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Key Points:
- Major drought events have been reconstructed in India during 1870–2016
- India experienced seven major drought periods (1876–1882, 1895–1900, 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015)
- Out of six major famines that occurred during 1870–2016, five are linked to soil moisture drought, and one (1943) was not

Supporting Information:
- Supporting Information S1

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Drought and Famine in India, 1870–2016

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Abstract Millions of people died due to famines in India in the nineteenth and twentieth centuries; however, the relationship of historical famines with drought is complicated and not well understood. Using station-based observations and simulations, we reconstruct soil moisture (agricultural) drought in India for the period 1870–2016. We show that over this century and a half period, India experienced seven major drought periods (1876–1882, 1895–1900, 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015) based on severity-area-duration analysis of reconstructed soil moisture. Out of six major famines (1873–74, 1876, 1877, 1896–97, 1899, and 1943) that occurred during 1870–2016, five are linked to soil moisture drought, and one (1943) was not. The three most deadly droughts (1877, 1896, and 1899) were linked with the positive phase of El Niño–Southern Oscillation. Five major droughts were not linked with famine, and three of those five nonfamine droughts occurred after Indian independence in 1947.

Plain Language Summary India witnessed some of the most famous famines during the late nineteenth and early twentieth centuries. These famines caused millions of deaths primarily due to widespread crop failure. However, the role of agricultural drought in these famines remains unrecognized. Using station-based observations and simulations from a hydrological model, we reconstructed agricultural droughts and established a linkage between famines and droughts over India. We find that a majority of famines were caused by large-scale and severe soil moisture droughts that hampered the food production. However, one famine was completely due to the failure of policy during the British era. Expansion of irrigation, better public distribution system, rural employment, and transportation reduced the impact of drought on the lives of people after the independence.

1. Introduction

Famine is defined as "food shortage accompanied by a significant number of deaths" (Dyson, 1991). India has a long history of famines that led to the starvation of millions of people (Passmore, 1951). During the era of British rule in India (1765–1947), 12 major famines occurred (in 1769–1770, 1783–1784, 1791–1792, 1837–1838, 1860–1861, 1865–1867, 1868–1870, 1873–1874, 1876–1878, 1896–1897, 1899–1900, and 1943–1944) which lead to the deaths of millions people (Maharatna, 1996). Many of these famines were caused by the failure of the summer monsoon, which led to widespread droughts and crop failures (Cook et al., 2010). Although no major famines have occurred since Indian independence in 1947, large-scale droughts in the second half of the 20th and early 21st centuries have continued to have devastating effects on India (Bhalme et al., 1983; Gadgil & Gadgil, 2006; Mishra et al., 2016; Parthasarathy et al., 1987). Droughts in the late eighteenth and early nineteenth centuries had progressively more severe effects due to a rising population, low crop yields, and lack of irrigation (Food and Agriculture Organization, 2010). Hence, an understanding of historical famine and drought in India relates to both physical factors associated with drought and agricultural productivity and management.

Soil moisture drought affects crop production and food security in India especially in the absence of irrigation (Mishra et al., 2014, 2018). Soil moisture droughts doubtless affected food production and famines in India before the widespread advent of irrigation in the midtwentieth century. However, the crucial role of soil moisture in famines in India has received little attention, perhaps due to the general absence of long-term observations. Most previous attempts to study eighteenth- and nineteenth-century droughts in India have been limited to meteorological (Bhalme et al., 1983; Mooley & Parthasarathy, 1984) or paleoclimate reconstructions (Cook et al., 2010) and mainly facilitate studies of the role of large-scale climate variability. Here we provide the first reconstruction of droughts based on soil moisture (their proximate link to dryland agriculture) for the last century and a half (1870–2016) and their relationship to famines. We use the Variable Infiltration Capacity (VIC) model to reconstruct soil moisture using methods similar to those demonstrated previously for the conterminous United States (Andreadis & Lettenmaier, 2006) and China (Wang et al., 2011).

