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RESEARCH ARTICLE

Quantifying the impact of global warming on precipitation patterns in India

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The past few decades have witnessed a change in precipitation patterns around the world. This change includes an increase in heavy precipitation and a decrease in light and moderate precipitation. Global/regional warming has been attributed as one of the major factors causing the observed change in precipitation patterns. Past studies over the Indian region have not focused much on quantification of the impact of warming on changes in precipitation patterns. The present research quantifies the impact of warming on precipitation patterns over the Indian region. For this purpose, rain gauge-based high-resolution gridded precipitation data from the India Meteorological Department (IMD) for 113 years between 1901 and 2013 are used to link the changes in precipitation patterns over India during the South West (SW) monsoon season with warming using a new method that focuses on inter-annual differences rather than time series. It has been reported that during the SW monsoon period, there is an increase of about 51.85% ± 19% in the top 10% precipitation for each degree (K) increase in temperature. Decreases of about 15–30%/K in low and moderate precipitation have also been reported *per* 1 K increase in temperature. The impact of warming is more severe over Western and North Eastern India and during July and August. An increase in heavy rainy days of about 46.53% ± 14% *per* 1 K increase in temperature has been reported over the Indian region. Low and moderate rainy days show a decrease of about 24.67% ± 9.53% for a unit degree increase in temperature. Results reported in this research point out increasing trends in droughts and floods due to increased heavy precipitation and decreased low and moderate precipitation in a warming environment.

KEYWORDS

climate change, convection, droughts and floods, global warming, precipitation extremes

1 | INTRODUCTION

Past researchers have reported changes in precipitation patterns as a result of global warming (Trenberth *et al*., 2003; Mishra and Liu, 2014; Lehmann *et al*., 2015; Donat *et al*., 2016). These changes include an increase in heavy precipitation and a decrease in light and moderate rain (Goswami *et al*., 2006; Lau and Wu, 2008; Rajeevan *et al*., 2008; Dash *et al*., 2009; O'Gorman, 2012; Villarini *et al*., 2013; Mishra and Liu, 2014). It is well known that warmer air can hold more water vapour. Trenberth *et al*. (2003) reported that for each degree (K) increase in global temperature, there is an increase of about 7% in water vapour, which causes the intensification of precipitation. An intensified rain storm precipitates heavily and removes the atmospheric water vapour that was available for light precipitation. Thus, an increase in global temperature causes an increase in heavy precipitation and a decrease in light and moderate precipitation. A synthesis of climate model projections presented by the Intergovernmental Panel on Climate Change (IPCC) indicates that there will be an increase in both the occurrence of intense precipitation events and the number of dry days over large portions of the world, including many areas that may see significant increases in both extremes (IPCC, 2007).

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India has witnessed frequent flood and drought disasters over the past few years (De *et al*., 2005; Mishra and Srinivasan, 2013; Mishra, 2015, 2016; Mishra and Rafiq, 2017). Model results project an intensification of rainfall over most of India, with the most intense rainfall events predicated to occur over Western India (WI) and North Eastern India (NEI) (Rupa Kumar *et al*., 2006). The Hadley Centre Coupled Model HadCM3 projects an increase in the magnitude of the heaviest rainfall over many parts of the world, including India (IPCC, 2012). Global climate models (GCMs) have difficulties in simulating extreme precipitation events due to coarser resolution. Rao *et al*. (2014) projected an increase in heavy precipitation over India by using the regional climate model PRECIS. Rupa Kumar *et al*. (1992) reported that there are areas over India with an increasing trend of rainfall, and other areas with decreasing trends. Goswami *et al*. (2006) examined the daily gridded rainfall data for 50 years (1951–2000) for a $1^\circ \times 1^\circ$ grid box derived from the India Meteorological Department (IMD) over the India region during the monsoon season and reported an increase of about 50% in heavy rainfall events (rain $\geq$ 100 mm/day) over the Central part of the Indian region (CI). They also reported a decrease in low and moderate rain events. Ramesh and Goswami (2007) reported a reduction in both the temporal and spatial extent of the monsoon over India. They identified a sharp decrease in rainy days over most parts of the Indian region during the rainy season. Guhathakurta and Rajeevan (2008) analysed rainfall data during the period 1901–2003 over subdivisions of India and reported an increase in monsoon rainfall over a majority of the subdivisions. Rajeevan *et al*. (2008) examined the variability of extreme rainfall events over India using 104 years (1901–2004) of daily gridded rainfall data and reported an increase in the risk of floods over the CI region. They derived an increase of 6% *per* decade in the level of heavy rainfall ($\geq$ 100 mm/day) over the CI region. This trend is smaller than that observed by Goswami *et al*., 2006, which is 10% *per* decade. These studies are limited to a selected region over the CI region only. Other important as well as widely divided regions such as the West and North East were not included in these studies. Krishnan *et al*. (2013) used a high-resolution climate model to examine future changes in monsoon rainfall in a changing climate. The results reported that the intensity of the summer monsoon has been significantly weakened during the past 50 years. Mishra and Liu (2014) investigated the precipitation pattern over India and reported a reduction in the frequencies of low and moderate rain, causing drought over India. Preethi *et al*. (2017) investigated the trends in the South and East Asian summer monsoon using data from 1901 to 2014. They reported an increasing trend in the summer monsoon over northern parts of the west coast of India. Roxy *et al*. (2017) examined data from 1950 to 2015 and reported a threefold increase in extreme precipitation events over the CI region.

