios. The maximum mean value is about 0.75°C in RCP8.5 (10-year period), whereas the minimum value is observed in RCP2.6 (50-year return value) at about 0.33°C. The standard deviations change in small increments across different scenarios for all return periods. For example, the standard deviation changes in 20-year return values are 0.47, 0.45, 0.41, 0.49°C under RCP2.6, 4.5, 6.0, and 8.5 scenarios, respectively.

The spatial distribution of different CMIP5 experiments for three different time periods (10, 20, and 50-year) return values of cold extreme (T_{min}) standard deviations are shown in Figure 7. A distinct feature of warm bias (up to 3.5° C) in eastern and western regions of India is observed in all scenarios at 20- and 50-year periods. In cold extremes, the 50-year return period standard deviation is higher compared to other return values under RCP2.6. The maximum mean value of $T_{min,50}$ is about 2.29°C in RCP2.6, while the minimum value ($T_{min,10}$) is observed in RCP8.5. The cold extremes have a larger variability comparing to warm temperature extremes. The mean maximum value of warm temperatures ($T_{max,50}$) is almost three times as large as the $T_{min,50}$ in RCP2.6. The variability of warm extremes (given by the standard deviation) are spatially fairly uniform in all the return periods, which is not the case for cold extremes under CMIP5 scenarios. Recent observational (Lee et al., 2014) and modeling (Kharin et al., 2007, 2013) studies have reported larger variability of warming in cold extremes compared to warm extremes across different return periods. This indicates that variability in cold temperature extremes is larger than those of warm temperature extremes over India.

4. Precipitation extremes

4.1 Historical and CRU precipitation extremes and differences

The spatial variations of Historical (top panel), CRU (middle panel), and the differences between the two (bottom panel) of extreme precipitation for three different return periods (10, 20, and 50-year) are shown in Figure 8. The three (10, 20, and 50-year) periods of precipitation extremes are computed from the GEV procedure by using monthly precipitation grids. From Figure 8, precipitation extremes increase significantly from the 10 to the 50-year period in both Historical and CRU observations. In CMIP5_historical runs the extreme precipitation appears to have a positive trend in the Interior Peninsula, which extends slightly into North Central (NC) part of India. The maximum trends, however is concentrated in the IP region. In the case of CRU, the increasing trend is observed over the IP and NC regions for the 20-year period, which also extends to most parts of India except for the southern tip and the Western Himalayan regions for the 50-year period. A widespread increase in extreme precipitation is observed in CRU for the 50-year period over the IP, NC, WC and EC regions. The differences between Historical and CRU extreme precipitations indicate that the CRU extreme values are slightly higher over the IP and NC, while Historical is slightly higher in the northern and southern parts of India for the 10- and 20-year periods. In the 50-year period, precipitation is higher in the Historical runs compared to CRU over the Interior Peninsula, Western Himalayan regions. However, extreme precipitation is lower in the Historical runs, in the northwest and extending to northwest and extending to north-

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central regions of India. The regional mean differences are -11.89%, -11.33% and 4.69% for all three (10, 20, and 50-year) periods, respectively.

The multi-model extreme precipitation differences for the 10-, 20-, and 50-year return periods during the period 2006-2100 for each CMIP5 scenarios (RCP2.6, 4.5, 6.0, and 8.5) relative to the 1901-2005 historical periods are shown in Figure 9. The northwestern region has the greatest decrease in all CMIP5 scenarios for all three return periods, which implies that the warmest region has the greatest decrease in extreme precipitation in future projections. The maximum mean difference is about ~23% in RCP8.5 for the 50-year return period. In comparison, future projections of extreme precipitation are slightly higher than Historical ones in the northern and some regions within Interior Peninsula. However, the Historical precipitation extremes are dominant in the 50-year period, and to a smaller extent in the 10-year period. The regional mean changes of extreme precipitation for the 50-year period are -10.4%, -12.9%, -4.3%, and -22.9% under the RCP2.6, 4.5, 6.0, and 8.5 scenarios, respectively. From Figure 9, the regional mean changes of future precipitation extremes are 1.9% and 5.9% in RCP2.6 (20-year period) and RCP6.0 (20-year period), respectively. Shashikanth et al. 2017 also found that significant changes in monsoon precipitation extremes during a 30-year period (2081-2100) compared to the historic period.

5. Conclusions

We have assessed the Historical and CRU precipitation and temperature extremes and likely future changes within them throughout India. We quantified the warm and cold temperatures as well as precipitation extremes of CMIP5 for all Representative Concentration Pathway scenarios (RCP2.6, 4.5, 6.0, and 8.5) for the future using a

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statistical model of climate extremes based on GEV distributions for the three return periods (10, 20, and 50-year). The most important findings of our analysis are summarized as follows:

Extreme warm values in Historical T_{max} in India appear to be rather moderate. The regional means of extreme maximum temperatures are 34.89, 36.42, and 38.14 ^{o}C for all three (10, 20, and 50-year) return periods, respectively, while the minimum extreme temperatures are 7.75, 4.19, -1.47 ^{o}C for those same return periods. Comparing the 10- to 50-year return periods, the warm extremes increase at about ~3 ^{o}C over northwestern, north central, and Interior peninsula regions. Cold extremes are decreased ~5 ^{o}C especially over the eastern and western regions of India.

The regional relative mean differences of Historical and CRU T_{max} extremes are 0.14, 0.01 and -0.20 ^{o}C for the three (10, 20, and 50-year) periods, respectively. Comparing the 10- and 50-year return periods shown that the relative changes of extreme temperatures decrease in Northwest, North central, and northern part of Interior peninsula, and increase over lower part of the west coast. The relative mean differences of CRU cold extremes are slightly higher than those of the Historical runs. The relative mean differences of cold extremes are -0.55, -0.64, and 0.28 ^{o}C for the three (10, 20, and 50-year) periods, respectively. CRU shows more changes in the cold extremes as opposed to warm extremes compared to the Historical extremes. Regionally, northwestern and northeastern regions of India show the highest changes.

Future T_{max} extreme temperatures increase in all RCP scenarios compared to historical temperatures, especially for the 20 and 50 year periods. The regional extreme mean values increase moderately compared to the historical values at about 1.85 and 2.92

^{o}C in the 50-year period under RCP6.0 and 8.5 scenarios. In the case of T_{min} extreme mean temperatures of RCP2.6 decrease by nearly 5 ^{o}C compared to the historical values, while the minimum extreme temperature mean in RCP8.5 increase by nearly 4 ^{o}C compared to historical temperatures in 50-year return period. It must be noted that the effect of increasing radiative forcing under higher concentration pathways is larger on cold temperatures compared to warm temperatures.