2. Data and Methods

We obtained 0.25° daily gridded precipitation data from the India Meteorology Department (IMD) for the period 1901–2016 (Pai et al., 2015), which we regridded to 0.5° spatial resolution by using synergic mapping algorithm as described in Maurer et al. (2002). Pai et al. (2015) developed the IMD gridded precipitation product using data from 6,995 observational stations across India using inverse distance weighting (Shepard, 1984). Orographic features and spatial variability in the Indian summer monsoon precipitation are well captured by the gridded precipitation (Pai et al., 2015). Because the IMD gridded precipitation product is available only for the post-1900 period, we developed a compatible product at 0.5° using station observations for 1870–1900. Data availability and the number of stations varied during this period; however, we were able to obtain reasonably complete precipitation data from 1,690 stations spread across India for most of the pre-1900 period. More detailed information on data preparation from observations, 20th Century reanalysis (20CR), and Berkeley Earth and data evaluation can be obtained from supporting information Text S1 (Compo et al., 2006; Dai et al., 2004; Wood et al., 2002).

We used the VIC (Liang et al., 1994) macroscale hydrology model (Text S2, Nijssen et al., 2001; Shuttleworth, 1993; Mishra et al., 2010), which simulates water and energy fluxes by taking soil and vegetation parameters and meteorological forcing as inputs. The VIC model has been widely applied for soil moisture drought assessments at a range of spatial scales (e.g., Andreadis & Lettenmaier, 2006; Mishra et al., 2014, 2018; H. L. Shah & Mishra, 2016a; R. Shah & Mishra, 2014; R. D. Shah & Mishra, 2015, 2016b; Sheffield, Goteti, et al., 2004; Sheffield, Ziegler, et al., 2004). We applied the VIC model at a daily time step for each 0.5° grid for 1870–2016 (see supporting information Text S2 for more details). We aggregated daily soil moisture for each grid to monthly to avoid the influence of precipitation and temperature variability within a month. This is important as we resampled daily precipitation and temperature from the 20CR, for which monthly aggregates are more accurate than daily values. We estimated soil moisture percentiles (SMP) using the empirical Weibull plotting position method (Andreadis & Lettenmaier, 2006). SMP less than 20 is categorized as drought (SMP 20–30: abnormally dry; 10–20: moderate drought; 5–10: severe drought; 2–5: extreme drought; and less than 2: exceptional drought; Svoboda et al., 2002). We estimated monthly soil moisture percentiles at 60-cm depth, which is a typical root zone depth for most crops, following Mishra et al. (2018).

We used severity-area-duration (SAD) analysis as developed by Andreadis and Lettenmaier (2006) and applied by Sheffield et al. (2009) and Wang et al. (2011) among others to identify major droughts during 1870–2016. We identified drought periods in time and space using the clustering algorithm of Andreadis and Lettenmaier (2006). The algorithm considers drought clusters with a minimum area threshold (0.1×10^6 km^2) for which drought duration and severity are computed. In the SAD analysis, duration is the primary variable; for a given duration of a prospective drought event, the SAD analysis performs a bivariate analysis of severity and area. Severity and area in the SAD analysis clearly are linked, as the severity, which is an average over the area, increases or decreases as the area contracts or expands. We estimated monthly soil moisture percentiles using the empirical Weibull distribution. We evaluated droughts of different duration, severity, and spatial extent (area) using SAD analysis. The severity of a drought is defined as

$$S = 1 - \frac{\sum \mathrm{SMP}}{t}$$

where S is drought severity, SMP is monthly soil moisture percentile (Sheffield, Goteti, et al., 2004), and t is drought duration (months). We calculated drought severity for 3-, 6-, 12-, 24-, and 48-month durations. It should be noted that a region can experience a drought of short (3 months) or long (12–48 months) duration where the short duration is within the time span of the longer duration, but the severity and areal extent for the “events” can be much different. We identified seven major drought periods from the SAD analysis. We identified famines and affected regions during the period of 1870–2016 from the literature (Table S1). We