The present study focuses on using high-resolution gridded data at 0.25° from the IMD to examine the precipitation patterns of India during the monsoon season in a warming environment by adopting an inter-annual difference technique (Liu *et al*., 2009; Mishra and Liu, 2014). Southern parts of India, including Tamil Nadu, Pondicherry and Andhra Pradesh, receive their maximum rain during the post-monsoon months of October–December, usually known as the North East monsoon season, while the Northern tip of India receives its maximum rainfall during the winter months of January–February (Sikka, 1980; Joseph *et al*., 1994; Gadgil *et al*., 2004; Wang, 2006). For this reason, the Southern and Northern tips of the Indian region are excluded from this study. Finer resolution of the IMD data used in the study helps in the investigation of the impact of global warming on monsoon rainfall over a smaller region, such as CI, WI or NEI. This study is crucial in the context of the frequent occurrence of floods and droughts over various parts of India during recent years (De *et al*., 2005; Mishra and Srinivasan, 2013; Mishra, 2015, 2016; Mishra and Rafiq, 2017). Precipitation patterns over these regions have changed significantly during recent decades.

2 | DATA AND STUDY REGION

For the present study, a rain gauge-based precipitation product developed by the IMD at $0.25^\circ \times 0.25^\circ$ spatial resolution was used (Pai *et al*., 2014). Pai *et al*. (2014) used rain gauge observations from 6995 stations to develop this product. They adopted the Shepard (1968) technique to interpolate rain gauge observations into a regular grid of $0.25^\circ \times 0.25^\circ$. The present study uses daily rainfall data from the IMD for 113 years (1901–2013). The National Climate Data Center (NCDC)-derived temperature data from the Global Historical Climatology Network (GHCN) (Lawrimore *et al*., 2011) was used in the present study to relate to precipitation patterns of India. Integrated precipitable water from The Modern-Era Retrospective Analysis for Research and Applications (MERRA) during 1980–2013 was also used to relate to warming (Wong *et al*., 2011). The area of study is illustrated in Figure 1. The black box represents the Indian region (excluding the Southern and Northern parts) used in this study (14–32 ° N, 66.5–99 ° E); Western India (WI) covers 16–27 ° N, 66.5–77 ° E; Central India (CI) covers 15–26 ° N, 73–87 ° E; and North Eastern India (NEI) covers 21–29 ° N, 83–99 ° E. Regions specified with black bars are not a part of the study area. Changes in precipitation extremes are related to warming using the inter-annual difference technique described in the next section.

3 | METHODOLOGY

For the present study, the inter-annual difference technique developed by Liu *et al*. (2009) was used. All the precipitation

