Increase in extreme precipitation events under anthropogenic warming in India

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\textbf{ABSTRACT}

India has witnessed some of the most devastating extreme precipitation events, which have affected urban transportation, agriculture, and infrastructure. Despite the profound implications and damage due to extreme precipitation events, the influence of anthropogenic warming on the intensity and frequency of extreme precipitation events over India remains poorly constrained. Here using the gridded observations and simulations from the Coupled model intercomparison project 5 (CMIP5) and Climate of 20th century plus (C20C+) detection and attribution (D&A) project, we show that the frequency and intensity of extreme precipitation events have increased in India during the last few decades. Along with the extreme precipitation, dew point temperature has also increased during 1979–2015. The scaling relationship between extreme precipitation and dew point temperature shows a super (more than 7% increase per unit rise in dew point temperature) Clausius-Clapeyron (C-C) relationship for the majority of south India. Moreover, southern and central India show a higher (10%/°C) scaling relationship than north India (3.5%/°C). Our analysis using the Hist (historic) and HistNat (historic natural) simulations from the CMIP5 and C20C+ projects confirms an increase in the frequency of extreme precipitation events under the anthropogenic warming. Moreover, we show that 1–5 day precipitation maxima at 5–500 year return period increases (10–30%) under the anthropogenic warming. The frequency of precipitation extremes is projected to rise more prominently in southern and central India in the mid and end of the 21st century under the representative concentration pathway (RCP) 8.5. Our results show a significant contribution of anthropogenic warming in the rise of the frequency of extreme precipitation, which has implications for infrastructure, agriculture, and water resources in India.

1. Introduction

Both climate model simulations and observations (Allen and Ingram, 2002; Ghosh et al., 2012; Hennessy et al., 1997; Mishra et al., 2012; Pall et al., 2007) have now confirmed that rising extreme precipitation events are linked with climate warming, which leads to an increased atmospheric moisture content (Willett et al., 2007). Extreme precipitation is projected to further intensify in the future under a warming climate (Ali and Mishra, 2017; Min et al., 2011). Historically, extreme precipitation events posed numerous challenges for the society including flooding, crop damages, health hazard, erosion, and water contamination (Guha-thakurta et al., 2011; Pall et al., 2011; Rajeevan et al., 2008).

Recently, India has faced extreme rainfall events that resulted in a large damage to infrastructure and affected lives of millions. The Bengaluru (in Southern India) floods in July 2016, caused by heavy rainfall, disrupted lives and halted transportation (The Hindu, 19 July 2016). The November–December 2015 South India flood (Tamil Nadu and Andhra Pradesh) affected 4 million people with economic damages of about $3 billion (USD) (Kottuwara, 2015). Moreover, the 2005 flood in Mumbai caused approximately 1094 lives (Bohra et al., 2006; Kumar et al., 2008). The 2013 Uttarakhand flood resulted in the loss of 6000 human lives and a total economic loss of US$3.8 billion (“Rapidly Assessing Flood Damage in Uttarakhand, India,” 2014). India-Pakistan floods in September 2014, which affected Jammu and Kashmir (North), resulted in substantial loss of lives (277 people in India and 280 people in Pakistan) and a total loss of 1.5 billion USD. Similar devastating flood events caused by heavy rainfall have occurred in the other parts of India in the recent past.

Climate warming causes an increase in the moisture holding capacity of the atmosphere (Trenberth et al., 2003), which can be explained by the Clausius-Clapeyron (C-C) relationship (Ali and Mishra, 2017; Mishra et al., 2012; Soden et al., 2006; Sun and Held, 1996). However, at higher temperatures in the tropics, a negative C-C scaling relationship is observed between extreme precipitation and surface air temperature (SAT), which is a statistical artifact due to temporarily local cooling effect (Bao et al., 2017; Wang et al., 2017; Zhang et al., 2017). In a recent study over India, Vittal et al. (2016) reported a negative relationship between surface air temperature and extreme precipitation over India, which is primarily due to localized cooling of air temperature due to monsoon season rainfall. Due to the negative C-C relationship between precipitation and SAT over the tropical regions, Lenderink and Van Meijgaard (2010) argued that dew point temperature (DPT) is a better prediction of extreme precipitation than surface air temperature over the tropics. More
recently, Ali and Mishra (2017) showed that daily and sub-daily extreme precipitation in India display a strong positive C–C scaling relationship (in contrast to SAT) with DPT, indicating SAT (as reported in Vittal et al., 2016) is not a good predictor of precipitation extremes in India (Ali and Mishra, 2017).