The spatial variability of CRU extreme precipitation rates is substantially larger compared to Historical extremes in all three return periods. Upon comparing 10-, and 50-year periods, changes in precipitation extremes are observed in both the location and scale of the distribution, especially over North Central and Interior Peninsula regions of India. In the other regions, CRU precipitation extreme changes increase slightly in the 50-year period. The regional mean relative difference of Historical and CRU precipitation extremes is observed the 50-year period at about -14.6%. It indicates that Historical precipitation extremes show smaller values compared to CRU in several regions in India. The past and future differences of extreme precipitation are significantly larger when comparing to Historical to RCP8.5, implying that increasing radiative forcing under higher greenhouse gas concentrations may lead to larger changes in precipitation extremes.

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authors would like to thank the National Center for Atmospheric Research (NCAR) for providing the CRU data.

Figure captions

Figure 1. Sample plot of Generalized Extreme Value (GEV) distribution return values, empirical and modeled fits with 95% confidence level, together with the map of India divided in the seven regions used in this study.

Figure 2. The historical maximum temperature (T_{max}; top panel), and minimum temperature (T_{min}; bottom panel) extremes for 10-year (left), 20-year (middle), and 50-year (right) periods during 1901-2005.

Figure 3. The difference between CMIP5_historical and CRU maximum temperature (T_{max}; top panel), and minimum temperature (T_{min}; bottom panel) extremes for (left) 10-year, (right), 20-year, and (right) 50-year periods during 1901-2005.

Figure 4. The (left) 10-year, (middle) 20-year, and (right) 50-year return values of CMIP5 multi-model mean of warm temperature extremes for the period 2006-2100 under RCP2.6 (1st row), RCP4.5 (2nd row), RCP6.0 (3rd row), and RCP8.5 (bottom row) scenarios, together with the regional average stated on top of each panel.

Figure 5. The (left) 10-year, (right) 20-year, and (right) 50-year return values of CMIP5 multi-model minimum temperature extremes projected in 2006-2100 under RCP2.6 (1st row), RCP4.5 (2nd row), RCP6.0 (3rd row), and RCP8.5 (bottom row) experiments, together with the regional means stated on top of each panel.

Figure 6. The CMIP5 inter-model standard deviations for the 10-year (left), 20-year (middle), and 50-year (right) return values of warm temperature extremes

simulated in the RCP2.6 (1st row), RCP4.5 (2nd row), RCP6.0 (3rd row), and RCP8.5 (bottom row) experiments, respectively.

Figure 7. The CMIP5 inter-model standard deviations for the 10-year (left), 20-year (middle), and 50-year (right) return values of cold temperature extremes simulated in the RCP2.6 (1st row), RCP4.5 (2nd row), RCP6.0 (3rd row), and RCP8.5 (bottom row) experiments, respectively.

Figure 8. The 10-year (left), 20-year (middle), and 50-year (right) return values of Historical (1st row), CRU (2nd row), and the relative change between Historical and CRU (%, bottom row) of precipitation extremes during 1901-2005.

Figure 9. The CMIP5 multi-model mean relative change (%) for the 10-year (left), 20-year (middle), and 50-year (right) return values of precipitation extremes between the historic values in 1901-2005 and the simulated values in 2006-2100 under RCP2.6 (1st row), RCP4.5 (2nd row), RCP6.0 (3rd row), and RCP8.5 (bottom row) scenarios, together with their regional means of relative changes on top of each panel.

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References:

Choi, G., Collins, D., Ren, G. Y. et al.: Changes in means and extreme events of temperature and precipitation in the Asia- Pacific network region, 1955-2007. Int. J. Climatol., 29, 1906-1925, 2009.

Fisher R. A., and Tippet, L. H. C.: Limiting forms of the frequency distribution of the of a sample, Proce. Cambridge Philos. Soc., 180-190,1928

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M.: Evaluation of climate models. In: Stocker TF et al (eds) Climate Change 2013: the physical science basis, Cambridge University Press, Cambridge, 741-866, 2013.

Flower, H. J., and Kilsby, C. G.: A regional frequency analysis of United Kingdom extreme rainfall from 1961to 2000, International Journal of Climatology, 23(11), 1313-1334. doi: 10.1002/(ISSN)1097-0088, 2003.

Gadgil, S.: The monsoon system: Land-sea breeze or the ITCZ?. J. Earth Syst. Sci., 5, 127. doi:10.1007/s12040-017-0916-x, 2018.

Gilleland, E., Katz, R.: Analyzing seasonal to interannual extreme weather and climate variability with the extremes toolkit. In 18th Conference on Climate Variability and Change, 86th American Meteorological Society (AMS) Annual Meeting, 20 January – 2 February, 2006, Atlanta, Georgia, 2006.

Harrish, I., Jones, P., Osborn, T., and Lister, D.: Updated high resolution grids of monthly climate observations-The CRU TS3.10 dataset, Int. J. Climatol., 34, 623-642. doi: 10.1002/joc.3711, 2014.

Jaruskova, D., and Rencova, M.: Analysis of annual maximum and minimal temperatures for some European cities by change point methods, Environmetrics, 19(3), 221-233. doi: /10.1002/env.865, 2008.

Jenkinson, A. F.: The frequency distribution of the annual maximum (or minimum) values of meteorological elements, Quart. J. Roy. Meteor. Soc., 81, 158-171, 1955.

Kharin, V. V., Zwiers, F. W., Zhang, X., and Hegerl, G. C.: Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations, J. Climatol., 20, 1419-1444, 2007.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-522
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 8 November 2018

Kharin, V. V., and Zwiers, F. W.: Estimating extremes in transient climate change simulations, J. Climatol., 18, 1156-1173, 2005.

Kharin, V. V., Zwiers, F. W., Zhang, X., and Wehner, M.: Changes in temperature and precipitation extremes in the CMIP5 ensemble, Climate Change, 119, 345-357, 2013.

Lamarque, J. –F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and Van Vuuren, D. P.: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application, Atmos. Chem. Phys., 10, 7017-7039. doi:10.5194/acp-10-7017-2010, 2010.

