Drought and famine in India, 1870-2016

Vimal Mishra[1], Amar Deep Tiwari[1], Reepal Shah[1], Mu Xiao[2], D.S. Pai[3], Dennis Lettenmaier[2]

1. Civil Engineering, Indian Institute of Technology, Gandhinagar, India
2. Department of Geography, University of California, Los Angeles, USA
3. India Meteorological Department (IMD), Pune

Abstract

Millions of people died due to famines caused by droughts and crop failures in India in the 19th and 20th centuries. However, the relationship of historical famines with drought is complicated and not well understood in the context of the 19th and 20th-century events. Using station-based observations and simulations from a hydrological model, 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 (SAD) 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. On the other hand, five major droughts were not linked with famine, and three of those five non-famine droughts occurred after Indian Independence in 1947. Famine deaths due to droughts have been significantly reduced in modern India, however, ongoing groundwater storage depletion has the potential to cause a shift back to recurrent famines.

1.0 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), twelve major famines occurred (in 1769-70, 1783-84, 1791-92, 1837-38, 1860-61, 1865-67, 1868-70, 1873-74, 1876-78, 1896-97, 1899-1900, and 1943-44) 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; *Parthasarathy et al.*, 1987; *Gadgil and Gadgil*, 2006; *Mishra et al.*, 2016]. Droughts in the late 18th and early 19th centuries had progressively more severe effects due to a rising population, low crop yields, and lack of irrigation [*FAO*, 2014]. Hence, an understanding of historical famine and drought in India relates both to 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 mid-20th 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 18th and 19th-century droughts in India have been limited to meteorological [*Bhalme et al.*, 1983; *Mooley and 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 U.S. [*Andreadis and 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 (SYMAP) algorithm as described in Maurer et al. (2002). *Pai et al.*, [2015] developed the IMD gridded precipitation product using data from 6995 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 degree 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 1690 stations spread across India for most of the pre-1900 period. We carefully checked the quality of data for each station as follows. We used the daily precipitation observations, and first determined, for each station, the number of months with complete records. We dropped (treated as missing) months with more than ten missing precipitation days. If precipitation data were available for 20 or more days in a month, the total (cumulative) precipitation for that month was considered for the analysis. We found that the number of stations after the quality check varied from about 517 in 1870 to more than 1600 in 1900 (Fig. S1). After the initial quality control, we estimated time (fraction of the 31 years from 1870 through 1900) with available data for each station (Fig. S2). We found that most of the stations have monthly precipitation data for more than 50% of the 1870-1900 period (Fig. S2). Therefore, we decided not to drop stations with missing data but rather to exclude months with large data gaps.

The station density in the pre-1900 period varied substantially over India. For instance, northern and peninsular India have higher station densities than western and east-central India (Fig. S2). Moreover, stations located in eastern India (except a few stations with long-term data) have relatively shorter records in comparison to the stations located in the north and southern India (Fig. S2). We also compared monthly precipitation over the 1870-1900 period with the long-term mean (1870-2016) to identify spurious values and outliers. Finally, using the monthly precipitation data for 1870-1900, we developed a gridded (0.5 deg) precipitation product for the entire country using the methods described in *Maurer et al.*, [2002].

We extracted daily precipitation, maximum and minimum temperatures, and wind speed from the 20th-century reanalysis (20CR, NOAA-CIRES 20th Century Reanalysis version 2c) from NOAA's Physical Science Division (PSD: https://www.esrl.noaa.gov/psd/data/20thC_Rean/) for 1851-2014. The 20CR data are available globally at 2.0º spatial and 6-hour, daily, and monthly temporal resolutions. All the variables from 20CR and regridded to 0.5º spatial resolution using the synergic mapping (SYMAP) algorithm as described in Maurer et al. (2002). Additional information on 20CR dataset can be found in *Compo et al.*, [2006]. More detailed information on data prepration from 20CR and Berkeley Earth can be obtained from supplemental section S1.

We compared mean precipitation for the monsoon period (June through September) as well as the water year (June through May) for 1870-1900 against the post-1900 (1901-1930) period (Fig S3). We found that the key features regarding the mean and spatial variability of precipitation are well captured in our gridded dataset for 1870-1900. Additionally, we compared precipitation and Palmer Drought Severity Index (PDSI: http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html) from Dai et al. (2004). All-India monthly precipitation anomalies from IMD and Dai are well correlated (correlation = 0.87, Fig. S4). Moreover, we found that spatial patterns of PDSI from our gridded precipitation and temperature products are consistent with PDSI from [*Dai et al.*, 2004] for the ten most severe (based on annual precipitation deficit) drought events in India during 1870-2014 (Fig. S5). Furthermore, air temperature from Berkeley Earth and IMD compare well for the overlapping period 1951-2014 (Fig. S6). The high-bias in temperature from IMD is mainly due to bias in the Himalayan region (Fig. S6), which is attributable to low gauge density in the region [Shah and Mishra, 2014; Mishra, 2015]. We note that the most severe drought and famines largely are to the south of this region.

