Atmospheric Research 284 (2023) 106601

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Unfolding unique features of precipitation-temperature scaling across India

Subhasmita Dash, Rajib Maity *

Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India

ARTICLE INFO

Keywords:
Precipitation
Temperature
Clausius-Clapeyron scaling
Spatio-temporal variation
Sub-daily scaling
Seasonality effect

ABSTRACT

Warming of the climate is now unequivocal. However, probable dynamics of changes in the precipitation regimes remains disputable under potential future warming. Theoretically, increasing atmospheric heat translates to increase the atmospheric moisture holding capacity at the Clausius-Clapeyron (C-C) scaling rate in the absence of moisture limitation, which in turn raises the possibilities of more intense precipitation events. Here we investigated the scaling relationship between observed and reanalysis precipitation with surface air temperature and dew point temperature at daily and sub-daily time scales on annual and season-wise basis. To reach a robust conclusion, entire Indian mainland is considered as the study area that spans across a vast climatic characteristics. More influential temperature dependence is found for heavier precipitation events than the lighter ones on annual basis as well as for different seasons. Negative and peak type scaling patterns between the daily surface air temperature (SAT) and precipitation is noticed across the different climatic regimes of the study region. In contrast, positive dependence between dew point temperature (DPT) and precipitation is obtained to be dominant across the study region. Negative sensitivity noticed for the daily surface temperature is mainly the consequence of the local cooling effect due to the occurrence of precipitation and the moisture limitation at higher end of the local temperature. In general, the scaling relation varies from season to season, which tend towards a negative scaling in hotter seasons, but a positive scaling in colder seasons. Extreme precipitation can be better portrayed by sub-daily temperature conditions prior to the start of the storm events. Scaling relationship obtained between the sub-daily precipitation and surface air and dew point temperature exhibits greater consistency in the relationship across the regions. The Western Ghats region is consistently noticed to exhibit a positive scaling relation, whereas rest of the country exhibits mostly a peak type relation. The SAT considered up to 6-h prior to the precipitation might not reflect the actual response of precipitation towards the temperature increase, possibly due to the prevailing cloudy conditions preceding the precipitation event. Findings of this study provides a better understanding related to the anticipated changes in precipitation regimes under future climate with a warming condition across different climatic regimes.

1. Introduction

Increased frequency of intensified precipitation events has been evidenced globally (Fischer and Knutti, 2012). Identified change in precipitation characteristics is one of the hydrological consequences induced from accelerated warming since 1950s as reported by Intergovernmental Panel on Climate Change (IPCC) in AR5 (Ross et al., 2018). However, the inherent association between two facets of climate change, i.e. global warming and increasing precipitation extremes remains debatable (Krishnan et al., 2016). As per a general agreement, warmer atmosphere leads to the availability of more precipitable water consequently resulting in precipitation events with amplified intensity. This consensus can be better justified through Clausius-Clapeyron (C-C) scaling relationship, which says that with 1 °C warming, moisture holding capacity of the atmosphere increases at a rate of approximately 7% (Lenderink and Van Meijgaard, 2010). The C-C scaling rate is established as a highly relevant constraint on precipitation extremes in a warming environment, as reported from various studies globally (Utsumi et al., 2011; Wang et al., 2017) and regionally (Hardwick Jones et al., 2010; Drobinski et al., 2016; Herath et al., 2018; Yong et al., 2021), over the last decade. However, the scaling rate is found to be sensitive to various factors, namely the study region (Panthou et al., 2014), temperature range (Utsumi et al., 2011), seasonal variability and precipitation accumulation duration (Pumo and Noto, 2021). For instance, Utsumi et al. (2011) found different types of scaling relationship at different latitudinal ranges. However, the precipitation and

* Corresponding author.
E-mail address: rajib@civil.iitkgp.ac.in (R. Maity).

https://doi.org/10.1016/j.atmosres.2022.106601
Received 9 March 2022; Received in revised form 27 December 2022; Accepted 30 December 2022
Available online 3 January 2023

temperature scaling relationship does not necessarily signify cause and effect directly since such relationship is influenced by different thermodynamic and dynamic components associated to different hydroclimatic regimes around the world (Lenderink and Fowler, 2017).

During last few decades, warming induced persistent increase in daily precipitation extremes are manifested by more than a half million fatalities around the world (Papalexiou and Montanari, 2019). Due to the precipitation extremes, India alone accounts for 10% of the global economic losses in terms of floods, landslides, droughts, torrential rainfall etc. (Roxy et al., 2017). Furthermore, during the last six decades, more than 250 flood events across the country brought about 825 million people under worst situations in terms of loss of lives and property (International Disaster Data Base, https://www.emdat.be/ accessed on 1st August 2019). India frequently experiences convective precipitation events (such as thunderstorms), which is significantly sensitive towards the thermodynamic aspects of the atmosphere (Berg et al., 2013; Ali and Mishra, 2017). Though, different temperature extremes contributing towards drought and extreme flood events are evidenced under anthropogenic warming over most of the South Asian countries including India, the studies involving association between temperature and precipitation are scarce (Naveendrakumar et al., 2019). Moreover, the findings of existing studies portray different viewpoints as well. For instance, Vittal et al. (2016), concluded the association between temperature and precipitation in India during the monsoon season to be insignificant. However, daily extreme precipitation is found to be negatively associated with temperature at major urban locations in India (Ali and Mishra, 2017). From a recent study by Sharma and Mujumdar (2019), local air temperature is obtained as the most influencing variable for the precipitation extremes in Mahanadi river basin, which is a major east flowing river basin in India.

Furthermore, urban areas in India are facing frequent flood events due to increase in short-duration precipitation extremes (Ali and Mishra, 2018). Climate warming and urbanization, according to previous studies, are intensifying the observed extreme precipitation intensities (Mukherjee et al., 2018). These events can cause flash floods, landslides, urban water-logging etc. leading to serious socioeconomic impacts (Roderick and Wasko, 2020). As a result, in rapidly urbanizing India, increase in the short-duration precipitation extremes poses challenges for storm water design. However, it remains unclear, how the short-duration precipitation extremes respond to the temperature rise. On the whole, insights into the impacts of warming on short-duration precipitation extremes is crucial towards deciding the climate change adaptation strategies.

Therefore, a comprehensive spatio-temporal analysis is essential for an improved understanding of the precipitation sensitivity to warming across India. Firstly, the precipitation-temperature relationship may be influenced by the climatic region/regime, which indicates the necessity to investigate the regional characterization. This motivates an analysis investigating spatial variation. Secondly, the seasonal precipitation patterns along with temperature variation over India is substantial, which is due to different weather systems driving the precipitation events during different seasons formed with different dynamics of meteorological parameters across the regions. This motivates an analysis investigating seasonal variation of the relationship between precipitation and temperature.

Thus, the objective of this study is to explore the scaling relationship of precipitation with surface air temperature and dew point temperature across Indian mainland for an improved understanding of the precipitation sensitivity to warming. Three distinct aspects are explored – spatial variation in the scaling relationship, seasonal variation with respect to annual observations and its variation with daily and sub-daily time scales.

2. Data and methods

2.1. Observed data

Daily gridded precipitation data with spatial resolution of 0.25° (latitude) × 0.25° (longitude) and maximum and minimum daily temperature data with spatial resolution of 1° (latitude) × 1° (longitude) across Indian mainland are collected from India Meteorological Department (IMD) (https://www.imdpune.gov.in/lrfindex.php, accessed in December, 2022). Based on the data availability for precipitation and temperature, a time frame of 70 years i.e., 1951–2020 is chosen for the analysis. The precipitation data is re-gridded to the same scale of temperature by using Inverse Distance Weighting method.

The daily rainfall records from 6955 rain gauge stations with varying availability periods were used. Out of these 6955 stations, 547 were IMD observatory stations, 494 were hydro-meteorology observatories and 74 are agromet observatories (Pai et al., 2015). The remaining are rainfall reporting stations maintained by the State Governments. The gridded temperature dataset was developed using the daily minimum (night time) and maximum (day time) temperature data from 395 synoptic stations spread uniformly over the country (Rohini et al., 2016). It may be noted here that a dense network of raingauge stations and a suitable gridding method may lead to better representation and a less representativeness error in the gridded datasets. As mentioned before, the daily gridded precipitation data is developed from 6955 stations across India and Shepard's interpolation method was used for gridding (Pai et al., 2014).

2.2. Reanalysis data

ERA5 reanalysis data for dew point temperature of 0.25° × 0.25° spatial resolution for the time period, 1951–2020, are utilized for deriving its relationship with the precipitation extremes. Further, the scaling of the sub-daily precipitation extremes with the dew point temperature and surface air temperature is explored in the recent past by utilizing the hourly precipitation and temperature data (at 2 m above ground level) over a 30 years time window, i.e., 1991–2020. The above mentioned datasets were derived from the ERA5 hourly data, and are available from the European Centre for Medium-Range Weather Forecasts website (https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset, accessed in December 2022).

