Dominance of summer monsoon flash droughts in India

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Abstract

Flash droughts intensify rapidly after onset and cause short-term but devastating impacts on agriculture and the ecosystem. However, the drivers and characteristics of flash droughts in India have not been examined. Here we use a well-calibrated and evaluated variable infiltration capacity (VIC) hydrological model to simulate root-zone soil moisture to identify flash droughts in India for 1951–2018 period. We show that flash droughts predominantly occur during the monsoon (June to September) in India. More than 80\% of the country-level flash droughts occurred during the monsoon season in India. Similarly, four out of six homogeneous precipitation regions experienced more droughts during the monsoon season than the non-monsoon season. The Himalayan and Peninsular regions experience more flash droughts during the non-monsoon season primarily due to precipitation caused by western disturbance and northeast monsoon. Long dry spell with significant negative anomalies of precipitation during the monsoon season and positive air temperature anomalies rapidly deplete soil moisture causing flash droughts. The major country-level flash droughts occurred during the monsoon season of 1979, 2001, 1958, and 1986. About 10\%–15\% of rice (Oryza sativa) and maize (Zea mays) grown area in each year is affected by flash droughts during the monsoon season in India. Flash droughts during the monsoon season in India can directly affect crop production and indirectly pose challenges for meeting increased irrigation water demands.

1. Introduction

Flash droughts is a recently identified extreme event (Pendergrass et al. 2020). Flash drought occur rapidly and lead to devastating impacts directly on agriculture and indirectly to water resources. Otkin et al. (2018) reported that flash droughts could cause a rapid intensification and quick depletion of soil moisture leading to vegetation stress. Flash droughts can be classified as agricultural droughts due to their direct association with soil moisture and crop stress. Therefore, soil moisture has been widely used as an indicator to identify flash droughts (Yuan et al. 2019b, Pendergrass et al. 2020). Unlike conventional drought that propagates slowly, flash drought is characterized by rapid onset and intensification caused by high evapotranspiration (ET) rates due to anomalously high temperatures, winds, and high incoming solar radiation (Chen et al. 2019). Therefore, flash droughts are associated with low soil moisture, extreme heat, and high ET (Mo and Lettenmaier 2015, Wang et al. 2016, Otkin et al. 2016).

Flash droughts can be driven by the lack of precipitation known as precipitation deficit flash drought (Mo and Lettenmaier 2016, Yuan et al. 2018). On the other hand, flash drought caused by anomalously high temperature is known as heatwave flash drought (Mo and Lettenmaier 2015). However, drivers and characteristics of flash droughts can vary regionally as well as in different seasons. For example, subtropical or temperate regions of the world can experience flash droughts anytime in a year. Previous studies reported the occurrence of flash droughts in the monsoon (China), which can significantly affect agriculture and ecosystem (Zhang et al. 2017b, Wang and Yuan 2018, Liu et al. 2020). However, the occurrence of flash droughts has not been examined in India.

Flash drought can have localized as well as to large-scale implications. The regional flash droughts can affect crop production and irrigation demands at
the local scale. For instance, the 2017 flash drought in the Northern Plains of the USA was limited to only two states (Gerken et al 2018, He et al 2019). However, a localized flash drought can become widespread due to persisted meteorological conditions and lead to substantial economic losses. The flash drought during May–August 2012 in the central USA affected a large area (Pendergrass et al 2020). As depleted soil moisture can influence air temperature, the onset and development of flash droughts can be better identified using coupled land-atmosphere system (Otkin et al 2013, McEvoy et al 2016, Nguyen et al 2019). However, soil moisture from off-line land surface models has been widely used for the assessment of flash droughts (Yuan et al 2019b).