We used the Variable Infiltration Capacity [*Liang et al.*, 1994] macroscale hydrology model, 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., [*Sheffield et al.*, 2004; *Andreadis and Lettenmaier*, 2006; *Mishra et al.*, 2014, 2018; *Shah and Mishra*, 2016]). We applied the VIC model at a daily time-step for each 0.5º grid for 1870-2016 (see supplemental section 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 as did [*Andreadis and 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 million km^2) for which drought duration and severity are computed. More information on SAD analysis can be obtained from *Andreadis and Lettenmaier*, [2006]. 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:

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

where S is drought severity, SMP is monthly soil moisture percentile, and t is drought duration (months). We calculated drought severity for 3, 6, 12, 24, and 48 months' duration. We identified seven major drought periods from the SAD analysis.

3. Results and Discussion

We first identified the major soil moisture drought periods in India using the SAD method applied to the 1870-2016 record (Fig. 1). We identified drought severity and area for 3-48 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 short- (3-6 months) and long-term (12-48 months) soil moisture droughts (Fig. 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 million km^2 area) soil moisture droughts occurred during 1895-1900 and 1908-1924 (Table S1). 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 million km^2) (Table 1). 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 million 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 S2 for details). 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 S2).

The 1908-1924 drought period was the most widespread in January 1908, October 1918, December 1920, and May 1921 (Tables S1 and S2). 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 (Fig. 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 S2). 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.

We estimated annual mean drought extent (%) using monthly soil moisture for 1870-2016 (Fig. S7). We found that mean annual drought extent was higher than 20% (of the country) averaged over all of the seven (1876-1882, 1895-1900, 1908-1924, 1937-1945, 1982-1990, 1997-2004, and 2011-2015) periods identified by the SAD analysis (Fig 1). Since the SAD analysis examines drought severity and duration of the largest spatial clusters, it may ignore fragmented clusters of lesser severity [*Andreadis and Lettenmaier*, 2006]. For instance, despite a few years between 1950 and 1980 that had large drought extents, they were not within the SAD envelope (Fig. S7a) because of the lack of spatial contiguity. The pooled data for 3-48 (from Fig. 1) months drought show that India witnessed frequent and widespread droughts during the pre-1900 (1870-1900) (Fig. S7b). Drought extents comparable to 1895-1900 period occurred only during 1908-1924 in the post-1900 record (Fig. S7b). Based on the areal coverage, pre-1900 droughts were much different (p-value <=0.05) in areal extent and severity [Fig. S7b,c] than those that occurred later. Out of the 20 largest monthly soil moisture droughts (Table S3) based on their areal coverage, only two (February 2001 and January 2003) occurred after 1924. Our results highlight that India witnessed frequent, severe, and widespread soil moisture droughts before 1900 that contributed to crop failures and famines. Crop failures due to drought before 1900 were prevalent; however, increased trade and demands of labor along with the credit and relief services from government significantly reduced the risk of widespread crop-failures and famine post-1900 [*McAlpin*, 1979].

We analyzed famines and associated causes during the century and a half period 1870-2016. Our focus is on root-zone soil moisture (60cm following Mishra et al., 2018) from which we identified famines that were coincident with soil moisture deficits. In particular, we identified five major famines (1873-1874, 1876-1878, 1896-1897, 1899-1900, and 1943-1944) that occurred during the 1870-2016 record. 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 1873-74 famine occurred in Bihar and Bengal, which were part of the northwestern province and Oudh during the British period. Depleted soil moisture created an exceptional drought (SMP <2.0) in Bengal and the western part of Bihar during June 1873 (Fig. 2a). Since the soil moisture drought in 1873 was centered in a relatively small domain, it was not identified by the SAD analysis (against the threshold of 0.1 million km^2). During the 1873 famine, soil moisture drought that affected more than 50% of Bihar and Bengal, was caused by a precipitation deficit in the pre-monsoon season (January to May), 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 during the post-monsoon season (October to December) [Fig.S7b]. We find only a moderate (0.5ºC) positive temperature anomaly during the pre-monsoon season in the region suggesting that precipitation deficit, rather than warmth, was the proximate cause of the drought. About 21.5 million people were affected by the 1873 famine, but little or no mortality was reported (IGI, 1907, *Hall-Matthews*, [2008]). The low mortality during the 1873 famine was mainly attributable to food imports from Burma and timely relief aid provided by the British government (IGI, 1907, *Hall-Matthews*, [2008]). The famine was over in 1874 with 17% surplus monsoon precipitation and good food production.