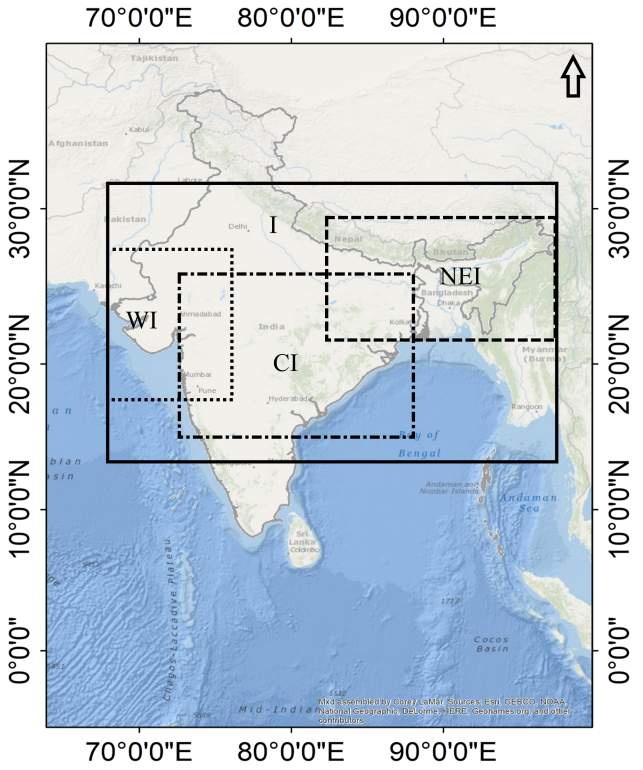


FIGURE 1 Area of study in India. The main black box shows the entire Indian region (except for Southern India and the Northern tip) used in this study; the WI box denotes Western India; the CI box denotes Central India; while the NEI box represents North Eastern India. Shaded regions are not part of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

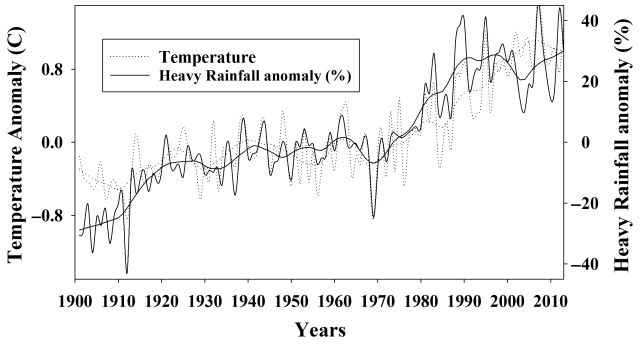


FIGURE 2 Seasonal variation of the heavy precipitation anomaly over Indian region (I) along with the global temperature anomaly. Smoothing has been done to eliminate fluctuation

events were classified into 10 bins with equal amounts of precipitation in increasing precipitation intensity. This defines the ranges of specific bins. The ranges were fixed throughout this study and then used to calculate precipitation spectra of different years. The 10 bins of precipitation intensity for each year were calculated by dividing the 113 years (1901–2013) of the average spectrum of precipitation intensity into 10 bins. Details of these bins for different cases are given in Table 1.

Mishra and Liu (2014) found that a difference in extreme precipitation is quasi-linearly proportional to the temperature difference. They reported that the change in precipitation intensity over India was better correlated with global temperature than local temperature because water vapour in most regions over India is regulated by large areas in the nearby ocean whose temperature tends to correlate well with the global mean temperature. This justifies the use of global temperature to relate to precipitation changes. The anomaly of heavy precipitation over the Indian region is plotted against the global temperature anomaly shown in Figure 2. Smoothing was performed to eliminate fluctuations caused by inter-decadal variations. Near-coherent variation of heavy precipitation with the global temperature anomaly can be observed. Peaks and troughs of heavy precipitation are consistent with those in the global temperature anomaly. Heavy precipitation shows a coherent variation with the temperature anomaly. The seasonal precipitation anomaly shows a correlation co-efficient (cc) of 0.84 with global temperature anomaly.

It was found that the difference in extreme precipitation is quasi-linearly proportional to the temperature difference. Scatter plot between changes in heavy precipitation and those in temperature is illustrated in Figure S1. It can also be noted from Figure S2 that global temperature is showing good correlation with regional temperature over India. Figure 3 shows the variation of integrated precipitable water vapour (from MERRA observations) with global temperature. Integrated precipitable water over India shows a coherent variation with global temperature. The precipitation difference, ΔP, between the precipitation amounts of any two years in each bin is divided by the global temperature difference, ΔT, for those same two years. $\Delta P/\Delta T$ are plotted against ΔT to explore the relationship between precipitation change as a function of global warming. An advantage of this technique over a time-series technique is a significant reduction of scattering of points and the convergence of the means of $\Delta P/\Delta T$ towards a constant when ΔT increases. The total number of data points in this technique is $(n - 1)/2$ times greater than those used in the time-series technique (where n is the number of years).

