A framework to incorporate spatiotemporal variability of rainfall extremes in summer monsoon declaration in India

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Keywords: drought, wet extremes, Indian monsoon

Abstract

The Indian summer monsoon rainfall is a lifeline for agricultural activities and the socio-economic development of more than 1 billion people. All-India averaged summer monsoon rainfall has about 10% variability from its long-term mean. A departure of all-India averaged precipitation within ±10% is declared a normal summer monsoon. Using the long-term (1901–2021) gridded rainfall observations, we highlight the limitations in the current approach to the declaration of the normal summer monsoon, which ignores the role of spatiotemporal variability of rainfall. Dry and wet extremes within the same monsoon season can lead to a normal monsoon. Moreover, different parts of the country face drought and wet extremes, while the summer monsoon can be declared normal. Considering the profound implications of dry and wet extremes on agricultural activities, we propose a novel framework to account for the rainfall variability in the declaration of the summer monsoon. The proposed framework accounts for the temporal variability through a combined severity coverage index, while spatial variability using a clustering approach. Based on the existing framework, we find that 84 years were declared normal in the last 121 years (1901–1921). However, 13 years (out of 84) were not normal based on the new framework due to dry and wet extremes occurring at different times and in different regions. The new framework of summer monsoon declaration can account for the occurrence of extremes and their implications for agriculture and water management.

1. Introduction

Indian summer monsoon rainfall is the lifeline for millions of people’s water availability and agricultural activities. India receives about 80% of the total annual rainfall during the four months (June–September) of the summer monsoon season. The summer monsoon season overlaps with one of the major crop-growing seasons (Kharif), and monsoon rain is a prominent water source for supporting agricultural activities (Gadgil and Gadgil, 2006; Gadgil and Kumar, 2006; Prasanna, 2014, Mishra et al, 2020). Failure of the summer monsoon leads to meteorological droughts hampering water availability and crop growth (Mishra, 2020). A substantial precipitation deficit in the summer monsoon season leads to agricultural and hydrological droughts affecting crop growth, food production, and reservoir storage. Prolonged summer monsoon rainfall breaks affect groundwater storage, with additional irrigation water requirements being only met by the groundwater pumping (Mukherjee et al, 2015, Asoka et al, 2017). The linkage between summer monsoon rainfall deficit and groundwater depletion in India has been well established (Asoka et al, 2017, Dangar et al, 2021). For instance, groundwater abstraction for irrigation increases substantially (Dangar and Mishra, 2021). On the other hand, surplus rainfall during the monsoon season increases the risk of flooding and challenges reservoir operations (Nagesh Kumar et al, 2009, Nanditha and
Mishra 2021). Therefore, both deficit and surplus summer monsoon rainfall cause detrimental impacts.

Several parts of the country, including the Indo-Gangetic Plain, western Ghats, and northeastern India, have experienced a significant decline in the summer monsoon rainfall over the last few decades (Krishnan et al. 2016, Asoka et al. 2018, Singh et al. 2019, Mishra 2020). The declining trends in the summer monsoon rainfall in these regions caused droughts affecting water resources and flood production (Mishra 2020). On the other hand, parts of western and central India have experienced an increase in summer monsoon rainfall (Asoka et al. 2018). The increased summer monsoon precipitation in these regions is primarily due to extreme rainfall, which contributes to flooding (Roxy et al. 2017, Mukherjee et al. 2018). Additionally, the variability of rainfall extremes during the monsoon season has increased (Ghosh et al. 2011), causing dry and wet spell frequency (Ghosh et al. 2011, Singh et al. 2014).

The India Meteorological Department (IMD) monitors the progress and state of the summer monsoon every year. At the end of the monsoon season, IMD declares the overall condition of the summer monsoon as drought (precipitation deficit), surplus, and normal (https://mausam.imd.gov.in/imd_latest/contents/monsoon_activity.php). Since the long-term variation in the summer monsoon rainfall is about ±10% from its mean, a threshold of 10% is used to declare drought or surplus monsoon (Gadgil and Gadgil 2006). For instance, if the rainfall deficit at the end of the season is more than 10%, then the year is declared a drought. On the other hand, if the summer monsoon rainfall exceeds 10%, the monsoon is surplus. All-India averaged summer monsoon rainfall anomaly within ±10% is considered normal. This declaration of the summer monsoon based on rainfall departure or more than 10% (one standard deviation) from its long-term mean is based on the Normal distribution of summer monsoon rainfall anomalies. Therefore, about 67% of years fall in the Normal category of the monsoon. Moreover, the definition of the normal monsoon is based on the statistical sense and not necessarily based on the impact of the rainfall variability during the summer monsoon season or in different parts of India. Therefore, this declaration of different states of the summer monsoon is based on all-India averaged rainfall and does not account for the spatial and temporal variability (i.e. spatial and intra-seasonal rainfall variability). As expected, even during the normal monsoon years, there can be considerable spatial variability in rainfall in the country. IMD provides rainfall anomalies at the district level to report the spatial variability in the summer monsoon rainfall. Similarly, IMD also develops weekly and monthly rainfall totals at district and sub-divisional levels along with the time series of active and break spells to account for temporal variability in summer monsoon rainfall.

All the information related to summer monsoon rainfall and its spatial and temporal variability prepared by IMD is available in the public domain. However, the declaration of the summer monsoon ‘Normal’ based on the standardized departure of all-India averaged rainfall from its long-term mean at the end of the season mean does not account for the anomalous nature of rainfall due to spatiotemporal variability.