Deleterious impacts of flash droughts on agriculture and ecosystem have been witnessed in many regions worldwide (Otkin et al 2016, Yuan et al 2018, Zhang et al 2019, Basara et al 2019, Nguyen et al 2019). The warming climate can further increase the intensity and frequency of flash droughts (Wang et al 2016, Yuan et al 2019b, Liu et al 2020). Despite the profound implications, flash droughts, their mechanism and characteristics in India have not been examined. Therefore, it remains unclear if flash droughts occur in India or not. Moreover, the dominant seasons of flash drought occurrence in India are not known. Understanding the occurrence and their seasonal variability is vital as flash droughts can be more detrimental in India due to intensive agriculture primarily in the rainfed regions. Moreover, in irrigated areas, the frequent flash droughts can lead to the increased frequency of irrigation, which is mostly from the groundwater pumping. Therefore, flash droughts might put more pressure on already depleting groundwater resources in India (Tiwari et al 2009, Rodell et al 2009, Asoka et al 2017). We use the root-zone soil moisture (60 cm, Mishra et al 2018) simulated using the well-calibrated and evaluated VIC model (Shah and Mishra 2016, Mishra et al 2018) to identify flash droughts in India. Also, we identify and investigate the occurrence of flash droughts at the regional scale and their implications for rice and maize grown areas during the monsoon season.

2. Data and methods

2.1. Dataset

Daily gridded observed precipitation and temperature were obtained from the India Meteorological Department (IMD) at 0.25° and 1° spatial resolution for 1951–2018 period, respectively. The gridded precipitation at 0.25° resolution is developed using more than 6500 gauge stations located across India (Pai et al 2014). A well-distributed network of rain gauge stations effectively captures spatial variability in precipitation across the country during the monsoon season (June–September). The observed gridded precipitation is widely used for hydrologic applications (Shah and Mishra 2016, Mishra et al 2018). In addition, the gridded precipitation dataset has been used for evaluating the satellite and reanalysis products (Shah and Mishra 2016, Mahto and Mishra 2019). The daily gridded maximum and minimum temperatures at 1° resolution is developed by Srivastava et al (2009) using more than 350 stations based on an inverse distance weighted method as described in Shepard (1964). Further, the daily gridded temperatures obtained from IMD was regridded to 0.25° using a Synergistic Mapping algorithm (Maurer et al 2002) to make it consistent with the gridded precipitation dataset.

2.2. The variable infiltration capacity (VIC) model

As soil moisture observations are not available for long-term (Mishra et al 2014), soil moisture from land surface models is widely used for the assessment of flash droughts and droughts (Mishra et al 2019, Yuan et al 2019b). We used the well-calibrated and evaluated the variable infiltration capacity (VIC) model to simulate soil moisture during the 1951–2018 period in India. The VIC model is a large-scale semi-distributed hydrologic model (Liang et al 1994, Gao et al 2009) that can simulate water and energy budget for each grid cell (Shah and Mishra 2016, Garg and Mishra 2019). The VIC model represents the sub-grid variability of precipitation, elevation and vegetation. The VIC model takes daily precipitation, maximum and minimum temperatures, and wind speed as meteorological input. Also, soil and vegetation parameters and vegetation library are required for each grid. We conducted the VIC model simulations at daily temporal resolution with observed precipitation and temperatures from IMD while wind speed from NCEP-NCAR reanalysis (Kalnay et al 1996). The vegetation parameters and vegetation libraries were extracted from the NOAA-AVHRR (Hansen et al 2000) and Land Surface Hydrology Group at the University of Washington (www.hydro.washington.edu), respectively. We used vegetation parameters in the form of the land use and land cover information which is globally developed using at 1 km spatial resolution (Hansen et al 2000, Sheffield and Wood 2007). The calibrated soil parameters from Shah and Mishra (2016) and Mishra et al (2018) were used. Shah and Mishra (2016) calibrated the VIC model against observed streamflow in the Indian sub-continental river basins. The VIC model was then evaluated for satellite-based ET and soil moisture (Shah and Mishra 2016.) Shah and Mishra (2016) reported satisfactory performance of the VIC model over the Indian sub-continental river basins.
We used root zone (60 cm, as in Mishra et al 2018) soil moisture to identify flash droughts in India.