Despite the strong positive relationship between DPT and precipitation extremes, our understanding of the scaling relationship (between DPT and precipitation extremes) remains limited to a few stations that are shown in Ali and Mishra (2017). The analysis of urban location shown in Ali and Mishra (2017) does not improve our understanding on spatial variability in the scaling relationship that may exist in India. Understanding the scaling relationship is vital to evaluate the role of anthropogenic warming on precipitation extreme under the current and future climate, which has been lacking in previous studies (Ali and Mishra, 2017; Ghosh et al., 2012; Mishra et al., 2014; Vittal et al., 2016).

Here, we use data from gridded observations; reanalysis product, CMIP5, and C20C+ to analyze observed and projected changes in extreme precipitation in India. Moreover, we estimate the relationship between DPT and extreme precipitation using the data from India Meteorological Department (IMD) and European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA-Interim). After establishing the relationship between DPT and precipitation extremes, we study the role of anthropogenic warming over the occurrence of these extreme precipitation events using data from the CMIP5 models and 50 simulations from the C20C+ project for the historic natural (HistNat) and historic (Hist) simulations. Finally, we estimate the impacts of anthropogenic warming on the changes in precipitation maxima and the frequency of precipitation extremes over India.

2. Methods and data

We obtained daily precipitation and maximum temperature from India Meteorological Department (IMD: http://imd.gov.in/Welcome%20To%20IMD/Welcome.php) at 0.25° spatial resolution. IMD developed gridded precipitation using observations from 6995 meteorological stations across India applying the inverse distance weighted scheme (Pai et al., 2014). For our analysis, we re-gridded this dataset to 1° spatial resolution using the Synergetic Mapping System (SYMAP) as described in (Maurer et al., 2002). The IMD precipitation and temperature have been used in many previous studies for analysis of hydro-climatic extremes (Mishra et al., 2014; Shah et al., 2014; Shah and Mishra, 2016, 2015). We obtained DPT from ERA-Interim, a global atmospheric reanalysis from the European Center for Medium Range Weather Forecasts (ECMWF; http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/), which is the improved reanalysis over ERA-40 (Dee et al., 2011). For our analysis, we obtained DPT at 1° spatial resolution and then daily values were obtained as an average of two 12-hourly values.

Daily precipitation data from Coupled Model Intercomparison Project Phase-5 (CMIP5, Table S1) were obtained and re-gridded to 1° spatial resolution using bilinear interpolation to make it consistent with observed and C20C+ data. We found only nine CMIP5 models with daily precipitation data for the Historic Natural (HistNat), Historic (Hist), and Representative Concentration Pathways (RCP) 8.5 scenarios. The RCP 8.5 corresponds to the pathway with the highest radiative forcings or greenhouse gas emissions compared to the other RCPs (Bates et al., 2008; Fisher et al., 2007). Moreover, the RCP8.5 scenario was selected to study the extreme precipitation events in the future as present emission scenarios are already either following or very close to the RCP 8.5 (Sanford et al., 2014). Since, the Hist scenario incorporates the anthropogenic forcings unlike the HistNat scenario, which only considers natural forcing; we used the Hist and HistNat scenario to estimate the anthropogenic effect on an occurrence of extreme precipitation events.

Daily precipitation data from 50 simulations of the CAM5.1 model under C20C+ (Folland et al., 2014) D&A project were obtained at 1° spatial resolution over the period (1959–2015) for the Hist and HistNat scenarios. The C20C+ project is a core sub-project of the World Climate Research Programme’s (WCRP) International Climate and Ocean-Variability, Predictability, and Change (CLIVAR) 5th workshop, held in Beijing in October 2010. One of the main purposes of the C20C+ project is to estimate the degree to which the historic and current damaging weather events can be attributed to the anthropogenic warming. We used this dataset to study the effect of anthropogenic emissions on extreme precipitation events along with the data from CMIP5-GCMs for the Hist and HistNat scenarios.

