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RESEARCH ARTICLE

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The impact of varying seasonal lengths of the rainy seasons of India on its teleconnections with tropical sea surface temperatures

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Abstract
We present in this paper the interannual variability of seasonal temperature and rainfall in the Indian meteorological subdivisions (IMS) for boreal winter and summer seasons that take in to account the varying length of the seasons. Our study reveals that accounting for the variations in the length of the seasons produces stronger teleconnections between the seasonal anomalies of surface temperature and rainfall over India with corresponding sea surface temperature anomalies of the tropical Oceans (especially over the northern Indian and the equatorial Pacific Oceans) compared to the same teleconnections from fixed length seasons over the IMS. It should be noted that the IMS show significant spatial heterogeneity in these teleconnections.

KEYWORDS
ENSO, Monsoon, teleconnection

1 | INTRODUCTION

The primary basis for seasonal prediction of the Indian monsoons has been the remote forcing of the tropical sea surface temperature (SST) anomalies, especially that related to El Niño Southern Oscillation (ENSO) (Charney and Shukla, 1981; Gowariker *et al.*, 1989; Thapliyal and Kulshrestha, 1992; Gershunov *et al.*, 2001; Delsole and Shukla, 2012; Rajeevan *et al.*, 2012; Ramu *et al.*, 2016). Over the years, the influence of the tropical Indian and the Atlantic Oceans has also been noted (Saji *et al.*, 1999; Goswami *et al.*, 2006; Krishnamurthy and Krishnamurthy, 2016). The ENSO-Indian summer monsoon (ISM) teleconnection has been widely studied, which shows a complex relationship at different lead/lag leading to contrasting interpretations of the teleconnection (Krishna Kumar *et al.*, 1999; Kirtman and Shukla, 2000; Gershunov *et al.*, 2001). The influence of the Indian ocean dipole and the tropical Atlantic Ocean on the ISM in contrast is far more subtle and at times used to understand the noncanonical ISM-ENSO seasons (Krishnamurthy and Kirtman, 2009; Yadav *et al.*, 2018). Nonetheless, despite these teleconnections, the seasonal prediction of the ISM continues to be a challenge (Ramu *et al.*, 2017; Pillai *et al.*, 2018).

On the other hand, despite the strong variability of the Indian Winter Monsoon (IWM) rainfall and its relatively strong teleconnection with ENSO (Ramaswamy,

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1972; Zubair and Ropelewski, 2006; Kumar *et al*., 2007; Rajeevan *et al*., 2012; Dimri *et al*., 2016; Misra and Bhardwaj, 2019; Sengupta and Nigam, 2019) the models continue to display poor fidelity of the IWM (Rajeevan *et al*., 2012; Sengupta and Nigam, 2019).

The concept of varying length of the ISM is not new (Goswami and Xavier, 2005; Noska and Misra, 2016; Misra *et al*., 2017a; Bombardi *et al*., 2019). In fact, Xavier *et al*. (2007) argue that the breakdown of the ISM-ENSO teleconnection in the recent decades is partly due to the inappropriate definition of fixed ISM. They further show that this teleconnection between ISM and ENSO remains steady when the varying length of the Indian meteorological subdivisions (IMS) is accounted. Similarly, Misra and Bhardwaj (2019) defined the onset, demise, and length of the IWM. In this study, we present a case to account for the variations in the length of both the ISM and IWM seasons to interpret the teleconnections of their corresponding seasonal surface temperature and rainfall anomalies with tropical SST anomalies at interannual timescales. As noted earlier, the variations in the length of the ISM and IWM is significant with both the onset and demise dates of the seasons showing considerable variations at interannual time scales (Misra *et al*., 2017a, 2017b; Misra and Bhardwaj, 2019). In the following section, we describe the methodology and the datasets followed by the presentation of the results in Section 3 and concluding remarks in Section 4.

2 | METHODOLOGY AND DATASETS

In this study, we are targeting the interannual scales of variability of seasonal rainfall (R) and surface temperature (T_s) over India at the resolution of the IMS outlined in Figure S1, which is the operational spatial scales at which the Indian Meteorological Department (IMD) target their forecasts to meet the consumer needs. Here, we take the area average of daily R and T_s at each of the IMS and compute the corresponding onset and demise of the summer and winter seasons for each of the years based on Bhardwaj and Misra (2019) and Misra and Bhardwaj (2019), respectively. The minima and the maxima in the cumulative anomaly curve of the daily precipitation anomaly (computed after removing the corresponding annual mean climatology) are diagnosed as the onset and the demise of the summer season over India (Bhardwaj and Misra, 2019). Similarly, the maxima and the minima in the partial cumulative anomaly curve of the daily surface minimum temperature anomaly (after removing the corresponding annual mean climatology) are diagnosed as the onset and the demise of the winter season over India (Misra and Bhardwaj, 2019). The partial cumulative anomaly curve is so called because this curve is constructed between the demise of the preceding and the onset of the following summer season, not over the full year.

Subsequently, we conduct an Ensemble Empirical Mode Decomposition (EEMD); Wu and Chung, 2009; Wu and Tsai, 2011) on the time series of the length of the season and the associated seasonal R and T_s anomalies for each of the IMS. EEMD is a data adaptive time series technique that does not make use of any predetermined basis functions (e.g., Fourier transform) to perform the temporal decomposition of the time series. An illustration of the temporal decomposition of the length of the summer season for the Gangetic West Bengal IMS by EEMD is shown in Figure S2. The EEMD in this case isolates three intrinsic mode functions (IMFs; Figure S2b, c, and d) and a residual time series, that usually describes the nonlinear trend or the lowest frequency oscillation in the time series (Figure S2e). Since we are interested in the variations at interannual scales, only IMF's 1 and 2 would be of interest to us while IMF3 and the residual component are at decadal and longer time scales. IMF's 1 and 2 are combined to reconstruct the filtered time series of the length of the summer season for the Gangetic West Bengal IMS. Likewise, similar filtering is done to the time series of seasonal length, rainfall, and surface temperature anomalies for both the summer and the winter seasons and for all IMS.

After filtering for the interannual time scales in the time series of the variable at each of the IMS we conducted an empirical orthogonal function (EOF) analysis on all of the time series as a way to reduce the dimensions. In this way, we isolated EOF1, which explained the most variance and was distinctly higher than the rest of the EOFs (Figures S3, S4, and S6). The filtering was done using the EEMD technique to isolate the interannual scales, which helped in maximizing the variance explained by the first EOF in every instance (Figures S3, S4, S5, S6, and S7). Similarly, we also conducted an EOF analysis and isolated EOF1 for the filtered seasonal rainfall and the surface temperature anomalies for fixed length seasons of December-January-February (DJF) and June-July-August (JJA) in Figures S5 and S7, respectively. The principal components (PCs) from the isolated EOF1 (Figures S3c and d, S4c and d, S5c and d, S6c and d, and S7c and d) were then used to correlate with the seasonal mean global SSTs to examine the teleconnections of primarily the tropical SSTs on the Indian seasonal climate variations. The seasonal mean SSTs were linearly detrended before the correlations were computed.

