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Spatiotemporal Variability of Seasonality of Rainfall Over India

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Key Points:
- Significant decreasing trends in both seasonality and rainfall are found over parts of central India, Indo-Gangetic plains, and Western Ghats
- There is a general decrease in the wet-season duration throughout India by around 10 to 20 days per century
- El Nino–Southern Oscillations and Indian Ocean sea surface temperatures strongly influence seasonality and rainfall over India

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Abstract We analyzed 113 years (1901–2013) of daily rainfall over India to investigate spatiotemporal variability of rainfall seasonality. Rainfall seasonality and mean annual rainfall were found to be high over the Western Ghats, central, and northeastern parts of India and over the Indo-Gangetic plains, and low over northwest, southern, and northernmost parts of India. Significant decreasing trends in seasonality coupled with decreasing rainfall were found over parts of central India, the Indo-Gangetic plains, and parts of Western Ghats. Trends in timing of peak rainfall indicate later occurrence in the season, especially over southern Indo-Gangetic plains, by ~10–20 days per century. In addition, there is a general decrease in the wet-season duration throughout India by ~10–20 days per century. El Niño–Southern Oscillation and Indian Ocean sea surface temperatures were found to strongly influence seasonality and rainfall over large parts of India. The changes to rainfall and its seasonality will have profound socioeconomic implications for India.

Plain Language Summary Daily rainfall data based on ground-based observations over India has been analyzed for the period 1901–2013 to investigate rainfall seasonality. Rainfall seasonality is found to be high over some parts of India and low over others. Analysis of trends in seasonality and total annual rainfall in the last 113 years reveal that there has been a significant decreasing trend in both over parts of central India, the Indo-Gangetic plains, and parts of Western Ghats. The timing of peak rainfall shows a tendency for later occurrence in the season, especially over southern Indo-Gangetic plains, by ~10–20 days per century. There is also a general decrease in the wet-season duration throughout India by ~10–20 days per century. El Niño–Southern Oscillations and sea surface temperatures over the Indian Ocean were found to strongly influence seasonality and rainfall over large parts of India. The changes to rainfall and its seasonality can potentially have significant socioeconomic implications for India.

1. Introduction

The annual rainfall over India occurs largely during summer (June–September) as the famous Indian summer monsoon, also known as the southwest monsoon and on average contributes ~75–80% of total annual rainfall over India (Deshpande et al., 2012; Kumar et al., 1992; Prabir et al., 2014; Ramage, 1971). The northeast monsoon (October–December) is restricted mainly to southeastern India and contributes ~30–60% of its total annual rainfall (Dimri & Chevuturi, 2016; Rajeevan et al., 2012; Sreekala et al., 2012). Although, the monsoon system is a stable climatological feature, year-to-year (interannual) variations play a major role in the country's socioeconomic well-being—especially the Indian economy strongly depends on agricultural production (16% to the total GDP comes from agriculture), which in turn strongly depends on the spatial and temporal rainfall distribution (Gadgil & Gadgil, 2006; Kumar et al., 2004; Rajeevan et al., 2012) due to limited availability of irrigation facilities. A large part of India's agriculture is rain fed, thus, the timing, magnitude, and duration of rainfall—that is, all aspects of seasonality—are highly critical for crop yield, which then has a direct and significant impact on the entire socioeconomic health of the country for at least a year. Therefore, understanding the seasonality is as important as the rainfall amount, which tends to be the focus of most of the research.