Both dry and wet extremes can occur during the same monsoon season (Singh et al. 2014, 2019), which can be declared as normal based on the all-India averaged rainfall anomalies. The fundamental issue with the existing approach is that drought and extreme wet periods within the same monsoon season can have profound implications. However, the declaration of the normal monsoon does not account for that (Rajeevan et al. 2010). Similarly, drought and wet extremes can occur in different parts of the country during the same monsoon season with detrimental impacts. However, the current approach to the monsoon declaration does not account for the spatial and temporal variability of the summer monsoon rainfall. In addition, drought and wet extremes have affected different parts of the country in the last few decades (Mishra et al. 2016, Roxy et al. 2017). For instance, Mishra et al. (2016) reported a decline in the summer monsoon rainfall over the Indo-Gangetic Plain while the monsoon rainfall has increased over western India (Asoka et al. 2018). Roxy et al. (2017) reported a three-fold rise in widespread extreme precipitation events during the monsoon season over central India. Therefore, the observed changes in the total rainfall and rainfall extremes during the summer monsoon season indicate the prominent role of spatial variability during the season. Similarly, Sahany et al. (2018) found a decline in the wet season duration and later occurrence of peak rainfall in the monsoon season. Intraseasonal variability of the summer monsoon rainfall is driven by active and break spells (Krishnamurthy and Shukla 2000, Rajeevan et al. 2010, Pai et al. 2009, 2016). Spatial and temporal variability in the summer monsoon rainfall and application of the indices have been widely discussed in previous studies (Kulkarni et al. 1992, Dwivedi et al. 2019). Notwithstanding the importance of rainfall variability, the declaration of the monsoon does not account for these spatiotemporal features. Here we provide a coherent framework to account for the temporal and spatial variability and hydrologic extremes in the monsoon declaration. We contrast and demonstrate the applicability of this new approach with an existing IMD approach at an all-India scale using a long-term (1901–2021) precipitation. We do not aim to diagnose the mechanism of anomalous summer monsoon rainfall. Rather, we use the existing criteria that defines surplus, deficit, and normal monsoon based on the long-term rainfall anomalies. We, then, propose a framework to incorporate the spatial and temporal variability of summer monsoon rainfall.
in the declaration. If the summer monsoon rainfall is deficit/surplus, a considerable part of the country experiences drought/extreme wet conditions. However, during the normal monsoon years, a significant part of the country may face both dry and wet extremes, which is not accounted in the declaration.

2. Data and methods

We obtained daily gridded precipitation at 0.25° spatial resolution, which was developed using more than 6900 observational stations across India (Pai et al. 2014). The high-resolution gridded precipitation (Pai et al. 2014) is an updated version of the dataset available at a relatively coarser resolution (1°, Rajeevan et al. 2006). The gridded precipitation captures spatial and temporal variability of the summer monsoon in India, especially the high rainfall in the core monsoon region and low rainfall in the semi-arid and arid areas of western India. The high rainfall in the foothills of the Himalayas and the Western Ghats are well resolved in the gridded dataset. The dataset has been widely used for hydrometeorological studies over India (Prakash et al. 2016, Shah and Mishra 2020, Mishra et al. 2021b).

We used daily precipitation to estimate weekly rainfall during the summer monsoon season (June-September). We identified 18 weeks during the monsoon season, and each week’s precipitation total was estimated. Moreover, we calculated total precipitation during the summer monsoon season to assess the all-India averaged rainfall anomaly against the long-term (1901–2021) mean. All-India averaged precipitation anomaly less than –10% were identified as the monsoon season droughts. On the other hand, the years with rainfall anomalies of more than 10% of the long-term mean were categorized as surplus monsoon years. Therefore, normal, surplus, or deficit monsoon declaration is based on the departure of more than one standard deviation. One standard deviation of the long-term summer monsoon rainfall is about 10% of the long-term mean.

We estimated precipitation anomalies for each week during the summer monsoon season to examine the temporal variability of the monsoon. Weekly precipitation anomalies were estimated against the long-term (1901–2021) mean of rainfall for the corresponding week. Drought/wet categories were identified as the monsoon season droughts. On the other hand, the years with rainfall anomalies of more than 10% of the long-term mean were categorized as surplus monsoon years. Therefore, normal, surplus, or deficit monsoon declaration is based on the departure of more than one standard deviation. One standard deviation of the long-term summer monsoon rainfall is about 10% of the long-term mean.

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We estimated a standardized precipitation index (SPI, Mckee et al. 1993) to examine the monsoon season drought in India and the selected regions. Since our focus is mainly on characterizing meteorological states, the role of temperature/potential evapotranspiration was not considered. We used the Standardized Drought Analysis Toolbox (Farahmand and AghaKouchak 2015) to estimate weekly and monthly SPI. Instead of a standard probability distribution, we used the empirical probability to derive nonparametric SPI using the Gringorten plotting position (Gringorten 1963, Farahmand and AghaKouchak 2015). We used SPI to examine the drought conditions during the summer monsoon season. For instance, a four month SPI at the end of September was used to analyze drought during the summer monsoon season. Similarly, a weekly SPI was used to investigate the drought/wet conditions for the corresponding week. Drought/wet categories were defined using the range of SPI as described in Svboda et al. (2002).

We obtained sea surface temperature (SST) data available at 2° spatial, and monthly temporal resolution from Extended Reconstructed SST v5 (Huang et al. 2017, 2018). Using monthly SST, the SST departure field was estimated after subtracting the global mean monthly SST from each grid as in Mishra et al. (2012). We calculated SST anomalies for the summer monsoon (June–September) season. Geopotential height and wind (u, v) at 850 hPa were obtained from ERA-20C reanalysis for 1900–2010 (Poli et al. 2016) and ERA5 (Hersbach et al. 2020) for the 2011–2021 periods. We constructed climatological and anomaly fields using geopotential height and wind datasets for the selected years.