The Indian Meteorological Department gridded analysis of rainfall (Pai *et al*., 2014a, 2014b) and surface temperature analysis (Srivastava *et al.*, 2009) were used in this study. The rainfall analysis is available at 0.25°×°.25° from 1900 to 2005. The surface temperature analysis is available at 1°x°1° grid at daily interval from 1969 to 2005. These datasets were area averaged over each IMS before the diagnosis of the onset and the demise of the summer and winter seasons. The SST analysis is the Extended Reconstructed SST version 5 (ERSSTv5) following Huang *et al.* (2017) and is available on 2°×°2° grid at monthly interval from January 1854 to March 2018. It may be stated that the teleconnections diagnosed in this paper with the tropical SST were identical when other alternative SST datasets were used. However, ERSSTv5 was used simply because it overlapped with our analysis period. In this paper, we conducted the analysis over the overlapping period of these datasets from 1969 to 2005.

3 | RESULTS

3.1 | Seasonal length variations

Figure 1 shows the climatological length of the winter and summer seasons for each of the IMS. From Figure 1a it can be noted that climatologically, the length of the

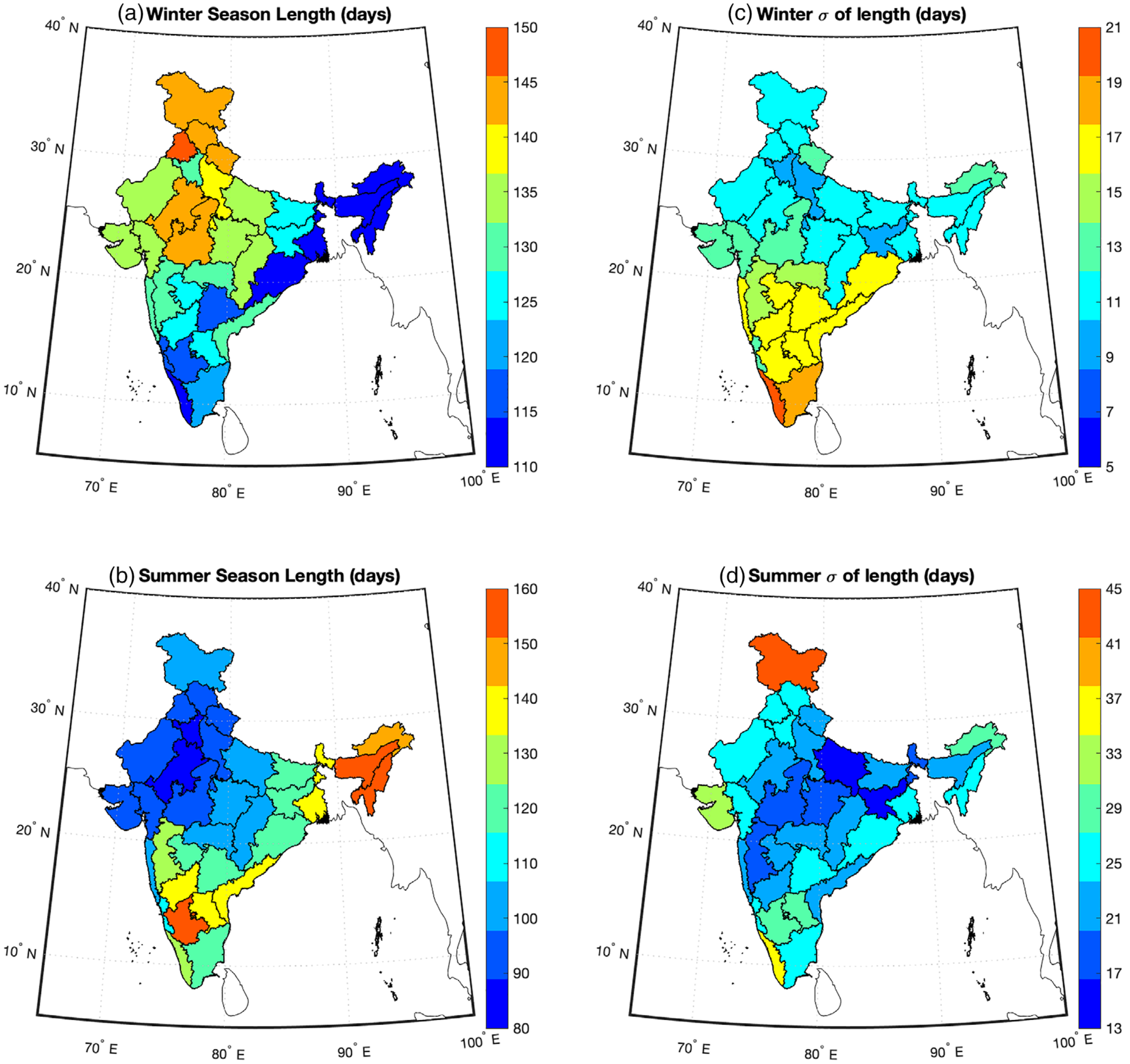

FIGURE 1 The observed climatological length (days) of (a) winter and (b) summer seasons for each of the meteorological subdivisions of India. The corresponding *SD* (days) are shown in (c) and (d)

winter season as defined here is longer in the northern, than in the southern part of India. In the summer, the season is longer in the southern and the northeastern part of India compared to northern India (Figure 1b). As noted in Misra *et al.* (2017a), the time series of the daily rainfall over the Deccan Plateau and northeast India shows that the premonsoon rainfall is indistinguishable from the summer monsoon rainfall and therefore, the rainy (or summer) season is longer in these regions than in the rest of India. The corresponding *SD* indicates that the variability of the length of the season is the largest in southeastern part of India during winter, (Figure 1c) while the variability in central India is least during summer (Figure 1d), respectively. In both the seasons, the IMS region of Kerala exhibits the largest interannual variations in the length of the season (Figures 1c, d).

The EEMD decomposition in Figure S2 for one of the IMS (Gangetic West Bengal) shows that the temporal variations have distinct frequencies that allows for unambiguous filtering of the low frequency variations. The first EOF and PC of the filtered time series of the length of the two seasons is shown in Figure S3. In both the seasons, the first EOF explains a more significant variance than the rest of the EOFs (not shown). The correlations of the PC from Figure S3 with the corresponding seasonal mean global SST (at zero lag) is shown in the Figure 2. The