Li, L., Hong, Y., Wang, J. H., Adler, R. F., Policicelli, F. S., Habib, S., Irwn, D., Korme, T., Okello, L.: Evaluation of the real-time TRMM-based multi-satellite precipitation analysis for an operational flood prediction system in Nzoia basin, lake Victoria, Africa, Natural Hazards, 50, 109-123, 2009.

Liu, B. H., Xu, M., Henderson, M., et al.: Taking China's temperature: daily range, warming trends, and regional variations, J. Climatol., 17, 4453-4462, 2004.

Mitchell, T. D., and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693-712, 2005.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747-756. doi:10.1038/nature08823, 2010.

Nadarajah, S.: Extremes of daily rainfall in west central Florida, Climate Change, 69, 325-342, 2005.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-522
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 8 November 2018

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Discussions

New, M., Hulme, M., and Jones, P.: Representing twentieth century space-time climate variability. Part 1: development of a1961-90 mean monthly terrestrial climatology, J. Climate, 12, 829-856, 1999.

New, M., Hulme, M., Jones, P. D.: Representing twentieth century space-time climate variability, II: development of 1901-1996 monthly grids of terrestrial surface climate, J. Climate, 13, 2217-2238, 2000.

Pickandas, J.: Statistical Inference Using Extreme Order Statistics, The Annals of Statistics, 3, 119-131, 1975.

Shashikanth, K., Ghosh, S., Vittal, H., and Karmakar, S.: Future projections of Indian summer monsoon rainfall extremes over India with statistical downscaling and its consistency with observed characteristics, Clim. Dyn., doi: 10.1007/s00382-017-3604-2, 2017.

Smith, T. M., Arkin, P. A., Sapiano, M. R. P.: Merged statistical analyses of historical monthly precipitation anomalies beginning 1990, J. Climatol., 23, 5755-5770, 2010.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc., 93, 485-498. doi:10.1175/BAMS-D-11-00094.1, 2012.

Trenberth, K.E.: Uncertainty in hurricanes and global warming, Science, 308, 1753-1754, 2005.

Trenberth, K.E., and Shea, D. J.: Relationships between Precipitation and Surface temperature, Geophys. Res. Let., 32, L14703, doi: 10.1029/2005GL022760, 2005.

Wang, L., Chen, W.: A CMIP5 multi model projection of future temperature, precipitation, and climatological drought in China, Int. J. Climatol., 34, 2059-2078, 2014.

Wang, Y. Q., and Zhou, L.: Observed trends in extreme precipitation events in China during 1961-2001 and the associated changes in large-scale circulation. Geophys. Res. Lett., 32, 4, 2005.

Yang, S. L., Feng, J. M., Dong, W. J., and Chou, J.: Analysis of extreme climate events over China based on CMIP5 historical and future simulations, Adv. Atmos. Sci., 31, 1209-1220, 2014.

You, Q. L., Kang, S. C., Aguilar, E., et al.: Changes in daily climate extremes in China and their connection to the large scale atmospheric circulation during 1961-2003, Clim. Dyn., 36, 2399-2417, 2011.

Zhang, L., Dong, M., and Wu, T. W.: Changes in precipitation extremes over Eastern China simulated by the Beijing Climate Center Climate System Model (BCC_CSM1.0), Clim. Res., 50, 227-245, 2011.

Table 1: Historical and CMIP5 different scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) precipitation and maximum and minimum temperature

Model Name	Historical 1901-2005		CMIP5 2006-2099							
	Stem	Pr	Stem				Pr			
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
CCSM4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CNRM-CM5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CSIRO-MK3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CanESM2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GFDL-CM3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GISS-E2-H	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GISS-E2-R	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HadGEM2-CC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HadGEM2-ES	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
IPSL-CM5A-LR	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MIROC-ESM	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MIROC5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MPI-ESM-LR	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MRI-CGCM3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
NorESM1-M	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
BCC-CSM1-1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
INMCM4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GFDL-ESM2M	N	N	N	N	N	N	N	N	N	N
BNU-ESM	N	N	N	N	N	N	N	N	N	N
IPSL-CM5A-MR	N	N	N	N	N	N	N	N	N	N
CANESM2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FGOALS-g2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CESM1-CAM5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Table 2: CRU and differences between CRU and historical maximum and minimum temperature and standard deviation for seven homogeneous regions for 10-, 20-, and 50-year return periods.

	CRU: T_{max}			CRU: T_{min}			CMIP - CRU : T_{max}			CMIP - CRU : T_{min}		
Regions	Avg ± std			Avg ± std			Avg ± std			Avg ± std		
	10 year	20 year	30 year	10 year	20 year	30 year	10 year	20 year	30 year	10 year	20 year	30 year
India	34.80 ± 5.87	36.46 ± 6.15	38.42 ± 6.83	9.77 ± 8.07	6.51 ± 8.39	1.86 ± 10.04	0.14 ± 1.19	0.01 ± 1.05	-0.20 ± 1.46	-0.55 ± 0.82	-0.64 ± 0.31	-0.95 ± 2.12
IP	37.51 ± 1.59	40.12 ± 2.19	43.92 ± 3.33	15.55 ± 1.92	13.72 ± 2.53	11.51 ± 3.48	0.27 ± 1.06	0.09 ± 1.33	-0.30 ± 2.08	-0.35 ± 0.29	-0.75 ± 0.61	-1.52 ± 1.42
EC	35.62 ± 1.41	36.78 ± 1.63	38.08 ± 2.07	17.48 ± 2.90	15.17 ± 3.37	11.67 ± 6.42	-0.29 ± 2.03	-0.17 ± 1.96	0.01 ± 0.83	0.31 ± 0.49	0.31 ± 0.49	0.61 ± 0.95
NC	37.91 ± 2.82	39.81 ± 3.03	41.91 ± 3.44	9.76 ± 2.67	5.76 ± 3.42	0.19 ± 5.32	1.33 ± 1.51	0.77 ± 1.36	-0.13 ± 1.43	-0.28 ± 0.45	0.03 ± 1.03	0.57 ± 1.57
NW	38.13 ± 4.26	39.37 ± 4.33	40.47 ± 4.42	8.16 ± 3.06	3.98 ± 1.72	-1.54 ± 1.88	1.14 ± 0.56	0.85 ± 0.53	0.49 ± 0.51	-0.89 ± 0.69	-1.32 ± 0.76	-2.75 ± 3.86
WC	34.59 ± 2.27	35.83 ± 2.59	37.41 ± 3.18	16.44 ± 2.77	14.43 ± 3.03	11.63 ± 5.03	-0.33 ± 0.93	0.21 ± 1.22	1.37 ± 1.57	-0.01 ± 0.58	-0.64 ± 0.26	-2.28 ± 2.09
NE	30.46 ± 5.48	31.44 ± 5.65	32.31 ± 5.86	6.69 ± 5.78	1.10 ± 4.45	-8.99 ± 6.68	-1.33 ± 1.96	-1.42 ± 2.01	-1.54 ± 2.03	-0.93 ± 0.96	-0.69 ± 1.38	-0.11 ± 2.03
WH	18.14 ± 5.52	19.59 ± 5.36	20.74 ± 5.23	-13.75 ± 7.14	-15.71 ± 8.39	-17.53 ± 7.32	-2.28 ± 1.52	-1.63 ± 1.15	-0.89 ± 1.76	-2.02 ± 0.68	-1.87 ± 0.68	-1.67 ± 0.68