Using the observations from IMD, we estimated annual maximum precipitation (AMP) for 1950–2015. We also estimated different thresholds ranging from 90 to 99th percentile of AMP for the reference period of 1971–2000 to represent more unusual extreme rainfall events that cause enormous damage to infrastructure and result in loss of lives. We estimated changes in the number of extreme precipitation events (above the selected threshold of AMP) from the Pre-1982 (1959–1982) to the Post-1982 period (1983–2014) using the observed precipitation data from IMD. We consider the post-1982 period as 1983–2014 due to the availability of C20C+ data only till 2014. Changes in the observed frequency of extreme precipitation events were estimated for the 90th, 95th, 97th, 98th, and 99th percentiles of AMP over the 30 years of the reference period (1971–2000).

We performed the Mann Kendall trend test (Kendall, 1975; Mann, 1945) at 5% significance level on the observed AMP for 1979–2015. Subsequently, we estimated changes in AMP over the same period by obtaining the slope of the trend from Sen’s method (Sen, 1968) and then multiplying the slope with the length of the period (1979–2015, 37 years). We analyzed changes in annual maximum DPT, which was obtained from the ERA-Interim reanalysis data for 1979–2015. Changes in mean and distribution with their statistical significance at 5% level were evaluated using the two-sided Rank-sum and KS tests, respectively.

To understand the relationship between extreme precipitation and DPT/SAT, we followed the method suggested by Zhang et al. (2017), which is based on fitting a generalized extreme value (GEV) distribution to maximum of daily precipitation with corresponding anomalies of mean SAT/DPT of the monsoon season (JJAS) as a covariate in the location parameter. The analysis was performed for wet events (daily precipitation depth greater than or equal to 1 mm) to avoid the influence of dry or low-rain days. We first identified the maximum precipitation amount for each of the monsoon season which was then normalized by dividing the median of maximum daily precipitation (for the monsoon season) for the period 1979–2015. Corresponding mean SAT/DPT anomalies were estimated for the period 1979–2015.

We estimated the change in the frequency of extreme precipitation due to anthropogenic forcings under the CMIP5 and C20C+ project’s Hist and HistNat scenarios. We estimated 95th percentile threshold of AMP for the HistNat scenario for the reference period (1971–2000), and the frequency of extreme precipitation events above this threshold was estimated for both the Hist and HistNat scenarios for the 1959–2005 period. The anthropogenic influence was then quantified as the difference in the frequency of extremes in these two (Hist and HistNat) scenarios. Differences in the frequency of extreme precipitation events were estimated for the individual models (CMIP5-GCMs) and runs (C20C+) and then their ensemble mean was taken. Moreover, statistical significance (at 5% level) in the changes in distribution and mean of the Hist and HistNat scenario was estimated using the two-sided Rank-Sum and KS tests, respectively.

Changes in the frequency of extreme precipitation events under the projected future climate are estimated using data from CMIP5 models. We estimated the all-India median bias (%) in AMP against observations during the reference period (1971–2000) (similar to Mishra et al., 2014) to identify the best and worst performing CMIP5 models. We estimated the all India median bias (%) in AMP for the CMIP5-GCMs and found that all the models underestimate observed (IMD) daily AMP (Table S2 and 3, Fig. S7), which is consistent with the findings of Mishra et al. (2014) and Jayasankar et al. (2015). We selected the four best GCMs (BEST-GCMs:}
CNRM-CM5, GFDL-CM3, GFDL-ESM2M, and MIROC-ESM) and the four worst GCMs (WORST-GCMs: HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, and MRI-CGCM3) out of the nine CMIP5-GCMs based on all India median bias (Table S2 and 3).