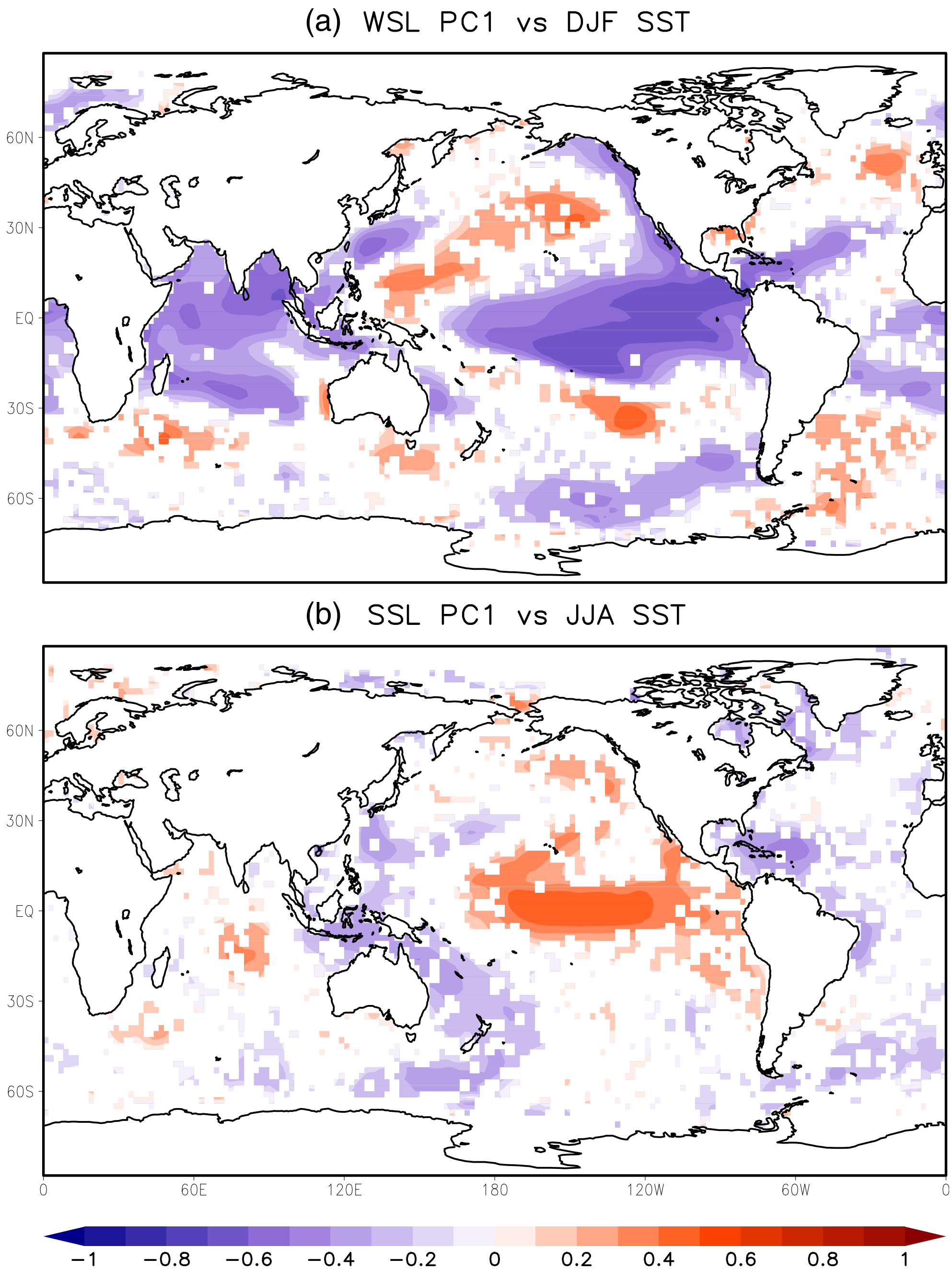

FIGURE 2 The correlation of detrended seasonal mean (a) DJF SST with winter seasonal length (WSL) PC from Figure S3c and (b) JJA SST and summer seasonal length (SSL) PC from Figure S3d. Correlations which are significant at 95% confidence interval according to the bootstrap method is shaded

negative correlations in the winter (Figure 2a) and the positive correlations in the summer (Figure 2b) over the tropical Pacific are prominent. In the winter season, the correlations over the tropical Indian Ocean is also equally strong and negative (Figure 2a). The negative correlations in Figure 2a suggests that the warm tropical eastern Pacific and the tropical Indian Oceans are likely to lead to shorter winter seasons in the regions of positive EOF patterns in Figure S3a. Likewise, cold SST anomalies over the tropical eastern Pacific and the tropical Indian Oceans are likely to lead to longer winter seasons in the regions of negative EOF patterns. For example, the IMS of Tamil Nadu and Kerala, and some regions in central and northwest India that display a negative EOF pattern in Figure S3a is likely to have a longer winter season with a warmer tropical Pacific and Indian Oceans, while a shorter winter season is expected with colder tropical Pacific and Indian Oceans. Similarly, shorter winter seasons with warmer or colder tropical Oceans are likely in Karnataka, coastal Andhra Pradesh, Orissa, Chhattisgarh, and other regions in coastal western parts of India, that display a positive EOF pattern in Figure S3a, respectively. Alternatively, longer winter seasons over Karnataka, coastal Andhra Pradesh, Orissa, Chhattisgarh, and other regions in coastal western parts of India that display a positive EOF pattern in Figure S3a are expected with warm SST anomalies of the tropical Oceans.

Similarly, the positive correlations in the summer season over the tropical eastern Pacific Ocean (Figure 2b) indicate that regions with negative EOF pattern in the summer (Figure S3b) like in central India (e.g., Madhya Pradesh, Vidarbha, Chhattisgarh) and in the eastern Gangetic Plains (e.g., Bihar, Jharkhand, Gangetic West Bengal) are likely to have shorter ISM seasons with