TABLE 1 Bin categories

Region	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
India (mm/day)	5.94	10.66	15.98	22.06	28.12	36.98	48.88	66.83	98.85	> 98.85
Central India (mm/day)	6.14	11.96	18.24	24.12	30.82	38.98	52.42	68.85	102.42	> 102.42
Western India (mm/day)	8.42	14.98	22.07	30.42	44.64	58.42	76.41	94.64	124.71	> 124.71
North Eastern India (mm/day)	8.88	15.97	24.78	32.73	47.84	62.73	78.72	103.78	133.76	> 133.76

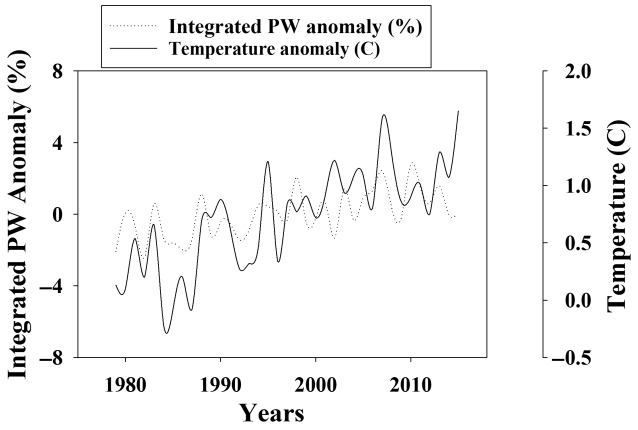


FIGURE 3 Seasonal variation of the integrated precipitable water (PW) over Indian region (I) along with the global temperature anomaly

4 | RESULTS AND DISCUSSIONS

4.1 | Changes in precipitation patterns over India (without the Northern and Southern tips)

Figure 4a shows the relationship between $\Delta P/\Delta T$ and ΔT over all India for the top 10% bin during the period 1901–2013. The percentage of precipitation is calculated from the absolute amount by normalizing to the total precipitation of the corresponding year. Normalization filters out the fluctuations caused by the inter-annual variability in the total precipitation and thus gives more consistent results. Note that ΔP between any two years during the period 1901–2013, with a total of $113 \times 112/2 = 6328$ data points in 113 years, is considered. It can also be noted that the number of data points is 56 times the number of data points (113) if a time series is used to estimate $\Delta P/\Delta T$ as a function of ΔT. Note again that $\Delta P/\Delta T$ converges to a constant (approximately 51%/K) with an increase in ΔT. Fluctuations in changes to heavy precipitation are observed for a smaller ΔT. Large errors (uncertainty) are associated with a small temperature difference (ΔT). However, errors decrease with an increase in ΔT and a stable value is achieved at a higher temperature with least error. The number of events is constant for each ΔT. For the present case, the number of events is 316 for each ΔT.

A statistically meaningful value for $\Delta P/\Delta T$ (51%/K) is obtained for the top 10% bin at high values of ΔT near 0.85 K. Figure 4a shows that heavy rainfall events (the top 10% bin, rainfall events > 98 mm/day) over the entire region have increased by about 51.85% ± 19% for a unit degree increase in global temperature. Joshi and Rajeevan (2006) also derived an increasing trend in heavy precipitation over most Indian regions using station data. However, they had not quantified the amount.

Note that these changes in precipitation extremes can also be influenced by natural factors such as the Indian Ocean Dipole (IOD), El Niño–Southern Oscillation (ENSO) and internal variability of the Indian monsoon.

An attempt was made to separate the impact of natural forcing from that of warming by considering only non-IOD and non-ENSO years (1901, 1904, 1907, 1908, 1912, 1915, 1920, 1921, 1927, 1929, 1931, 1932, 1934, 1936, 1937, 1939, 1943, 1947, 1948, 1951–1953, 1956, 1959, 1960, 1962, 1966, 1967, 1969, 1971, 1976, 1977, 1979, 1990, 1993, 1995, 2001–2003, 2005, 2006, 2008 and 2009).

Figure 4b shows that the impact of warming is less when compared with the combined impact of warming and natural forcing on changes in precipitation patterns. However, this difference is within the standard deviation (SD) of both the data sets.

A similar analysis can be done for other bins of precipitation intensity. The results are summarized in Figure 5. Note that low to moderate rainfall (one to six bins) has decreased by about 15–30%/K over India during the monsoon period (June–September).

Most parts of the Indian region receive very heavy rainfall during July and August (Ramesh Kumar and Prabhu Desai, 2004; Wang, 2006). Changes in the precipitation spectrum over India during July and August were examined separately.