The second most notable famine occurred during 1876-1878, which has also been called the Great Famine of Southern India, or Madras Famine [*Dyson*, 1991; *Lardinois*, 2009; *Cook et al.*, 2010]. As identified by the SAD analysis, 3- and 6-month soil moisture deficits lead to drought throughout much of southern India (Fig 1 and Fig. 2). The drought covered more than 87% of the famine-affected region in November 1876 (Fig. 2), which remained under drought until October 1877. North India (and especially the central, north-western provinces, and Punjab) experienced an extreme to exceptional soil moisture drought in 1877. In August 1877, about 56.6% of the country experienced soil moisture drought (Table S2, Fig. 2). The famine-affected region had an extent of 79% and 78%, respectively in August and September 1877 (Fig. S7f). Similar to the 1873 famine, air temperature did not play a major role in the soil moisture anomaly (drought) in 1876 (Fig. S7d). 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]. The 1876-1877 famine in the south and north India affected more than 50 million people (IGI, 1907) of which about 5.5 million perished [*Fieldhouse*, 1996].

The 1895-1900 drought period identified by the SAD analysis includes two famines: 1896-97 and 1899-1900. During October 1896 to January 1897, more than 57% of the country was affected by soil moisture drought (Table S2). The famine of 1896-97 started in the Bundelkhand area (Agra province in the British era) in north India (Fig. S7g). 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) (Fig. S7h). The 1896-97 famine affected 69.5 million people in India (IGI, 1907) and caused the death of 5 million people as relief measures failed in the central province [*Fieldhouse*, 1996].

The population was still recovering from the 1896-97 famine when the 1899-1900 famine started with a monsoon failure in central and western India (Fig. 2). More than 56% of the country was in soil moisture drought between September 1899 and February 1900 (Table S2). 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 (Fig. S7i). 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 from July till December 1899 (Fig. S7j). 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 [*Fieldhouse*, 1996; *Fagan*, 2009]. 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 during August and December 1941 (Table S1 and S2) – prior to the famine. Based on all-India averaged soil moisture drought extent, in 1943, the drought-affected only about 12% of the country (Fig. S7a). Therefore, this was the only famine that does not appear to be linked directly to soil moisture drought and crop failures (Fig. S8a). The famine-affected region received 15, 3, 9, and 4% above normal precipitation during June, July, August, and September of 1943 (Fig. S8b). We find that the Bengal famine was likely caused by other factors related at least in part to the ongoing Asian Theater 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). Furthermore, inflation of the rupee between March and May 1943 [*Sen*, 1976] resulted in rice prices five to six times higher than before the famine. The situation was exacerbated by the failure of the British government to declare a state of famine to avoid an increase in aid (FIC, 1945). We note that aside from the 1943 Bengal Famine, all the other famines in the 1870-2016 appear to be related at least in part to widespread soil moisture drought.

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. We hypothesize that during the famine era; the population mostly relied on agriculture for food and employment. Therefore, 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 resulted not only in massive crop failures and food shortages, but also they shattered the rural economy. Landless agricultural laborers did not find employment, food prices increased, and trade was often slow to move food to drought affected regions [*Dreze*, 1988]. Therefore, there was a compounding effect of soil moisture drought and population density during famines that enhanced the drought risk to much of the population.

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]. The commitment to save human lives at any cost (IGI, 1907), importing of rice from Burma and timely relief helped to avoid human mortality (IGI, 1907) during 1873. Moreover, as an unprecedented move, affected villages were inspected by British officials to identify people who needed relief during the 1873 famine [*Hall-Matthews*, 1996]. The other four (1876, 1877, 1896-97, and 1899) famines were also caused by droughts, which were more severe and widespread than 1873. Moreover, human mortality was substantially higher in the other four droughts than in the 1873-74 famine, which can be attributed to policy failures and mismanagement [*Davis*, 2001; *Ferguson*, 2004]. A free trade policy, export of agricultural produce, neglect of agricultural investment, and taxation policies aggravated the adverse impacts of famines caused by droughts [*Sen*, 1982; *Davis*, 2001; *Mander*, 2009]. The 1943 Bengal famine was not caused by drought rather but rather was a result of a complete policy failure during the British era. More generally, we find that most of the famines resulted from a combination of droughts and policy failures.

Finally, we identify the major soil moisture drought periods in the post-1900 period that were not coincident with famines (Fig. 3 and Table S2). 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 drought 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 (Fig. 3). In October 1918, more than 65% of the country was affected by soil moisture drought (Fig. 3a). The drought during October 1918 affected most of the regions in India except northeastern and western parts (Fig. 3). Similarly, the 1908-1924 drought had covered a large area (65.4%) in December 1920 (Fig. 3), which prominently affected central India. The soil moisture drought of 1908-1924 period affected more than 50% of the country in May 1921 (Table S2)

The 1937-1945 drought period had the largest extent in August 1941, which affected 46.8% (mainly northwestern and southern regions) of India (Fig. 3c). Similarly, the drought period of 1982-1990 identified by the SAD analysis affected 47.3% (western and central parts) of the country in August 1987 (Fig. 3d, Table S2). In 1987, western India received 25% or less precipitation of the long-term mean monsoon season precipitation [*Krishnamurti et al.*, 1988]. The 1997-2004 drought period had more than 47% areal extent between November 2000 and March 2001(Table S2). The soil moisture drought (1997-2004) peaked in February 2001 and affected 56% of the country while in January 2003 54% of the country was affected by the drought (Fig. 3e, Table S2). Drought affected 300 million people in India in 2002 (EM-DAT). *Bhat*, [2006] reported that the drought in 2002 was mainly caused by a 56% precipitation deficit in July. The most recent drought period identified by the SAD analysis occurred in 2011-2015 with the largest extent in October 2015 (Fig. 3f, Table S2). The drought in October 2015 was mainly centered in the Indo-Gangetic Plain and had severe impacts on surface and groundwater resources [*Mishra et al.*, 2016]. We find that aside from the 1908-1924 period, droughts in post-1900 were less widespread than that occurred pre-1900 (Table S2, Fig. S7).