The impacts of drought or prolonged wet periods are often measured using the severity and area affected. Drought can be categorized into: Abnormally dry (D1), moderate drought (D2), severe drought (D3), extreme drought (D4), and exceptional drought (D5). The area under different drought categories can be linked with the drought impacts. For instance, more severe consequences can be expected if a large area is under exceptional drought. As drought involves several aspects (intensity, duration, and coverage), it is difficult to compare the severity of two drought events in the same region (Martin et al. 2020). Drought Severity Coverage Index (DSCI, Akyuz 2017, Johnson et al. 2020, Smith et al. 2020) was designed to provide an integrated measure considering the area under different drought categories for each week. A weight of 1–5 was assigned to the drought area under each category (D1–D5), multiplied by the drought area (%) under different categories:

\[ DSCI = 1(D1) + 2(D2) + 3(D3) + 4(D4) + 5(D5) . \]  

Similarly, we estimated the Wet Severity Coverage Index (WSCI) using the area under different wet categories (W1–W5) as:

\[ WSCI = 1(W1) + 2(W2) + 3(W3) + 4(W4) + 5(W5) . \]  

DSCI and WSCI were estimated for 18 weeks during the summer monsoon season June-September (IJAS). Active and break spells and associated dry and wet extremes within the summer monsoon season are driven by low-pressure systems and cyclonic storms,
which are short-time scale systems (Ajayamohan et al 2010, Revadekar et al 2016, Tomas et al 2021). Ajayamohan et al (2010) showed that extreme rainfall events during the monsoon season are strongly associated with synoptic disturbances. However, at a seasonal time scale, extreme rainfall events are independent of seasonal mean rainfall. We incorporated temporal variability of dry and wet extremes during the monsoon season using cumulative DSCI and WSCI for the 18 week period. Cumulative DSCI and WSCI at the end of the monsoon season represent the overall drought and surplus/wet summer monsoon conditions, respectively (figure S1). We estimated Combined Severity Coverage Index (CSCI) as the sum of cumulative DSCI and WSCI for the summer monsoon season. Therefore, CSCI accounts for the spatial-temporal variability of the dry and wet conditions during the monsoon season. The departure of more than one standard deviation of CSCI can be considered as the monsoon season with high temporal variability in the combined dry and wet extremes. Hence, the years with the CSCI of more than one standard deviation can be considered ones that experience extremes during the summer monsoon season regardless of the normal monsoon declaration.

We identified homogeneous precipitation clusters in India (Shah and Mishra 2020) to account for the spatial variability of rainfall during the summer monsoon season (figure S2). A novel spatial clustering algorithm that uses traditional interpoint distance metric (Singh and O’Gorman 2014), ensuring the minimum size of each cluster was used (Sanderson et al 2019). We identified eight clusters with similar drought characteristics in India (Shah and Mishra 2020). A detailed description of clustering can be found in Sanderson et al (2019) and Shah and Mishra (2020). Clusters that experienced drought (SPI < −0.8) and wet conditions (SPI > 0.8) for each summer monsoon season were identified. During the summer monsoon, clusters that experienced extreme wet conditions (SPI > 1.5) were also identified. Dry extremes are often widespread, while wet extremes are localized. To avoid the localized impact of extreme rainfall in a cluster, we considered SPI threshold exceeding 1.5 for wet extremes in a cluster. On the other hand, a cluster was considered affected by dry extremes if the area averaged SPI was less than −0.8.

3. Results

3.1. The role of temporal variability

First, we examined the temporal variability of India’s 2021 summer monsoon season rainfall. The temporal variability of weekly rainfall shows that India experienced both dry and wet extremes during the summer monsoon season (figure 1(a)). As the all-India averaged precipitation anomaly fell within ±10% (one standard deviation), the 2021 summer monsoon was declared normal by the IMD (Gadgil and Gadgil 2006). The weekly precipitation anomaly (%) show wet condition in the early summer monsoon season, followed by the two long rainfall breaks during July and August (figure 1(a)). Extreme precipitation in several parts of the country created wet conditions at the end of the summer monsoon season (figure 1(a)). The temporal variability of rainfall shows extreme dry and wet conditions in the same monsoon season. We estimated weekly DSCI and WSCI for the summer monsoon season of 2021, which show high DSCI during July and August while high WSCI during June and September. Several parts of the country, especially central India, experienced extreme to exceptional category drought during the fifth and tenth week of the 2021 summer monsoon season. In contrast, a large part of the country experienced extreme wet conditions during the 17th and 18th weeks of the monsoon season. Both extreme dry and wet conditions posed challenges associated with drought and floods affecting water resources, agriculture, and the socio-economic well-being of the people. Notwithstanding the severe implications, the 2021 summer monsoon normal declaration based on the statistical framework raises questions on the methodology associated with the declaration that does not account for intra-seasonal rainfall variability.