Seasonality in a given climatic parameter (e.g., rainfall, temperature, and winds) provides a reasonable degree of predictive ability of the climatic conditions during a given period of the year as compared to other periods (say, e.g., mapping of rainfall seasonality over India to the JJAS period provides the generic information that this period of the year is wetter than other periods of the year over India). Seasonality of rainfall is an important factor in planning and management of resources—for example, agriculture decisions of planting, fertilizer application and harvesting depend on the seasonal strength of the rainfall. Seasonality in rainfall regimes is typically quantified by analyzing monthly distribution of rainfall climatology (Walsh & Lawler, 1981), using metrics such as relative length and rainfall amount in wet and dry seasons for specific locations. Rarely do such metrics define seasonality over a smaller region in the larger context, that is, relative strength of seasonality over a region as compared to its neighboring regions. Meaningful seasonality comparisons over different locations in a larger region can be made only if there is some quantitative metric accounting for rainfall regimes (Adejuwon, 2012; Walsh & Lawler, 1981). Attempts to quantify rainfall regimes have been made in the past (Ayoade, 1970; Markham, 1970; Nieuwolt, 1974), but they have not been very successful in comparison of rainfall seasonality over different locations in a larger-scale context (Walsh & Lawler, 1981). Walsh and Lawler (1981) suggested that at least five aspects of rainfall regimes are important, namely, absolute seasonality (length of dry and wet seasons), relative seasonality (contrasts in rainfall amounts during the year), number of rainfall maxima and minima, timing of rainfall maxima and minima, and year-to-year variability and reliability of rainfall distributions. In this the authors proposed a simple index of rainfall seasonality and used it to map two different areas—tropical Africa, and British Isles. In another study Sumner et al. (2001) analyzed seasonality of rainfall over Spain using the seasonality index derived by Walsh and Lawler (1981). Pascale et al. (2015) used the concept of relative entropy and seasonality index (described in Feng et al., 2013) to evaluate rainfall from observational data sets and historical simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) on a global scale. They reported that even amongst observational data sets, there exist large differences in rainfall seasonality on local scales. In regard to CMIP5 simulations, they found that for a given model, positive biases in relative entropy were produced by strong positive bias in rainfall during the wet months and strong negative bias during the preceding and following months, whereas negative biases in relative entropy were primarily due to strong positive bias in rainfall during months preceding the wet season. Dhakal et al. (2015) used a new circular statistics framework to assess temporal changes in dates of annual maximum daily rainfall in Maine, USA, and reported that seasonality of the annual daily maximum rainfall showed nonstationarity, although the changes were different for different stations across the state.

In this work, we used the seasonality index proposed by Feng et al. (2013) based on mutual information and entropy and for the first time applied this to gridded daily in situ rainfall over India. Further, we investigated the links between temporal variability of the seasonality to large-scale climate forcings. The data used are described followed by a brief description of methodology and then by the results and discussion.

2. Data

Daily average rainfall (mm/day) on a 0.25° × 0.25° grid (developed by Rajeevan et al., 2006, and Pai et al., 2014) was obtained for the period 1901–2013 from National Climate Centre of India Meteorological Department (IMD). The data set is based on daily rainfall records from 6,955 rain gauge stations spread across India. As noted in Pai et al. (2014), the spatial density of stations is not uniform across the country. The south Peninsula has the highest density, whereas the density is relatively low over northernmost parts of India, northwest India, northeast India, and eastern parts of central India. Inverse distance weighted interpolation technique was used to generate the gridded data set from station data. In order to construct the seasonality indices, monthly rainfall values are computed at each grid point.

Indices of large-scale climate drivers were computed from Hadley Centre sea ice and sea surface temperature (HadISST) data set (Rayner et al., 2003). Specifically, average SSTs over the NINO34 region (5°S to 5°N and 170°W to 120°W), which capture the El Niño-Southern Oscillation (ENSO) in the equatorial Pacific, and average SSTs over western equatorial Indian Ocean (WEIO; 10°S to 10°N and 50°E to 70°E) and southeastern equatorial Indian Ocean (SEEIO; 10°S to 0°N and 90°E to 110°E), which capture the Indian Ocean Dipole, were computed.