2.3. Methods

The overall framework of data processing and methodology is briefed in Fig. 1. The precipitation, surface air temperature (SAT_{max} and SAT_{min}), and the dew point temperature (DPT) data are analyzed for two cases: (i) daily scale, and (ii) sub-daily scale. The daily analysis is carried out for the annual and season-wise cases. In order to capture the response of sub-daily precipitation events to temperature increase, each precipitation event is paired with the 3-h mean temperature centered around 6-h, 12-h, 24- h and 48-h time lags prior to the start of the precipitation event.

Following the data processing, empirical relationship between precipitation and temperature are derived by using the binning method. At each grid intersection, precipitation values on wet days (days with precipitation >1 mm) are paired with corresponding temperature. The precipitation-temperature pairs are placed into 20 bins, marked by different percentiles (starting from <5th percentile to >95th percentile) of the temperature at a specific grid intersection. This ensures more/less equal number of pairs in across the bins. This approach is selected instead of equal width temperature bins as Indian mainland spans over a wide variety of climate regimes and an equal temperature width may lead to empty bins for the higher and lower temperature ranges. The temperature range for each bin varies across grid intersections and the median temperature is considered as the representative temperature for

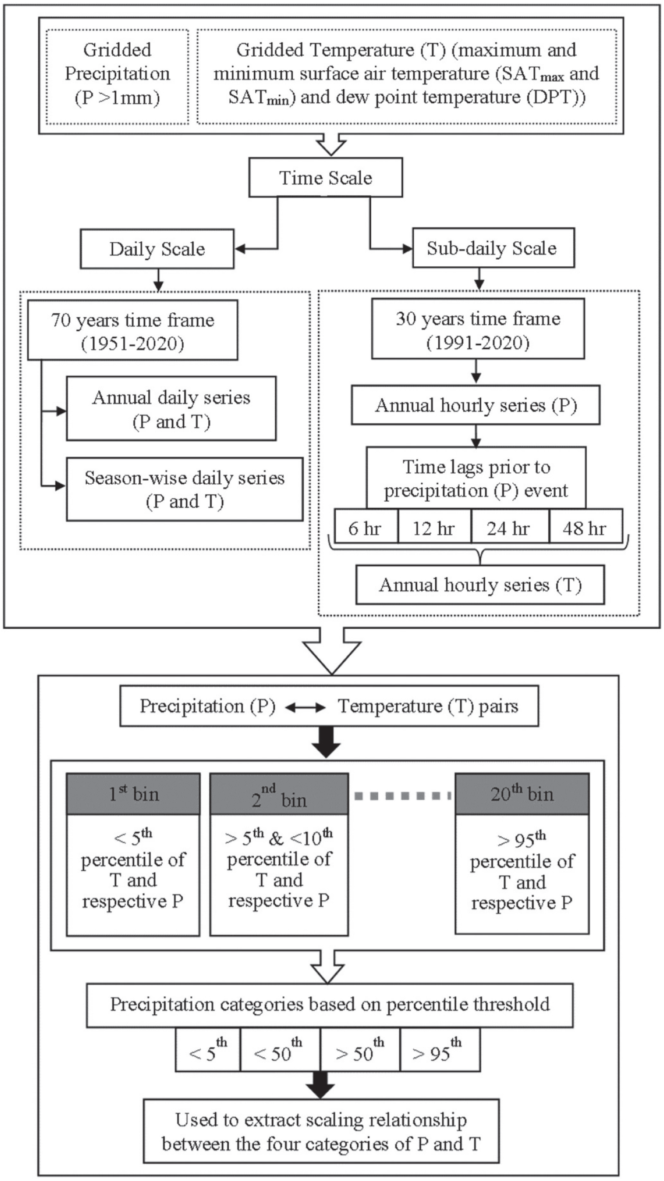

Fig. 1. Data processing and methodological outline.

the respective bin. Precipitation events corresponding to each of the bins are grouped into four categories – i) extreme precipitation (greater than 95th percentile), ii) above average (greater than 50th percentile including extreme precipitation), iii) below average (less than 50th percentile including very low), and iv) very low (less than 5th percentile). Analysis is carried out for each category separately to separate out the relationship characteristics, if any.

The underlying relationship between change in precipitation from P_a to P_b (P_a and P_b refers to a specific category of precipitation corresponding to two bins with representative temperature T_a and T_b, respectively) and corresponding change in temperature from T_a to T_b is empirically expressed as,

$$P_b = P_a(1+\alpha)^{\Delta T} \tag{1}$$

where $\Delta T = T_b - T_a$, and α is the precipitation-temperature scaling coefficient. The value of α is equal to 6.8% per °C at 25 °C, being equivalent to C-C scale (Herath et al., 2018). From eq. (1), the scaling coefficient can be estimated as,

$$\alpha = \left(e^{\frac{\ln P_b - \ln P_a}{T_b - T_a}} - 1\right) \times 100\% \tag{2}$$

Assuming that the association between precipitation and temperature need not be linear, Kendall's tau (τ), which is a scale-free measure of association, is used to evaluate the association between various categories of precipitation and their corresponding temperature and values at 5% significance level are considered as statistically significant (Maity, 2022).

3. Results

3.1. Scaling relationship between daily precipitation and temperature

To start with, entire time period of 70 years (1951–2020) is considered as a single time frame and different features of relationship between precipitation and temperature based on the annual daily series are assessed across the Indian mainland. The scaling association of precipitation (four categories as mentioned in the methods section) with respect to the entire temperature (SAT_{min}, SAT_{max} and DPT) range are extracted. Broadly, patterns describing the scaling relationship are divided into three types, i.e., negative, positive and peak (Fig. 2). A negative relationship signifies decrease in precipitation with increase in temperature and the reverse is noted as a positive scaling type. Peak type scaling refers to a combination of positive and negative association, wherein, the precipitation increases with the temperature up to a specific temperature (inflection point/temperature), followed by decreasing precipitation with further increase in temperature. The peak type scaling is further divided into two types i.e., positive dominated and negative dominated, based on the inflection point. If the inflection point lies on the right half of the set of precipitation-temperature pairs, then the relationship is of positive-peak type (Fig. 2(d)) and the reverse is considered as negative-peak type scaling (Fig. 2(c)).

In Fig. 3, spatial distribution of the scaling types over India is represented. Whole of the country exhibited negative and peak type relationship between precipitation and maximum temperature (Fig. 3(a)) with distinct spatial patterns. Southern part of the country along with the northern Himalayan region exhibits negative scaling relationship, whereas the peak type relationship is noticed over rest of the country. Similar to the southern tropical regions of India, negative scaling type is also obtained for the stations located in tropical Australian region (Herath et al., 2018). Considering minimum temperature (Fig. 3(b)), most of the country exhibited peak type scaling apart from some regions in the peninsular part of India, which possessed negative scaling in case of the extreme and above average precipitation events. Area with peak pattern increases as the precipitation intensity decreases considering both minimum and maximum daily temperature. However, taking the dew point temperature into account, the country exhibited positive and peak type relationship (Fig. 3(c)). The positive scaling is mostly noticed across the peninsular region and it covers more area for less intense precipitation events.

The scaling rate α (as mentioned in the methods section) corresponding to different scaling types between the temperature and precipitation is estimated. In case of negative (positive) type, the decrease (increase) of precipitation with the increase in temperature is noticed for the entire range of local temperature. This decreasing (increasing) scaling rate is computed at each grid exhibiting negative (positive) type for each category of precipitation. For the regions with peak type relation, the scaling rate of the more extended precipitation-temperature pairs segment is considered to represent the scaling rate of the entire set. More precisely, for the positive dominated peak and negative dominated peak patterns, corresponding dominant segments are taken and the scaling rates are estimated. Spatial distribution of the scaling rate involving maximum temperature (SAT_{max}), minimum temperature (SAT_{min}), and dew point temperature (DPT) is shown in Fig. 4. For both SAT_{max} and SAT_{min}, the extreme precipitation showed negative