Next, we contrast the spatial-temporal variability of rainfall during the driest and wettest summer monsoon based on the all-India averaged precipitation anomalies from 1901 to 2021 (figure S3). The driest summer monsoon occurred in 1972, with around 22.6% precipitation deficit from the long-term mean. On the other hand, the wettest summer monsoon was recorded in 1917, with 21.5% surplus rainfall. Most of India witnessed drought during the summer monsoon of 1972, which was more prominent in the central region (figure S3(a)). For instance, a large part of Maharashtra experienced an exceptional drought in 1972 (figure S3(a)). The driest summer monsoon experienced most of the weeks dry with precipitation anomalies around −70% (figure S3(b)). Only a few weeks witnessed positive precipitation anomalies during the summer monsoon season. The temporal variability of precipitation deficit was reflected in the cumulative DSCI, which was considerably higher during the 7–10th weeks of the monsoon season (figure S3(c)). Monsoon weeks with a moderate rainfall surplus resulted in moderate cumulative WSCI during 1972 (figure S3(d)). A large part of India witnessed a surplus summer monsoon during 1917, with western India being exceptionally wet (figure S3(e)). Except for the three weeks, the entire monsoon season experienced a surplus monsoon, which was more prominent during the end of the season (figure S3(f)). Temporal variability of the extreme wet season for the 1917 summer monsoon is...
Figure 1. Temporal variability of precipitation during the 2021 summer monsoon season (June–September) in India. (a) Weekly all-India precipitation anomaly (%) during the monsoon season of 2021, (b) weekly drought severity coverage index (DSCI) during the monsoon season of 2021, and (d) weekly wet severity coverage index (WSCI) during the summer monsoon of 2021. (d)–(g) Standardized Precipitation Index (SPI) for the 5th, 10th, 17th, and 18th week of the summer monsoon season showing drought and wet conditions. Overlaid black polygons in (d)–(g) show major clusters for precipitation variability during the summer monsoon season.

reflected in the cumulative DSCI and WSCI (figures S3(g) and (h)).

We examined the linkage between precipitation anomalies during the summer monsoon and cumulative DSCI and WSCI for the 1901–2021 period (figures 2, S4 and S5). Cumulative DSCI and WSCI capture the temporal variability of both dry and wet extremes during the monsoon (figures S1, S4, and S5). During 121 years, 23 experienced more than a 10% deficit in the summer monsoon season precipitation and were declared drought years. During the last 121 years, the top five worst drought years based on the failure of summer monsoon rainfall occurred in 1972 (−22.6% deficit), 1918 (−22%), 2002 (−20.6%), 2009 (−19.8%), 1979 (−19.4%) (figure 2(a)). Similarly, 14 years were surplus monsoon years with precipitation exceeding 10% of its long-term mean. The wettest five years were 1917 (21.6%), 1988 (16.4%), 1975 (16%), 1961 (15.8%), and 1933 (15.1%) (figures 2(a) and (b)). All the drought years witnessed higher cumulative DSCI indicating the prolonged monsoon breaks that put a large part of the country under drier conditions (figures 2(c), (d) and S1). While the driest summer monsoon of 1972 also had the highest cumulative DSCI (1957.6), the cumulative DSCI showed a negative relationship ($r = −0.88$) with the monsoon season precipitation anomaly. For instance, the overall rainfall deficit during 2002 (−20.6%) is higher than in 2018 (−13.7%). 2018 has a higher cumulative DSCI than 2002, indicating the importance of the temporal variability of the summer monsoon rainfall. Similarly, cumulative WSCI is strongly linked ($r = 0.89$) with precipitation anomaly during the summer monsoon season (figure S1). Our results show that cumulative DSCI and WSCI capture the temporal variability of summer monsoon season precipitation and area affected by drought and wet extremes. In contrast, the declaration of the summer monsoon based on the all-India total summer monsoon rainfall does not account for the rainfall variability.

We combined the cumulative DSCI and WSCI for the summer monsoon season to obtain the temporal development of the CSCI over the 1901–2021 period (figures 2(g) and (h)). A high value of CSCI indicates a robust temporal variability of dry and wet extremes during the monsoon season. High CSCI during the summer monsoon season can be due to high cumulative DSCI or WSCI indicating the dominance of dry or wet extremes. On the other hand, relatively higher cumulative DSCI and WSCI can also contribute to high CSCI in case of domination of both dry and wet extremes during the same monsoon season, as in the summer monsoon of 2021. When drought and wet extremes occur at different times during the monsoon season, precipitation totals over the entire season may not capture the influence of the intra-seasonal variability. In these cases, the summer monsoon is likely to be declared normal based on the statistical framework followed by IMD, notwithstanding the profound implications of dry and wet extremes.
Seven years were reported as drought from the top ten CSCI years (figures 2(g) and (h)). The other three years (2005, 2006, and 1991) were normal monsoon years. Therefore, our results show that during these three years, the country most likely witnessed drought and wet extremes at different times during the monsoon season. Overall, we demonstrate that high temporal variability during the summer monsoon can cause both dry and wet extremes, which are not usually considered in the declaration of the normal summer monsoon based on the current framework.

### 3.2. The role of spatial variability

Next, we examined the role of spatial variability of the summer monsoon rainfall on the monsoon declaration (figure 3). For instance, if different regions experience dry and wet extremes, all-India averaged precipitation during the summer monsoon season can be normal based on the all-India rainfall anomaly at the end of the season. Both dry and wet extremes can affect the affected regions, which is not reflected if the monsoon is declared normal. We divided the country into eight clusters (figure S2) based on the long-term precipitation (Shah and Mishra 2020) to understand the regional variability of dry and wet extremes during the summer monsoon season. Both drought and surplus monsoon years exhibited negative and positive 4 month SPI at the end of the monsoon season (figure 3(a)). Out of 121 years (1901–2021), 84 years were declared normal monsoon. Several clusters experienced drought (SPI < −0.8) during the normal monsoon in India (figure 3(b)). All eight clusters witnessed drought in one year (figure 3(b), table S1). Moreover, four regional clusters (C1, C6, C7, and C8) experienced drought in 12 or more years during the 84 normal monsoon years. We identified years in which clusters experienced drought, and the summer monsoon was declared normal. Our results show that a few clusters experienced extreme to exceptional category droughts, which may have posed severe water management and agriculture challenges. For instance, during the normal monsoon years, two
Figure 3. Spatial variability of drought during the normal summer monsoon in India, 1901–2021. (a) All-India averaged four month standardized precipitation index (SPI) for the summer monsoon season for 1901–2021 period. Red bars in (a) show drought years with all-India averaged rainfall deficit more than 10% during the summer monsoon season, blue bars in (a) show surplus years with precipitation anomaly more than 10%. Gray bars in (a) show the normal monsoon years. (b) Number of years when clusters experienced drought (SPI < −0.8) during the normal summer monsoon during 1901–2021 period. (c)–(j) Four month SPI at the end of September for eight clusters in India. Red bars show the years when the summer monsoon was declared normal and clusters experienced drought. Geographical location of the clusters can be seen in the supplemental figure S1.