Projected change in the frequency of extreme precipitation was estimated for the future climate under the RCP 8.5. Since models have a bias in daily precipitation against observations; we used standardized departure as a measure of extreme precipitation threshold in CMIP5-GCMs. Since we were interested in the frequency of unusual extreme precipitation events in the projected future climate, we selected only the events that were rarely observed in the past. To do so, we considered the event with the highest annual maximum precipitation during the observed (IMD) reference period (1971–2000). Then the standardized departure was estimated for that event and based on this standardized departure, a precipitation threshold was selected for the historic reference period (1971–2000) of CMIP5-GCMs. Precipitation threshold estimated for the historic reference period was then used to estimate the frequency of extreme precipitation events under the projected future climate.

3. Results and discussion

We first analyzed the observed changes in annual maximum precipitation (AMP) for the period of 1979–2015 (Fig. 1a) using the nonparametric Mann Kendall trend (Kendall, 1975; Mann, 1945) and Sen’s slope (Sen, 1968) method. The period of 1979–2015 was selected as the ERA-Interim data are available for this period only. We find that AMP has increased over the majority of India except for a few regions including the Gangetic Plain, northeastern India, and Jammu and Kashmir (Fig. 1a). Changes in AMP during the period of 1979–2015 vary between −20 and +20% (Fig. 1a). Despite the increasing trend in AMP in the majority of grids, they did not pass the statistical significance at 5% level. The decline in AMP in the Gangetic Plain region can be attributed to a
significant reduction in the monsoon season rainfall (Mishra et al., 2016, 2012) driven by the increased atmospheric aerosols (Bollasina et al., 2011) and warming of the Indian Ocean (Mishra et al., 2012; Roxy et al., 2015). We find that the increase in AMP is more prominent in Southern India (SI, latitude <22.5°) than in North India (NI, latitude > 22.5°) during the 1979–2015 (Fig. 1a and b). We find that the median change (of all the grids) in AMP in SI is higher than that in NI (Fig. 1b). Moreover, distribution of change in AMP in south and north India are statistically significant (Fig. 1c).

Our results show that the majority (more than 80%) of extreme precipitation events occur during the monsoon season (Fig. S1), which indicates that the negative relationship between SAT and precipitation extremes is largely driven by precipitation-temperature coupling in the monsoon season. We find a negative relationship between SAT with precipitation extremes (Fig. S2), which highlights that SAT is not a good predictor of precipitation extremes in India as shown in Ali and Mishra (2017). Since DPT is a better predictor of extreme precipitation over the tropical regions (Ali and Mishra, 2017; Lenderink et al., 2011), we analyzed changes in the annual maximum DPT for 1979–2015 (Fig. 1d). We find that annual maximum DPT has increased across India (Fig. 1d) with more variability in the northern India (Fig. 1e). Both changes in mean and distribution of annual maximum DPT were not found to be significantly different (Fig. 1f). A similar increase was also found in mean annual daily DPT in India during 1979–2015 (figure not shown). Dew point temperature can be considered as a measure of atmospheric humidity (Lenderink et al., 2011), which affects extreme precipitation in the tropical regions (Ali and Mishra, 2017; Lenderink et al., 2011). The rise in DPT in 1979–2015 is an indicator of change in atmospheric humidity and air temperature over India. Singh et al. 2008 also reported a rise in humidity in India, which is consistent with the findings of Dai (2006) and Krishnan et al. (2016). Moreover, Willett et al. (2007) attributed changes in surface humidity to anthropogenic warming, which is projected to increase under the projected future climate (Lee and Wang, 2014).

We estimated the frequency of extreme precipitation events based on various 90–99th percentile thresholds of AMP for the reference period during the period of 1959–2014. Changes in the frequency of extreme precipitation were estimated for the pre and post-1982 periods (Fig S3). We find that increase in the frequency of extreme precipitation events is more prominent in the southern India regardless of the threshold (90–99th percentile). We find that the variability in the frequency of extreme precipitation events has declined in the northern India while increased in the southern India in the pre and post-1982 periods (Fig. 1h). Significant changes in the distribution of the frequency of extreme precipitation were found during the post-1982 period (Fig. 1h) in the southern India. Overall, we find that the annual maximum precipitation and the frequency of extreme precipitation events have increased in India during the last few decades. The increase in extreme precipitation (frequency and magnitude) is more prominent in the southern and central India while the Gangetic Plain and other regions experienced a decline. Apart from the extreme precipitation, DPT has also increased over India during 1979–2015.