IP = Interior Peninsula; EC = East Coast; NC = North Central; NW = North West; WC = West Coast; NE = North East; WH = Western Himalayas.

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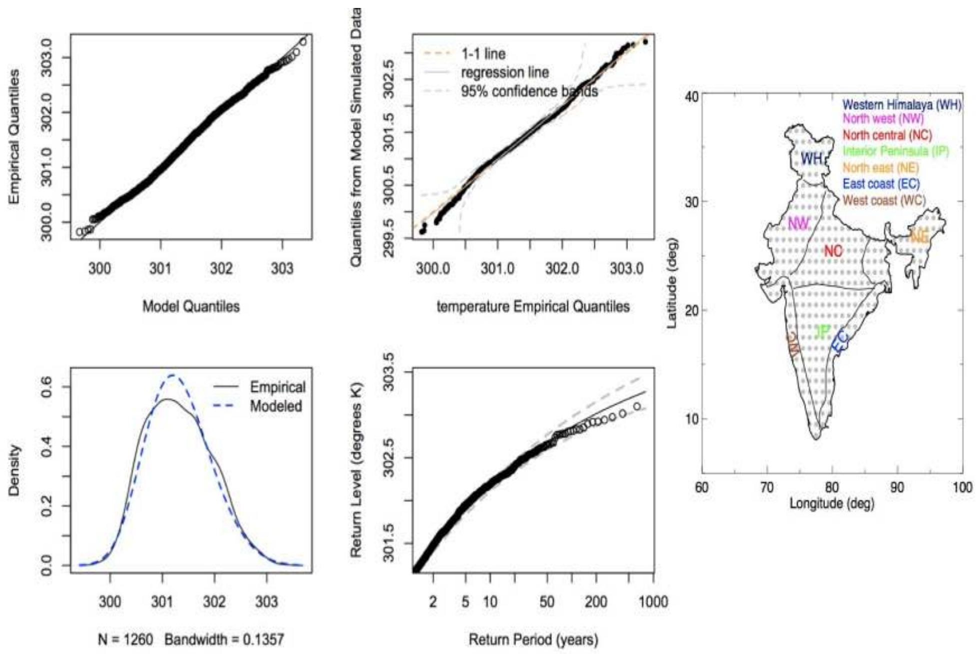

Figure 1

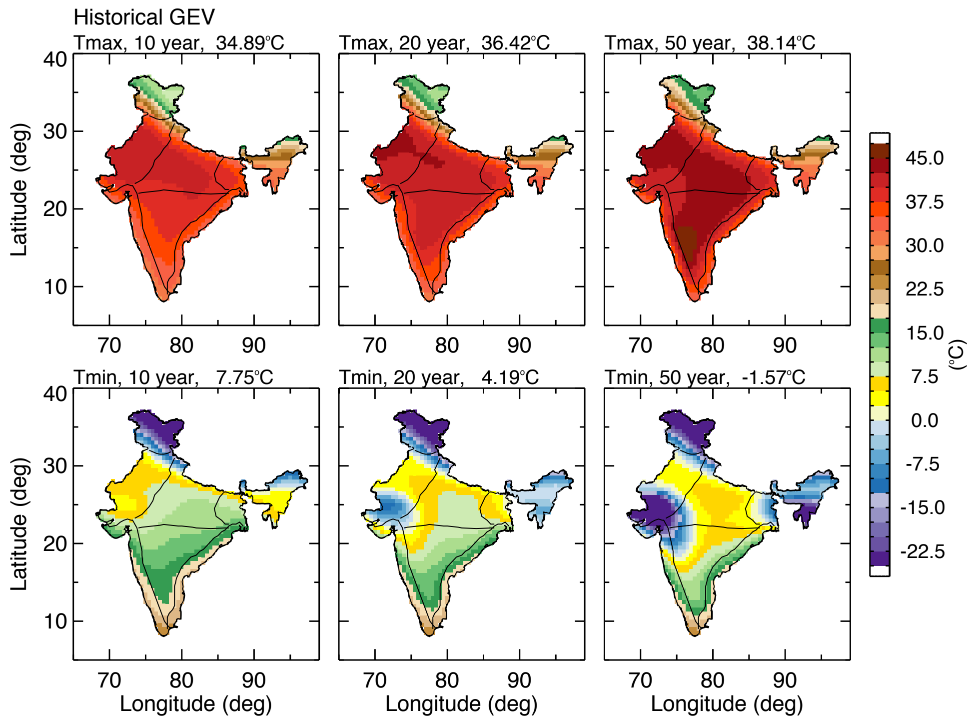
Historical GEV
Tmax, 10 year, 34.89°C
Tmax, 20 year, 36.42°C
Tmax, 50 year, 38.14°C
Tmin, 10 year, 7.75°C
Tmin, 20 year, 4.19°C
Tmin, 50 year, -1.57°C
Latitude (deg)
Longitude (deg)
10
20
30
40
70
80
90
45.0
37.5
30.0
22.5
15.0
7.5
0.0
-7.5
-15.0
-22.5
(°C)