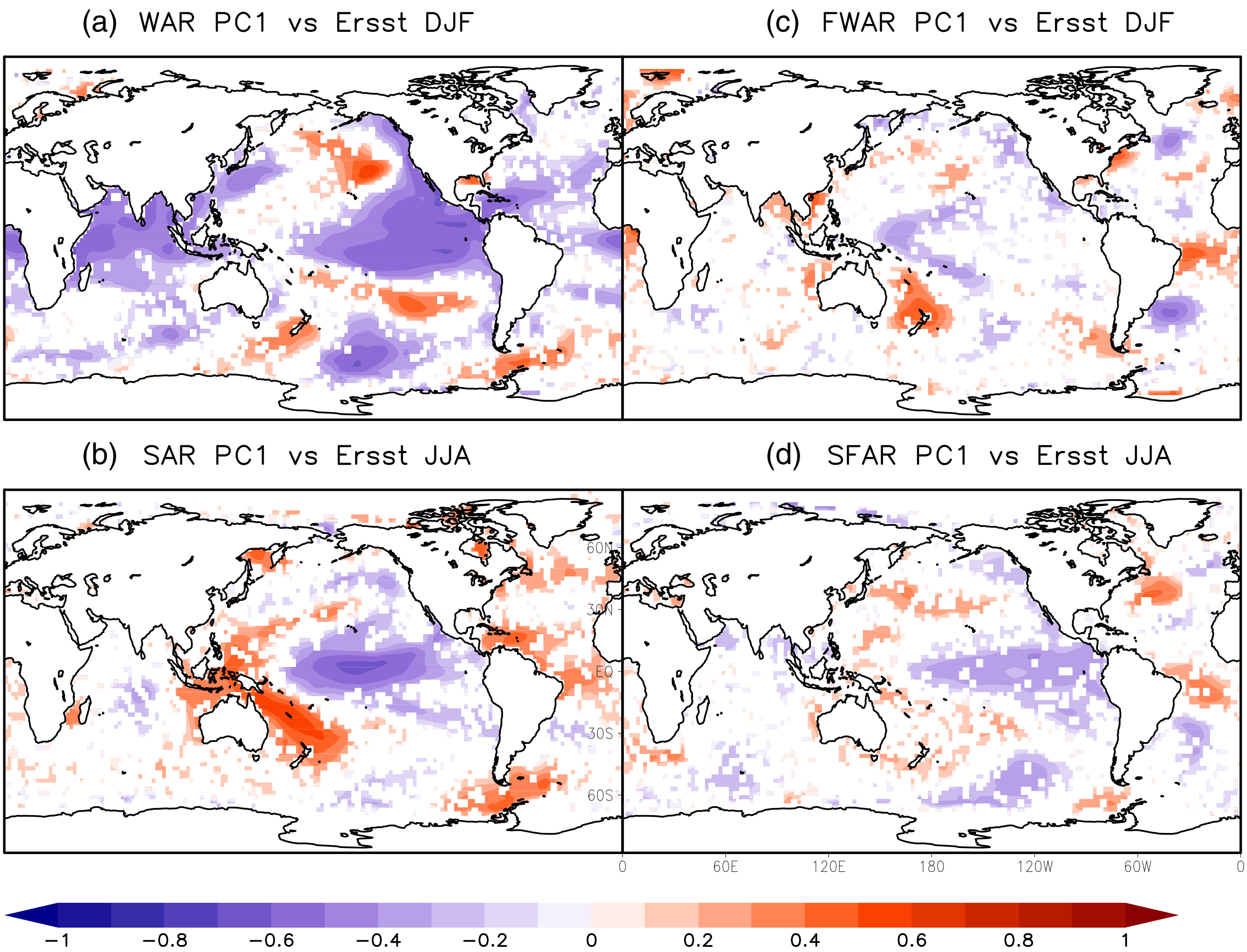

FIGURE 3 The correlation of the seasonal mean (a) DJF SST with varying seasonal length winter rainfall (WR) PC from Figure S4c and (b) JJA SST with varying seasonal length summer rainfall (SR) PC from Figure S4d. Similarly, the correlations of the seasonal mean (c) DJF SST with fixed length winter rainfall (FWR) PC from Figure S5c and (d) JJA SST with fixed length summer rainfall (FSR) PC from Figure S5d. Correlations that are significant at 95% confidence interval according to the bootstrap method is shaded. The SST is detrended

warmer SST's in the tropical eastern Pacific Ocean or alternatively longer ISM seasons with colder SST's in the tropical eastern Pacific Ocean. Likewise, regions of positive EOF pattern in Figure S3b (e.g., coastal Andhra Pradesh, Orissa, Kerala) suggests that summer season could be longer or shorter with warmer or colder tropical eastern Pacific Ocean, respectively. Earlier studies have noted such spatial heterogeneity with adjacent IMS regions having teleconnections of opposite signs with the tropical Pacific SST anomalies (Kurths *et al.*, 2019).

3.2 | Seasonal rainfall anomalies

The PC of the first EOF of the seasonal rainfall anomalies computed for varying length of the season (Figure S4) shows a very strong contemporaneous correlation with the tropical Pacific and the Indian Oceans in the winter season, (Figure 3a) and similarly in the summer season but only over the tropical eastern Pacific Ocean (Figure 3b). The strong negative correlations of Figure 3a with the positive patterns of EOF1 in Figure S4a over southeast India (e.g., coastal Andhra Pradesh, Telangana, and Tamil Nadu) suggests that these regions have a higher likelihood of deficit seasonal winter rainfall anomalies with warmer in the tropical eastern Pacific and Indian Oceans are alternatively surplus winter rainfall anomalies with colder tropical eastern Pacific and Indian Oceans. Furthermore, the negative correlations in Figure 3a suggests that warm SST anomalies in the tropical Pacific and Indian Oceans are likely to result in wetter winter seasonal anomalies over northern India (e.g., western Uttar Pradesh, Uttarakhand, Punjab, Haryana, Himachal Pradesh, Jammu, and Kashmir), where a negative EOF pattern is displayed (Figure S4a). Alternatively, these regions could experience drier winter seasonal anomalies with cold SST anomalies over tropical Pacific and Indian Oceans. Similarly, the negative correlations in Figure 3b and the EOF pattern of the filtered summer seasonal rainfall anomalies in Figure S4b indicate that warmer SST anomalies increase the likelihood of drier summer seasonal anomalies over most of India with a positive EOF pattern except in southeastern India (e.g., Rayalaseema and coastal Andhra Pradesh).

Contrasting the correlations in Figures 3a, b with the correlations of the PCs from the first EOF of the seasonal rainfall anomalies from fixed length seasons (Figure S5) in Figures 3c, d show that the teleconnections with the SST anomalies of the tropical Oceans are significantly diminished in both the seasons. For example, the teleconnection of the winter seasonal rainfall anomalies for the DJF season over the tropical Pacific is insignificant (Figure 3c) while the correlations are weaker in the JJA season (Figure 3d) compared to the correlations shown in Figure 3b.

3.3 | Seasonal temperature anomalies

Similarly, the seasonal temperature anomalies for both winter and summer seasons over India display a stronger teleconnection with the tropical Oceans when we account for varying length of the season compared to fixed length seasons of the ISM and the IWM (Figure 4). In the winter season, the correlations are far stronger in Figure 4a, for seasonal temperature anomalies for varying length of the season compared to the fixed season anomalies (Figure 4c). The negative correlations in Figure 4a suggest that warm tropical Pacific is associated with colder winter seasonal anomalies over India or warmer winter seasonal anomalies over India are associated with cold tropical Pacific. It may be stated that although the correlations for summer seasonal temperature anomalies with varying length of the season in the summer with tropical Pacific (Figure 4)) are comparable to the correlations of the fixed JJA seasonal temperature anomalies (Figure 4d), the correlations over the northern Indian Ocean are substantially weaker in the latter compared to the former.

These results clearly suggest that accounting for the variations in the length of the season boosts, the teleconnection signal of the co-variations between the tropical Oceans (Pacific and northern Indian Ocean) and Indian seasonal anomalies of surface temperature and rainfall in both winter and summer seasons. These results indicate that by ignoring the variations in the length of ISM and IWM seasons, a significant fraction of the variance of the Indian monsoons explained by the tropical oceans is lost.

4 | CONCLUSIONS

This study clearly shows that the teleconnections of both the summer and the winter seasonal anomalies of surface temperature and rainfall over India are stronger with the tropical oceans if we account for the variations in the length of their seasons. This enhancement of the teleconnection is enabled from the fact that the variations in the length of the seasons are significant and show a covariation in all instances with tropical Pacific SST anomalies and in some instances, additionally with SST anomalies of the tropical Indian Ocean (e.g., winter seasonal anomalies of surface temperature and rainfall). These covariations robustly show that warm or cold