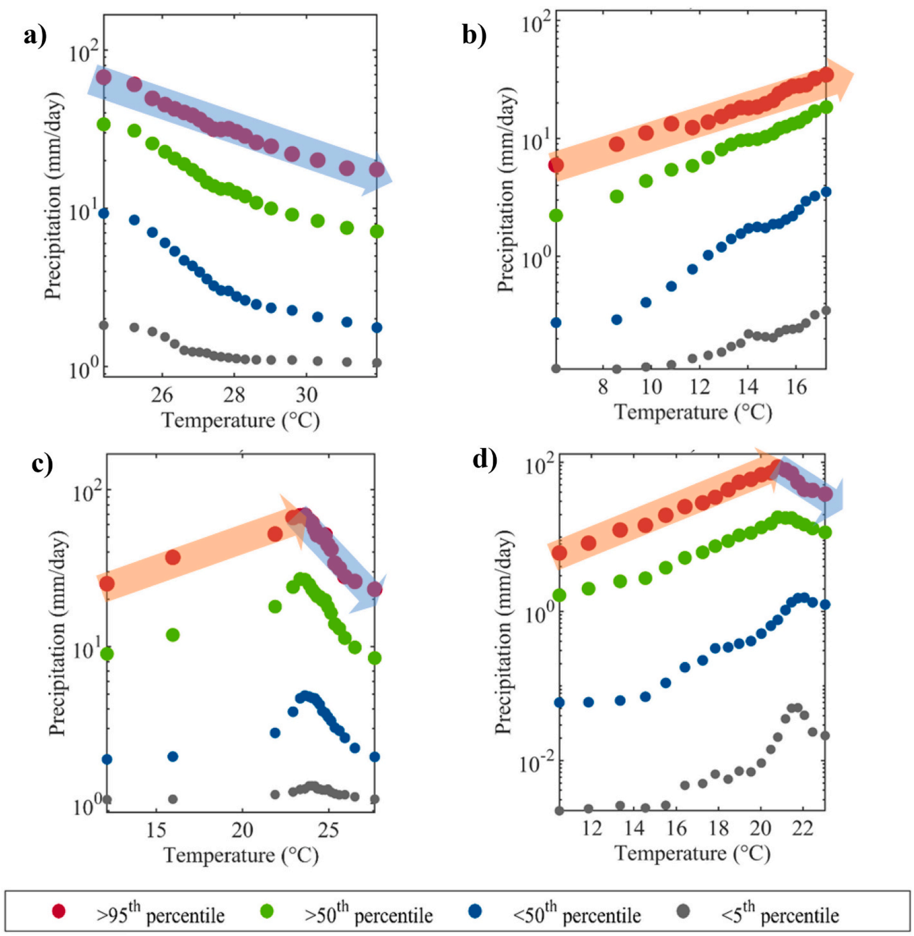

Fig. 2. Illustration of different types of scaling relationship between temperature and precipitation, namely, a) negative type, b) positive type, c) peak type (negative dominated) and d) peak type (positive dominated), considering four categories of precipitation. Different colours of data values corresponds to different percentiles of precipitation mentioned. The blue transparent arrow indicates the negative type scaling and the red arrow shows the positive type scaling. The Y-axis is in logarithmic scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sensitivity to temperature increase across most of the country. However, considering the DPT, precipitation increases with increase in temperature for most of the regions. Across the eastern and central part of the country, extreme precipitation events (precipitation >95P) exhibited negative scaling rate towards the DPT. In regions with positive scaling rate, increase in precipitation with DPT mostly exceeded the C-C rate i.e., 7%/°C. Further, the Himalayan region is found to be the least sensitive to warming for all three cases. Among the four categories of precipitation, low precipitation magnitudes are found to be less sensitive to temperature increase.

3.2. Season-wise variations in the daily precipitation-temperature relationship

In India, a wide range of weather conditions is experienced throughout the year owing to high seasonal variation of different hydrometeorological variables including precipitation and temperature. This necessitates to quantify the extent to which the weather patterns across different seasons influence the relationship between these two variables. Previously, seasonality effect on precipitation dependence of temperature is also detected over different parts of the globe, e.g., Europe (Berg et al., 2009), China (Zhou and Wang, 2017) and Russia (Aleshina et al., 2021). In this study, four seasons as defined by the India Meteorological Department (IMD) are considered: JF (January and February), MAM (March to May), JJAS (June to September, also known as monsoon period) and OND (October to December). Considering the entire time period, i.e., 1951–2020, relationship between precipitation and temperature (SAT_{min}, SAT_{max} and DPT) across the four seasons are evaluated. Similar to the annual case, temperature is found to be more influential for heavier precipitation than lighter precipitation for all the four seasons. Owing to this, here the relationship between extreme precipitation events and their corresponding temperature are discussed. Association in terms of Kendall's tau between extreme precipitation and temperature is explored at 5% significance level. Different spatial patterns of association between the two variables are found across the country in four of the seasons (Fig. 5). Considering the maximum temperature (SAT_{max}), significant negative association is noticed over most of the country across all four seasons. During the monsoon season, stronger negative association is obtained as compared to the other seasons. However, across some regions it is found that extreme precipitation increases with increase in minimum temperature (SAT_{min}) during OND and JF. Conversely, during the other two seasons, MAM and JJAS, negative association between the two variables is noticed across most of the country. Like it is seen in case of SAT_{max}, for SAT_{min} also the monsoon season exhibited stronger negative association among all. Considering the dew point temperature (DPT), whole of the country showed positive dependence with extreme precipitation events during all the seasons apart from the monsoon. During the monsoon season, peninsular and north western parts exhibited positive association, whereas, the eastern and north eastern regions showed decrease in extreme precipitation events towards the increase in DPT. Further, across the Western Ghats insignificant association is noticed with DPT during the monsoon. Irrespective of the temperature in concern, eastern and north eastern regions of the country possessed negative association with extreme precipitation during the monsoon season. Over the northeast region, contrasting nature of association during non-monsoon (significantly positive) and monsoon (significantly negative) seasons can be interpreted as hot and wet, and cool and dry conditions go hand-in-hand during non-monsoon season, whereas the reverse might be true for the monsoon season.

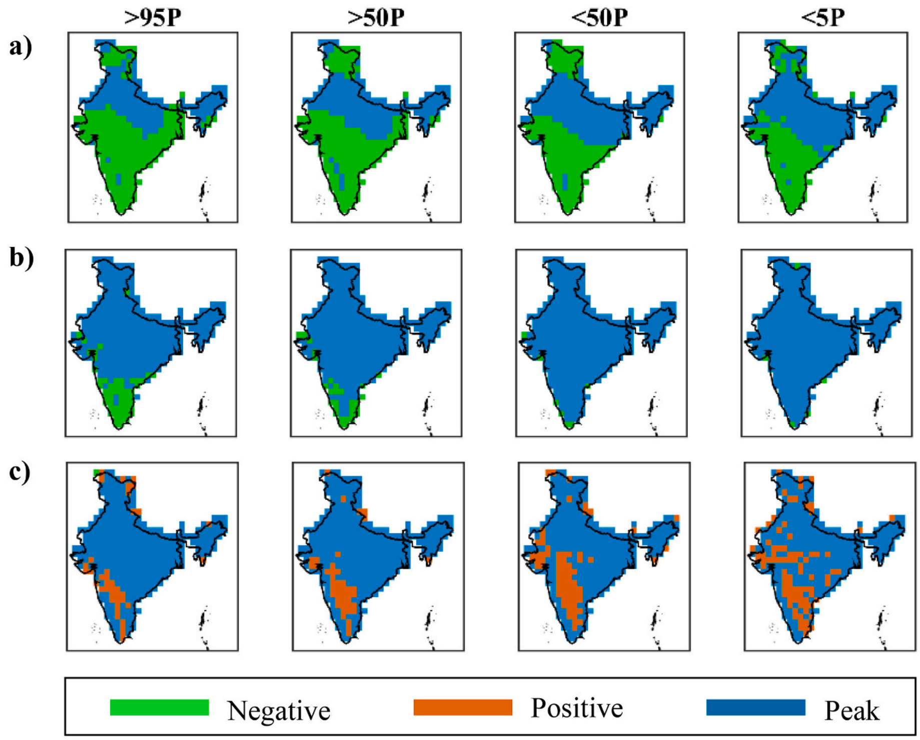

Fig. 3. Spatial distribution of types of scaling relationship between daily annual precipitation and a) maximum temperature (SAT_{max}), b) minimum temperature (SAT_{min}), and c) dew point temperature (DPT) across India for four categories of precipitation, i.e., extreme (>95P), above average (>50P), below average (<50P), and very low (<5P), where P stands for percentile.

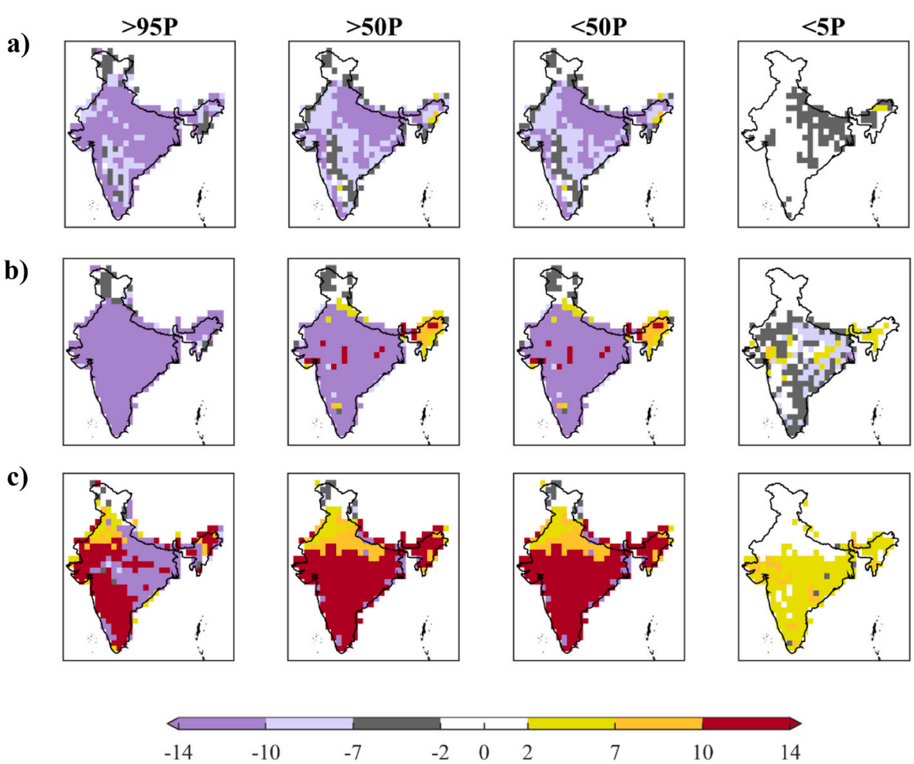

Fig. 4. Rate of scaling (percentage per °C) between precipitation and a) maximum temperature (SAT_{max}), b) minimum temperature (SAT_{min}), and c) dew point temperature (DPT) for four categories of precipitation, i.e., extreme (>95P), above average (>50P), below average (<50P), and very low (<5P), where P stands for percentile.