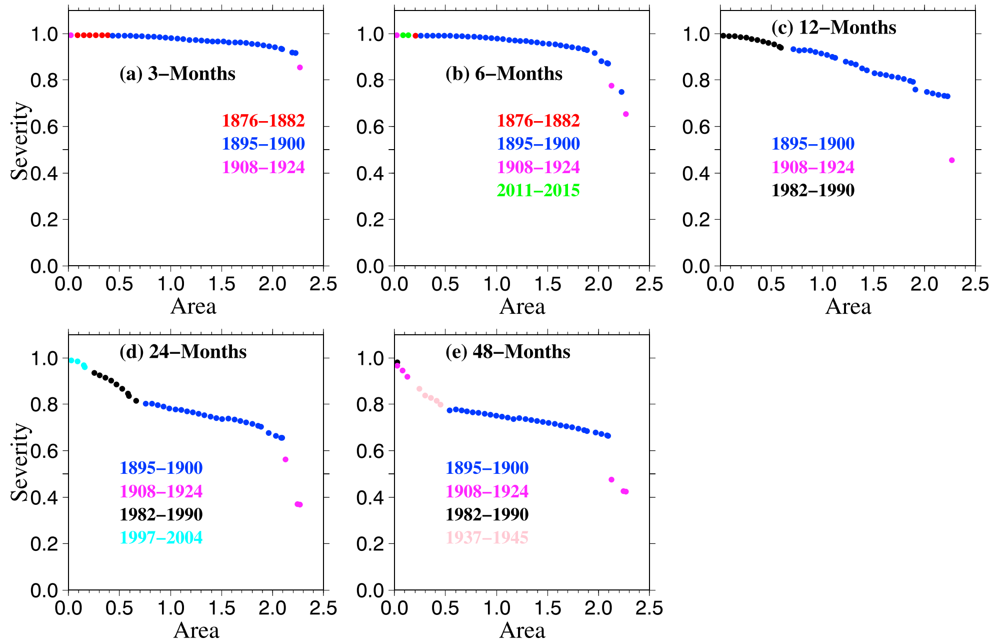

Figure 1. Severity-area-duration curves for the major drought periods in India during 1870–2016 for (a) 3-, (b) 6-, (c) 12-, (d) 24-, and (e) 48-month durations. Severity and area ($\times 10^6$ km^2) for seven major drought periods were estimated using severity-area-duration analysis.

constructed sea surface temperature (SST) anomalies for the monsoon season for the major droughts that caused famines using National Oceanic and Atmospheric Administration's extended reconstructed SST version 5 (Huang et al., 2017).

3. Results and Discussion

3.1. All India Droughts Identified Using SAD Analysis

We first identified the major soil moisture drought periods in India using the SAD analysis applied to the 1870–2016 record (Figure 1). We identified drought severity and area for 3- to 48-month durations as indicated above so as to include both short- and long-term droughts in India. Our analysis indicated that 1876–1882, 1895–1900, 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015 are the major periods for soil moisture droughts (Figure 1). India experienced 3- and 6-month soil moisture droughts during 1876–1882, while during 1895–1900 both short- and long-term droughts occurred. Most severe and widespread (more than 2.0× 10^6 km^2 area) soil moisture droughts occurred during 1895–1900 and 1908–1924 (Table S2). In comparison to the 1895–1900 drought that covered almost the entire country (~65% of total area), the 1876–1882 drought period was mainly located in the southern part of the country and had a smaller extent (0.40× 10^6 km^2; Table S2). Among all of the seven major drought periods, the most recent (2011–2015) was exceptionally severe (severity = 0.99) but not widespread like the 1895–1900 drought (area = 0.13× 10^6 km^2).

We further analyzed the ten months with the most widespread drought conditions within each of the major drought periods (1876–1882, 1895–1900, 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015) obtained from the SAD analysis (see Table S3). We find that during the 1876–1882 drought period, the most widespread drought conditions occurred in August 1877 with coverage of 56.6% of the area of the country. From April to July of 1876, more than 36% of the country's area experienced soil moisture drought. Moreover, a major part of the country remained under soil moisture drought until February 1878. Similarly, for the 1895–1900 period, the most widespread extent of drought occurred in December 1896 (64.2%) followed by December 1899 (61.4%). More than 60% of India was under soil moisture drought between October and December 1896 (Table S3).