We estimated the relationship between maximum daily precipitation (IMD) and mean DPT from ERA-Interim for the monsoon season for 1979–2015 (Fig. 2). A strong positive C-C relationship can be observed in the median value of maximum daily precipitation (i.e., 2yr return level) for the monsoon season in response to rise in DPT. We find that in the majority of India, the trend rate is higher than the C-C rate of 7% increases in extreme precipitation in response to 1 °C rise in DPT (Fig. 2a). Moreover, maximum daily precipitation in the monsoon season shows a higher (10%/°C for South and 3.5%/°C for North India) scaling coefficient for the south India in comparison to the north India (Fig. 2b). A statistically significant difference in the distribution of the scaling coefficient was found for the north and South India (Fig. 2c).

The higher scaling coefficient in southern India suggests that extreme monsoon season precipitation in the region is more sensitive to the rise in DPT. These results explain the possible reasons for prominent increases in the magnitude and frequency of extreme precipitation events in the southern India. Vittal et al. (2016) reported a negative relationship between extreme precipitation and SAT and argued that the climate warming does not influence extreme precipitation over India. This negative relationship between extreme precipitation and SAT may arise due to statistical artifact due to temporarily local cooling (Bao et al., 2017; Wang et al., 2017; Zhang et al., 2017). Our results show that DPT is a better predictor of extreme precipitation than SAT over India, which is consistent with the findings of Ali and Mishra (2017) and Lenderink et al. (2011). Increases in extreme precipitation in southern and central India can also be linked to other factors related to the large-scale changes in climate. For instance, Mishra et al. (2012) showed a dipole mode related to increase in the monsoon season precipitation in southern India and decline in northern India is driven by the sea surface temperature in the Indian Ocean. Moreover, Pfahl et al. (2017) reported that regional patterns of the observed and projected extreme precipitation are linked with the dynamical scaling. Therefore, understanding of dynamic and thermodynamic contribution separately on changes in extreme precipitation in India is essential.

Consistent with our results of increased DPT in the observed climate, atmospheric humidity and air temperature is projected to increase under the anthropogenic warming climate (Sherwood et al., 2010). Therefore, we focus on the effect of anthropogenic warming on extreme precipitation events over India. For that, we estimated the frequency of extreme precipitation events (above 95th percentile) in the Hist and HistNat scenarios (Fig. 3) from the CMIP5 and C20C+ datasets. Based on the multimodel ensemble mean from nine CMIP5-GCMs (Table S1) and
Fig. 3. (A) Multimodel ensemble (MME) mean (of 9 CMIP5-GCMs) frequency of extreme precipitation events for the Natural (HistNat) scenario for the period of 1959–2005. (b) Same as in (a) but for the Historical (Hist) scenario. The frequency of extreme events for Hist and HistNat was estimated based on threshold obtained as 95th percentile of AMP for the period (1971–2000) of HistNat scenario. (c) MME mean of difference (Hist-HistNat) in the frequency of extreme precipitation events for HistNat and Hist scenario. (d) Empirical probability distributions for the MME mean frequency of extreme precipitation events for the HistNat (black) and Hist (red) scenarios during the period of 1959–2005. (e) All India average of ensemble mean frequency of extreme precipitation events for the HistNat and Hist scenarios during the period of 1959–2005. Error bars in (e) represent intermodel variability (1 standard deviation) in the frequency of extreme precipitation. Statistical significance for mean and distribution of frequency of extreme precipitation in the HistNat and Hist scenarios was estimated at 5% significance level using the two-sided Rank-Sum and KS tests, respectively. (f–j) Same as in (a–e) but for the 50 runs from CAM5.1 of the C20C+ project. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
ensemble mean from 50 runs of CAM5.1 from the C20C+ project, we find that the number of extreme precipitation events in the Hist scenario is higher than in the HistNat scenario in the majority of India (Fig. 3 and Fig. S4). From the ensemble mean of the results obtained from the nine CMIP5-GCMs, we find that during 1959–2005, the frequency of extreme precipitation has increased over India (1–2 events), while the ensemble mean of the results from 50 simulations of the CAM5.1 over the period (1959–2014) show an increase of 4–6 events under the Hist scenario (Fig. 3). We find a higher frequency of extreme precipitation events over central India (Fig. 3) under the Hist scenario in both CMIP5 and C20C+ simulations. Moreover, the results showed that both mean and distribution of extreme precipitation events have changed significantly (p-value < 0.05) under the anthropogenic warming (Fig. 3 d, e, i and j). Increase in the frequency of precipitation events is consistent for the pre and post-1982 scenarios for the HistNat and Hist simulations (Fig. S5–6).