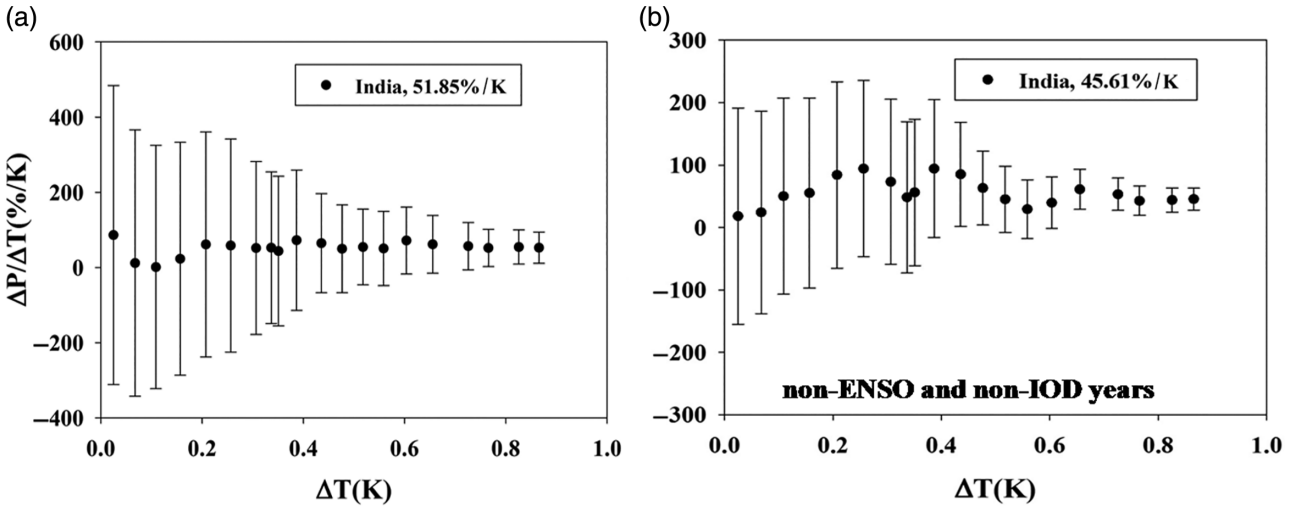


FIGURE 4 (a) $\Delta P/\Delta T$ of the top 10% bin of precipitation intensity over India (I) as a function of ΔT; and (b) $\Delta P/\Delta T$ of the top 10% bin of precipitation intensity over India as a function of ΔT during the non-Indian Ocean Dipole (IOD) and non-El Niño–Southern Oscillation (ENSO) years. Vertical bars denote 1 SD (standard deviation)

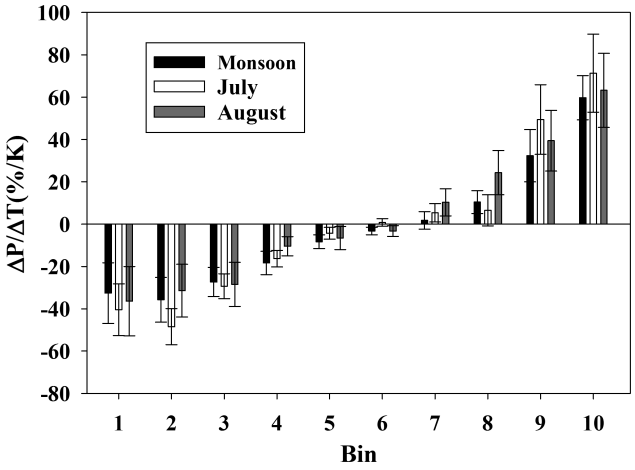


FIGURE 5 Changes in precipitation within each of 10 intensity bins over India (I) for a 1 K increase in global temperature. Bars represent trends during the monsoon period, July and August

Figure 5 shows that heavy rainfall events (the top 10% bin) have increased by about 75.43% ± 14% and 68.24% ± 11%/K during July and August respectively. This increase is much more than that for the whole monsoon period. It can also be observed that there is an increase of 0.08 K *per* decade in temperature (from NCDC temperature anomaly data) during the period 1901–2013, so the total increases in heavy rainfall *per* decade are about 4.2%, 6.03% and 5.46% during the monsoon (June–September), July and August respectively. Sen Roy and Balling (2004) also found an increasing trend in heavy rainfall over India, but did not quantify it.

4.2 | Changes in precipitation patterns over the CI, WI and NEI regions

The impacts of warming on precipitation patterns over the CI, WI and NEI regions were examined separately. Results over the CI region are compared with previous studies by Goswami *et al*. (2006) and Rajeevan *et al*. (2008).