3. Entropy-Based Seasonality Metrics

As mentioned above, we use the seasonality index proposed by Feng et al. (2013) to analyze seasonal rainfall regimes over India. At each grid point, for each month we compute the long-term mean monthly rainfall accumulation ($\bar{r}_m$) and divide by the mean annual rainfall accumulation ($\bar{R}$), which gives monthly rainfall probability distribution ($\bar{p}_m$). The concentration of rainfall in the wet season is quantified by relative entropy ($\bar{D}$) by computing the departure of the monthly rainfall probability distribution ($\bar{p}_m$) from a uniform distribution (q_m = 1/12) as shown in equation (1) below. The entropy captures the concentration of rainfall during a year. Seasonality index over a grid point is the product of relative entropy and spatially normalized rainfall. For spatial normalization, the mean annual rainfall accumulation $\bar{R}$ over each grid point is divided by its spatial maximum ($\bar{R}_{max}$). Thereafter, over each grid point a dimensionless long-term seasonality index ($\bar{S}$) is computed by multiplying the spatially normalized mean annual rainfall accumulation ($\bar{R}$ / $\bar{R}_{max}$) with the corresponding relative entropy ($\bar{D}$) as shown in equation (2) below.

$$\bar{D} = \sum_{m=1}^{12} \bar{p}_m \log_2 (\bar{p}_m / q_m) \tag{1}$$

$$\bar{S} = \bar{D} * \left(\bar{R}/\bar{R}_{max}\right) \tag{2}$$

The seasonality index is zero when mean annual rainfall is distributed uniformly throughout the year, and maximum when concentrated in a single month. The lowering of seasonality index is caused by reduction in either the total annual rainfall accumulation or reduction in relative entropy. Low-seasonality regions have high $\bar{D}$ and low $\left(\bar{R}/\bar{R}_{max}\right)$ or vice-versa, whereas high-seasonality regions are a result of intermediate or high values of both parameters. It is to be noted here that although relative entropy captures the concentration in rainfall, and may be treated as a measure of seasonality, in order to exclude regions with low annual rainfall, the total rainfall is also taken into account while defining the seasonality index. This is not to mean that the regions with low annual rainfall have less seasonality but just that the focus of the seasonality index as defined here is on regions with high annual rainfall.

For each grid point and for each year the timing of the peak rainfall and duration of the rainy season were obtained by computing the centroid C_k according to equation (3) (first moment of $r_{k,\ d}$) and duration $Z_k$using equation (4) (second moment of $r_{k,\ d}$) as given below:

$$C_k = \frac{1}{R_k} \sum_{d=1}^{365} d r_{k,d} \tag{3}$$

$$Z_k = \sqrt{\frac{1}{R_k} \sum_{d=1}^{365} |d - C_k|^2 r_{k,d}} \tag{4}$$

It is to be noted that for computing the timing and duration, daily rainfall data have been used for improved accuracy as compared to the monthly accumulations. In equations (3) and (4) the subscript “d” represents “daily” instead of “m” denoting “monthly” in equation (1) above. To compute the trends in normalized rainfall, relative entropy, seasonality index, timing, and duration, the corresponding quantities are first computed for each grid point and for each year, followed by computation of the Mann-Kendall trend (e.g., Helsel & Hirsch, 1992).

4. Results

We first show the climatology of the seasonality metrics, followed by their spatial-temporal trends and links to large-scale climate forcings.

4.1. Climatology of Seasonality

Spatial maps of normalized mean annual rainfall, relative entropy, seasonality index, timing, and duration are shown in Figure 1. Mean annual rainfall is high (Figure 1a) over northeast and along the Western Ghats on the west coast; moderate rainfall over central, and central northeast India; low rainfall over northwest and southern peninsula—This is the familiar climatological pattern of all India rainfall. Relative entropy (Figure 1b) is higher over western India, Western Ghats, and central India, and lower over southern peninsula, eastern coast, northeast, and northernmost parts of India. High entropy indicates concentration of rainfall in time