Our results are consistent with the findings of Min et al. (2011) showing that the anthropogenic climate warming can lead to increased extreme precipitation events in the majority of the northern hemisphere. Our results differ from the findings of Mondal and Mujumdar (2015) who did not find a significant contribution of anthropogenic warming in the increase in one-day annual maximum precipitation, which they attributed to underestimations of regional precipitation extremes by the climate models. However, Krishnan et al. (2016) using simulations at high resolution showed an increase in the frequency of extremes in the core monsoon region of India under increased greenhouse gas emission scenario. While our results show an increase in the frequency of extreme precipitation events under the anthropogenic warming over India, attributing a single extreme precipitation event to climate warming is challenging. van Oldenborgh et al. (2016) analyzed the role of anthropogenic warming on the Chennai flooding in 2015 and found that the event cannot be attributed to only anthropogenic greenhouse gases emissions. They argued that greenhouse forcing and atmospheric aerosols have opposite impacts (Kumari et al., 2007) on extreme precipitation events and when both of these rises in the atmosphere, attribution to a single factor is difficult. We have not specifically looked at the separate contribution of atmospheric aerosols and greenhouse forcing on the changes in the extreme precipitation, which is important to consider in the future research.

We estimated precipitation maxima for 1–5 days durations and 5–500 year return period using the data from the Hist and HistNat simulations from the C20C+ project (Fig. 4). Precipitation maxima for the selected return periods and durations were estimated for the period of 1959–2014 using the Generalized Extreme Value (GEV) distribution using AMP from each of the 50 runs. Then, we estimated ensemble mean difference (Hist-HistNat) to estimate the contribution of anthropogenic warming (Fig. 4). We find a consistent increase in precipitation maxima for 1, 3, and 5 days durations and 50 and 500 years return period for the Hist scenario (Fig. 4a–f). We do not find any consistent rise in precipitation maxima with the increase in duration (Fig. 4g–h). However, we find that the contribution of anthropogenic warming increases with the return period.
For instance, all India median difference between precipitation maxima from the Hist and HistNat scenarios was about 10–12% (Standard deviation $\approx 3.71–4.48\%$) for the 50 year return period, which increases to 14–17% (Standard deviation $\approx 6.32–8.09\%$) for the 500 year return period. A similar increase was found for other return periods (5–200 years) for the Hist scenario (Fig. S8). Our results highlight the implications of anthropogenic warming as demonstrated by the C20C+ simulations for future stormwater designs. Moreover, we also find that rare extreme precipitation events can be more intensified under the anthropogenic warming. Similar findings are reported in Singh et al. (2014) who analyzed the June 2013 extreme precipitation event in Uttarakhand and reported that the likelihood of such events is higher under the anthropogenic warming.

Next, we estimated changes in the frequency of extreme precipitation events under the future climate using the CMIP5 simulations (Fig. 5, Fig. S9). The frequency of extreme precipitation was estimated using a threshold calculated based on standardized departure (see Methods for more details). For this, we use ALL nine CMIP5-GCMs, the four BEST-GCMs, and the four WORST-GCMs. The changes in the frequency of precipitation events were estimated for the Near (2010–2039), Mid (2040–2069) and End (2070–2099) terms under RCP 8.5. Based on the results from the All, BEST and WORST-GCMs ensemble mean, we find that the frequency of extreme precipitation is projected to rise, however, more prominently in the southern and central parts of India, which is consistent with the results for the observed climate. For instance, all India median projected frequency of extreme precipitation events from ALL-GCMs (all nine) for south India (SI) was about 4, 10, and 12 events in the 30-year of the Near, Mid, and Far periods. On the other hand, all India median projected frequency from ALL-GCMs for north India (NI) was 1, 2, and 4 events for the Near, Mid, and Far periods, respectively (Fig. 5, Fig. S9).
Fig. 59). Projections of the frequency of extreme precipitation events were largely similar for the BEST and WORST-GCMs, which may be due to the relatively smaller sample size (9 GCMs). However, we notice that the BEST-GCMs project more extreme precipitation events in northern India in late 21st century. Moreover, the frequency of extreme precipitation in India is projected to rise more in the late 21st century.