2.3. Identification of flash drought

Daily gridded datasets (precipitation, mean temperature, and soil moisture) were converted to pentad (5 d). Daily soil moisture and temperature were averaged for 5 d to estimate pentads while daily precipitation was summed for the 5 d. Therefore, a total of 73 pentads were obtained for each year. Out of 73 pentads, 25 pentads fall in the monsoon season (from 31st to 55th pentads in a calendar year) and the rest 48 pentads (from 1st to 30th and 56th to 73rd pentads) represent the non-monsoon season. We used soil moisture pentad to estimate flash drought to avoid high frequency (day-to-day) variability, as mentioned in the previous studies (Christian et al 2019, Nguyen et al 2019). Since flash droughts are closely associated with soil moisture deficit (Otkin et al 2018, Yuan et al 2019b), we used the VIC model simulated root-zone soil moisture to identify flash droughts in the monsoon and non-monsoon seasons in India. Flash droughts can also be identified using other indices such as Evaporative Stress Index (Anderson et al 2016, Otkin et al 2016, Nguyen et al 2019), Evaporative Demand Drought Index (Hobbins et al 2016, Mcevoy et al 2016), which primarily capture the soil moisture response to increased ET and potential ET. Moreover, precipitation (Hunt et al 2014) and vegetation (Sun et al 2015) indices can also be used to identify flash droughts.

We estimated the soil moisture percentile for each pentad using the empirical Weibull distribution considering the 1951–2005 period as reference. The primary assumption of rapid intensification (Otkin et al 2018) was incorporated in the identification of flash droughts using soil moisture (figure 1(b)). Flash drought was defined if soil moisture percentile falls below 20th percentile from above 40th percentile in less than four pentads. A similar approach based on soil moisture percentile for flash drought identification was used in Ford and Labosier (2017) and Yuan et al (2019b). A flash drought terminates if depleted soil moisture rises to 25th percentile. Other than the rapid onset of flash droughts, we also used a threshold for the duration of flash drought (figure 1(b)). The minimum duration of four pentads while a maximum duration of 18 pentads was considered for a flash drought. The maximum duration of 18 pentads was used to exclude persistent long-term droughts. Therefore, flash droughts that persisted longer and turned into conventional droughts were excluded from the analysis. More details of flash drought identification methodology are presented in figure 1(b). We identified flash droughts during the monsoon (June–September) and non-monsoon (October–May) seasons for the 1951–2018 period in India.

3. Results and discussion

3.1. Flash droughts during the monsoon and non-monsoon seasons

First, we estimate the seasonal distribution of flash droughts that occurred during the 1951–2018 period in India (figure 2). All India averaged VIC model simulated root-zone soil moisture was used to identify flash droughts (figure 2). We identified 39 country-level flash droughts during the 1951–2018 period (table S1 (available online at https://stacks.iop.org/ERL/15/104061/mmedia)). A majority (~82%) of the country-level flash droughts occurred during the monsoon season. On the other hand, only a small fraction (~18%) of the total flash droughts occurred in the non-monsoon season (figure 2(a)). We divided the Indian region into six homogeneous regions (central north-east (CNE), Himalayan region (HR), north-east (NE), north-west (NW), Peninsular region (PR) and west-central (WC)) based on the precipitation distribution to understand regional-scale variability of flash droughts in India (figure 1(a)). We then identified flash droughts for each homogeneous region using the area-averaged VIC model simulated root zone soil moisture. Regional-scale assessment of flash droughts is essential to understand the dominant season of their occurrence in different parts of the country. Our results show that the CNE, NE, NW, and WC witnessed a majority of flash droughts in the monsoon season during the 1951–2018 period. For instance, about 75%, 60%, 100%, and 85% of the total flash droughts occurred during the monsoon season in CNE, NE, NW, and WC regions, respectively (figure 2). The two regions (HR and PR) experienced slightly more flash droughts during the non-monsoon season than the monsoon season during 1951–2018 period (figure 2).