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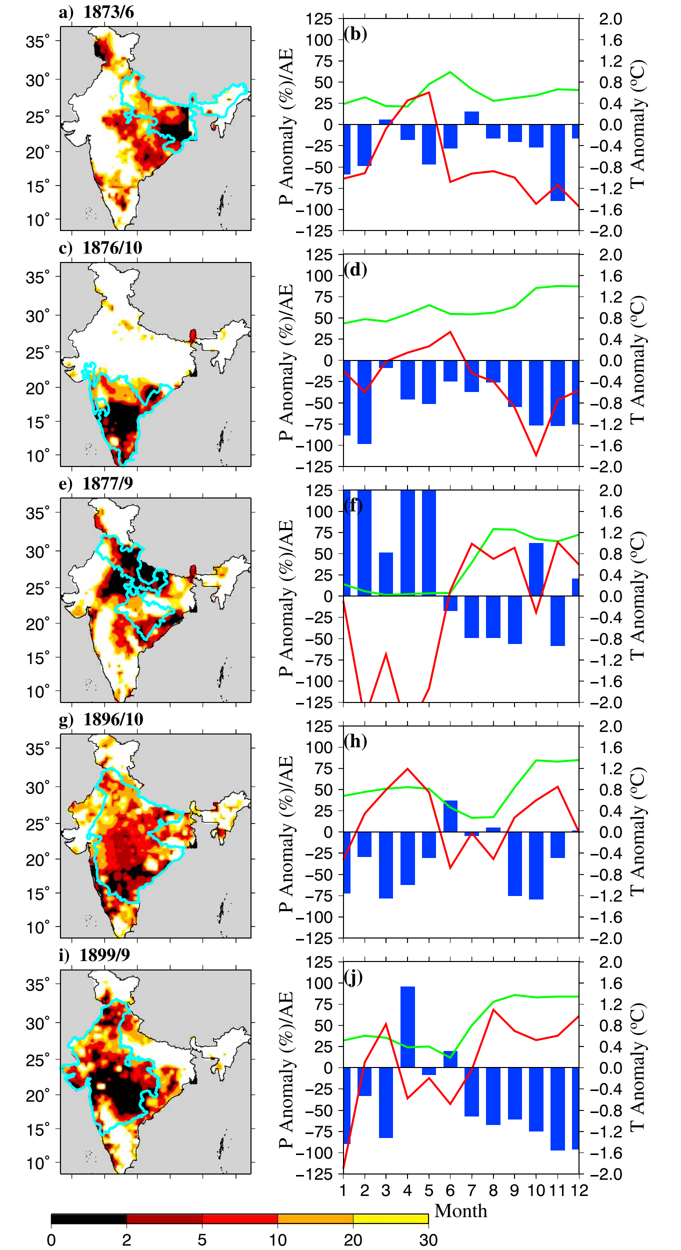

Figure 2. Soil moisture droughts that were coincident with famines. (a) The extent of drought during June 1873. Cyan polygon shows the famine-affected regions that were identified by the British provinces from the map of British India (W. H. Allen and Co.—Pope, G. U., 1880). (b) Monthly precipitation (blue, %) and temperature (red, °C) anomalies and areal extent (green, %) of soil moisture drought. (c–j) Same as (a) and (b) but for different famines during 1870–1900 in India. The region with soil moisture percentile above 30 is shown with white in (a), (c), (e), (g), and (i) and represents no-drought condition.

The 1908–1924 drought period was the most widespread in January 1908, October 1918, December 1920, and May 1921 (Tables S2 and S3). Soil moisture drought in October 1918 and in December 1920 covered more than 65% of the country. The 1908–1924 drought period was widespread; however, the drought was less severe than that of 1895–1900 (Figure 1). The 1937–1945 drought period was of a lesser extent than 1895–1900 and 1908–1924. The month with the largest extent (46.8%) during the 1937–1945 period was August 1941. Similarly, during the 1982–1900 period, drought covered 47.3% of the country in August 1987 (Table S3). During the 1997–2004 period, the drought was most widespread in February 2001 (56%) and January 2003 (54.4%). The most recent drought period identified by the SAD analysis occurred during 2011–2015, which had the largest extent (43%) in October 2015. Overall, the SAD analysis shows that the frequency and severity of major soil moisture drought periods was greatest before 1924.