or more clusters experienced drought 22 times out of the total 84 years. Eleven times three or more clusters experienced drought during the normal monsoon years. Similarly, different parts of the country witness extreme wet conditions during the summer monsoon, which may not reflect the normal monsoon declaration for the 2021 monsoon season.

We identified five declared normal years during which four or more clusters were under drought (SPI < −0.8) (figure 4). The summer monsoon was declared normal in 1925 (precipitation anomaly = −3.1%), 1928 (−8.6%), 1939 (−5.5%), 1974 (−8.4%), and 2017 (−5.6%) during the last 120 years (figure 4). During the monsoon season of 1925, a large part of western India was affected by drought, while the central-eastern part received a rainfall surplus. Out of eight, four clusters (C1, C3, C5, and C6) witnessed drought, while two (C2 and C7) witnessed wet conditions (figures 4(a) and (b)). One cluster (C7) experienced extreme wet conditions as the four month SPI at the end of the monsoon season exceeded 1.5 (figure 4(b)). Drought and wet conditions in different parts of the country contributed to an overall monsoon rainfall anomaly of −3.1%. North-central and parts of peninsular India were under drought, while northeastern and a few other regions were moderately wet during the 1928 monsoon (figures 4(c) and (d)). Four clusters were under drought, while none experienced wet conditions during the summer monsoon of 1928 (figure 4(d)). We also found
Figure 4. Spatial variability of drought and wet clusters during the normal summer monsoon years in India. (a) Four month SPI at the end of the summer monsoon season of 1925, (b) four month SPI of eight clusters at the end of the summer monsoon season in 1925. Red and blue bars show the clusters that experienced drought and wet conditions during the monsoon, respectively. Figures (c) and (d) same as (a) and (b) but for the monsoon season of 1928, (e) and (f) same as (a) and (b) but for the monsoon season of 1939, (g) and (h) same as (a) and (b) but for the monsoon season of 1974, and (i), (j) same as (a), (b) but for the monsoon season of 2017.
considerable spatial variability in precipitation during the monsoon season of 1939 (figures 4(e) and (f)). For instance, western India experienced extreme drought while the eastern part received surplus monsoon rainfall in 1939 (figure 4(e)). Four clusters (C1, C2, C4, and C5) were under drought, while one (C8) experienced extreme wet conditions (SPI > 1.5).

Similarly, in 1974, western and part of eastern India experienced extreme drought during the summer monsoon season (figures 4(g) and (h)). On the other hand, northeastern India received surplus monsoon rainfall in 1974. Six clusters (C1–C5 and C7) were under drought, while three (C1, C5, and C7) experienced extreme drought (figure 4(h)). On the other hand, one cluster (C8) received surplus monsoon rainfall (SPI > 2.5). The exceptional wet conditions in the northeastern region contributed to reducing the all-India averaged deficit in the summer rainfall, and consequently, the whole monsoon season was declared normal. For example, the case of the 2017 summer monsoon was declared normal given that the precipitation deficit was less than 10%, while at the regional scale, different clusters experienced hydrologic extremes (figures 4(i) and (j)). The north-central part was affected by drought, while western India received surplus monsoon rainfall (figure 4(i)). Four clusters witnessed drought. At the same time, one (C1) experienced wet conditions during the monsoon of 2017 (figure 4(j)).

We examined the temporal variability of the normal monsoons (1925, 1928, 1939, 1974, and 2017), which had four or more clusters under drought (figure S6). All the five years experienced dry and wet monsoon weeks exhibited by the weekly precipitation anomalies. Weekly DSCI and WSCI agree with the precipitation anomalies (figure S6). Overall, drought and wet conditions in different parts of the country during the same monsoon season can lead to the declaration of the normal summer monsoon.

### 3.3. Framework to incorporate spatial and temporal variability

The current methodology to declare the summer monsoon normal is based solely on the all-India averaged precipitation anomaly. As one standard deviation of India’s long-term summer monsoon rainfall is about 10% of its mean, the departure beyond 10% is declared as drought or surplus monsoon. Therefore, if the all-India averaged summer monsoon precipitation anomaly is within ±10%, the monsoon is declared normal regardless of its temporal and spatial variability. However, the method of declaring the summer monsoon solely based on a statistical framework has issues as it does not account for the temporal and spatial variability of the summer monsoon precipitation in India. Both temporal and spatial variations in rainfall can considerably affect water availability, agriculture, and infrastructure. Our results show that the temporal variability of the summer monsoon rainfall can lead to drought and wet extremes during the same season, impacting various sectors. On the other hand, droughts and floods can occur in different parts of the country and deficit, and surplus summer monsoon rainfall anomalies can cancel each other out, leading to a normal monsoon.