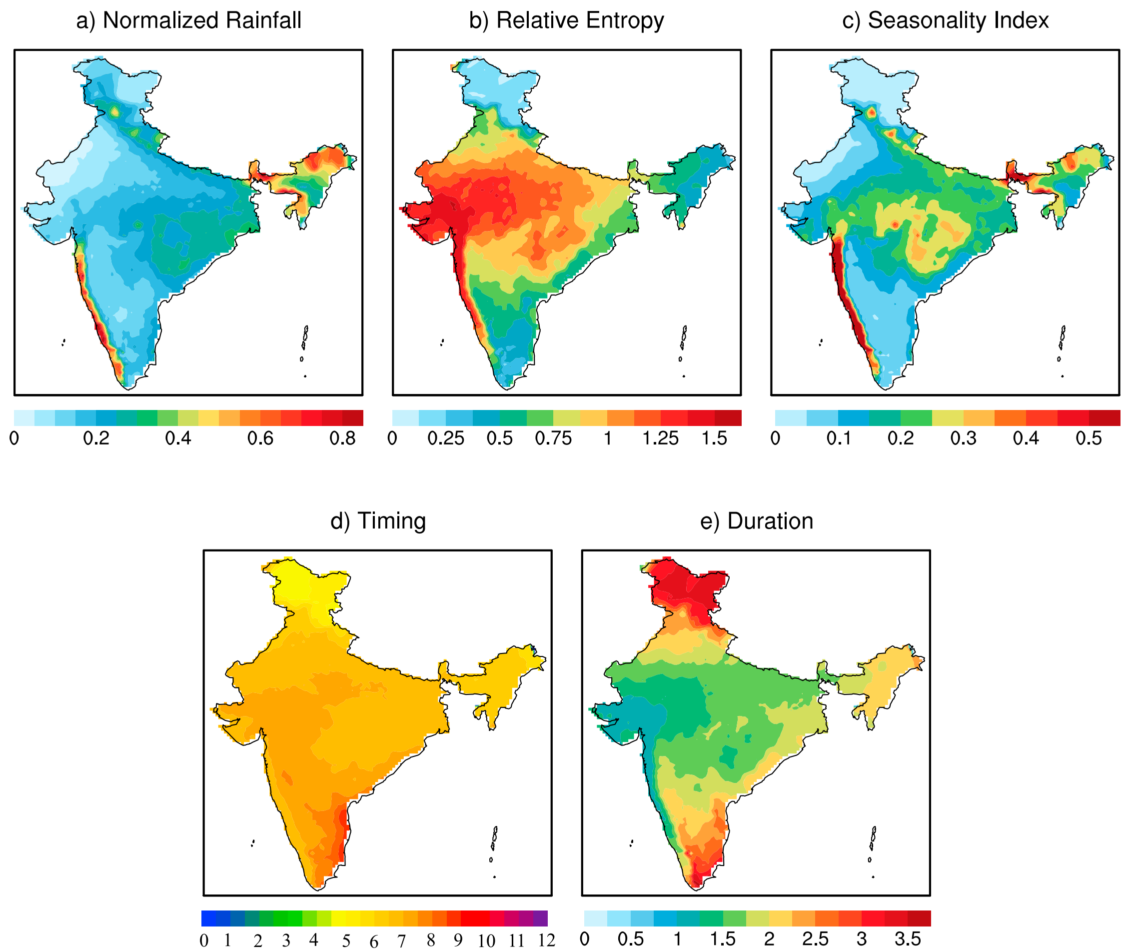

Figure 1. Patterns of (a) spatially normalized annual rainfall accumulation (fraction of the spatial maxima), (b) relative entropy (deviation from uniform distribution), (c) seasonality index, (d) timing of rainfall peak in the wet season, and (e) duration of the wet season for the period 1901–2013. The timing and duration are in months.

over the year—that is, sharp seasonality of rainfall. Lower entropy indicates rainfall throughout the year—which is the case over peninsular India, east coast, and northeast. The spatial pattern of entropy in Figure 1b clearly indicates this.