4. Conclusions

In summary, we conclude that:

- A series of famines from 1870 through 1943 killed well over ten million people in India. All but one of the major famines in this period are linked to soil moisture drought, and all but one occurred prior to 1900. The only one major famine (1943-44) that occurred post-1900 period was mainly a result of the British era (and World War 2) policy failures, rather than soil moisture drought.

- 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. Nonetheless, there is some evidence that post-1900 droughts have been less severe than those earlier in our period of analysis; of the ten most severe soil moisture droughts (based on monthly extents) we identified, six occurred in the pre-1900 period (first 30 years of our 146-year period of record).

- 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 [*Aiyar*, 2012], rural employment generation, transportation, and groundwater-based irrigation [*Aiyar*, 2012]. While this is a remarkable accomplishment, the population continues to grow, and there are limits to the primary proximate causes of famine elimination. Furthermore, rapid depletion of groundwater in northern India [*Rodell et al.*, 2009; *Asoka et al.*, 2017] raises concerns for food and fresh water security in India.

Acknowledgment: The work is financially supported by the grants from the Ministry of Water Resources, India. All the data used in this study are freely available from IMD (www.imd.gov.in), 20CR (https://www.esrl.noaa.gov/psd/data/20thC_Rean/), and Berkeley-Earth (http://berkeleyearth.org).

Figures:

Figure 1. Severity-Area-Duration (SAD) curves for the major drought periods in India during 1870-2016 for (a) 3-month, (b) 6-month, (c) 12-month, (d) 24-month, and (e) 48-month durations. Severity and area (million km^2) for seven major drought periods were estimated using SAD analysis.

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, %), temperature (red, ºC) anomalies and areal extent (green,%) of soil moisture drought. (c-j) same as (a,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,i) represents no drought condition.

Figure 3. 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 represents no drought condition