Figure 2

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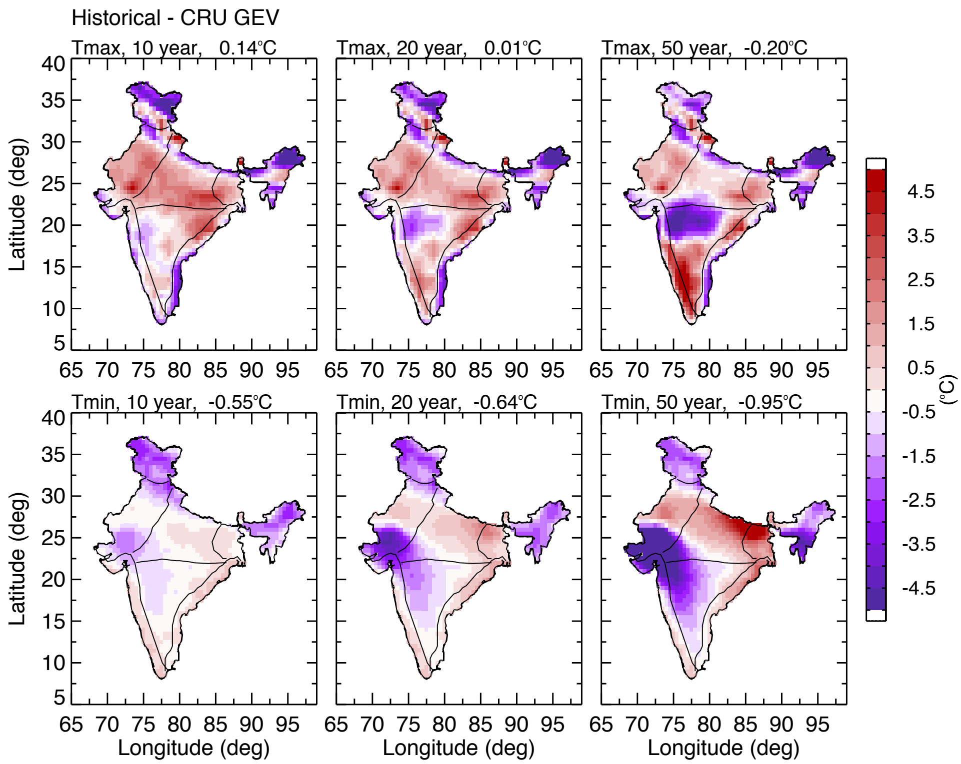

Figure 3

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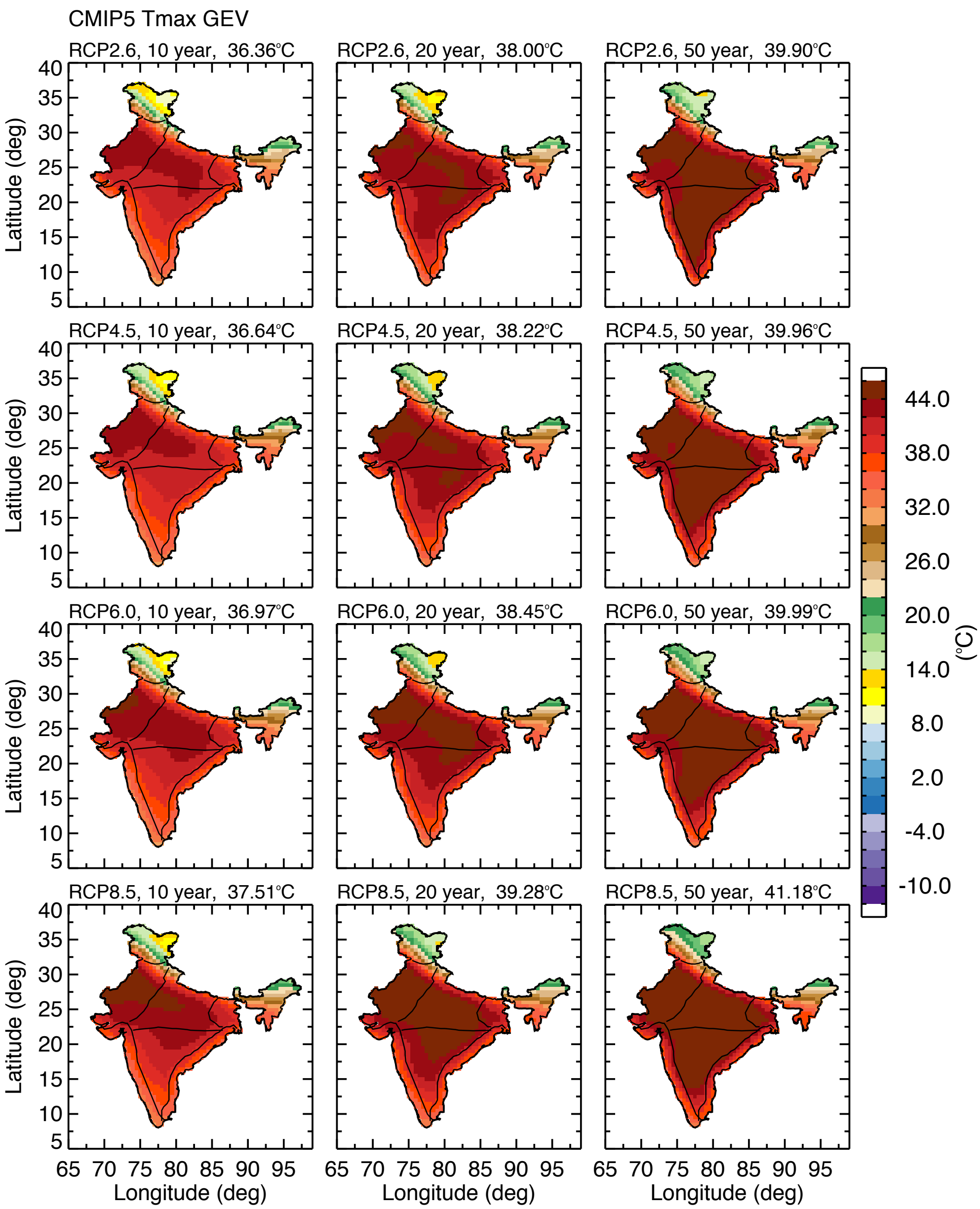