The seasonality index (Figure 1c) is found to be high over Western Ghats, central, and northeastern parts of India and over the Indo-Gangetic region, and low over northwest, southern, and northernmost parts of India. The high seasonality over Western Ghats, central India, and northeast India is attributed to the high normalized rainfall over these regions, most of which occurs during summer monsoon season. Notably, over Western Ghats, both normalized rainfall as well as relative entropy are high, thus leading to very high values of seasonality index. Low seasonality over northwest and southern India is due to the low values of normalized rainfall, although the corresponding relative entropy is in the midrange. The high seasonality over central India and Indo-Gangetic plains is because of intermediate values of both annual rainfall and relative entropy. Over southern India, relative entropy as well as mean annual rainfall both are small and hence the seasonality index is low. The interesting interplay between the distribution of rainfall captured by the entropy measure and mean annual rainfall is quite clear in the spatial map of seasonality.

The timing of peak rainfall is mainly during July–August over most of the country and during September–November in southeastern peninsula (see Figure 1d). Duration is shorter over western coast and northwest regions, whereas it is high in southern peninsula, north, east coast, and northeastern India, intermediate over rest of the country. The spatial climatological maps of various attributes of seasonality provide a richer insight into seasonality.

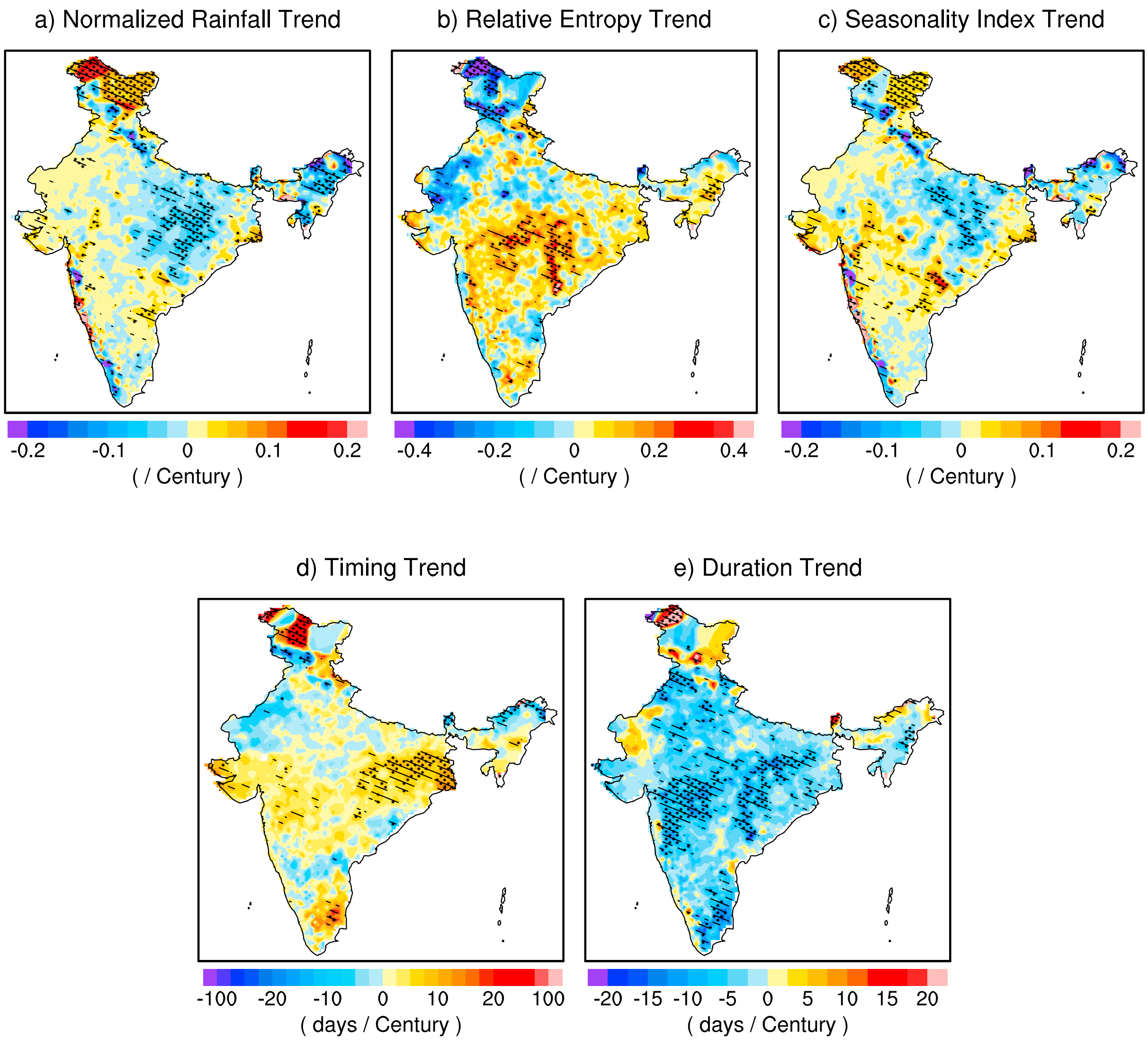