Figure 6 shows the precipitation trends over the CI, WI and NEI regions during the last 11 decades. There are about 59.76% ± 20.32%/K, 62.71 ± 24.78%/K and 77.52 ± 28.41%/K increases in heavy precipitation events (the top 10% bin) over the CI, WI and NEI regions respectively. Global temperature shows an increase of about 0.08 K *per* decade during the period 1901–2013. Thus, the CI region shows a decadal increasing trend of about 4.8% in heavy precipitation. Rajeevan *et al*. (2008) reported an increasing trend of about 6% *per* decade in frequency of heavy precipitation over the CI region. Thus, the present results are consistent with Rajeevan *et al*. (2008). Goswami *et al*. (2006) reported an increase of about 50% in heavy rainfall (the top 10%) over the CI region during the past five decades. Note that the domain of the CI region selected by Goswami *et al*. was slightly different than that used in the present study. Increasing trends of about 5.02 and 6.21 *per* decade in heavy precipitation over the WI and NEI regions were reported respectively.

Figure 7 shows the precipitation trends (for each precipitation bin) over the CI, WI and NEI regions during the monsoon period, July and August. Note that the impact of warming is more during July and August. The paper reports increases of about 71.32% ± 22.67% and 63.23% ± 17.82% *per* 1 K increase in global temperature over the CI region during July and August respectively. A decrease of about 18–32%/K in low and moderate precipitation over the CI region during the monsoon season is also reported here. These decreases are greater during July. Similarly, increases of about 77.78% ± 18.72% and 91.56% ± 26.64% *per* 1 K increase in global temperature can be observed during July over the WI and NEI regions respectively. These scale to increases of about 6.22% and 7.32% *per* decade in heavy precipitation in July over the WI and NEI regions respectively. Dash *et al*. (2009) also observed the increase in heavy rainfall events over the NEI region. However, Goswami *et al*. (2006) derived a decreasing trend in heavy rainfall events over this region. The paper also reports a decrease of about 10–38%/K in low and moderate precipitation (bins 1–5) over the NEI region. This result is consistent with the observation of Konwar *et al*. (2012).

Increases of about 62.89% ± 18.67%/K, 77.78% ± 17.43%/K and 69.23% ± 18.45%/K in heavy precipitation events (top 10% bin) over the WI region during the monsoon (June–September), July and August have been reported. These scale to an increase in heavy precipitation of about 5.03%, 6.22% and 5.53% *per* decade during the monsoon, July and August respectively. Increasing trends of heavy rainfall events over the WI region were also reported by Sen Roy and Balling (2004) and Dash *et al*. (2009). There is about a 10–45%/K reduction in the low to moderate rainfall. Dash *et al*. (2009) also reported a significant reduction in the low to moderate rain events.

4.3 | Changes in heavy, low and moderate rainy days

Based on the thresholds shown in Table 1, heavy rainy days are defined for India and the CI, WI and NEI regions. Following

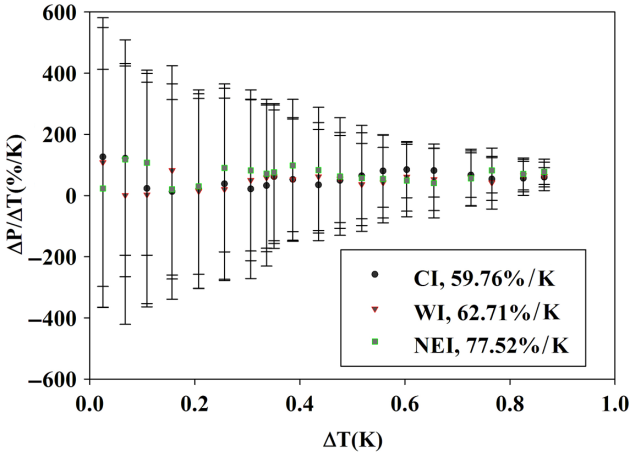


FIGURE 6 $\Delta P/\Delta T$ of the top 10% bin of precipitation intensity over Central India (CI) (circles), Western India (WI) (triangles) and North Eastern India (NEI) (squares) as a function of ΔT. Vertical bars denote 1 SD (standard deviation) [Colour figure can be viewed at wileyonlinelibrary.com]