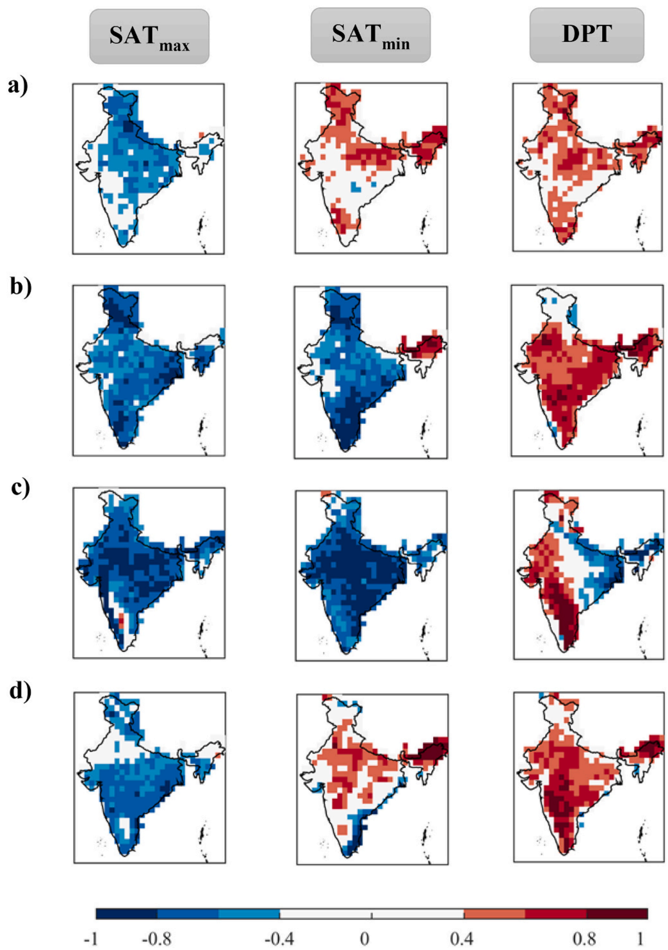

Fig. 5. Association (in terms of Kendall's tau) between temperature (SAT$_{max}$, SAT$_{min}$ and DPT) and extreme precipitation (i.e., >95th percentile) in the four different seasons - (a) JF, (b) MAM, (c) JJAS, and (d) OND. Insignificant values lie between ±0.4 at 5% significance level (shown in white colour).

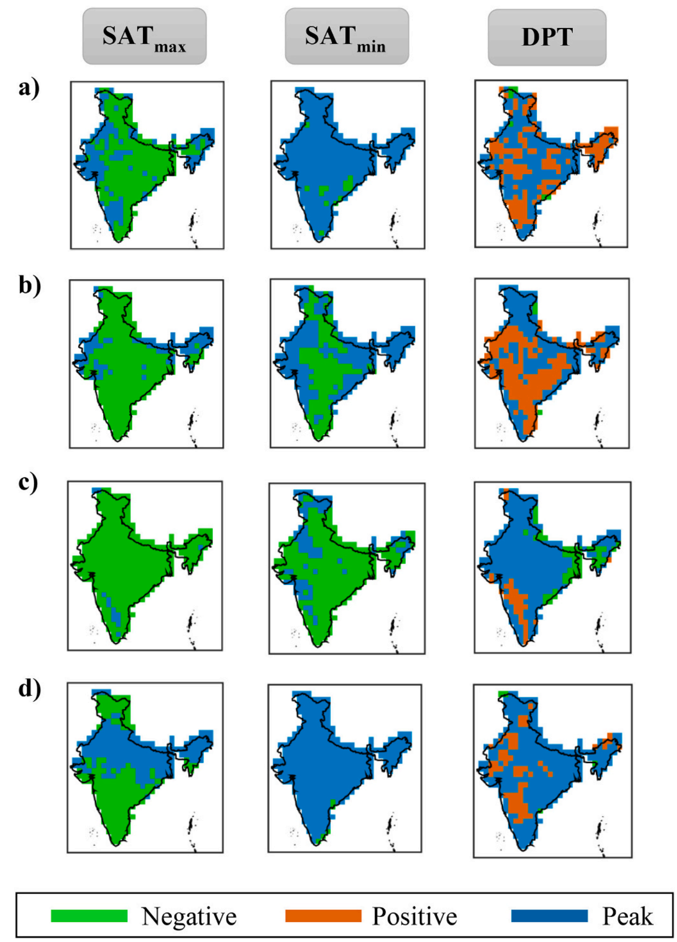

Fig. 6. Spatial distribution of type of scaling relationship between extreme precipitation (i.e., >95th percentile) and temperature (SAT$_{max}$, SAT$_{min}$, and DPT) during four seasons – (a) JF, (b) MAM, (c) JJAS and (d) OND.

The season-wise spatial distribution of scaling type over the country is shown in Fig. 6. Most of the country possessed negative type relationship between precipitation and SAT$_{max}$ during JJAS, MAM and JF, whereas, during OND, negative type is noticed over southern India and the northern parts except the Himalayan region exhibited peak pattern of scaling. Considering SAT$_{min}$, mostly peak type scaling is observed across the country during the JF and OND seasons. However, monsoon season exhibited negative scaling for most of the country. During the summer season (MAM), a relatively different spatial distribution pattern is noted, wherein a vertical strip extending from north to south through the central regions of India exhibited negative type and the rest of the country is noticed with peak type. In the case of DPT, positive type and peak type scaling are noticed across the country during all the seasons. However, during the monsoon season, few patches of negative scaling is noticed across the eastern boundary and northeast regions. More areas with positive scaling relation are noticed during the JF and MAM seasons, and the reverse is noted during the monsoon season. Moreover, the negative association followed by the negative scaling between precipitation and temperature is found to be more consistent and spatially more extensive during the monsoon season as compared to the other seasons as well as the entire year considering SAT$_{max,}$ SAT$_{min}$ and DPT.

Here, it can be mentioned that the significant positive association and peak type relationship observed with SAT$_{min}$ and DPT across the country suggests longer and steeper increasing branch of precipitation-temperature pairs up to the inflection point, and shorter decreasing branch following the inflection point. Further, the significant positive (negative) association along with positive (negative) type scaling observed in case of DPT indicates that precipitation increases (decreases) with the increase in temperature over the entire range of observed temperature across those regions. However, regions noticed with insignificant association mostly exhibit peak type scaling. This indicates that the inflection temperature lies approximately in the halfway within the range of observed temperature in these regions.