Figure 2. Patterns of Mann-Kendall trends for (a) spatially normalized annual rainfall accumulation, (b) relative entropy, (c) seasonality index, (d) timing of rainfall peak in the wet season, and (e) duration of the wet season for the period 1901–2013. The stippled points are significant at 95% level using the two-tailed Student's *t* test, and the hatched region significant at 90% level.

4.2. Trends in Seasonality

Trends of the seasonality metrics (see Figure 1) are shown in Figure 2. Trends were computed using Mann-Kendall nonparametric trend test (see, e.g., Helsel & Hirsch, 1992) and statistically significant regions at 95% confidence level are stippled. Regions with trends statistically significant at 90% confidence level are hatched to visualize the larger-scale context of changes in the seasonality metrics. Significant reduction in rainfall over Indo-Gangetic plain and Northeast India can be seen and somewhat over western coast (Figure 2a). This reduction is consistent with other findings (Kumar et al., 1992; Prabir et al., 2014). Relative entropy shows an increasing trend over central India and decrease in the north (Figure 2b). This indicates that there is a tendency for the annual rainfall to be more concentrated over central India and being more spread out over the north. Seasonality index shows a decreasing trend over Indo-Gangetic plains, west coast, and isolated parts in central and northeast India (Figure 2c). Eastern coast and northern peninsular India show an increase in seasonality (Figure 2c). The decrease in seasonality over parts of central India and Western Ghats is mainly due to the decreasing trend in normalized mean annual rainfall, while over west central India, it is increased due to small positive trend in both normalized rainfall and relative entropy. The timing of peak rainfall does not show widespread significant trend, except for increasing trend over a small