Figure 4

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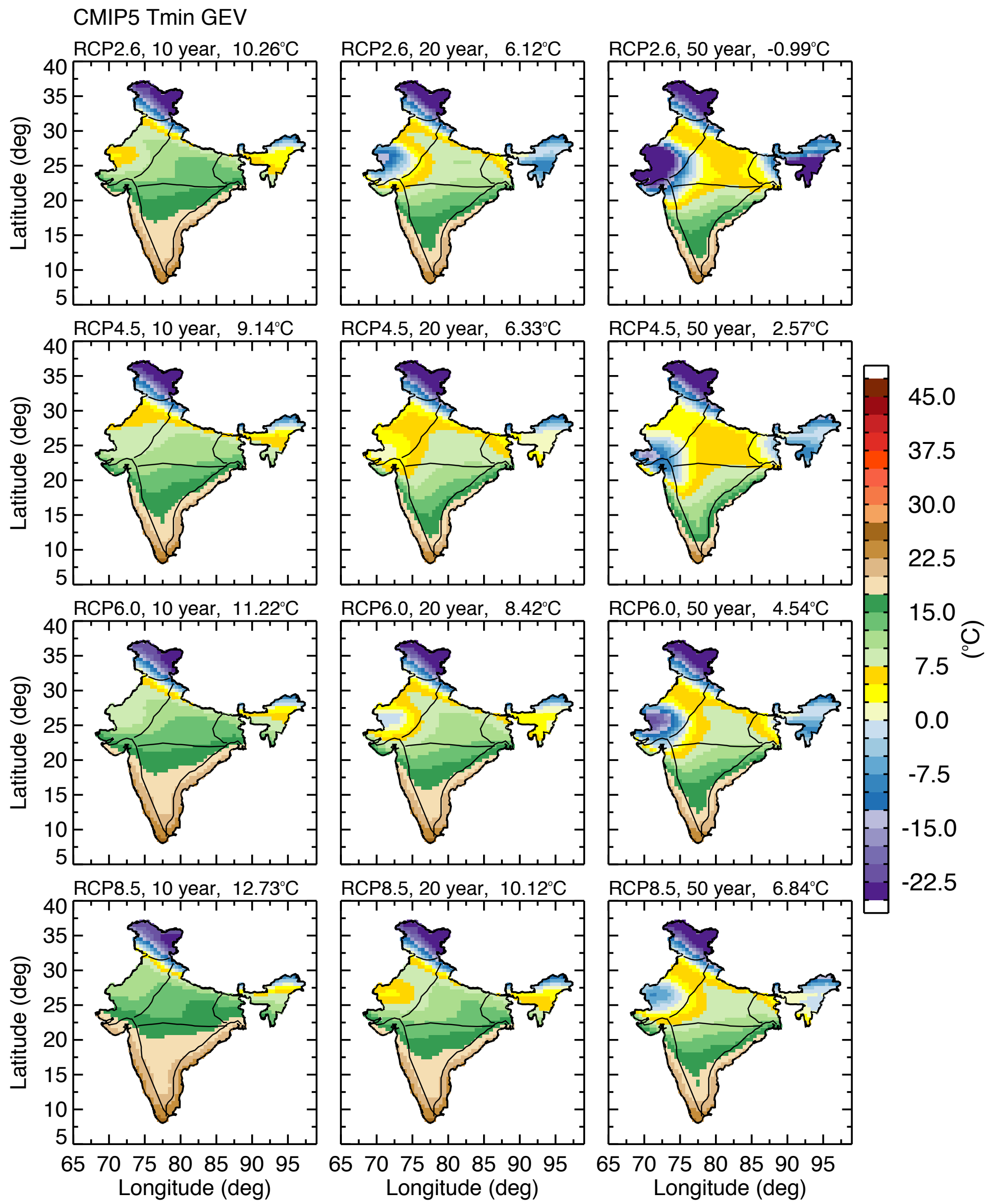

Figure 5

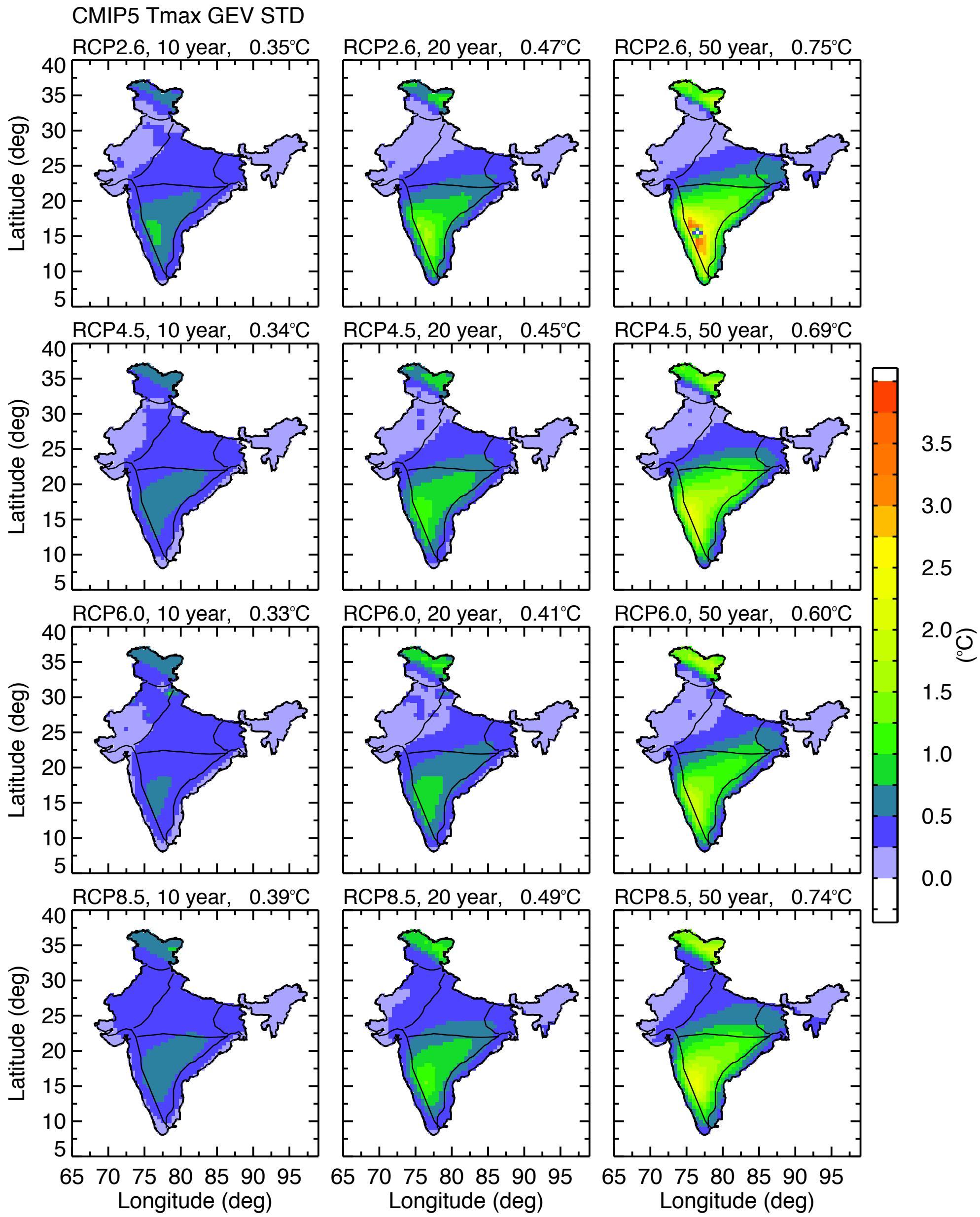
CMIP5 Tmax GEV STD
RCP2.6, 10 year, 0.35°C
RCP2.6, 20 year, 0.47°C
RCP2.6, 50 year, 0.75°C
RCP4.5, 10 year, 0.34°C
RCP4.5, 20 year, 0.45°C
RCP4.5, 50 year, 0.69°C
RCP6.0, 10 year, 0.33°C
RCP6.0, 20 year, 0.41°C
RCP6.0, 50 year, 0.60°C
RCP8.5, 10 year, 0.39°C
RCP8.5, 20 year, 0.49°C
RCP8.5, 50 year, 0.74°C
Latitude (deg)
Longitude (deg)
(°C)