Varying scaling rates with different spatial patterns are evidenced during the four seasons (*Fig. S1)*. Over most of the country, negative scaling rate of >10% per °C increase in SAT$_{max}$ is obtained across all the seasons. With increase in the SAT$_{min}$, extreme precipitation is found to be increasing during OND and JF seasons across most of the country, at a rate mostly greater than the C-C scaling rate i.e., 7%/°C. In case of DPT, apart from the monsoon season, the entire country exhibited positive scaling rate, mostly greater than the C-C scaling rate. As a consequence of the noticed negative type scaling over the eastern and northeast regions during the monsoon, these regions showed negative scaling rate and rest of the country showed positive sensitivity. Overall, the precipitation-temperature scaling relationship varies from season to season across India. For instance, the SAT$_{min}$ exhibited contrasting scaling rates during the cold (i.e. positive scaling during OND and JF) and hot (i.e. negative scaling during MAM and JJAS) seasons across most of the regions. Considering the maximum temperature, spatial pattern of scaling during OND exhibits more similarity with the annual pattern than the other three seasons. Mostly the positive scaling rate is noticed across India in case of dew point temperature. The spatial coverage of such positive scaling is more during the non-monsoon

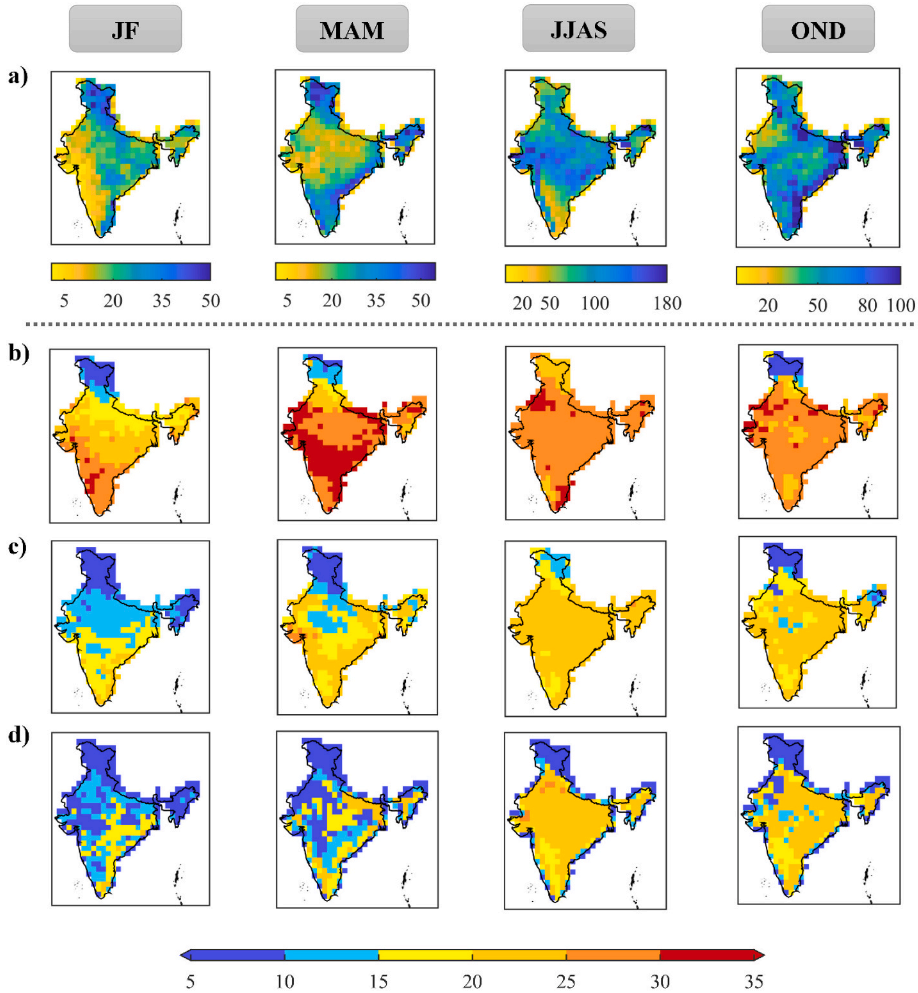

Fig. 7. Spatial distribution of (a) peak precipitation (mm/day) and corresponding temperature (°C) b) SAT_{max}, c) SAT_{min}, and d) DPT in the scaling relationship considering daily extreme precipitation across India for the four seasons, JF, MAM, JJAS, and OND.

period.

Next, season-wise peak precipitation and its corresponding temperature are evaluated across the country (Fig. 7). The peak precipitation refers to the precipitation corresponding to inflection temperature in case of peak type scaling relationship or to the lowest (highest) value of the entire temperature range in case of negative (positive) scaling relationship. During the monsoon season, stronger peak precipitation of intensity >100 mm/day is noticed over western coastal regions, eastern and central parts of the country, and during OND the same is noticed over extreme eastern regions of the country. During MAM, higher precipitation is noticed across the eastern and western coastal regions along with the northeast regions. The temperature corresponding to the peak precipitation is found to be spatially more uniform during JJAS and OND, wherein peak SAT_{max} lies between 25 °C to 30 °C, and peak of the SAT_{min} and DPT lies between 20 °C to 25 °C, over the country except the Himalayan region. Higher peak SAT_{max} of magnitude greater than or equal to 30 °C - 35 °C is found during MAM in the eastern coastal and central parts of the country. During JF and MAM, most of the country receives peak precipitation at DPT around 5 °C to 15 °C. Contrasts in inflection SAT_{max} ranges i.e., (20–25) °C and (5–15) °C is noticed over the northern Himalayan region between monsoon and non-monsoon seasons, respectively.

The quantitative relationship between precipitation and temperature is theoretically linked to the Clausius-Clapeyron scaling equation that indicates about 7% (C-C scaling rate) increase in the daily precipitation with per degree rise in temperature. In this study, the relationship between extreme precipitation and the corresponding DPT on the same day resulted in positive scaling rates mostly greater than the C-C rate across the country. However, considering the daily minimum and maximum temperature data, a decreasing dependency of extreme precipitation with temperature is obtained towards the higher end of temperature range considering annual as well as season-wise cases. For instance, most of the country exhibited peak type scaling considering the minimum temperature (SAT_{min}) and negative scaling for maximum surface temperature (SAT_{max}). In the regions exhibiting peak type relationship, increase in precipitation with temperature is experienced up to the inflection point, whereas, the regions exhibiting negative scaling relationship, the local temperature always remains higher than the temperature corresponding to the inflection point (Wang et al., 2017). This negative scaling can result owing to various hydrometeorological factors such as varying large scale atmospheric circulations (Seager et al., 2010; Ali et al., 2021a), cloud dynamics (Trenberth et al., 2003) and moisture limitation due to depletion of soil moisture (Haerter and Berg, 2009). Furthermore, the negative scaling relationship is found to be more consistent and spatially extensive during the south west monsoon season. During the monsoon season, most of the regions in India receive the maximum proportion of the annual precipitation with relatively more frequent heavy precipitation events and longer wet spells as compared to the other seasons.

As a consequence, the observed negative sensitivity can be linked with the localized cooling associated with the precipitation event. This localized cooling refers to the decrease in the temperature during a precipitation event for various reasons, including evaporative cooling, or movement of cold air associated with the precipitation (Visser et al., 2020). As a result, the same day temperature coincident with precipitation event may not truly reflect the temperature that occurred when the precipitation was actually formed. It can be examined by pairing the precipitation events with the temperature several days before the occurrence of the precipitation. Towards this, we evaluated the dependence of precipitation with temperature (SAT_{max}, SAT_{min}, and DPT) from 1, 3 and 5 days earlier to the considered event (Figs. S2-S4). It is noticed that using SAT_{max} prior to 1-day of the extreme precipitation event led to a reduced negative scaling rate across the entire country apart from the Western Ghats region, which receives the maximum proportion of the annual total precipitation in India along with less variability in annual temperature. This strong negative association between precipitation and the previous day temperature over the Western Ghats possibly results from the longer spell heavy precipitation events (Mudbhatkal and Amai, 2018), which produces a stronger and extended cooling effect on the local air temperature. Further, consideration of the 3-days and 5-days lagged SAT_{max}, the negative scaling rate changes to positive scaling rate across northeast and northern parts of the country. Likewise, the negative scaling noticed in case of the same day SAT_{min} reverses the sign considering its lagged state across some parts of the country including northeast and eastern regions. Furthermore, the spatial coverage exhibiting positive scaling for the lagged SAT_{min} was more for the lower precipitation magnitudes as compared to the extreme precipitation case. Interestingly, when the 1-day lagged DPT is paired with the extreme precipitation events, the entire country is noticed with positive scaling rate excluding few grids on the eastern coast. Further, it can be seen that the central regions, northeast and the Western Ghats, which experience more frequent extreme precipitation events, possess stronger positive scaling rates with 3-days and 5-days lagged DPT.

The above discussion suggests that consideration of temperature on the same day of the occurrence of precipitation event results in a negative sensitivity due to the local cooling effect, and a temperature prior to the start of precipitation better represents the atmospheric conditions related to the precipitation event. This conception is more justified, when the dew point temperature (DPT) is considered. However, taking the previous day SAT preceding the precipitation event had relatively less influence on the scaling rate.