The four regions (CNE, NE, NW and WC) primarily fall in the core monsoon zone (Rajeevan et al 2012). Therefore, a majority of the flash droughts in these regions occur during the monsoon season. On the other hand, the HR receives considerable precipitation during the winter season from the western disturbance (Dimri et al 2015). Similarly, parts of the PR receive precipitation during the north-east monsoon (October–December) (Rajeevan et al 2012). Therefore, considerable rainfall in the non-monsoon season in these two regions help to replenish soil moisture and positive temperature anomalies in the non-monsoon season can trigger flash droughts. Flash droughts during the monsoon season are mainly driven by the significant negative anomalies of precipitation (monsoon break). A prolonged significant negative precipitation anomaly in the monsoon season causes air temperature to rise, which in turn, rapidly deplete soil moisture. Also, the combination of significant negative precipitation...
anomaly and positive temperature anomalies can lead to increased atmospheric water demands (Yuan et al 2019a). The rate of soil moisture depletion and atmospheric aridity can be further exacerbated by land-atmosphere feedbacks, creating favourable conditions for flash droughts (Zhou et al 2019, Yuan et al 2019a). Overall, we find that regional scale, as well as country-level flash droughts, predominantly occur during the monsoon season in India. Only two regions (HR and PR) experience more flash droughts in the non-monsoon season than the monsoon season in India.

Since most of the flash droughts in India occurred in the monsoon season, we further analyzed the frequency of monsoon season flash droughts in India. We estimated fraction of total pentads that experienced flash droughts for each grid in the

Figure 1. Flash drought identification in India. (a) Six homogeneous precipitation regions in India classified by India Meteorological Department (IMD). (b) A schematic representation of flash drought identification method. Soil moisture (SM) decreases from above 40th percentile to below 20th percentile in no more than four pentads during a flash drought. Once the declined soil moisture increases back to above 25th percentile, flash drought terminates. The green (high SM percentile) to dark red (low SM percentile) colour variation represents the wet and dry condition of soil moisture, respectively.
monsoon season during 1951–2018 (figure 2(h)). As expected, the core monsoon region of central and eastern India witnessed the highest frequency of flash droughts (figure 2(h)). The regions that experience frequent flash droughts include CNE, NE, and Western Ghats (figure 2(h)). In contrast, arid and semi-arid regions of western India, Deccan plateau, and the PR experienced the least frequency of flash droughts in the monsoon. Overall, we find that flash droughts are mainly concentrated in the monsoon season in the majority of India, which can have implications for the crops (rice and maize) grown in the Kharif (June–September) season.

3.2. Major flash droughts in India during 1951–2018

Next, we identified the country-level major flash droughts that occurred in India during 1951–2018 (figure 3 table S1). We used all-India and regionally averaged VIC model simulated root-zone soil moisture to examine the occurrence of major flash droughts. We selected the top four major flash droughts based on peak intensity (based on soil moisture percentile) and duration to examine their spatial extent and precipitation and air temperature anomalies (figure 3). If the peak intensity of two flash droughts was the same, then the flash drought with the longer duration was assigned, the higher rank (table S1). The four major country-level flash droughts occurred in the monsoon season of 1979, 2001, 1958 and 1986, respectively (figure 3, table S1). The 1979 flash drought rapidly intensified and was the worst flash drought during the entire period. The 1979 flash drought had a duration of ten pentads, and the average standardized anomaly of temperature during the flash drought was more than 0.5 (table S1). The flash drought of 1979 considerably affected north-central India and Indo-Gangetic Plain (figures 3(a) and (b)). The flash drought of 1979 started on 45th pentad and achieved its peak intensity in the next three pentads (48th pentad). During the peak of the 1979 flash drought, soil moisture depleted below 5th percentile (figure 3(a)). The lack of rainfall and positive temperature anomaly of more than 2 °C resulted in quick depletion of soil moisture (figure 3(a)). The anomalously high temperature and significant low precipitation anomalies during the summer monsoon were the key drivers of the flash drought of 1979.