Figure 6

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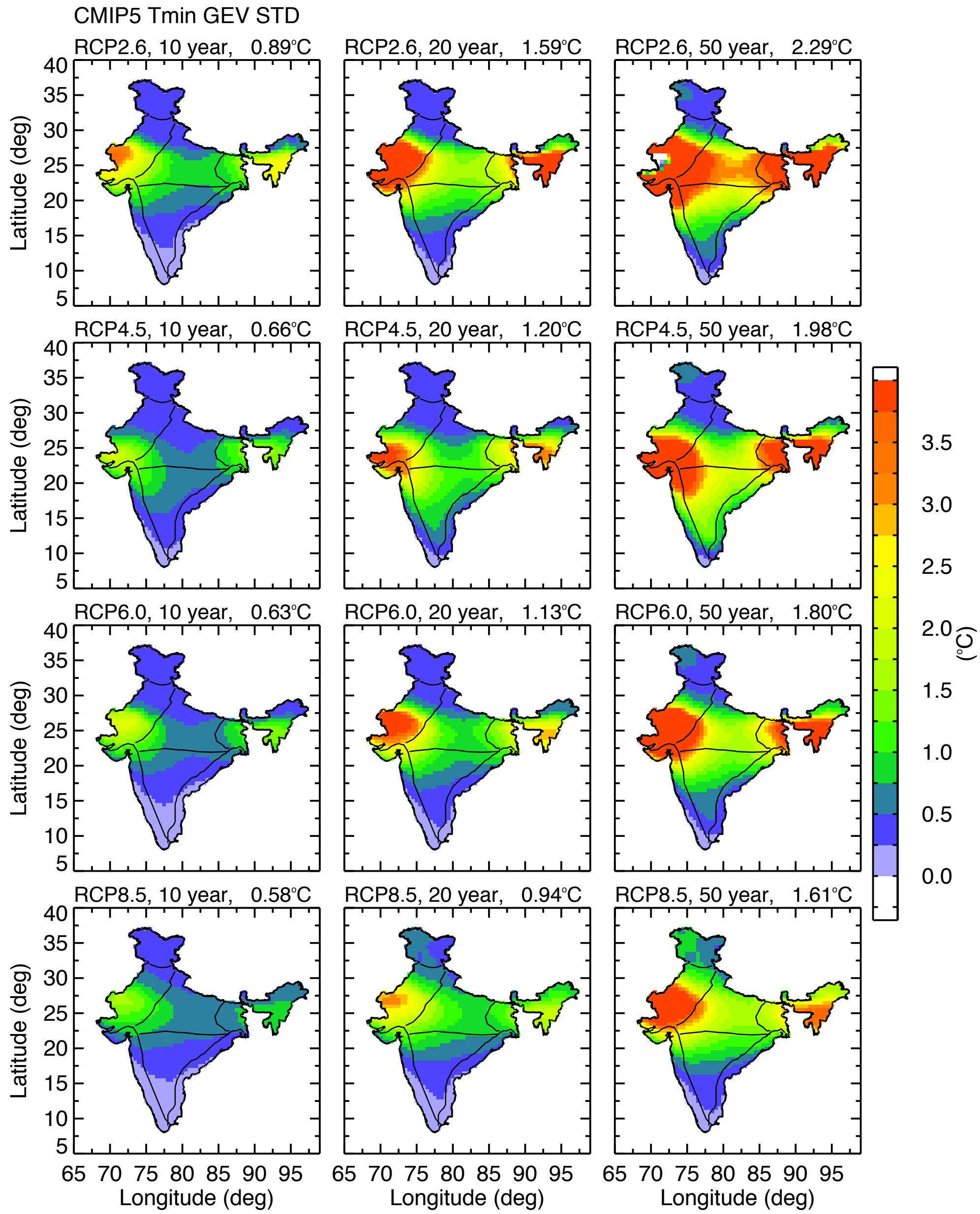