Next, the influence of moisture availability on the Clausius-Clapeyron (C-C) relation is explored. The C-C relationship links temperature and humidity i.e., the intensification of precipitation extremes with warming can be explained from the increase in humidity or available moisture (Huang et al., 2021). Dew point is the temperature, a parcel of air needs to be cooled at constant pressure for saturation (100% relative humidity) to occur. Hence, when the dew point temperature and air temperature are equal, the air is said to be in saturated condition. The term dew point depression is the difference between air temperature and DPT, and is a direct estimate of relative humidity. To this end, the relationship between SAT, DPT and precipitation magnitude is evaluated. For this, four grids from four climatologically homogeneous regions i.e., peninsular India, central India, northeast and north west India are considered. From Fig. 8, it can be noted that, with increase in the maximum surface air temperature (SAT_{max}) beyond a certain limit, the

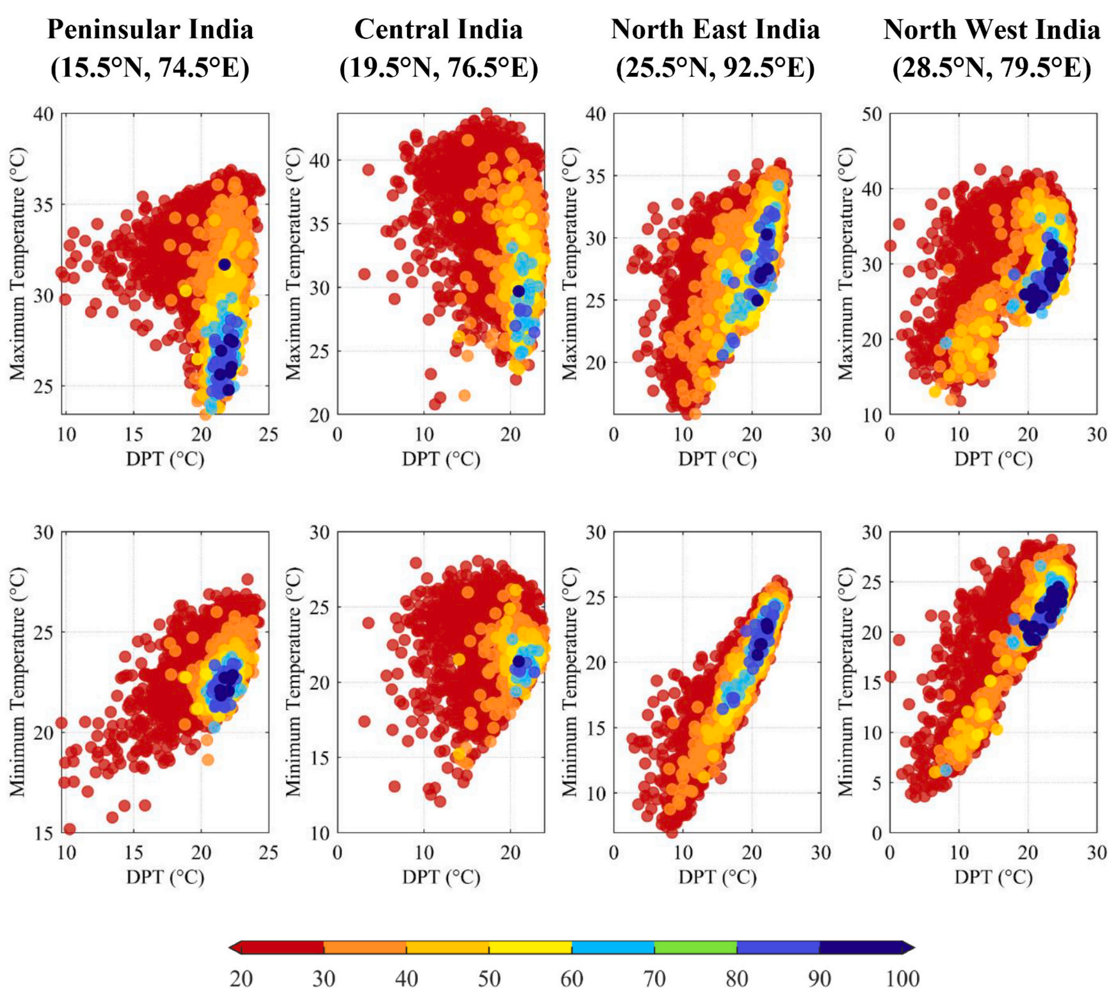

Fig. 8. Association between daily surface air temperature (SAT_{max} and SAT_{min}) (in y-axis), dew point temperature (DPT) (in x-axis) and precipitation magnitude (mm/day), indicated through the colour tone shown in colorbar.

dew point temperature is decreasing or not deviating much for many data points, prominent in case of the grids located in peninsular and central India. It can be further noted that the higher precipitation magnitudes occur when the deviation of DPT from the surface temperature is the least. For instance, the higher extreme precipitation events (noted with dark blue shade) have occurred when both the DPT and SAT_{max} are close to each other, mostly lying in 20–25 °C and 25–30 °C ranges, respectively. It suggests that the humidity does not increase proportionately to the surface temperature, i.e., higher temperatures are not associated with higher moisture content. This limitation in the available moisture at higher end of the local temperature could lead to the noticed negative scaling.

3.3. Scaling between sub-daily precipitation and temperature

It is quite evident that the observed negative sensitivity partly results from the consideration of same day precipitation and temperature data while neglecting the within-day temperature variations due to occurrence of the precipitation event. Therefore, exploration of the relationship between sub-daily precipitation and temperature across India can be beneficial towards this. Further, short-duration precipitation extremes can cause flash floods, landslides leading to serious socioeconomic impacts (Ali et al., 2021b), which calls for evaluating the changes in sub-daily precipitation with temperature increase. Here, the ERA5 reanalysis hourly precipitation and temperature data are utilized owing to the limitation of observed hourly data considering entire India. Each extreme precipitation event is paired with the 6-h, 12-h, 24-h and 48-h lagged air temperature and dew point temperature corresponding to the preceding precipitation event. Fig. 9 (a) *and* (c) represent the spatial variation of scaling type across India for the four time lags. Notable difference in the scaling is noticed between the precipitation and temperature on daily and sub-daily scale. The scaling between extreme precipitation and the surface air temperature mostly exhibits peak type across the country for all the lags. However, positive scaling over the Western Ghats region is capture when 12-h lag is considered, which is not seen in case of 6-h lagged temperature. It suggests that, over the said region, SAT 6- h prior to the precipitation might not be reflecting the actual response of precipitation towards the temperature increase. It can be due to the cloudy conditions prevailing over the region preceding the precipitation event. Consistent negative scaling is noticed over the eastern peninsular region across the four time lags. Further, considering the sub-daily dew point temperature, mostly peak type relation is observed across the country similar to the scaling with daily dew point temperature. Positive scaling type is noticed over the peninsular regions mostly and the area with positive scaling increases with the time lags. The discrepancy noticed in the scaling relationship type with/without the consideration of within-day variations in the surface air temperature (i.e., the negative scaling noticed over most of the country when considering the daily SAT) indicates that the daily air temperature may not correspond to the true atmospheric state when the precipitation event is generated.

Similarly, the scaling rate between sub-daily precipitation and SAT at

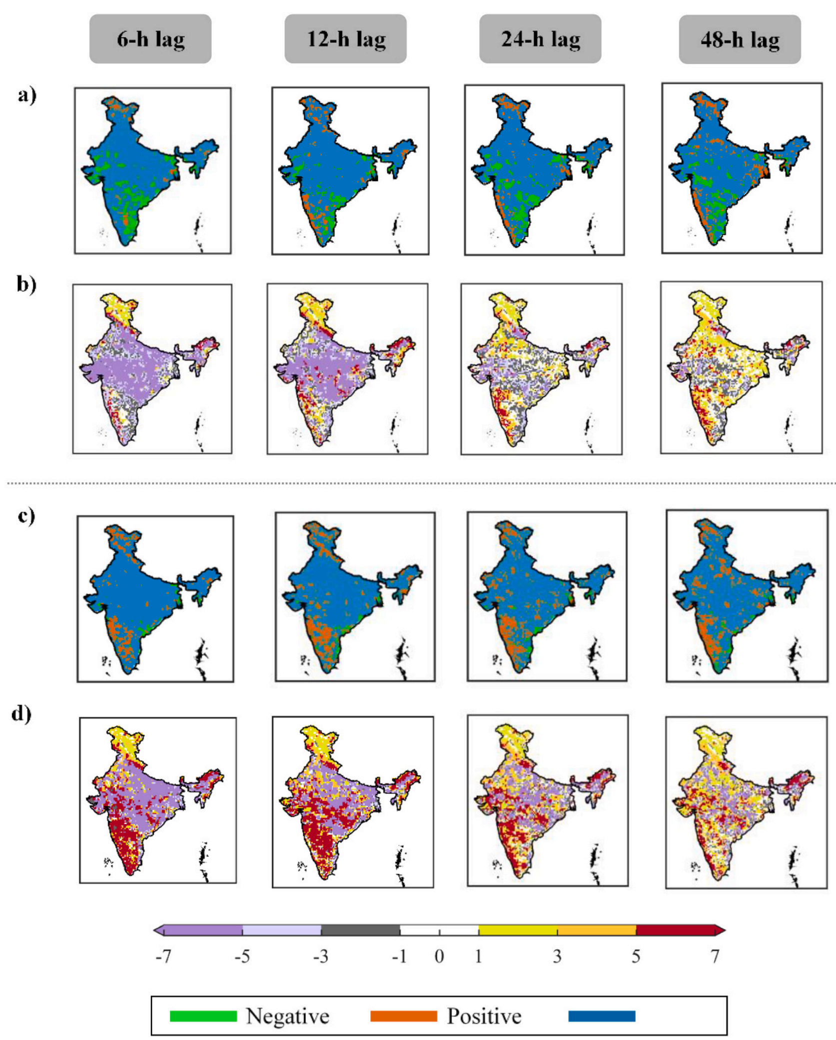

Fig. 9. Spatial distribution of type of scaling relationship (a and c) and rate of scaling (%/ °C) (b and d) between sub-daily extreme precipitation (i.e., >95th percentile) and lagged a) and b) surface air temperature (SAT) and c) and d) dew point temperature (DPT). The sub-daily temperature is considered at various time lags: 6-h, 12-h, 24-h and 48-h, with respect to the occurrence of considered precipitation event. Legend indicating the scaling types corresponds to a) and c), and the colorbar belongs to b) and d).