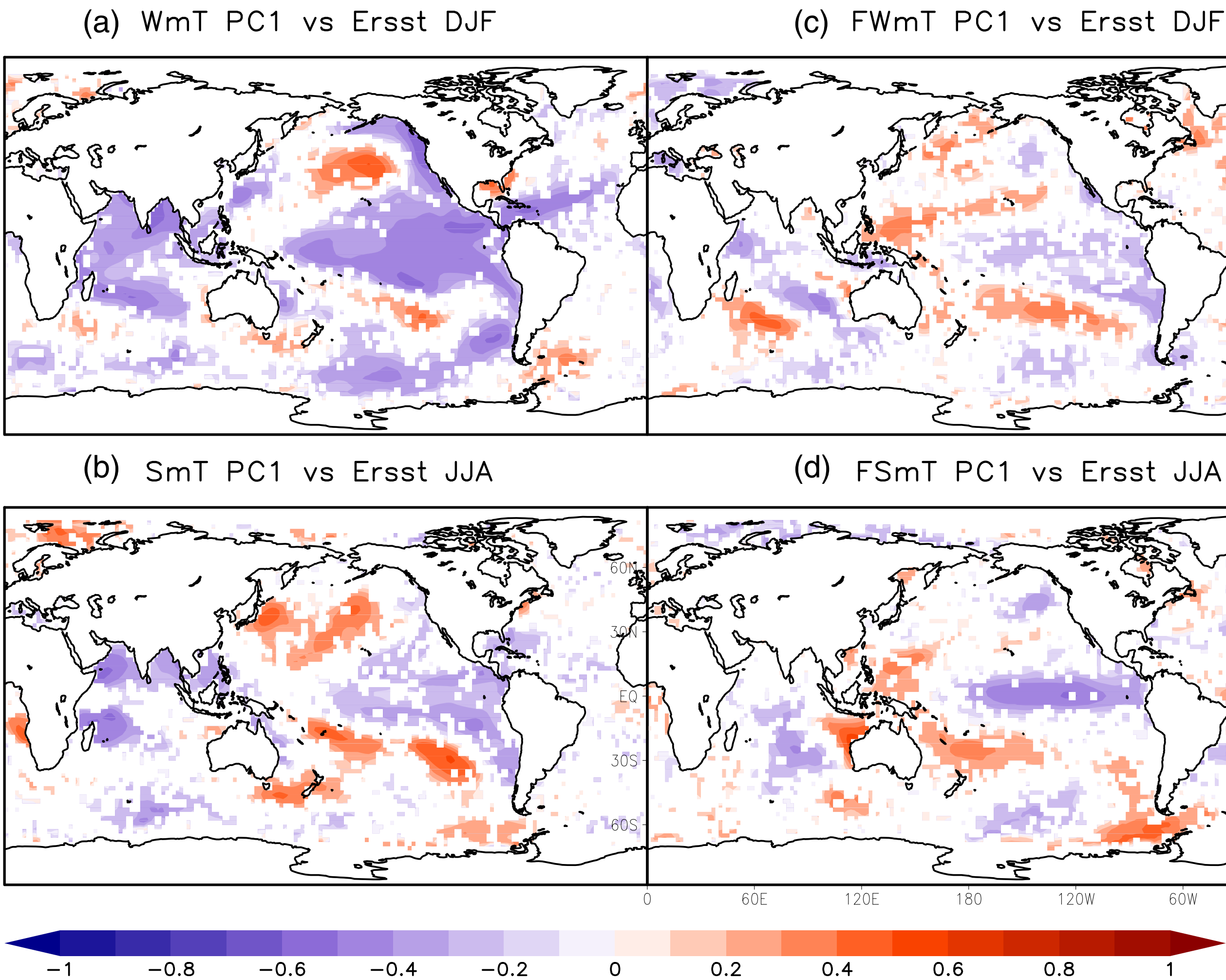

FIGURE 4 The correlation of the seasonal mean (a) DJF SST with varying seasonal length winter temperature (WT) PC from Figure S6c and (b) JJA SST and varying seasonal length summer temperature (ST) PC from Figure S6d. Similarly, correlations of detrended seasonal mean (c) DJF SST with fixed length winter temperature (FWT) PC from Figure S7c and (d) JJA SST and fixed length summer temperature (FST) PC from Figure S7d. Correlations that are significant at 95% confidence interval according to the bootstrap method is shaded. The SST is detrended

tropical Pacific and Indian Oceans are associated with colder or warmer surface temperature anomalies across India in the winter season, respectively. Similarly, warm tropical Pacific and Indian Oceans are related to drier or wetter winter anomalies in southeastern India or northern India, respectively. It is indicated that ENSO events are related to the modulation of the westerly disturbances that bring copious rainfall to northern India in the winter season (Dimri *et al.*, 2016). Therefore, the teleconnections exhibited by the winter anomalies over northern India in this paper is consistent with such an interpretation. In this study, a robust negative correlation is shown between the winter rainfall anomalies over southeastern India with the tropical Pacific, which at the outset seems contrary to previous studies (Rajeevan *et al.*, 2012; Sengupta and Nigam, 2019). However, the earlier studies have reported comparatively much weaker correlations and have used a different season for IWM (e.g., October–November–December). In our study, the seasons vary from one IMS to the other with the southeastern part of India (including Tamil Nadu, Rayalseema, and coastal Andhra Pradesh) exhibiting a climatological onset and demise dates of November 6 and March 13, respectively.

Likewise, we show that wetter and colder or drier and warmer summer seasonal anomalies of surface temperature and rainfall over most of India are associated with cold or warm tropical Pacific SST anomalies, respectively. These teleconnections are robust and stronger with the inclusion of the variations of the length of the season. This study gives further hope for pursuing seasonal prediction of the Indian monsoons from potentially exploiting the variations in the length of the seasons. Although, the predictability of the onset and demise of the seasons is yet to be ascertained.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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Supplementary Material

The Impact of Varying Seasonal Lengths of the Rainy Seasons of India on its Teleconnections with Tropical SSTs

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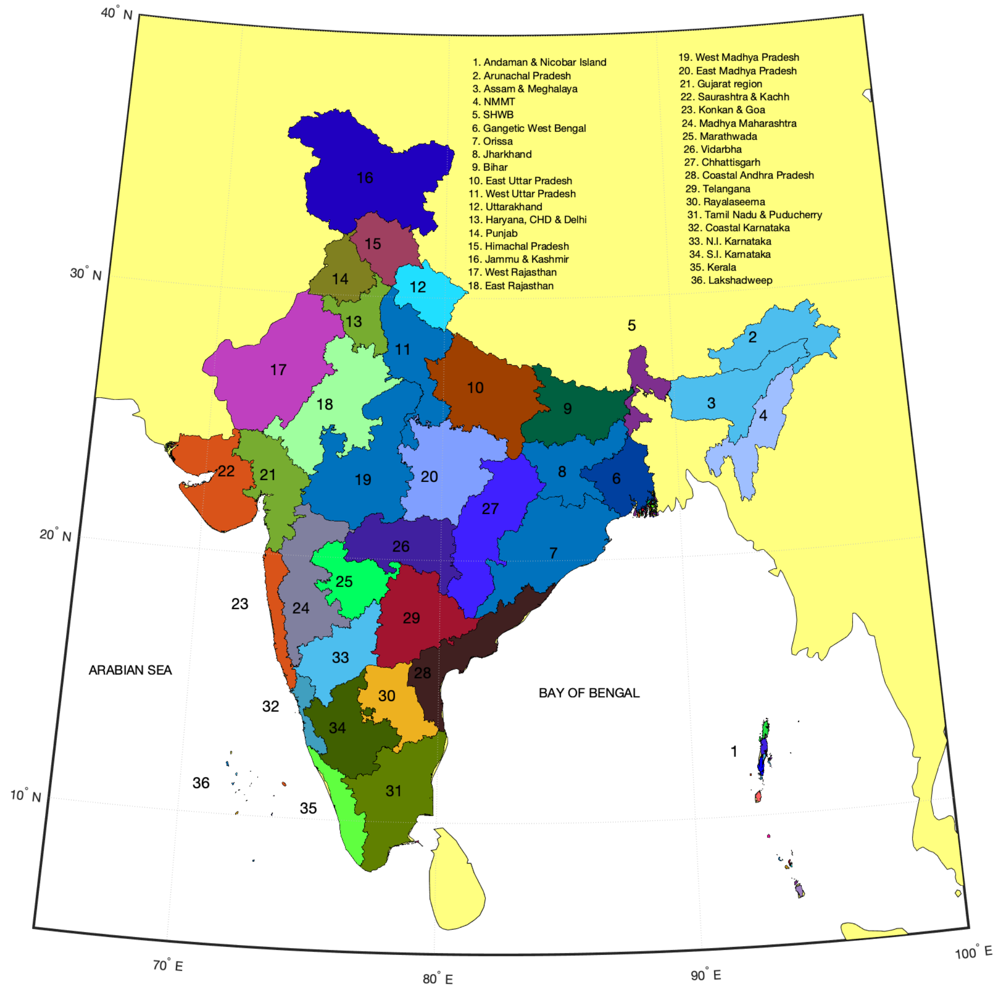

Figure S1: The outline of the 36 meteorological sub-divisions of India.