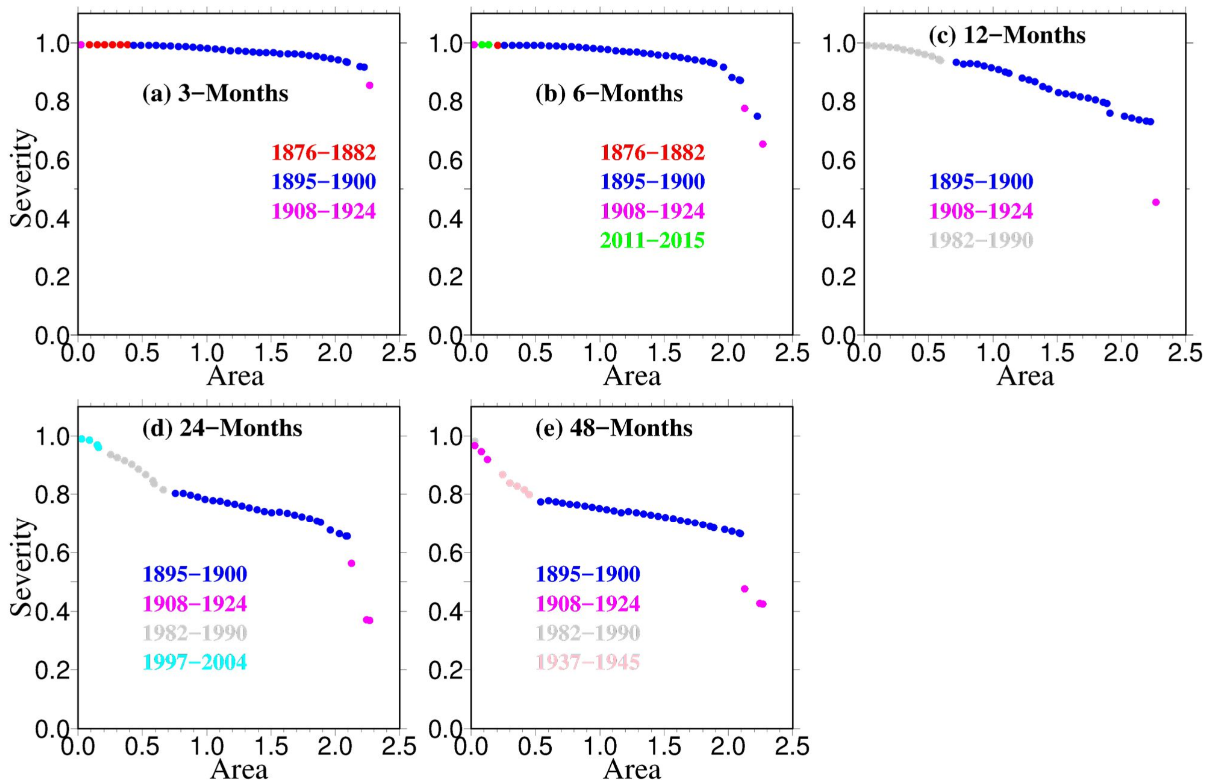

Figure 1. Severity-Area-Duration (SAD) curves for the major drought periods in India during 1870-2016 for (a) 3-month, (b) 6-month, (c) 12-month, (d) 24-month, and (e) 48-month durations. Severity and area (million km^2) for seven major drought periods were estimated using SAD analysis.

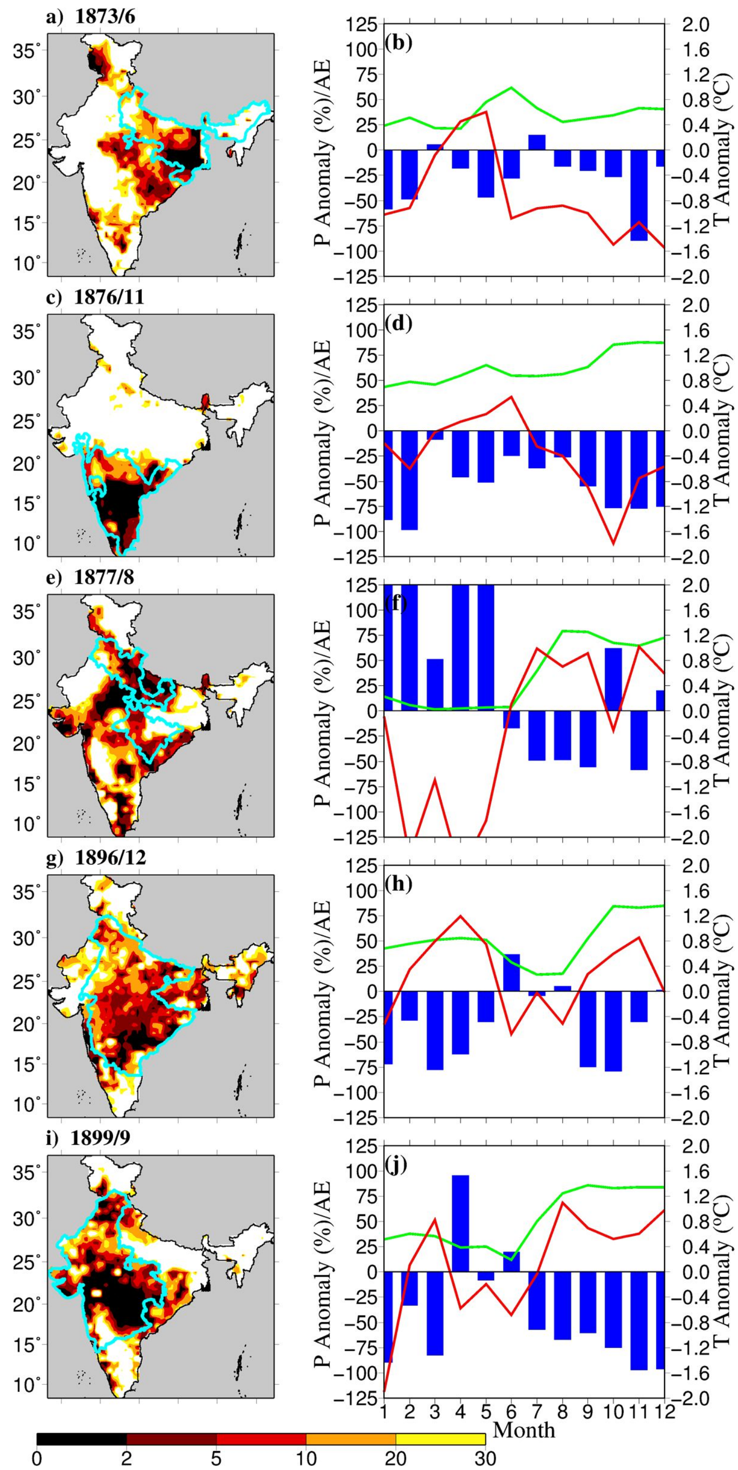

Figure 2. Soil moisture droughts that were coincident with famines. (a) The extent of drought during June 1873. Cyan polygon shows the famine-affected regions that were identified by the British Provinces from the map of British India (W. H. Allen and Co. - Pope, G. U. (1880)). (b) Monthly precipitation (blue, %), temperature (red, ºC) anomalies and areal extent (green,%) of soil moisture drought. (c-j) same as (a,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,i) represents no drought condition.