6-h lag (Fig. 9(b)) is found to be mostly negative across the country apart from the Western Ghats and Himalayan region. However, the negative rate of scaling turns into positive with the increase in time lags. In case of the dew point temperature (Fig. 9(d)), mostly positive scaling is observed similar to that observed while considering the daily data. The hourly precipitation extreme increases at a higher rate over the peninsular region with increase in the DPT. Furthermore, higher negative scaling rate is captured across the same regions in the central and northern parts of the country for both SAT and DPT. Here, it is inferred that in the regions with peak scaling type and negative rate of scaling, the increase in precipitation with temperature is experienced for the shorter branch of the scaling relation, whereas the reverse is experienced for the longer branch. In other words, the inflection point occurs at the lower end of the local temperature, which leads to the negative scaling rate over the said regions. With the increase in time lags, decrease in areas with stronger positive scaling is obtained in case of DPT and the converse is noticed in case of SAT. Moreover, the extreme precipitation can be better described by sub-daily temperature conditions before the start of storm events, resulting in positive scaling rates with increased consistency with the Clausius-Clapeyron relation across India. The effect of different temporal resolution (daily, hourly and sub-hourly) on the C-C scaling relationship is evaluated in earlier studies also at different parts of the world, e.g., Australia (Visser et al., 2020), China (Gao et al., 2018, 2020), Italy (Pumo and Noto, 2021) and Europe (Vergara-Temprado et al., 2021). Gao et al. (2020) evaluated the scaling relationship at daily scale and found the peak type of scaling to be dominant across China. Sub-daily temperature conditions better describe the precipitation dynamics across Australia as compared to the daily temperature (Visser et al., 2020). Across Italy, the scaling rate at hourly and sub-hourly scale showed sub C-C scaling rates (lower than the theoretical C-C scaling rate) considering DPT up to nearly 22 °C (Pumo and Noto, 2021). However, with increase in the precipitation accumulation duration, the scaling rate further decreased. Some studies reported a super C-C rate (higher than the theoretical C-C scaling rate) of scaling when considering the climate variables at hourly scale (Lenderink and Van Meijgaard, 2008; Lenderink et al., 2011; Lochbihler et al., 2017). However, this inference is found to be true for the spatial domains experiencing low local/regional temperature conditions in general. Over the Austrian south-eastern Alpine foreland region, consideration of the climate data at daily, hourly and sub-hourly scales exhibited a sub C-C, C-C and super C-C rate, respectively (Schroeer and Kirchengast, 2018). The findings of our study establishes that the scaling relationship also depends on other factors including geographic and climatic characteristics of the region. Considering different types of temperature, we found that DPT, as a direct proxy for absolute humidity, better portrays the precipitation scaling relationship as compared to the SAT considering daily and hourly time scales. Therefore, different factors including precipitation type, temperature type, regional climate characteristics, time scale, and season can influence the temperature-precipitation scaling relationship.

Finally, it is worthwhile to note here that, finer the spatial resolution of precipitation and temperature data, more accurate scaling relationship at regional/local scale can be captured. In that sense, station based observations are most accurate. However, gridded datasets have their own merits in the context of availability and applicability for the analysis at larger spatial scales and to investigate spatial variations, if any. This is due to the spatial continuity in the gridded data, which is advantageous over the discrete station measurements. This is adopted for this pan-India analysis that spans over a vast geographical extent. As both precipitation and temperature date were spatially averaged within the grid in a gridded format, their general inter-relationship and nature of spatial variation across India is expected to remain same even after the spatial averaging.

4. Conclusions

Most debated consensus regarding close linkage of precipitation with temperature is assessed for Indian mainland in this study. The scaling relationship between observed precipitation and temperature is evaluated at daily and sub-daily scales, considering four different categories of precipitation based on percentile thresholds. Considering the entire study period, 1951–2020, the scaling between daily precipitation and maximum and minimum surface temperature and dew point temperature is explored for annual and season-wise cases. The analysis for sub-daily precipitation and temperature is carried out for the most recent 30 years period, i.e., 1991–2020. More influential temperature dependence is found for heavier precipitation events than the lighter ones on an annual basis as well as for different seasons. Negative and peak scaling between the daily surface temperature (SAT) and precipitation is noticed across the country. However, reduced negative sensitivity with consideration of the SAT prior to the precipitation occurrence indicates that the local cooling effect due to the precipitation event contributes towards the observed negative sensitivity. Heavier the precipitation, stronger negative dependence will result from larger cooling contribution from the precipitation event. In contrast, positive dependence between dew point temperature (DPT) and precipitation is obtained across most of the country suggests the precipitation dependence on relative humidity, which is better captured by the dew point temperature. Furthermore, notable difference in the spatial pattern of scaling across the four seasons, i.e., JF, MAM, JJAS and OND is obtained. The temperature seasonality effect on the scaling relationship is more pronounced in case of minimum SAT, wherein the hotter (cold) seasons are noticed with negative (positive) sensitivity across the country.

Extreme precipitation can be better described by sub-daily temperature conditions before the start of storm events. Spatially more consistent scaling pattern is obtained between the sub-daily precipitation and surface air and dew point temperature across the country. The Western Ghats region is consistently noticed with positive scaling association, whereas, rest of the country exhibited the peak type mostly. However, SAT considered up to 6-h prior to the precipitation might not reflect the actual response of precipitation towards the temperature increase, possibly due to the prevailing cloudy conditions preceding the precipitation event. Consistent negative scaling is noticed over the eastern peninsular region irrespective of the time lags. Like the scaling daily DPT, the sub-daily DPT also showed positive scaling over the peninsular regions mostly and the area with positive scaling increases with the time lags. The dew point temperature is a robust indicator of available moisture and precipitation and shows consistency across the daily and sub-daily time scales. However, in case of SAT, the sub-daily scale analysis provides more robust and justifiable scaling across the country than that on the daily scale, indicating the need towards the consideration of sub-daily variations in the temperature conditions.

In brief, the findings from this study deliver useful insights on annual and season-wise characteristics of the relationship between different categories of precipitation and temperature in different regions across the country on daily and sub-daily scales. With these findings, assessment of precipitation events under future warming may be a potential future scope of this study.

CRediT authorship contribution statement

Subhasmita Dash: Formal analysis, Software, Validation, Writing – original draft. **Rajib Maity:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is freely accessible from the mentioned sources (refer to the Data and Methods section).

Acknowledgement

Authors wish to acknowledge the partial support from the sponsored projects supported by Ministry of Earth Science, Government of India.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2022.106601.

References

Aleshina, M.A., Semenov, V.A., Chernokulsky, A.V., 2021. A link between surface air temperature and extreme precipitation over Russia from station and reanalysis data. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/ac1cba.

Ali, H., Mishra, V., 2017. Contrasting response of rainfall extremes to increase in surface air and dewpoint temperatures at urban locations in India. Sci. Rep. 7, 1–15. https://doi.org/10.1038/s41598-017-01306-1.

Ali, H., Mishra, V., 2018. Increase in subdaily precipitation extremes in India under 1.5 and 2.0 °C warming worlds. Geophys. Res. Lett. 45, 6972–6982. https://doi.org/10.1029/2018GL078689.

Ali, H., Fowler, H.J., Lenderink, G., Lewis, E., Pritchard, D., 2021a. Consistent Large-Scale Response of Hourly Extreme Precipitation to Temperature Variation over Land. Geophys. Res. Lett. 48 https://doi.org/10.1029/2020GL090317.

Ali, H., Peleg, N., Fowler, H.J., 2021b. Global scaling of rainfall with dewpoint temperature reveals considerable ocean-land difference. Geophys. Res. Lett. https://doi.org/10.1029/2021gl093798.

Berg, P., Haerter, J.O., Thejll, P., Piani, C., Hagemann, S., Christensen, J.H., 2009. Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature. J. Geophys. Res. Atmos. 114, 1–9. https://doi.org/10.1029/2009JD012008.

Berg, P., Moseley, C., Haerter, J.O., 2013. Strong increase in convective precipitation in response to higher temperatures. Nat. Geosci. 6, 181–185. https://doi.org/10.1038/ngeo1731.