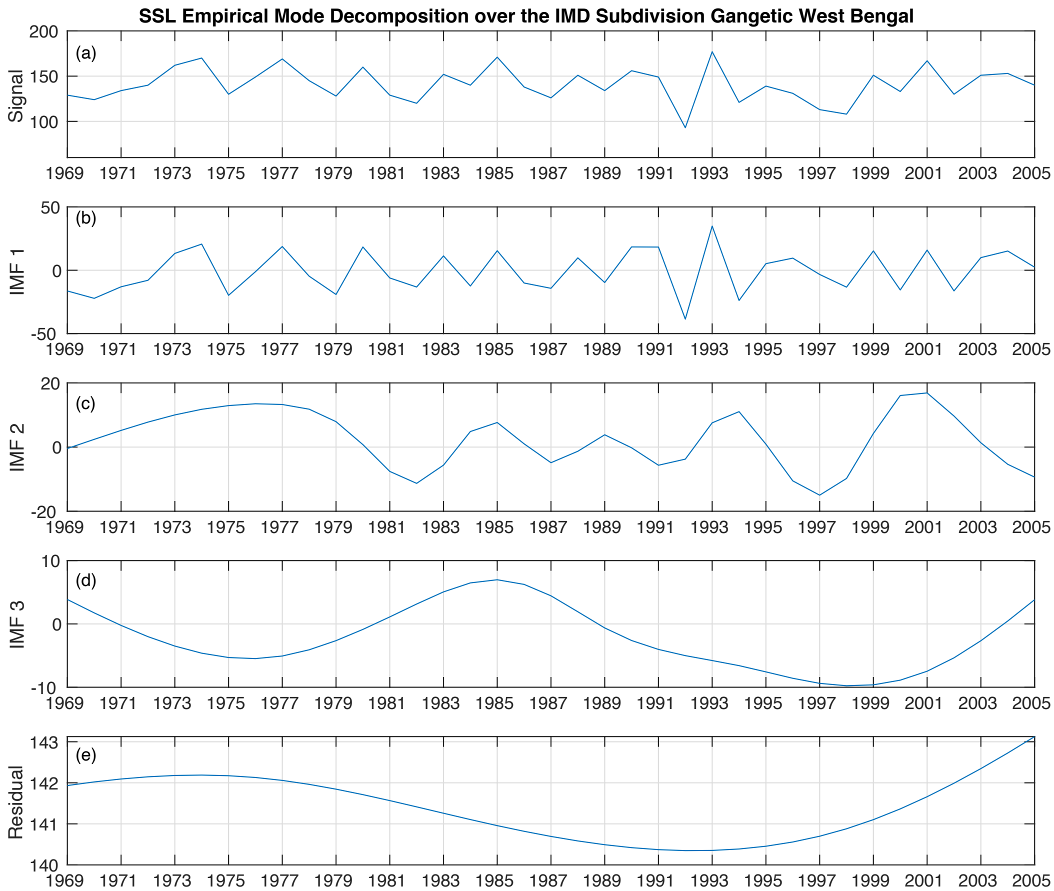

Figure S2: a) Time series of the length of the summer season over the Indian meteorological subdivision of Gangetic West Bengal (see Fig. S1). The sample decomposition of the time series shown in (a) is performed by using Empirical Ensemble Mode Decomposition (EEMD) that isolates Intrinsic Mode Functions (IMF) (b) IMF1 (c) IMF2, (d) IMF3, and (e) a residual component.

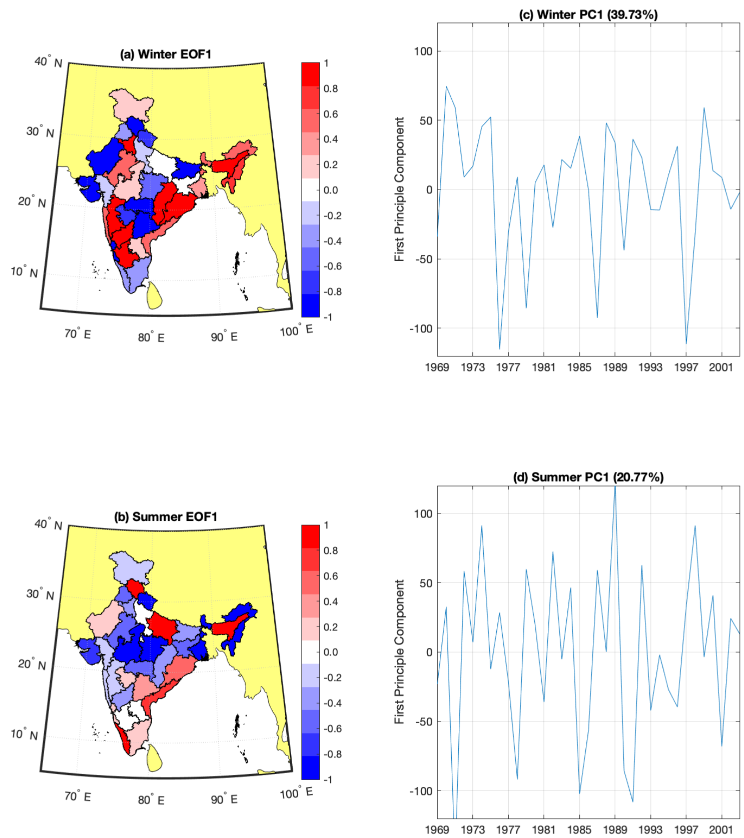

Figure S3: The first EOF of the interannual component of the length of a) winter and b) summer, seasons with its corresponding (c, d) PC. The fractional variance explained by each of the EOF is indicated in percentage in each of the (c, d) panels.