The flash drought of 2001 was the second most severe flash drought followed by 1958 and 1986 during the 1951–2018 (figure 3). The 2001 flash drought started on 48th pentad and terminated on 56th pentad with a duration of eight pentads (figure 3(c)). The flash drought affected a vast region of north and central India (figure 3(d)). The dry-spell in the monsoon season precipitation followed by increased air temperature caused the flash drought in 2001 (figures 3(c) and (d)). Similarly, the flash drought of 1986 was also occurred due to the monsoon break (figure 3(e)). The 1986 flash drought started on 48th pentad, persisted for eight pentads, and terminated on 56th pentad (figure 3(g)). The 1986 flash drought was the most widespread among all
the four major flash droughts (figure 3(h)). Unlike the three flash droughts (1979, 2001 and 1986) that occurred due to monsoon break, the 1958 flash drought primarily occurred due to delay in the monsoon onset (figure 3(e)). The flash drought of 1958 lasted for ten pentads (28th–38th pentads) and terminated after an active phase of the monsoon in August 1958 (figure 3(e)). The 1958 flash drought was mainly centred over the Indo-Gangetic Plain (figure 3(f)). Anomalously low precipitation and high-temperature anomalies amplified the peak intensity of the major flash droughts that occurred during the monsoon season. Overall, the occurrence of major flash droughts dominates during the monsoon season. The monsoon season flash droughts in India are mainly caused by negative precipitation anomalies during the monsoon season or the late onset of the summer monsoon rainfall.

Soil moisture is replenished during the summer monsoon, and monsoon breaks along with the positive temperature anomalies can cause soil moisture depletion. Rapid depletion of soil moisture results in flash droughts during the monsoon season in India. A majority of the flash droughts in India occur during the monsoon season. The Indian summer monsoon precipitation is driven by large-scale climate
variability (Mishra et al 2012, Loo et al 2015). The large scale ocean-atmospheric phenomena such as Indian Ocean Dipole and El-Nino Southern Oscillation have a remarkable influence on the summer monsoon (Ashok et al 2004), which predominantly controls the frequency and intensity of droughts in India (Kumar et al 2013, Mallya et al 2015). Therefore, onset and the strength of the summer monsoon can be associated with sea surface temperature over the Indian and Pacific oceans (Mishra et al 2012, Roxy et al 2015). However, temperature anomalies over land can contribute to soil moisture depletion during the monsoon break (Loo et al 2015). Thus, both localized (temperature anomalies) and large-scale factors that control monsoon breaks and late onset can influence the occurrence of flash droughts in India.

3.3. The regional occurrence of flash drought in India

Next, we identified the regional scale flash droughts occurred during 1951–2018 (figure 4). Flash droughts can occur at a regional scale with intense local impacts (Wang and Yuan 2018, Christian et al 2019, Liu et al 2020). We examined the occurrence of flash droughts in the six homogeneous precipitation regions in India (figure 4). We find that flash droughts can evolve locally, and their impacts can be limited to only a small geographical area (~0.33 million km²). Based on the peak intensity and duration of flash droughts, we selected the most severe flash drought from each of the homogeneous regions during 1951–2018 (figure 4). CNE and NE regions experienced the most severe flash drought in the beginning (1–5 June) of the summer monsoon of 2009 (figures 4(b) and (f)). Anomalously low precipitation and positive temperature anomalies caused rapid soil moisture depletion (figures 4(a) and (e)). The 2009 flash drought later turned to a country-level drought. Similarly, flash drought in 1955 started on 27th pentad in the HR and terminated on 37th pentad due to anomalously high precipitation (figures 4(c) and (d)). The NE region experienced the most severe flash drought in 2009, which was caused by the monsoon season precipitation deficit (figures 4(e) and (f)). The semiarid north-west (NW) India experienced a severe flash drought in 1955 (figures 4(g) and (h)). Similar to the other flash droughts, the 1955 flash drought in NW was also caused by dry-spell during the monsoon season. On the other hand, an active spell of the monsoon season precipitation helped the NW region to recover from the flash drought (figures 4(g) and (h)). Southern India (PR) experienced a localized flash drought in 1952 during the monsoon season. The flash drought (1952) started from 40th pentad and terminated on 58th pentad (figure 4(i)). The PR region receives precipitation during the northeast monsoon. Therefore, the 1952 flash drought in PR lasted beyond the summer monsoon season. Similarly, in 1971, the WC region witnessed a regional-scale flash drought that started on 40th pentad and terminated on 49th pentad (figure 4(k)). The 1971 flash drought mostly affected the semiarid region of the Deccan plateau (figure 4(l)). The number of flash droughts occurred in each of the homogeneous regions are almost double in comparison to the number of country-level flash droughts during the 1951–2018 period (tables S2–S7). Therefore, the regional scale flash droughts are more frequent in comparison to the country-level flash droughts.