Accounting for spatial and temporal variability of the summer monsoon rainfall is essential to examining the implications of drought and wet extremes in India. We estimated cumulative DSCI and WSCI that measure drought and wet extremes during the summer monsoon season. The CSCI integrates dry and wet extremes during the 18 weeks of the summer monsoon season. Thus, CSCI measures the temporal variability of the summer monsoon season precipitation. Therefore, the departure of CSCI with more than one standard deviation can be considered a basis for identifying the summer monsoon season with high temporal variability. Any year with less than 10% departure from its long-term mean should have CSCI departure less than or equal to one standard deviation to be considered normal from the long-term mean and temporal variability perspective. As there have been several years since the summer monsoon was declared normal, several clusters experienced drought and wet extremes. To account for the spatial variability of the summer monsoon season, we used a 4 month SPI for different regional clusters at the end of September. Out of the total of eight clusters, if more than three clusters experience drought (SPI < −0.8) or extreme wet (SPI > 1.5) conditions during the summer monsoon season, the year can then not be declared as the normal monsoon. Therefore, we recommend three-step criteria to examine if the summer monsoon rainfall was normal or not, including (1) all-India averaged summer monsoon rainfall departure should be within ±10%, (2) standardized departure of CSCI should be less than 1, and (3) not more than three clusters should be under drought or extreme wet conditions.

To further illustrate this aspect, we identified 13 years declared normal based on the all-India averaged summer monsoon rainfall (table S2), with summer rainfall anomalies within ±10% of their long-term mean. Out of these 13 summer monsoon seasons, eight (1962, 1971, 1984, 1991, 2001, 2005, 2006, and 2008) summer monsoon had more than one standard deviation of CSCI, which indicate the high intra-seasonal rainfall variability leading to severely dry and wet conditions. We estimated the area under drought and wet conditions each week during the summer monsoon season (figure S7). We find drought and wet conditions affected the country during the summer monsoon season. Therefore, drought and wet extremes occurred, which might have implications for water resources and agriculture. Similarly, five (1925, 1928, 1939, 1974, and 2017) out of these thirteen years had high spatial variability...
of the summer monsoon season. More than three clusters witnessed drought or extreme wet conditions in all five years. We estimated anomalies of geopotential height (850 hPa), wind (850 hPa), and SST during the summer monsoon season for these 13 years (figures S8–S10, table S3) to examine the anomalous patterns in SST and atmospheric fields. While these anomaly fields do not represent intra-seasonal (or temporal) variability in rainfall during the summer monsoon season, these exhibit abnormal conditions during the monsoon season. During the summer monsoon season, westerly winds transport moisture from the Indian ocean to land due to low pressure/ geopotential height in the northern and central parts of the country as shown by climatological fields constructed for the 71 normal years during 1901–2021 (figure S8). We find that several years (among 13) experienced positive SST anomalies over the Pacific Ocean (figures S9 and S10). Warmer SST anomalies over the Pacific are linked with a reduction in the summer monsoon rainfall over India (Kumar et al 1999, Mishra et al 2012). In a few years (1971, 1974, 1962, and 2001), cool SST anomalies were observed over the Pacific Ocean during the summer monsoon season. Atmospheric anomalies of geopotential height and wind do not show a consistent pattern for all the selected years, which is expected (figures S9 and S10) as these can be influenced by both temporal and spatial variability in the monsoon rainfall. However, positive geopotential anomalies and anticyclonic wind patterns can be seen for the years that witnessed drought in some parts of the country (figures S9 and S10). As anomalies are based on the seasonal mean, these may not capture the temporal variability of the summer monsoon rainfall reflected by the cumulative CSCI. Moreover, drought and wet extremes during these years did not affect the entire country. Therefore, unlike in the previous studies (Webster and Yang 1992, Wang et al 2008), relatively stronger monsoon circulation anomalies were not observed. Overall, incorporating spatial and temporal variability of dry and wet extremes in the monsoon declaration can be essential for understanding the impacts of extremes in India.

4. Summary and conclusions

India experiences droughts and floods during the summer monsoon season, impacting water availability, agricultural activities, and the socio-economic well-being of millions of people. Moreover, drought and wet extremes can occur during the same monsoon season. However, the temporal and spatial variability and occurrence of drought and wet extremes are not accounted for in the normal summer monsoon declaration. Out of 121 years, 84 summer monsoon seasons were declared normal. On the other hand, 23 years were drought years, and 14 years experienced surplus monsoon. The drought years 1972, 1918, and 2002 experienced the highest precipitation deficit during the summer monsoon. The 1917 summer monsoon was the wettest, with 21.6% more rainfall than its long-term mean. Drought and surplus years affected a large part of the country. However, a profound temporal and spatial variability in rainfall and associated extremes was noted during the normal monsoon years. For instance, in the summer monsoon of 2021, the initial and final phases of the summer monsoon were wetter than normal, while a large part of the country was affected by drought during the mid-season. However, the 2021 summer monsoon was declared normal based on rainfall anomaly.

We accounted for the temporal and spatial variability of the summer monsoon using a CSCI and clustering approach. The occurrence of wet and drought extremes during different times of the summer monsoon season was estimated using the cumulative WSCI and DSCI, respectively. Similarly, we identified eight homogenous clusters based on the long-term summer monsoon rainfall. Out of 84 normal monsoon years, we found that 13 had high temporal and spatial variability that was not accounted for as the declaration was based on the rainfall anomaly only. During the five years, more than three (out of a total eight) clusters experienced drought or extreme wet conditions. Moreover, in the remaining eight years, the standardized departure of CSCI was more than one, indicating high temporal variability of rainfall during the summer monsoon season. Around 1000 people lost their lives due to extreme precipitation and floods in India and considerable damage to agriculture in the 2017 monsoon, which was declared normal (DWE 2017). Similarly, around 2051 people lost their lives due to floods and heavy rain during the summer monsoon season of 2005 (DWE 2005). Gujarat and Maharashtra states were the worst affected. However, the summer monsoon was declared normal, with a surplus precipitation of 9.6%. Part of the northeastern region witnessed moderate to severe drought during the summer monsoon of 2005. During the normal summer monsoon of 2008, 1800 people lost their lives due to floods (DWE 2008). Therefore, our findings highlight that spatial and temporal variability in mean and extreme rainfall must be incorporated in the declaration of the summer monsoon.