Our findings of increasing precipitation extremes under the projected climate are consistent with Vital et al. (2016). However, Vital et al. (2016) attributed the increase to the overestimation of the relationship between surface air temperature and precipitation in the CMIP5 models. However, on the contrary to the findings of Vital et al. (2016), Wang et al. (2017) confirmed a super C-C relationship over the tropics in the CMIP5 models under the future climate. Increase in precipitation extremes, as shown by the scaling relationship, is not only driven by the changes in local DPT/SAT but also large-scale variability associated with the atmosphere and climate (Flahil et al., 2017; Roxy et al., 2015). Therefore, changes in DPT/SAT alone cannot explain the changes in the extreme precipitation under the observed and projected future climate. Moreover, Turner and Slingo (2009) argued that the future changes in extreme precipitation will be based on surface warming and C-C relationship under the increased greenhouse gases in the atmosphere. Our results from the CMIP5-GCMs and C20C+ simulations confirm that extreme precipitation events increase under the anthropogenic warming. The projected increase in precipitation maxima at 1–5 day durations in India may have implications for infrastructure and agriculture.

4. Conclusions

We analyzed observations and model simulations from the CMIP5 and C20C+ detection and attribution projects to evaluate changes in the observed climate, the influence of anthropogenic warming on the extreme precipitation events, and projected changes in the frequency of extreme precipitation events in India. Based on our findings, the following conclusions can be made:

1) Annual maximum precipitation has increased in the majority of India during the period of 1979–2015. The increase in annual maximum precipitation is more prominent in southern India than that of in northern India. The Gangetic Plain region experienced a decline in annual maximum precipitation, which can be attributed to the decline in the monsoon season precipitation. Moreover, mean and annual maximum dew point temperatures have also increased in the majority of India during 1979–2015. The frequency of extreme precipitation events has increased substantially over the southern and central India during the post-1982 period. Therefore, observations show a rise in both annual maximum and frequency of extreme precipitation events in India during the recent decades.

2) The scaling relationship was estimated between dew point temperature and extreme precipitation for the period of 1979–2015 using observed precipitation from IMD and dew point temperature from ERA-Interim reanalysis. We find that a majority of India showed a super C-C relationship (scaling coefficient more than 7%/°C) with dew point temperature indicating an increase in extreme precipitation with dew point temperature. Moreover, southern India showed a stronger relationship (10%/°C) between maximum daily precipitation and mean DPT for the monsoon season than north India (3.5%/°C).

3) The influence of anthropogenic warming on the frequency of extreme precipitation events was estimated using the Hist and HistNat simulations from the CMIP5 and C20C+ datasets. Both the datasets showed a significant increase (2–4 events more) in the frequency of extreme precipitation events under the Hist scenario. Moreover, precipitation maxima of 1–5 days duration and 5–500 year return period showed an increase (10–30%) under the Hist scenario. The difference in magnitude of precipitation maxima was higher for higher return periods. Our results from the two datasets confirm a significance influence of the anthropogenic warming on extreme precipitation over India.

4) The frequency of extreme precipitation events is projected to increase under the projected future climate in India. The increase in the frequency of extreme precipitation is projected to be more prominent in southern India. Moreover, the increase in the frequency is projected to rise further in the late 21st century under the RCP 8.5. The projected rise in the frequency of extreme precipitation is likely to have implications for infrastructure, agriculture, water resources, and energy sectors in India.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jwace.2018.03.005.

References