The mechanism and drivers of flash droughts are the same for both country-level and regional scale flash droughts. A majority of flash droughts at the regional scale are caused by the precipitation deficit during the monsoon season and amplified by the warm temperature anomalies. However, the flash droughts that occur during the non-monsoon season can be driven by heatwaves. Recent studies highlighted the association between cooccurrence of drought and heatwaves in triggering flash droughts due to land-atmosphere feedbacks (Miralles et al 2019, Ye et al 2019). Also, change in the land cover due to anthropogenic activities such as deforestation, urbanization, and agricultural practices also contribute to the local warming, which can attribute to depletion of soil moisture (Yuan et al 2018, 2019b, Hoell et al 2019).

3.4. Impact of flash drought on Kharif crops in India

Since the majority of country-level and regional scale flash droughts occur during the monsoon season, these can have profound implications on food production and water management. The Kharif season is a crucial crop growing season in India, in which, rice and maize are grown in large part of the country. Precipitation deficit and lack of soil moisture during a flash drought can lead to reduced yields of rice and maize (Davis et al 2018, Kayatz et al 2019). We identified the rice and maize grown areas during the monsoon season in India (figure 5). We selected the top three flash droughts based on intensity and duration for both rice and maize cultivation area (tables S8 and S9). To do so, we aggregated area-averaged soil moisture for the rice and maize grown regions in India. We find that flash droughts of 1979, 1976, and 1982 are the three most severe flash droughts that might have affected the rice cultivation during the monsoon season in India (figure 5). A large part of the rice cultivated region of the Indo-Gangetic Plain and eastern India was severely affected by the 1979 flash drought (figures 5(a) and (b)). The flash drought in 1976 primarily affected rice cultivation in eastern and peninsular India (figure 5(c)). On the other hand, the flash drought of 1982 during the monsoon season was widespread, mainly affecting the eastern and northeastern regions (figure 5(d)).

Similarly, the maize grown area was influenced by the major flash droughts occurred in 1972, 1976
Figure 4. The regional scale flash droughts that occurred during the 1951–2018 period. (a) Soil moisture percentile (Y-axis, left) and standardized anomalies of precipitation and air temperature (Y-axis, right) of the flash drought in CNE that occurred in the monsoon season of 2009. (b) Spatial extent of the 2009 flash drought (CNE) during its peak intensity shown by soil moisture percentile. (c), (d) Same as (a), (b) but for the 1955 flash drought in HR. (e), (f) Same as (a), (b) but for the 2009 flash drought in NE. (g), (h) same as (a), (b) but for the 1955 flash drought in NW. (i), (j) same as (a), (b) but for the 1952 flash drought in PR, and (k), (l) same as (a), (b) but for the 1971 flash drought in WC. The yellow shaded region in (a), (c), (e), (g), (i), (k) shows the duration of flash drought. Soil moisture percentile and standardized precipitation/temperature anomalies are estimated using the all-India average root-zone (60 cm) soil moisture. Soil moisture percentiles between 30 and 70 show normal conditions (white), 0–30 represent dry conditions and higher than 70 represent wet condition.

and 2015 (figures 5(f)–(h)). Unlike, the rice grown regions, the maize grown areas are mainly located in the central and peninsular India (figure 5(e)). The spatial coverage of soil moisture conditions during the peak of flash droughts showed that the land was extremely dry due to anomalously low precipitation and high temperature. These conditions rapidly depleted soil moisture below 5th percentile (tables S8 and S9) in the rice and maize dominated regions during the monsoon season in India. We also calculated the total rice and maize area (%) affected by the flash droughts in each year. We find that at least 15% of the rice and maize cultivation area is affected by flash droughts each year (figures S2(a) and (b)). The median rice and maize grown area affected by flash droughts in the monsoon season was 21.5% during the 1951–2018 period. Overall, we find that flash droughts can be localized, large-scale, and region-specific posing challenges for crop production and water management in India.