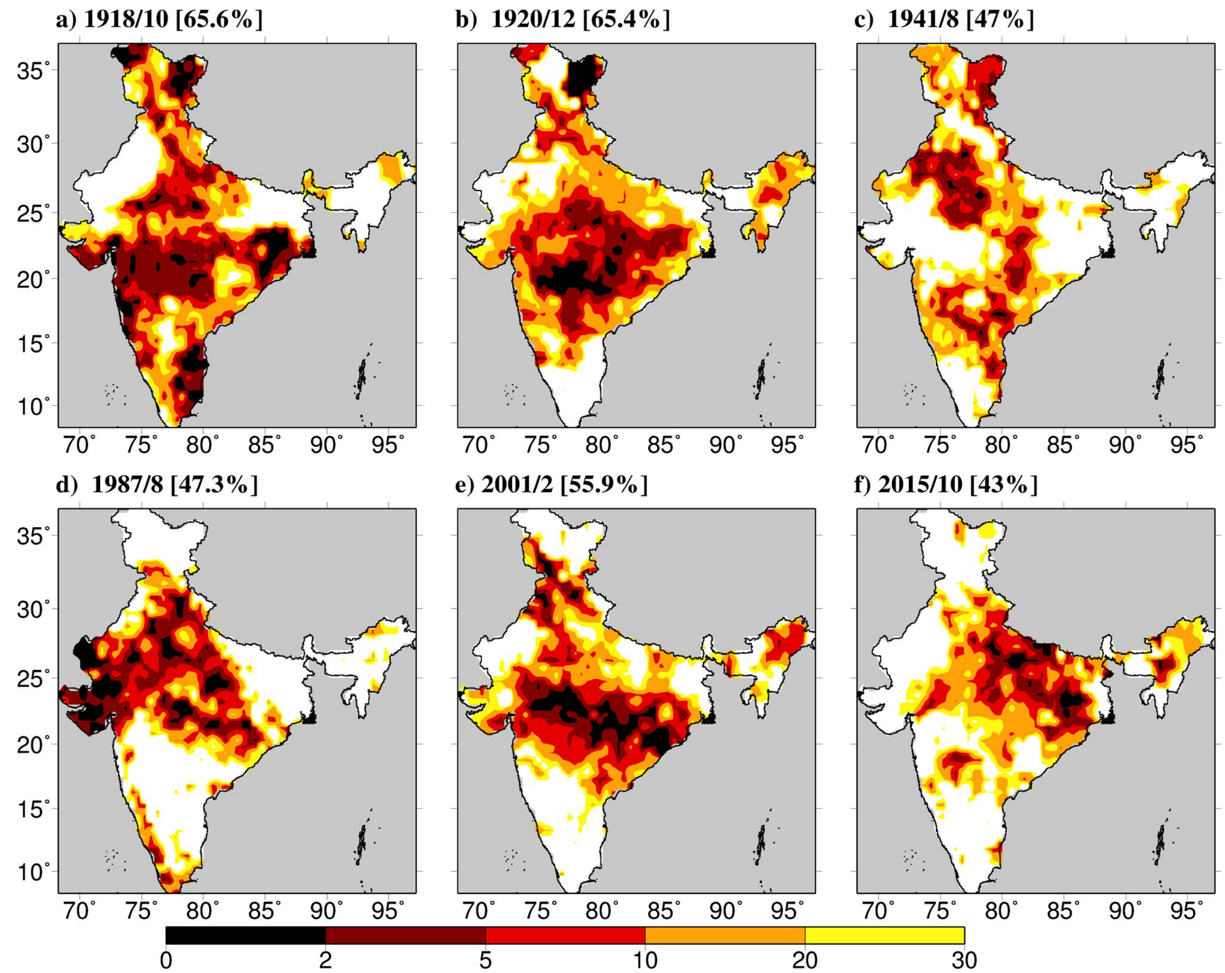

Figure 3. Major soil moisture droughts and their areal coverage (%) that were not associated with famines. The region with soil moisture percentile above 30 is shown with white represents no drought condition

References

Aiyar, S. (2012), Drought not a big calamity in India anymore, Times of India (https://blogs.timesofindia.indiatimes.com/Swaminomics/drought-not-a-big-calamity-in-india-anymore/).

Andreadis, K. M., and D. P. Lettenmaier (2006), Trends in 20th century drought over the continental United States, *Geophys. Res. Lett.*, *33*(10), 1–4, doi:10.1029/2006GL025711.

Asoka, A., T. Gleeson, Y. Wada, and V. Mishra (2017), Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India, *Nat. Geosci.*, *10*(2), 109–117, doi:10.1038/ngeo2869.

Attwood, D. W. (2005), Big is ugly? How large-scale institutions prevent famines in Western India, *World Dev.*, *33*(12), 2067–2083, doi:10.1016/j.worlddev.2005.07.009.

0493(1980)108<1197:LSDAMC>2.0.CO;2.