The proposed framework can be used to examine the spatial and temporal variability of extremes during the monsoon season for any year, regardless of whether a year is normal. For instance, cumulative WSCI can provide the role of temporal variability of wet extremes for a surplus monsoon year. At the same time, the number of clusters with positive SPI (SPI greater than +1.5) can highlight the regions that witnessed wet extremes during the summer monsoon season. On the other hand, cumulative DSCI can highlight the role of the temporal variability of dry extremes during a deficit monsoon year. The clusters
with a deficit (SPI less than $-0.8$) can help us identify the regions affected by drought. Based on the findings, we conclude the following:

- The existing declaration of the summer monsoon rainfall condition is based on the all-India averaged rainfall at the end of the season. All India precipitation anomalies above 10% and less than $-10\%$ represent the drought and surplus monsoon season. The normal summer monsoon is declared if the all-India average rainfall anomaly is within $\pm10\%$ from its long-term mean.

- Prolonged active and break spells during the monsoon season led to wet and drought extremes, which can occur during the same season. Occurrences of drought and wet extremes at different times can still lead to a normal monsoon at the end of the season, notwithstanding the profound implications. The combined severity and coverage index (CSCI) incorporate temporal variability in the summer monsoon rainfall and associated extremes.

- Spatial variability of rainfall and drought/wet extremes is considered using the clustering approach. Any monsoon season to be declared normal should have two-thirds or more clusters free from drought or extreme wet conditions.

- Considering the all-India averaged precipitation anomaly, CSCI, and clustering approach, we identified 13 years that should not have been declared normal out of 84 normal monsoons during the last 121 years. The proposed framework considers the spatial and temporal occurrence of drought and wet extremes and can be essential for impact assessment.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

**Acknowledgments**

We acknowledge the funding from the Monsoon Mission, Ministry of Earth Sciences and UNICEF. Data availability from the India Meteorological Department (IMD) is greatly appreciated.

**Authors Contribution**

V M designed the study, conducted the analysis, and wrote the first draft. V M, A D T, and R K discussed the findings and contributed to final draft.

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**References**

Ayajamohan R S, Merryfield W J and Kharin V V 2010 Increasing trend of synoptic activity and its relationship with extreme rain events over Central India J. Clim. 23 1004–13

Akyuz F A 2017 Drought Severity and Coverage Index. United States Drought Monitor (Lincoln, NE: The University of Nebraska-Lincoln) (available at: https://droughtmonitor.unl.edu/About/AbouttheData/DSCI.aspx) (Accessed 4 May 2022)

Asoka A, Glesson T, Wada Y and Mishra V 2017 Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India Nat. Geosci. 10 109–17

Asoka A, Wada Y, Fishman R and Mishra V 2018 Strong linkage between precipitation intensity and monsoon season groundwater recharge in India Geophys. Res. Lett. 45 5536–44

Dangar S, Asoka A and Mishra V 2021 Causes and implications of groundwater depletion in India: a review J. Hydrol. 596 126103

Dangar S and Mishra V 2021 Natural and anthropogenic drivers of the lost groundwater from the Ganga River basin Environ. Res. Lett. 16 114009

Disastrous weather events 2005 Climate Research and Services, India Meteorological Department (IMD) Pune (available at: www.imdpune.gov.in/library/public/)

Disastrous weather events 2008 Climate Research and Services, India Meteorological Department (IMD) Pune (available at: www.imdpune.gov.in/library/public/)

Disastrous weather events 2017 Climate Research and Services, India Meteorological Department (IMD) Pune (available at: www.imdpune.gov.in/library/public/)

Dwivedi S, Uma R, Lakshmi Kumar T V, Narayanan M S, Pokhrel Sand RH Kripalani 2019 New spatial and temporal indices of India summer monsoon rainfall Theor. Appl. Climatol. 135 979–90

Farahmand A and Agha-Kouchak A 2015 A generalized framework for deriving nonparametric standardized drought indicators Adv. Water Resour. 76 140–5

Gadgil S and Gadgil S 2006 The Indian monsoon, GDP and agriculture Econ. Polit. Wky. 41 4889–95

Gadgil S and Rupa Kumar K 2006 The Asian monsoon—agriculture and economy The Asian Monsoon (Berlin: Springer) pp 651–83

Ghosh S, Das D, Kao S C and Ganguly A R 2011 Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes Nat. Clim. Change 2 86–91

Gringorten I I 1963 A plotting rule for extreme probability paper J. Geophys. Res. 68 813–4

Hershbach H et al 2020 The ERAS global reanalysis Q. J. R. Meteorol. Soc. 146 1999–2049

Huang B et al 2017 Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons J. Clim. 30 8179–205

Huang B et al 2018 Evaluating SST analyses with independent ocean profile observations J. Clim. 31 5015–30

Johnson L E, Geli H M E, Hayes M J and Smith K H 2020 Building an improved drought climatology using updated drought tools: a New Mexico food-energy-water (FEW) systems focus Front. Clim. 2 15

Krishnamurthy V and Shukla J 2000 Intraseasonal and interannual variability of rainfall over India J. Clim. 13 4366–77