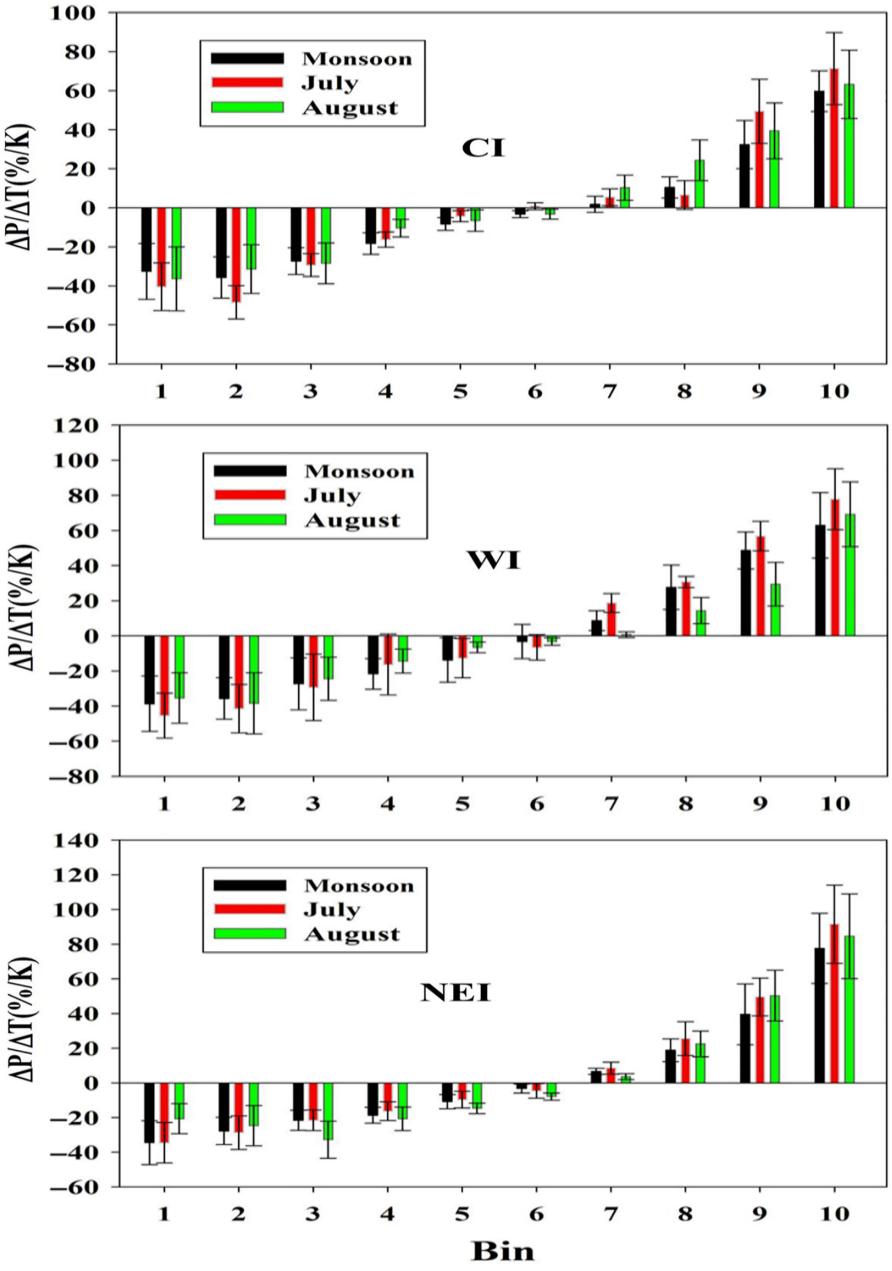


FIGURE 7 Changes in precipitation over Central India (CI), Western India (WI) and North Eastern India (NEI) within each of 10 intensity bins for a 1 K increase in global temperature. Bars represent trends during the monsoon period, July and August [Colour figure can be viewed at wileyonlinelibrary.com]

the methodology adopted above, changes in heavy rainy days (ΔD) are related to changes in temperature. Figure 8 shows the relationship between $\Delta D/\Delta T$ and ΔT over India and the CI, WI and NEI regions for the top 10% bin during the period 1910–2013. The frequency of heavy rain has increased by 46.53 ± 14%/K over India. This scales to an increase of about 3.72% *per* decade in heavy rainy days over India. There are considerable increases of about 38.71% ± 12%/K, 28.92% ± 8.8%/K and 64.57% ± 18%/K in heavy rainy days over the CI, WI and NEI regions respectively. Increases in heavy rainy days over the NEI region are consistent with the observations of Dash *et al.* (2009).