Bhalme, H. N., D. A. Mooley, and S. K. Jadhav (1983), Fluctuations in the Drought/Flood Area over India and Relationships with the Southern Oscillation, *Mon. Weather Rev.*, *111*(1), 86–94, doi:10.1175/1520-0493(1983)111<0086:FITDAO>2.0.CO;2.

Bhat, G. S. (2006), The Indian drought of 2002 - A sub-seasonal phenomenon?, *Q. J. R. Meteorol. Soc.*, *132*(621), 2583–2602, doi:10.1256/qj.05.13.

Compo, G. P., J. S. Whitaker, and P. D. Sardeshmukh (2006), Feasibility of a 100-year reanalysis using only surface pressure data, *Bull. Am. Meteorol. Soc.*, *87*(2), 175–190, doi:10.1175/BAMS-87-2-175.

Cook, E. R., K. J. Anchukaitis, B. M. Buckley, R. D. D. Arrigo, G. C. Jacoby, and W. E. Wright (2010), Asian Monsoon Failure and Megadrought During the Last Millennium, *Science (80-.).*, *486*(April), 486–490, doi:10.1126/science.1185188.

Dai, A., K. E. Trenberth, and T. Qian (2004), A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming, *J. Hydrometeorol.*, *5*(6), 1117–1130, doi:10.1175/JHM-386.1.

Davis, M. (2001), Late Victorian Holocausts: El Nino Famines and the Making of the Third World, *Verso Books*, doi:10.1017/CBO9781107415324.004.

Devereux, S. (2000), Famine in the twentieth century, *IDS Work. Pap. 105*, *1*, 40.

Dreze, J. (1988), Famine Prevention in India, *Polit. Econ. Hunger*, *2*, 13–22, doi:10.1111/j.1467-7717.1991.tb00460.x.

Dyson, T. (1991), On the demography of South Asian famines part II, *Popul. Stud. (NY).*, *45*(2), 279–297, doi:10.1080/0032472031000145446.

Fagan, B. (2009), Floods, Famines, and Emperos: El Nino and the Fate of Civilization, *Basic Books*.

FAO (2014), *The state of world fisheries and aquaculture*, Rome, Italy.

Ferguson, N. (2004), *Empire: The Rise and Demise of the British World Order and the Lessons for Global Power*.

Fieldhouse, David (1996), "For Richer, for Poorer?", in Marshall, P. J., *The Cambridge Illustrated History of the British Empire*, Cambridge: Cambridge University Press. Pp. 400, pp. 108–146, ISBN 0-521-00254-0

Gadgil, S., and S. Gadgil (2006), The Indian monsoon, GDP and agriculture, *Econ. Polit. Wkly.*, (November 25), 4887–4895, doi:10.2307/4418949.

Guha, S. (2006), *Environment and Ethnicity in India, 1200-1991*.

Imperial Gazetteer of India (IGI), volume III 1907

Hall-Matthews, D. (1996), Historical roots of famine relief paradigms: Ideas on dependency and free trade in India in the 1870s, *Disasters*, *20*(3), 216–230, doi:10.1111/j.1467-7717.1996.tb01035.x.

Hall-Matthews, D. (2008), Inaccurate conceptions: Disputed measures of nutritional needs and famine deaths in colonial India, *Mod. Asian Stud.*, *42*(6), 1189–1212, doi:10.1017/S0026749X07002892.

Krishnamurti, T. N., H. S. Bedi, W. Heckley, and K. Ingles (1988), Reduction of the Spinup Time for Evaporation and Precipitation in a Spectral Model, *Mon. Weather Rev.*, *116*(4), 907–920, doi:10.1175/1520-0493(1988)116<0907:ROTSTF>2.0.CO;2.

Lardinois, R. (2009), Famine, Epidemics and Mortality in South India: A Reappraisal of the Demographic Crisis of 1876-1878, *Econ. Polit. Wkly.*, *20*(11), 454–465.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *J. Geophys. Res.*, *99*(D7), 14415–14428, doi:10.1029/94JD00483.

Maharatna, A. (1996), The Demography of Famines: an Indian Historical Perspective, *Dr. Diss. London Sch. Econ. Polit. Sci. (United Kingdom)*.

Mander, H. (2009), Barefoot: Colonial legacy of famine codes, *Chennai, India: The Hindu*, 13th September.

Maurer, E. P., A. W. Wood, J. C. Adam, and D. P. Lettenmaier (2002), A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, *Am. Meteorol. Soc.*, *21*(2), 116–119, doi:10.1175/JCLI-D-12-00508.1.

McAlpin, M. B. (1979), Dearth, Famine, and Risk: The Changing Impact of Crop Failures in Western India, 1870-1920, *J. Econ. Hist.*, *39*(1), 143–157, doi:10.1017/S0022050700096352.

McGinn, P. (2009), Capital, "Development" and Canal Irrigation in Colonial India, *Inst. Soc. Econ. Chang.*, 29.