Krishnan R, Sabin T P, Vellore R, Mujumdar M, Sanjay J, Goswami B N, Hourdin F, Dufresne J L and Terray P 2016 Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world Clim. Dyn. 47 1007–27
Kulkarni A, Kripalani R H and Singh S V 1992 Classification of summer monsoon rainfall patterns over India Int. J. Climatol. 12 269–80
Kumar K K, Rajagopalan B and Cave M A 1999 On the weakening relationship between the Indian monsoon and ENSO Science 284 2156–9
Martin J T et al 2020 Increased drought severity tracks warming in the United States’ largest river basin Proc. Natl Acad. Sci. USA 117 11328–36
Mckee T B, Doesken NJ and Kleist J 1993 The relationship of drought duration and duration to time scales 8th Conf. Appl. Climatol. pp 17–22
Mishra V 2020 Long-term (1870–2018) drought reconstruction in context of surface water security in India J. Hydrol. 580 124228
Mishra V, Aadhar S, Asoka A, Pai S and Kumar R 2016 On the frequency of the 2015 monsoon season drought in the Indo-Gangetic Plain Geophys. Res. Lett. 43 12102–12
Mishra V, Thirumalai K, Jain S and Aadhar S 2021b Unprecedented drought in South India and recent water scarcity Environ. Res. Lett. 16 054007
Mishra V, Thirumalai K, Singh D and Aadhar S 2020 Future exacerbation of hot and dry summer monsoon extremes in India npj Clim. Atmos. Sci. 3 1–9
Mukherjee A, Saha D, Harvey C F, Taylor R G, Ahmed K M and Bhanja S N 2015 Groundwater systems of the Indian sub-continent J. Hydrol. Reg. Stud. 4 1–14
Mukherjee S, Aadhar S, Stone D and Mishra V 2018 Increase in extreme precipitation events under anthropogenic warming in India Weather Clim. Extremes 20 45–53
Nagesh Kumar D, Ballarsingh F and Srinivasa Raju K 2009 Optimal reservoir operation for flood control using folded dynamic programming Water Resour. Manage. 24 1045–64
Nanditha J S and Mishra V 2021 On the need of ensemble flood forecast in India Water Secur. 12 100086
Pai D S, Bha te J, Sreejith O P and Hatwar H R 2009 Impact of MJO on the intraseasonal variation of summer monsoon rainfall over India Clim. Dyn. 36 41–55
Pai D S, Rajeevan M, Sreejith O P, Mukhopad hyay B and Sahthra S N 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
Pai D S, Sridhar L and Ramesh Kumar M R 2016 Active and break events of Indian summer monsoon during 1901–2014 Clim. Dyn. 46 3921–39
Polé P et al 2016 ERA-20C: an atmospheric reanalysis of the twentieth century J. Clim. 29 4083–97
Prakash S, Mitra A K, Pai D S and AghaKouchak A 2016 From TRMM to GPM: how well can heavy rainfall be detected from space! Adv. Water Resour. 88 1–7
Prasanna V 2014 Impact of monsoon rainfall on the total foodgrain yield over India J. Earth Syst. Sci. 123 1129–45
Rajeevan M, Bha te J, Kale J D and Lal B 2006 High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells J. Clim. 19 296–306
Rajeevan M, Gadgil S and Bha te J 2010 Active and break spells of the Indian summer monsoon Geophys. Res. Lett. 37 5786–92
Ravadekar J V, Varikoden H, Preethi B and Mujumdar M 2016 Precipitation extremes during Indian summer monsoon: role of cyclonic disturbances Nat. Hazards 81 1611–25
Roxy M K, Ghosh S, Pathak A, Athulya R, Mujumdar M, Murtugudde R, Terray P and Rajeevan M 2017 A threefold rise in widespread extreme rain events over central India Nat. Commun. 8 1–11
Sahany S, Mishra S K, Pathak R and Rajagopalan B 2018 Spatiotemporal variability of seasonality of rainfall over India Geophys. Res. Lett. 45 7140–7
Sanderson B M, Wobus C, Mills D, Zarakas C, Crimmins A, Sarofim M C and Weaver C 2019 Informing future risks of record-level rainfall in the United States Geophys. Res. Lett. 46 5963–72
Shah D and Mishra V 2020 Drought onset and termination in India J. Geophys. Res. Atmos. 125 e2020JD030271
Singh D, Ghosh S, Roxy M K and McDermid S 2019 Indian summer monsoon: extreme events, historical changes, and role of anthropogenic forcings Wiley Interdiscip. Rev. Clim. Change 10 e571
Singh D, Tsang M, Rajaratnam B and Diffenbaugh N S 2014 Observed changes in extreme wet and dry spells during the South Asian summer monsoon season Nat. Clim. Change 4 456–61
Singh M S and O’Gorman P A 2014 Influence of microphysics on the scaling of precipitation extremes with temperature Geophys. Res. Lett. 41 6037–44
Smith K H, Tyre A J, Tang Z, Hayes M J and Adnan Akyuz F 2020 Calibrating human attention as indicator monitoring #drought in the twittersphere Bull. Am. Meteorol. Soc. 101 E1801–19
Svoboda M et al 2002 The drought monitor Bull. Am. Meteorol. Soc. 83 1181–90
Thomas T M, Bala G and Srinivas V 2021 Characteristics of the monsoon low pressure systems in the Indian subcontinent and the associated extreme precipitation events Clim. Dyn. 56 1859–78
Wang B, Wu Z, Li J, Liu J, Chang C-P, Ding Y and Wu G 2008 How to measure the strength of the East Asian summer monsoon J. Clim. 21 4449–63
Webster P J and Yang S 1992 Monsoon and ENSO: selectively interactive systems Q. J. R. Meteorol. Soc. 118 877–926