Drobinski, P., Alonzo, B., Bastin, S., Da Silva, N., Muller, C., Ipsl, L.M.D., Polytechnique, E., Paris-saclay, U., Polytechnique, E., 2016. Scaling of precipitation extremes with temperature in the French Mediterranean region : what explains the hook shape ? J. Geophys. Res. Atmos. 121, 3100–3119. https://doi.org/10.1002/2015JD023497.Received.

Fischer, E.M., Knutti, R., 2012. Robust projections of combined humidity and temperature extremes. Nat. Clim. Chang. 3, 126–130. https://doi.org/10.1038/nclimate1682.

Gao, X., Zhu, Q., Yang, Z., Liu, J., Wang, H., Shao, W., Huang, G., 2018. Temperature dependence of hourly, daily, and event-based precipitation extremes over China. Sci. Rep. 8, 1–10. https://doi.org/10.1038/s41598-018-35405-4.

Gao, X., Guo, M., Yang, Z., Zhu, Q., Xu, Z., Gao, K., 2020. Temperature dependence of extreme precipitation over mainland China. J. Hydrol. 583, 124595 https://doi.org/10.1016/j.jhydrol.2020.124595.

Haerter, J.O., Berg, P., 2009. Unexpected rise in extreme precipitation caused by a shift in rain type? Nat. Geosci. 2, 372–373. https://doi.org/10.1038/ngeo523.

Hardwick Jones, R., Westra, S., Sharma, A., 2010. Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity. Geophys. Res. Lett. 37, 1–5. https://doi.org/10.1029/2010GL045081.

Herath, S.M., Sarukkalige, R., Van Nguyen, V.T., 2018. Evaluation of empirical relationships between extreme rainfall and daily maximum temperature in Australia. J. Hydrol. 556, 1171–1181. https://doi.org/10.1016/j.jhydrol.2017.01.060.

Huang, D., Zhu, J., Xiao, X., Cheng, J., Ding, Y., Qian, Y., 2021. Understanding the sensitivity of hourly precipitation extremes to the warming climate over eastern China. Environ. Res. Commun. 3 https://doi.org/10.1088/2515-7620/ac17e1.

Krishnan, R., Sabin, T.P., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B.N., Hourdin, F., Dufresne, J.L., Terray, P., 2016. Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. Clim. Dyn. 47, 1007–1027. https://doi.org/10.1007/s00382-015-2886-5.

Lenderink, G., Fowler, H.J., 2017. Hydroclimate: understanding rainfall extremes. Nat. Clim. Chang. 7, 391–393. https://doi.org/10.1038/nclimate3305.

Lenderink, G., Van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. Nat. Geosci. 1, 511–514. https://doi.org/10.1038/ngeo262.

Lenderink, G., Van Meijgaard, E., 2010. Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. Environ. Res. Lett. 5 (2) https://doi.org/10.1088/1748-9326/5/2/025208.

Lenderink, G., Mok, H.Y., Lee, T.C., Van Oldenborgh, G.J., Bilt, D., Observatory, K., Kong, H., 2011. Scaling and Trends of Hourly Precipitation Extremes in Two Different Climate Zones – Hong Kong and the Netherlands 3033–3041. https://doi.org/10.5194/hess-15-3033-2011.

Lochbihler, K., Lenderink, G., Siebesma, A.P., 2017. The spatial extent of rainfall events and its relation to precipitation scaling. Geophys. Res. Lett. 44, 8629–8636. https://doi.org/10.1002/2017GL074857.

Maity, R., 2022. Statistical Methods in Hydrology and Hydroclimatology. https://doi.org/10.1007/978-981-10-8779-0.

Mudbhatkal, A., Amai, M., 2018. Regional climate trends and topographic influence over the Western Ghat catchments of India. Int. J. Climatol. 38, 2265–2279. https://doi.org/10.1002/joc.5333.

Mukherjee, S., Aadhar, S., Stone, D., Mishra, V., 2018. Increase in extreme precipitation events under anthropogenic warming in India. Weather Clim. Extrem. 20, 45–53. https://doi.org/10.1016/j.wace.2018.03.005.

Naveendrakumar, G., Vithanage, M., Kwon, H.H., Chandrasekara, S.S.K., Iqbal, M.C.M., Pathmarajah, S., Fernando, W.C.D.K., Obeysekera, J., 2019. South Asian perspective on temperature and rainfall extremes: a review. Atmos. Res. 225, 110–120. https://doi.org/10.1016/j.atmosres.2019.03.021.

Pai, D.S., Sridhar, L., Rajeevan, M., Sreejith, O.P., Satbhai, N.S., Mukhopadhyay, B., 2014. Development of a new high spatial resolution (0.25° × 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam 65, 1–18. https://doi.org/10.54302/mausam.v65i1.851.

Pai, D.S., Sridhar, L., Badwaik, M.R., Rajeevan, M., 2015. Analysis of the daily rainfall events over India using a new long period (1901–2010) high resolution (0.25° × 0.25°) gridded rainfall data set. Clim. Dyn. 45, 755–776. https://doi.org/10.1007/s00382-014-2307-1.

Panthou, G., Mailhot, A., Laurence, E., Talbot, G., 2014. Relationship between surface temperature and extreme rainfalls: a multi-time-scale and event-based analysis*. J. Hydrometeorol. 15, 1999–2011. https://doi.org/10.1175/JHM-D-14-0020.1.

Papalexiou, S.M., Montanari, A., 2019. Global and regional increase of precipitation extremes under global warming. Water Resour. Res. 2018WR024067 https://doi.org/10.1029/2018WR024067.

Pumo, D., Noto, L.V., 2021. Exploring the linkage between dew point temperature and precipitation extremes: a multi-time-scale analysis on a semi-arid Mediterranean region. Atmos. Res. 254 https://doi.org/10.1016/j.atmosres.2021.105508.

Roderick, T.P., Wasko, C., 2020. An Improved Covariate for Projecting Future Rainfall Extremes ?, pp. 1–11. https://doi.org/10.1029/2019WR026924.

Rohini, P., Rajeevan, M., Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. Sci. Rep. 6, 1–9. https://doi.org/10.1038/srep26153.

Ross, R.S., Krishnamurti, T.N., Pattnaik, S., Pai, D.S., 2018. Decadal surface temperature trends in India based on a new high-resolution data set. Sci. Rep. 8, 2–11. https://doi.org/10.1038/s41598-018-25347-2.

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., Rajeevan, M., 2017. A threefold rise in widespread extreme rain events over central India. Nat. Commun. 8, 1–11. https://doi.org/10.1038/s41467-017-00744-9.

Schroeer, K., Kirchengast, G., 2018. Sensitivity of extreme precipitation to temperature: the variability of scaling factors from a regional to local perspective. Clim. Dyn. 50, 3981–3994. https://doi.org/10.1007/s00382-017-3857-9.

Seager, R., Naik, N., Vecchi, G.A., 2010. Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. J. Clim. 23, 4651–4668. https://doi.org/10.1175/2010JCLI3655.1.

Sharma, S., Mujumdar, P.P., 2019. On the relationship of daily rainfall extremes and local mean temperature. J. Hydrol. 572, 179–191. https://doi.org/10.1016/j.jhydrol.2019.02.048.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. 84 https://doi.org/10.1175/BAMS-84-9-1205, 1205-1217+1161.

Utsumi, N., Seto, S., Kanae, S., Maeda, E.E., Oki, T., 2011. Does higher surface temperature intensify extreme precipitation ? Geophys. Res. Lett. 38, 1–5. https://doi.org/10.1029/2011GL048426.

Vergara-Temprado, J., Ban, N., Schär, C., 2021. Extreme sub-hourly precipitation intensities scale close to the Clausius-Clapeyron rate over Europe. Geophys. Res. Lett. 48 https://doi.org/10.1029/2020GL089506.

Visser, J.B., Wasko, C., Sharma, A., Nathan, R., 2020. Resolving inconsistencies in extreme precipitation-temperature sensitivities. Geophys. Res. Lett. 47 https://doi.org/10.1029/2020GL089723.

Vittal, H., Ghosh, S., Karmakar, S., Pathak, A., Murtugudde, R., 2016. Lack of dependence of Indian summer monsoon rainfall extremes on temperature: an observational evidence. Sci. Rep. 6, 1–12. https://doi.org/10.1038/srep31039.

Wang, G., Wang, D., Trenberth, K.E., Erfanian, A., Yu, M., Bosilovich, M.G., Parr, D.T., 2017. The peak structure and future changes of the relationships between extreme precipitation and temperature. Nat. Clim. Chang. 7, 268–274. https://doi.org/10.1038/nclimate3239.

Yong, Z., Xiong, J., Wang, Z., Cheng, W., Yang, J., Pang, Q., 2021. Relationship of extreme precipitation, surface air temperature, and dew point temperature across the Tibetan Plateau. Clim. Change 165. https://doi.org/10.1007/s10584-021-03076-2.

Zhou, C., Wang, K., 2017. Quantifying the sensitivity of precipitation to the long-term warming trend and interannual-decadal variation of surface air temperature over China. J. Clim. 30, 3687–3703. https://doi.org/10.1175/JCLI-D-16-0515.1.