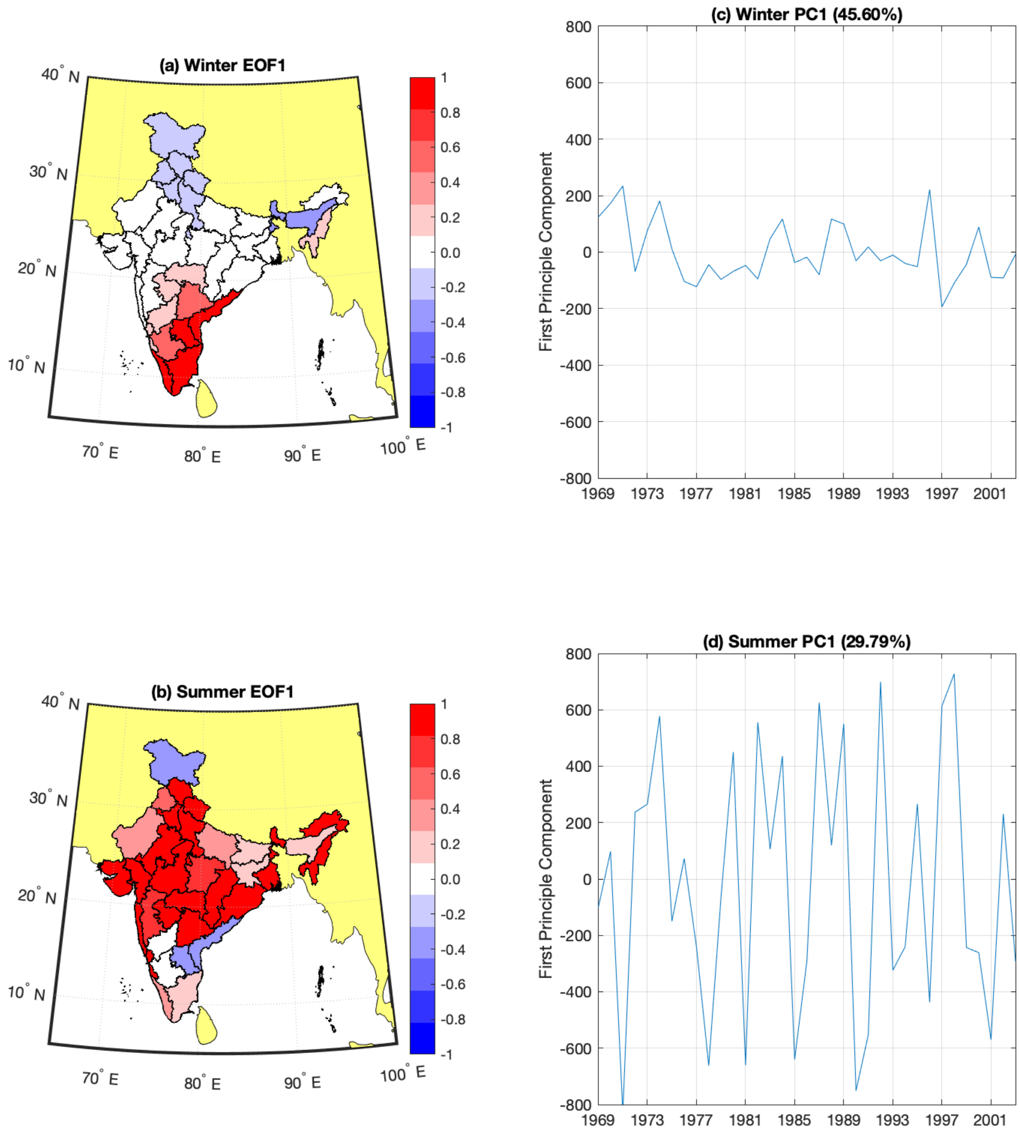

Figure S4: The first EOF of the interannual component of the seasonal rainfall anomaly of varying length of a) winter and b) summer seasons with its corresponding (c, d) PC. The fractional variance explained by each of the EOF is indicated in percentage in each of the (c, d) panels.

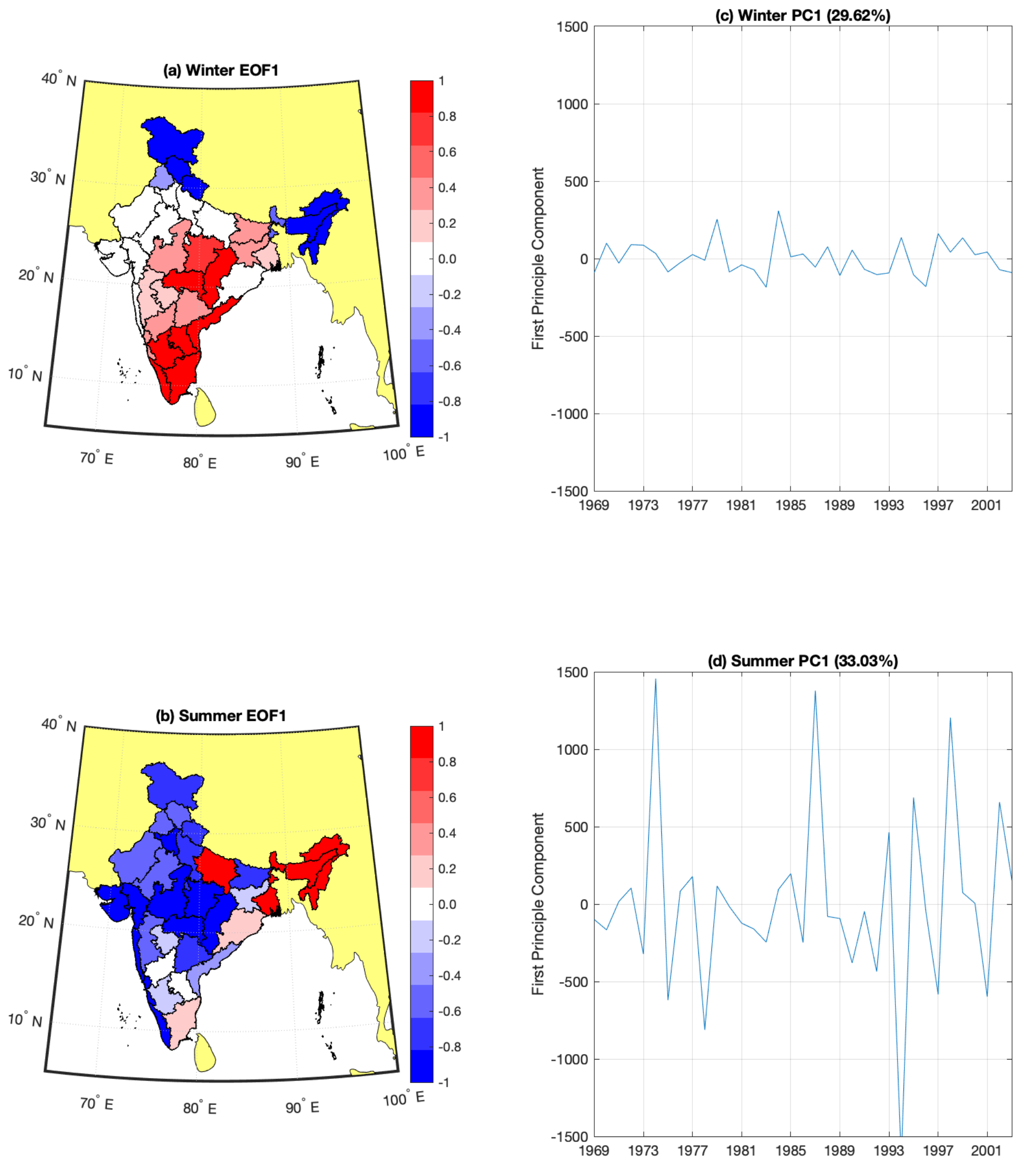

Figure S5: The first EOF of the interannual component of the seasonal rainfall anomaly of fixed length a) winter (DJF) and b) summer (JJA) seasons with its corresponding (c, d) PC.