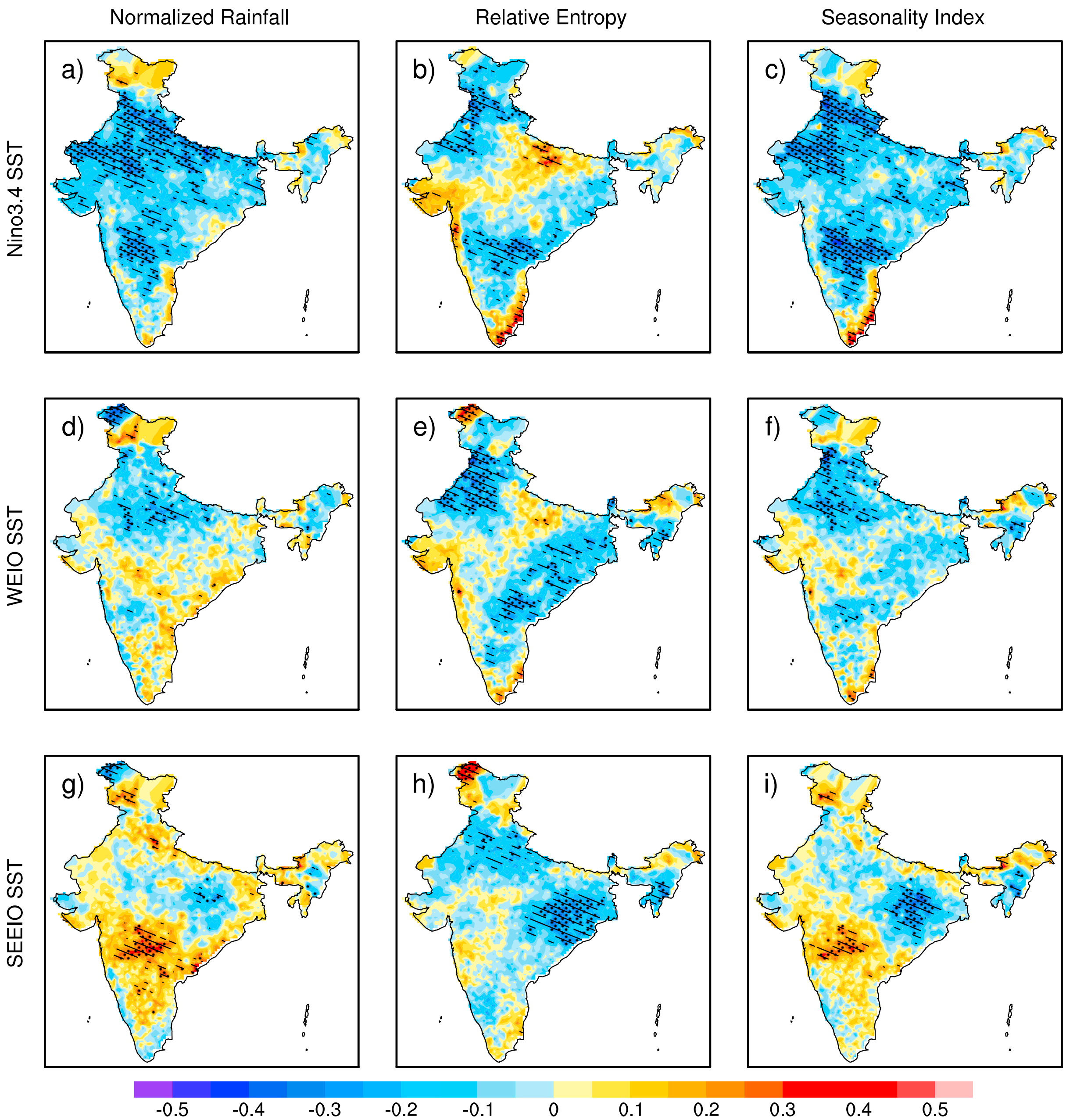

Figure 3. Patterns of zero-lag correlation coefficient for spatially normalized annual rainfall accumulation, relative entropy, and seasonality index with SSTs of NINO3.4 region (a–c, first row), western equatorial Indian Ocean region (d–f, second row), and eastern equatorial Indian Ocean region (g–i, third row). The stippled points are significant at 95% level using the two-tailed Student's *t* test and the hatched region significant at 90% level. Individual time series have been detrended before computing the correlation coefficients. SEEIO = southeastern equatorial Indian Ocean index; SST = sea surface temperature; WEIO = western equatorial Indian Ocean index.

region of northern part of the east coast. The increasing trend indicates a delay in the peak seasonal rainfall of ~10 days over a century, which is substantial and impacts crop planting and other agriculture decisions. The seasonal duration shows decreasing trend over most of the country with statistically significant regions being central India and the tip of southern peninsula. This indicates that the rainfall season is shrinking over most of the country by 10–20 days over a century, which has serious implications for the socioeconomic health of India. The trends in timing and duration together indicate delayed peaking of the rainfall combined with reduction in duration, hinting at a delayed onset coupled with an on-time or early withdrawal of the summer monsoon.