3.2. Major Famines in India During 1870–2016

Next, we analyzed famines (Table S1) and associated causes during the century and a half period 1870–2016. Our focus is on root zone soil moisture (60 cm following Mishra et al., 2018) from which we identified overlaps between famines and soil moisture droughts. In particular, we find five major famines (1873–1874, 1876–1878, 1896–1897, 1899–1900, and 1943–1944) based on the past literature that occurred during the 1870–2016 record (Table S1). Three of the famines are consistent with the drought periods identified by the SAD analysis. The two exceptions are 1873–1874 and 1943–1944. Those two sequences of years were not identified as drought periods in our SAD analysis likely because either (a) they were too localized to appear on the SAD envelope curves or (b) the famine was not coincident with soil moisture deficits and likely was caused by some other factor (e.g., failure of food distribution systems). The identification of major droughts using the SAD analysis is for the entire country, while the famines were located in different regions of India (Figure 2 and Table S1). Therefore, there inevitably is some disparity in the drought periods we identify from continental scale soil moisture and the temporal extent of the famines.

The 1873–1874 famine occurred in Bihar and Bengal, which were part of the northwestern province and Oudh during the British period (Table S1). Long-term precipitation deficit (based on 12-month anomaly based on moving average) of 13.5% caused soil moisture deficit (~10%) in June 1873 (Figure S8). The deficit in the monsoon season precipitation started in 1872 and continued until the monsoon season of 1874 (Figure S8). Depleted soil moisture primarily due to precipitation deficit created an exceptional drought (SMP $<$ 2.0) in Bengal and the western part of Bihar during June 1873 (Figures 2a and S8). Since the soil moisture drought in 1873 was centered on a relatively small domain, it was not identified by the SAD analysis (against the threshold of 0.1×10^6 km^2). During the 1873 famine, soil moisture drought that affected more than 50% of Bihar and Bengal (Figures 2 and S8) was caused by a long-term precipitation deficit that started during the monsoon season of 1872, which was further worsened by 25% below-normal precipitation in the famine-affected region in June 1873. The precipitation deficit in June might have caused a reduction in the area under cultivation, and the region did not get any relief in drought till the end of the monsoon season of 1874 (Figure S8). We find that precipitation deficit, rather than warmth, was the proximate cause of the drought (Figures 2 and S8). About 21.5 million people were affected by the 1873

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famine, but little or no mortality was reported (Hall-Matthews, 2008; IGI, 1907). The low mortality during the 1873 famine was mainly attributable to food imports from Burma and timely relief aid provided by the British government (Hall-Matthews, 2008; IGI, 1907). The famine was over in 1874 with 17% surplus monsoon precipitation (Figure S8) and good food production.

The second famine occurred during 1876–1878 (Table S1), which has also been called the Great Famine of southern India, or Madras Famine (Cook et al., 2010; Dyson, 1991; Lardinois, 2009). Precipitation deficit started from 1875, which affected southern India until mid-1878 (Figure S8). In October 1876, the precipitation deficit was about 41% that created significant soil moisture depletion (deficit of 12.5%) in the region (Figure S9). As identified by the SAD analysis, soil moisture deficits led to drought throughout much of southern India (Figures 1, 2, and S9). The drought covered more than 85% of the famine-affected region in October 1876 (Figure 2), which remained under drought until October 1877. Soil moisture drought in 1876 caused crop failures in south India (Roy, 2006). However, the British government exported a substantial amount of wheat to England during this time, which made the region especially vulnerable (Guha, 2006).

North India (and especially the central and northwestern provinces and Punjab) experienced an extreme to exceptional soil moisture drought in 1877. Poor monsoon season precipitation in 1876 and 1877 led to an accumulated precipitation deficit of more than 27% in the famine-affected region in September 1877 (Figure S10). The precipitation deficit caused anomalously high (1.3 °C) air temperature that resulted in a soil moisture deficit of 13% in September 1877 (Figure S10). In September 1877, about 48% of the country experienced soil moisture drought (Table S3 and Figure 2). The famine-affected region had an extent of 79% and 78%, respectively, in August and September 1877. The 1876–1877 famine in south and north India affected more than 50 million people (IGI, 1907) of which about 6.1 to 10.3 million (Table S1) perished (Davis, 2001; Fieldhouse, 1996).