4. Discussion and conclusions

Flash droughts in the monsoon season can have implications for agriculture and water management in India. Since flash droughts cause a rapid depletion of soil moisture, irrigation water demands can considerably increase in the agricultural regions (Fereres and Soriano 2007). For instance, intensive
Environ. Res. Lett. 15 (2020) 104061

S S Mahto and V Mishra

Figure 5. The rice and maize area affected by the major flash droughts during the 1951–2018 period in India. (a) Major and minor rice area coverage (shown by dark and light green colours, respectively) in the Kharif season in India. (e) same as (a) but for maize. (b)–(d) Three major flash droughts that occurred in 1979, 1976 and 1982 and affected the rice grown area during the monsoon season. (f)–(h) Three major flash droughts that occurred in 1972, 1976 and 2015 and affected the maize grown area during the monsoon season. The district level data for the area under rice and maize crops was taken from India ministry of agriculture, directorate of economics and statistics. Flash droughts were identified using root-zone (60 cm) soil moisture averaged over the rice and maize grown areas.

irrigation, mostly through groundwater pumping, is being used to meet crop water requirement during the deficit periods in the Indo-Gangetic Plain (Aggarwal et al 2004). The area under rice and maize cultivation over the Indo-Gangetic Plain and in other parts can witness increased irrigation water demands during flash droughts. Moreover, agricultural water demand is projected to rise under the warming climate (New et al 2012), which can result in increased irrigation water demands, especially during flash droughts in India. Groundwater is a major source for irrigation in north India, which has significantly declined due to groundwater abstraction for irrigation (Asoka et al 2017). Frequent flash droughts during the monsoon season in northern India can indirectly influence groundwater storage to meet the increased irrigation demands. Most of the water managers around the globe use groundwater storage to mitigate the impacts of flash droughts (Castle et al 2014). Crop production was affected by major flash droughts occurred in 1979, 1986, and 2001 (Zhang et al 2017a). We showed the dominance of the summer monsoon flash droughts in India using the VIC model simulated soil moisture. There may be variations in the flash drought identification based on the choice of indicator. Therefore, other indicators based on ET, vapor pressure deficit, and vegetation growth can be used for flash droughts estimation in India. Moreover, the VIC model simulated soil moisture does not account for the influence of irrigation and the role of irrigation on flash droughts can be examined. Overall, flash drought, though mostly occur during the monsoon season in India, can have far-reaching implications for agriculture and water management. The adverse impacts of flash droughts in India may increase in the future under the warming climate.

Based on our findings, the following conclusions can be made:

- The summer monsoon rainfall is the primary source to replenish soil moisture after hot summers in India. Flash droughts in India mainly occur during the monsoon season due to replenished soil moisture. A considerably long dry spell with significantly low precipitation anomalies during the monsoon results in an increase in air temperature. Increased air temperature and precipitation deficit together cause a rapid depletion of soil moisture leading to flash drought. Therefore, flash droughts in the monsoon season are primarily caused by the monsoon breaks. However, flash droughts can also occur due to delayed onset of the summer monsoon.
- The majority of the country-level and regional scale flash droughts in India occur during the monsoon season. More than 82% of country-level flash droughts occurred during the monsoon season in India. Out of six, only two regions (HR and PR) experienced more flash droughts in the non-monsoon season than that of the monsoon season, which can be attributed to rainfall that these two regions receive from western disturbance and northeast monsoon, respectively.
• A total of 39 country-level flash droughts occurred in India during 1951–2018. Based on peak intensity and duration, the major country-level flash droughts were identified during the 1951–2018 period. The top all-India level flash droughts occurred during the monsoon season of 1979, 2001, 1958, and 1986. Except one (1958), all the other major flash droughts occurred in the mid to late monsoon season. The frequency of regional-scale flash droughts is substantially higher than the country-level flash droughts. The core-monsoon region in India experiences more frequent flash droughts during the monsoon season than the other regions.

• A large part of the rice and maize grown area was affected by the flash droughts during 1951–2018. About 10%–15% of rice and maize grown area is affected by the flash droughts each year in India. Therefore, increased frequency of flash droughts during the monsoon season in the future can have implications for agricultural production and irrigation water demands in India.

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Data availability statement

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

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