Figure 7

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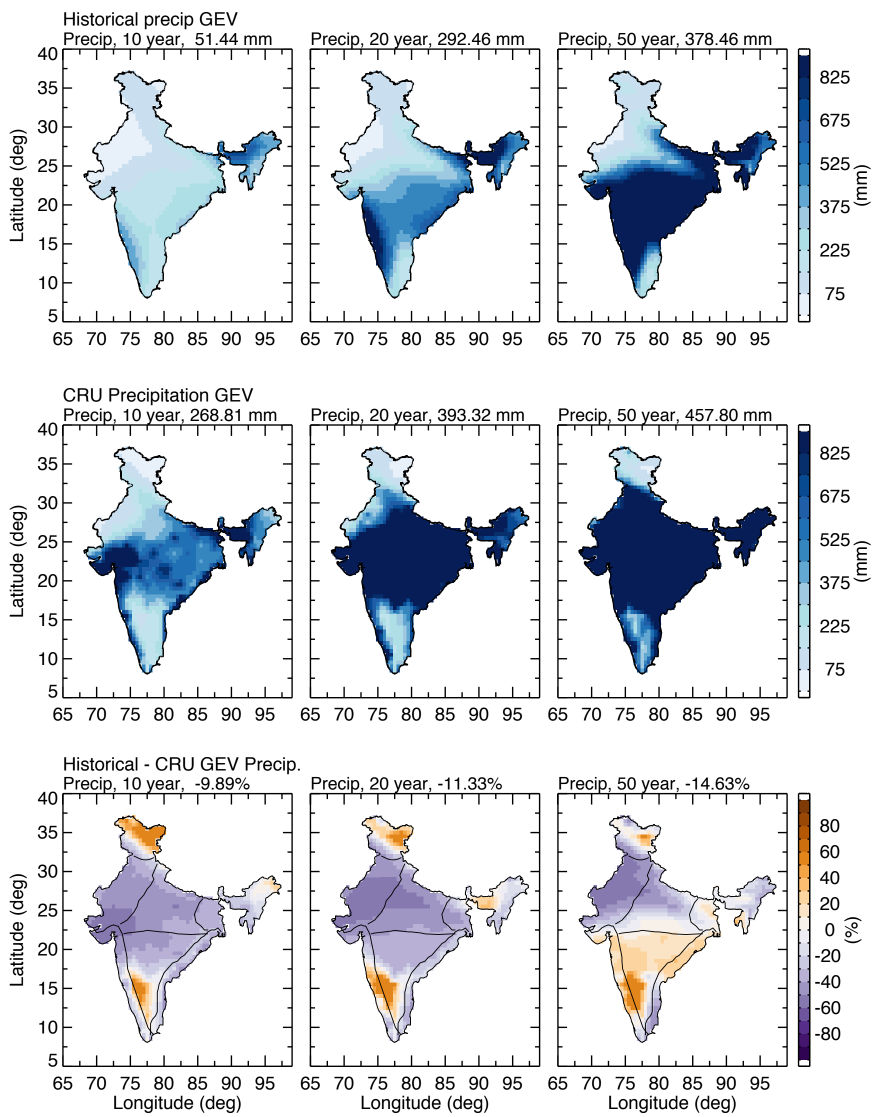

Figure 8

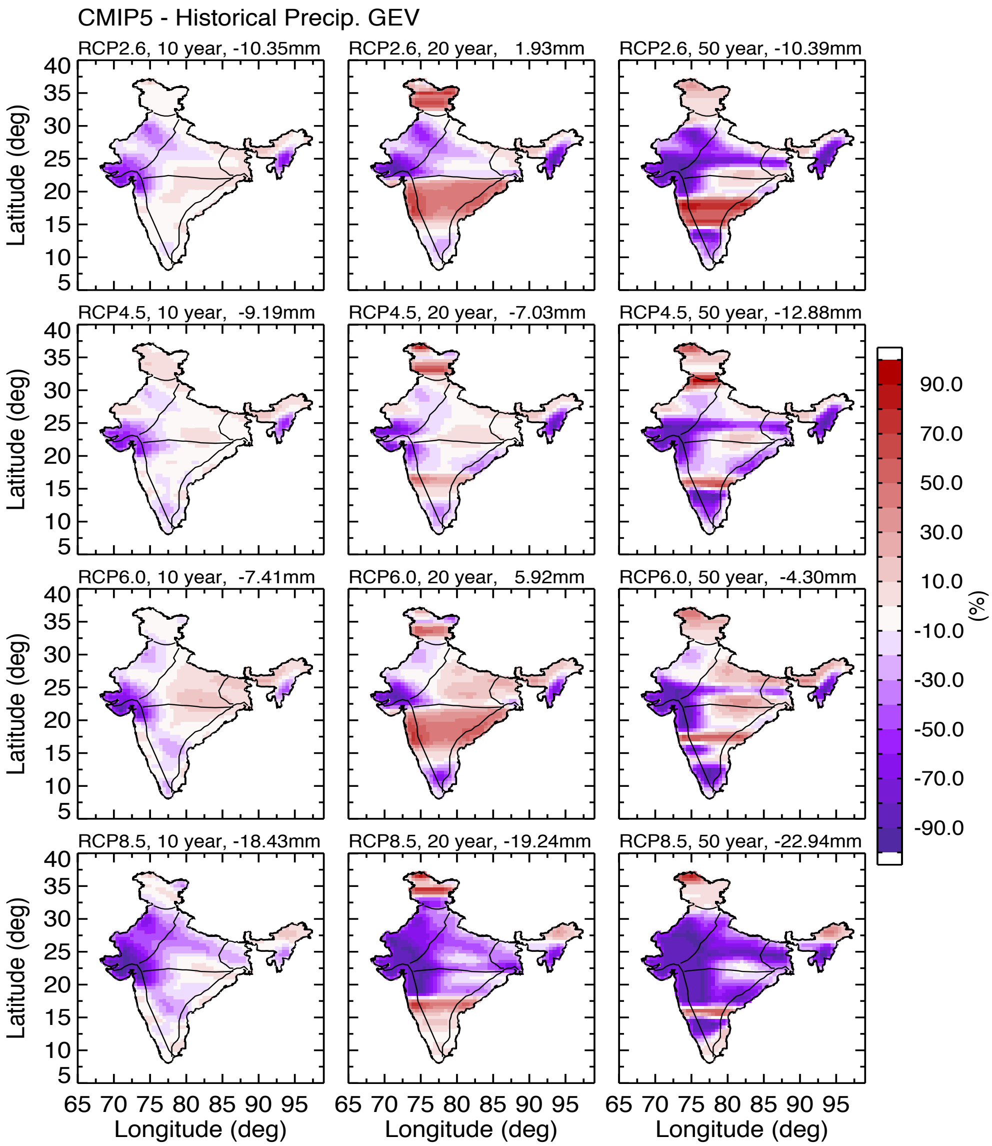
CMIP5 - Historical Precip. GEV
RCP2.6, 10 year, -10.35mm
RCP2.6, 20 year, 1.93mm
RCP2.6, 50 year, -10.39mm
RCP4.5, 10 year, -9.19mm
RCP4.5, 20 year, -7.03mm
RCP4.5, 50 year, -12.88mm
RCP6.0, 10 year, -7.41mm
RCP6.0, 20 year, 5.92mm
RCP6.0, 50 year, -4.30mm
RCP8.5, 10 year, -18.43mm
RCP8.5, 20 year, -19.24mm
RCP8.5, 50 year, -22.94mm
Latitude (deg)
Longitude (deg)
40 35 30 25 20 15 10 5
65 70 75 80 85 90 95
90.0 70.0 50.0 30.0 10.0 -10.0 -30.0 -50.0 -70.0 -90.0
(%)

Figure 9