The 1895–1900 drought period identified by the SAD analysis includes two famines: 1896–1897 and 1899–1900. During October 1896 to January 1897, more than 57% of the country was affected by soil moisture drought (Table S3). The 1896–1897 famine was caused by a precipitation deficit that started with a poor monsoon in 1895 and continued till the end of 1897 (Figure S11). A large region was affected by the soil moisture deficit (11%), which was caused by the combined impact of precipitation deficit (~17%) and above-normal temperature anomaly (1.0 °C; Figure S11). The famine of 1896–1897 started in the Bundelkhand area (Agra province in the British era) in north India (Figures 2 and S11). More than 82% of the famine-affected region was under soil moisture drought during October to December 1896, which overlaps with the major crop growing season (November to March; Figure S11). The 1896–1897 famine affected 69.5 million people in India (IGI, 1907) and caused the death of 5 million people (Table S1) as relief measures failed in the central province (Fieldhouse, 1996).

The population was still recovering from the 1896–1897 famine when the 1899–1900 famine started with a monsoon failure in central and western India (Figures 2 and S12). Below-normal monsoon season precipitation in 1898 affected the region and continued till the end of 1900 (Figure S12). The combination of substantial (~46.7%) precipitation deficit and above-normal air temperature (1.2 °C) resulted in a widespread soil moisture deficit in the region, which peaked (15.5% deficit) in September 1899 (Figure S12). More than 56% of the country was in soil moisture drought between September 1899 and February 1900 (Table S3). From July 1899 till June 1900, more than 50% of the famine-affected region experienced soil moisture drought that peaked in September 1899 with 85% coverage (Figures 2 and S12). In the famine-affected region, the monsoon season precipitation deficit was 57%, 67%, and 60%, respectively, in July, August, and September, while air temperature was above normal starting July till December 1899 (Figure 2). The soil moisture drought in 1899–1900 resulted in major crop failure in the famine-affected region, and food could not be exported from the other regions of the country due to lack of transportation or availability of food (Dreze, 1988). The 1899 famine affected 59.5 million people (IGI, 1907) with mortality estimates of 1 to 4.5 million (Table S1; Fagan, 2009; Fieldhouse, 1996). Deccan and Bombay had the highest mortality rates (Attwood, 2005). Apart from human mortality, a large number of cattle died due to acute shortage of fodder (IGI, 1907).

The last major famine in the British era occurred in 1943, which is also known as the Bengal Famine. The famine resulted in 2–3 million deaths (Devereux, 2000). Our SAD analysis identified 1937–1945 as a period under drought based on severity, area, and duration. However, we find the drought was most widespread

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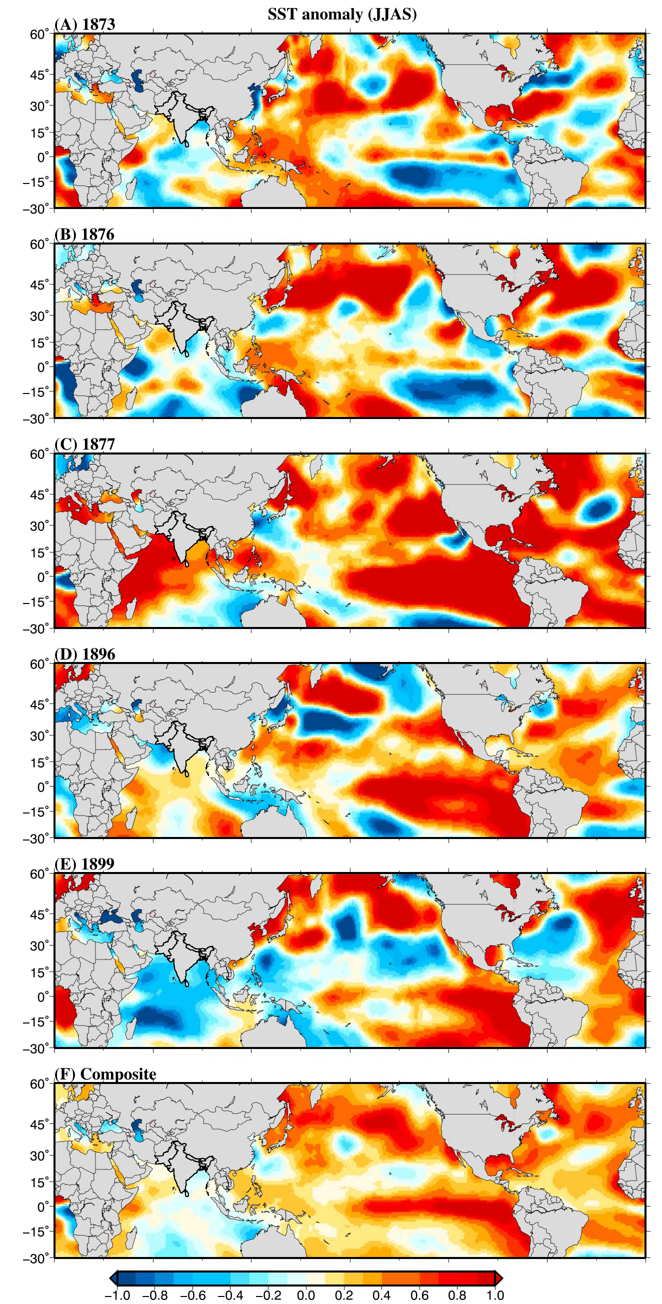