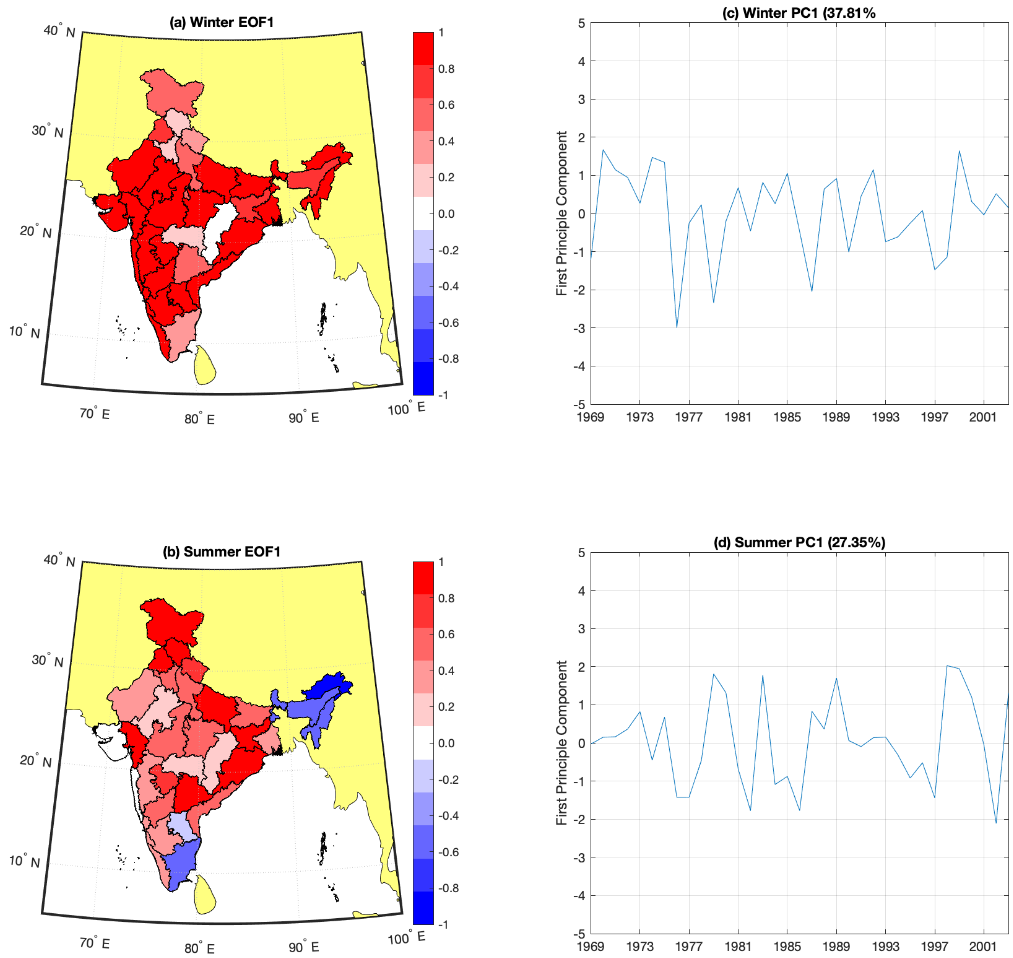

Figure S6: The first EOF of the interannual component of the seasonal temperature anomalies of varying length of a) winter and b) summer seasons with its corresponding (c, d) PC.

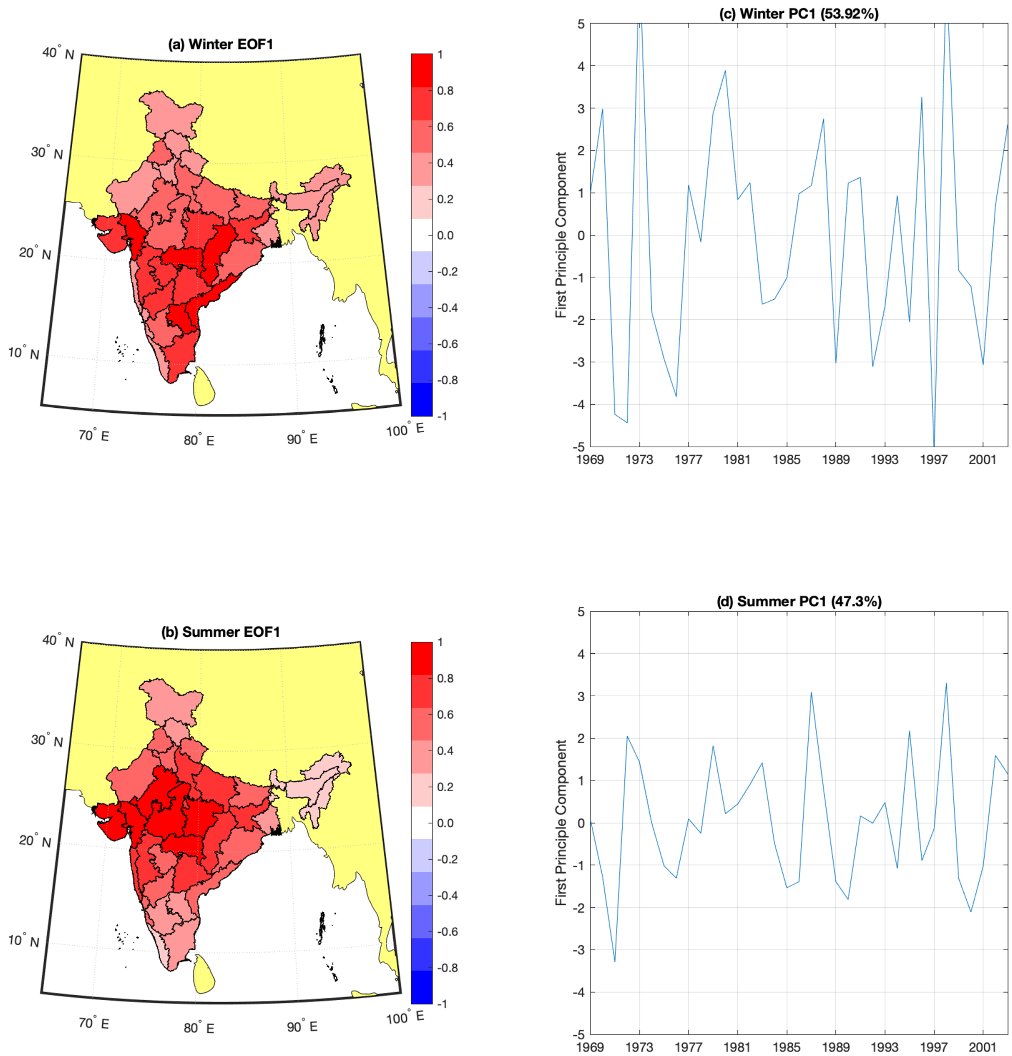

Figure S7: The first EOF of the interannual component of the seasonal temperature anomalies of fixed length a) winter (DJF), b) spring (MAM), c) summer (JJA), and d) fall (SON) seasons with its corresponding (e-h) PC.