Similarly, low and moderate rainy days are defined using Table 1 (bins 1–5). The results are presented in Figure 9. The frequency of low and moderate rainy days has decreased by about 24.67% ± 9.53%/K over India. Thus, a decadal decreasing trend of about 1.97% is observed over India. Also reported are decreases of about 28.43% ± 10.32%/K, 44.54% ± 18.8%/K and 55.18% ± 20.43%/K for low and moderate rainy days over the CI, WI and NEI regions respectively.

A reduction in light to moderate rain cases contributes to drought events because low to moderate rain events (5 to < 100 mm/day) contribute to about 85.8% of seasonal rainfall over India (Goswami *et al.*, 2006; Konwar *et al.*, 2012).

Thus, global warming causes heavy rainy days to be increased at the expense of low and moderate rainy days, and thus contributes to an increase in droughts and floods over the Indian region.

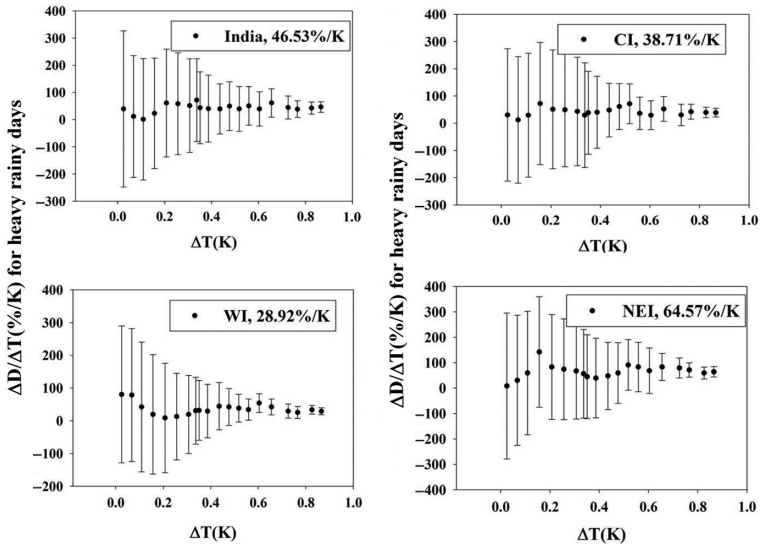


FIGURE 8 Changes in heavy rainy days ($\Delta D/\Delta T$) as a function of ΔT for India, Central India (CI), Western India (WI) and North Eastern India (NEI). Vertical bars denote 1 SD (standard deviation)

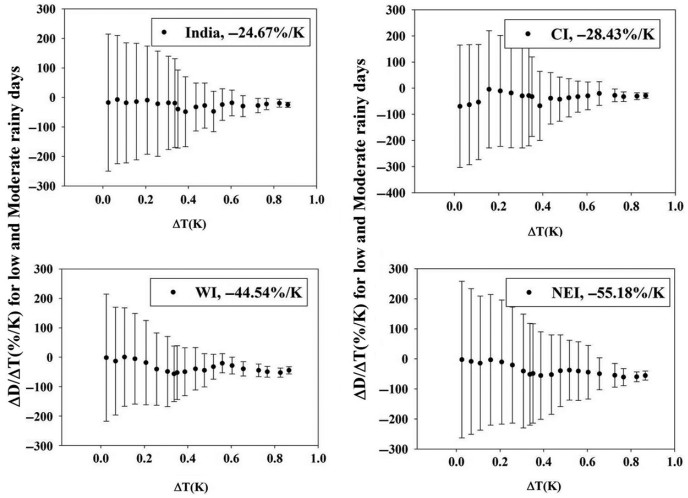


FIGURE 9 Changes in low and moderate rainy days ($\Delta D/\Delta T$) as a function of ΔT for India, Central India (CI), Western India (WI) and North Eastern India (NEI). Vertical bars denote 1 SD (standard deviation)

5 | CONCLUSIONS

Precipitation patterns over India in warming climate were examined in the present paper using an inter-annual difference technique. The impact of warming on the precipitation pattern was also quantified. An increase in heavy precipitation and a decrease in light and moderate precipitation was reported. There is about a 4.2% increase *per* decade in the top 10% precipitation during the monsoon period over India. Increases of about 4.8%, 5.02% and 6.21% *per* decade are reported over Central, Western and North Eastern India respectively. These increases are more severe during July and August. Frequent heavy precipitation events cause rain-generated floods (Bates *et al.*, 2008). It is likely that the increase in frequency and the intensity in precipitation are responsible for a significant increase in flood cases, particularly over Central, Western and North Eastern India, during the past few decades. There are reductions in low to moderate rain events. A global rise in temperature presents a serious threat to life, causing drought and flood-like events.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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