Figure 3. (a–e) Sea surface temperature (SST, °C) anomaly for the monsoon season (June-July-August-September) for droughts that caused famines in India, and (f) SST anomaly composite for all five (1873, 1876, 1877, 1896, and 1899) droughts.

during August and December 1941 (Tables S2 and S3)—prior to the famine. This was the only famine that does not appear to be linked directly to soil moisture drought and crop failures (Figures S13 and S14). The famine-affected region received 15%, 3%, 9%, and 4% above-normal precipitation during June, July, August, and September of 1943 (Figure S13). We find that the Bengal famine was likely caused by other factors related at least in part to the ongoing Asian threat of World War II including malaria, starvation, and malnutrition (Sen, 1976). In early 1943, military and political events adversely affected Bengal's economy (Tauger, 2009), which was exacerbated by refugees from Burma (Maharatna, 1996). Additionally, wartime grain import restrictions imposed by the British government played a major role in the famine (FIC, 1945). We note that aside from the 1943 Bengal famine, all the other famines in 1870–2016 appear to be related at least in part to widespread soil moisture drought.

3.3. Famines and SST Conditions

Out of six major famines we identified in our study period, five were caused by soil moisture droughts, which were primarily driven by the monsoon (June to September) failures. As year-to-year variability of the Indian summer monsoon is linked with SST anomalies in tropical Pacific Ocean (Mishra et al., 2012), we constructed SST anomalies for the monsoon seasons prior to the droughts that caused famines (Figure 3). We find that the 1873 Bihar-Bengal and 1876 south India famines were not associated with the positive phase (El Niño) of El Niño–Southern Oscillation (ENSO; Figures 3a and 3b). In fact, these two (1873 and 1876) major droughts that caused famines during negative phases (La Niña) of ENSO. The other three (e.g., 1877, 1896, and 1899) droughts occurred during strong El Niños (Figures 3c–3e). The composite of all five droughts that caused famine reveals a strong influence of El Niño that resulted in the major monsoon failures (Figure 3). Recently, Singh et al. (2018) reported that the 1870–1876 period that had two (1873 and 1876) famines in India occurred during cool tropical Pacific conditions. Our results show that the droughts that occurred during 1873 and 1876 did not affect a large area of India (Figure 2). All India monsoon season rainfall was 2% above the long-term mean in 1873 while 6% below long-term mean in 1876. While El Niño is the major driver of monsoon season droughts (Mishra et al., 2012), precipitation anomalies in 1873 and 1876 are not associated with the warm phase of ENSO.

3.4. Droughts that Did Not Cause Famine

Finally, we identify the major soil moisture drought periods in the post-1900 period that were not coincident with famines (Figure 4 and Table S1). For each post-1900 drought period identified by the SAD analysis (e.g., 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015), we selected the month with the greatest areal coverage for our analysis. We find that soil moisture droughts in October 1918 and December 1920 are comparable (based on areal coverage) to those that occurred in December 1896 and December 1899, which were associated with famines (Figure 2). In October 1918, more than 65% of the country was affected by soil moisture drought (Figure 4a). Similarly, the 1908–1924 drought had covered a large area (65.4%) in December 1920 (Figure 4), which prominently affected central India. The 1937–1945 drought period had the largest extent in August 1941, which affected 46.8% (mainly northwestern and southern regions) of India (Figure 4c). Similarly, the drought period of 1982–1990 affected 47.3% of the country in August 1987 (Figure 4d and Table S3). The 1997–2004 drought period had more than 47% areal extent between November 2000 and March 2001(Table S3). The soil moisture drought (1997–2004) peaked in February