Mishra, V. (2015), Climatic uncertainty in Himalayan water towers, *J. Geophys. Res. Atmos.*, 1–17, doi:10.1002/2014JD022650.Received.

Mishra, V., R. Shah, and B. Thrasher (2014), Soil Moisture Droughts under the Retrospective and Projected Climate in India*, *J. Hydrometeorol.*, *15*(6), 2267–2292, doi:10.1175/JHM-D-13-0177.1.

Mishra, V., S. Aadhar, A. Asoka, S. Pai, and R. Kumar (2016), On the frequency of the 2015 monsoon season drought in the Indo-Gangetic Plain, *Geophys. Res. Lett.*, *43*(23), 12,102-12,112, doi:10.1002/2016GL071407.

Mishra, V., R. Shah, S. Azhar, H. Shah, P. Modi, and R. Kumar (2018), Reconstruction of droughts in India using multiple land surface models (1951-2015), *Hydrol. Earth Syst. Sci.*, *2000*(March), 1–22.

Mooley, D. A., and B. Parthasarathy (1984), Fluctuations in All-India summer monsoon rainfall during 1871-1978, *Clim. Change*, *6*(3), 287–301, doi:10.1007/BF00142477.

Pai, D. S., L. Sridhar, M. R. Badwaik, and M. Rajeevan (2015), Analysis of the daily rainfall events over India using a new long period (1901–2010) high resolution (0.25° × 0.25°) gridded rainfall data set, *Clim. Dyn.*, *45*(3–4), 755–776, doi:10.1007/s00382-014-2307-1.

Parthasarathy, B., N. A. Sontakke, A. A. Monot, and D. R. Kothawale (1987), Droughts/floods in the summer monsoon season over different meteorological subdivisions of India for the period 1871–1984, *J. Climatol.*, *7*(1), 57–70, doi:10.1002/joc.3370070106.

Passmore, R. (1951), Famine in India an Historical Survey, *Lancet*, *258*(6677), 303–307, doi:10.1016/S0140-6736(51)93295-3.

Rodell, M., I. Velicogna, and J. S. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*(7278), 999, doi:10.1038/nature08238.

Roy, T. (2006), *The Economic History of India, 1857-1947*.

Sen, A. (1976), Famines as Failures of Exchange Entitlements, *Econ. Polit. Wkly.*, *11*(31/33), 1273–1280, doi:10.2307/4364836.

Sen, A. (1982), Poverty-and-famines│Amartya-Sen│1981.pdf, *Oxford, Clarendon Press*, 187–194.

Shah, R., and V. Mishra (2014), Evaluation of the Reanalysis Products for the Monsoon Season Droughts in India, *J. Hydrometeorol.*, *15*(4), 1575–1591, doi:10.1175/JHM-D-13-0103.1.

Shah, R. D., and V. Mishra (2015), Development of an Experimental Near-Real-Time Drought Monitor for India*, *J. Hydrometeorol.*, *16*(1), 327–345, doi:10.1175/JHM-D-14-0041.1.

Shah, R. D., and V. Mishra (2016), Utility of Global Ensemble Forecast System (GEFS) Reforecast for Medium-Range Drought Prediction in India, *J. Hydrometeorol.*, *17*(6), 1781–1800, doi:10.1175/JHM-D-15-0050.1.

Sheffield, J., A. D. Ziegler, E. F. Wood, and Y. Chen (2004), Correction of the high-latitude rain day anomaly in the NCEP-NCAR reanalysis for land surface hydrological modeling, *J. Clim.*, *17*(19), 3814–3828, doi:10.1175/1520-0442(2004)017<3814:COTHRD>2.0.CO;2.

Sheffield, J., C. R. Ferguson, T. J. Troy, E. F. Wood, and M. F. McCabe (2009), Closing the terrestrial water budget from satellite remote sensing, *Geophys. Res. Lett.*, *36*(7), 1–5, doi:10.1029/2009GL037338.

Shepard, D. S. (1984), Computer Mapping: The SYMAP Interpolation Algorithm, in *Spatial Statistics and Models*, edited by G. L. Gaile and C. J. Willmott, pp. 133–145, Springer Netherlands, Dordrecht.

Svoboda, M., and Coauthors, 2002: The Drought Monitor. *Bull. Amer. Meteor. Soc.*, **83**, 1181–1190, https://doi.org/10.1175/1520-0477(2002)083<1181:TDM>2.3.CO;2.

Tauger, M. (2009), The British Famine Crises of World War II, *Br. Sch.*, *I*(2), 421–440.

Wang, A., D. P. Lettenmaier, and J. Sheffield (2011), Soil moisture drought in China, 1950-2006, *J. Clim.*, *24*(13), 3257–3271, doi:10.1175/2011JCLI3733.1.

Wood, A. W., E. P. Maurer, A. Kumar, and D. P. Lettenmaier (2002), Long-range experimental hydrologic forecasting for the eastern United States, *J. Geophys. Res. D Atmos.*, *107*(20), 1–15, doi:10.1029/2001JD000659.