4.3. Seasonality Links to Large-Scale Climate Forcings

To understand the large-scale drivers of seasonality, we correlated the seasonality metrics with ENSO and Indian Ocean dipole SST indices, described earlier. In particular, we used NINO34, WEIO, and SEEIO, defined earlier. The indices were correlated with normalized rainfall, relative entropy, and seasonality indices at each grid location and corresponding maps of spatial correlations are shown in Figure 3. Normalized rainfall exhibits negative correlation with NINO34 (Figure 3a) over most of the country, as expected and described in literature (Azad & Rajeevan, 2016; Kripalani & Kulkarni, 1997; Kumar et al., 1999; Rajeevan & McPhaden, 2004; Rajeevan & Pai, 2007; Sikka, 1980). Wherein, a warmer eastern/central tropical Pacific Ocean, that is, El Niño conditions, lead to a suppression of rainfall over India due to subsidence of Walker circulation. Correlation with relative entropy and seasonality are similar (Figures 3b and 3c), with strong negative correlations over central and northwest India. This indicates that El Niño conditions reduce the seasonal and peak rainfall and making the rainfall more spread out within the season—that is, decreasing entropy and consequently the seasonality.

Western equatorial and southeastern equatorial Indian Ocean temperatures negatively impact rainfall over Indo-Gangetic plains (Figures 3d and 3g). For example, Roxy et al. (2015) reported that the observed decreasing trend in summer monsoon rainfall over many parts of India could be due to the increasing SST trends over the western equatorial Indian Ocean. Relative entropy has limited significant correlations with the Indian Ocean temperatures; however, seasonality over Indo-Gangetic plains is negatively correlated with both East and West Indian Ocean temperatures, more so with West. Both rainfall and seasonality over Jammu and Kashmir region (northernmost parts of India) show positive correlation with both East and West Indian Ocean temperatures. These correlations indicate that ENSO and equatorial Indian Ocean SSTs have a significant influence in modulating the seasonality. Spatial and temporal asymmetry in the teleconnection between ENSO and monsoon rainfall over India (Gill et al., 2015) with mediation from Indian Ocean SSTs is likely responsible for the diversity in these correlation patterns.

5. Summary and Discussion

Large changes in rainfall seasonality over India, expressed in terms of timing, duration, and magnitude, are identified in this paper. Decreasing trends in seasonality of rainfall and mean annual rainfall were found to be high over the Western Ghats, central, and northeastern parts of India and over the Indo-Gangetic region, and low over northwest, southern, and northernmost parts of India. Analysis of timing of peak rainfall indicates a tendency for later occurrence in the season, especially over southern Indo-Gangetic plains by 10–20 days per century, coupled with a general decrease in the duration of the wet season throughout the country by 10–20 days per century. These shifts in seasonality have also been shown to be linked to ENSO and Indian Ocean SSTs—which echo the findings of delay in summer monsoon post 1976 by Sahana et al. (2015) due to regime shift in the tropical Pacific SSTs. These findings suggest a gradual delay in the onset date of the Indian summer monsoon over time.

The delay in seasonality in conjunction with declining trend in mean annual rainfall will have significant negative impacts on agriculture and water resources and, consequently, the general economy of the Indian subcontinent. The delay leads to disruption of planting and harvesting of crops, which are largely rain fed—for example, unseasonal rains were reported in six Indian states leading to severe crop damage during 2016. The seasonality shifts also impacts the ecology and the surface and groundwater water resources—which are already under severe stress due to population increase. In Lee et al. (2008) they show that premonsoon spring season irrigation over vast areas of India potentially leads to delayed monsoon and weaker early season rainfall. This factor of land use and land cover changes and its influence on rainfall seasonality needs to be systematically probed. Also of interest will be to further these analyses to investigate the space-time variability of seasonality in a warmer climate by probing the CMIP5 outputs. The insights from all of these analyses will be of immense help to policy makers in devising robust strategies for adapting various sectors—agriculture, water resources, energy, tourism, and so forth, to new monsoon climate regime.

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