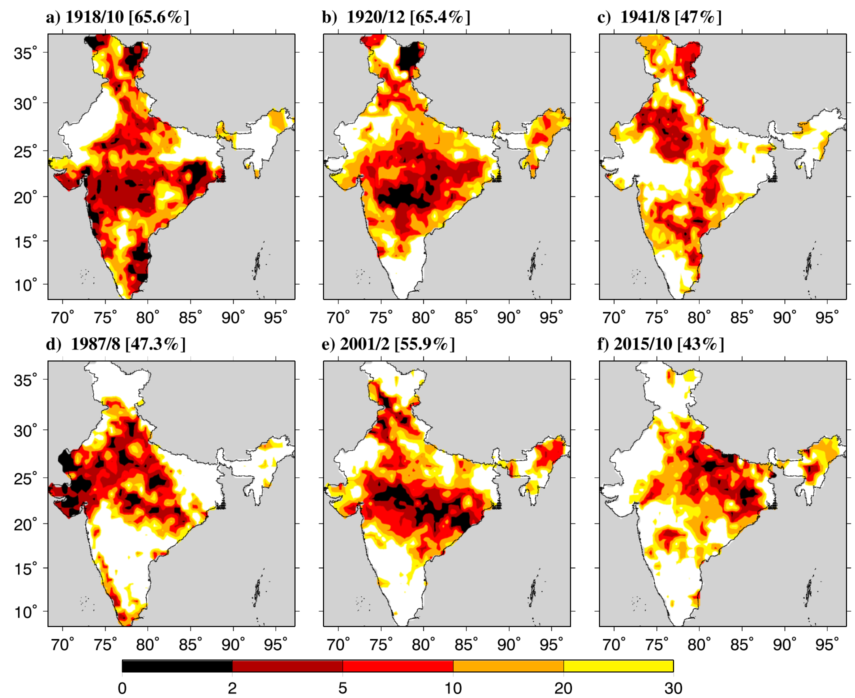

Figure 4. Major soil moisture droughts and their areal coverage (%) that were not associated with famines. The region with soil moisture percentile above 30 is shown with white and represents no-drought condition.

2001 and affected 56% of the country (Figure 4e and Table S3). The most recent drought period identified by the SAD analysis occurred in 2011–2015 with the largest extent in October 2015 (Figure 4f and Table S3).

4. Discussion and Conclusions

Limited irrigation (McGinn, 2009) and low crop yields almost certainly combined with soil moisture droughts leading to crop failures and food shortages in the era of British rule. Soil moisture droughts resulted in crop failures that not only affected food availability but also the livelihood of much of the population, especially given that a transportation system was not in place to ship food from one place to another. Dreze (1988) reported that British era droughts not only resulted in massive crop failures and food shortages but also shattered the rural economy. Among the six famines identified above, 1873 and 1943 provide some important insights. For instance, despite the monsoon failure and drought in 1873 in Bihar and Bengal provinces, there was minimal mortality (Hall-Matthews, 2008). Moreover, human mortality was substantially higher in the other four droughts than in the 1873–1874 famine, which can be attributed to policy failures and mismanagement (Davis, 2001; Ferguson, 2004). The 1943 Bengal famine was not caused by drought but rather was a result of a complete policy failure during the British era.

A series of famines from 1870 to 1943 killed well over 10 million people in India. All but one of the major famines in this period are linked to soil moisture drought. Out of five major droughts that caused famines in India, three were driven by the positive SST anomalies (El Niño) in the tropical Pacific Ocean. India has experienced soil moisture droughts that were as severe as those that accompanied the deadly pre-1900 famines (for instance, 1918 and 1920). The fact that these droughts did not lead to famine deaths appears to be the result mostly of more effective government responses. Despite substantial population growth between 1900 and 2016, famine deaths have been essentially eliminated in modern India. The primary reasons are better food distribution and buffer food stocks, rural employment generation, transportation, and groundwater-based irrigation (Aiyar, 2012). Rapid depletion of groundwater in northern India (Asoka et al., 2017; Rodell et al., 2009) raises concerns for food and freshwater security in India. Our results showing the linkage between droughts and famine in India have implications for food and freshwater security of the region.

Acknowledgments

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