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Research Article

The Changing Relationship between Surface Temperatures and Indian Monsoon Rainfall with the Phase of ESI Tendency

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Effective Strength Index (ESI) is the relative strength of NAO and SO. ESI tendency is the algebraic difference between April-ESI and January-ESI and it represents the simultaneous evolution of NAO and SO from winter to spring. During positive (negative) phase of ESI tendency, NAO restores positive (negative) phase and SO restores negative (positive) phase before the beginning of summer season. Thus during contrasting phases (positive and negative) of ESI tendency, the evolution of NAO and SO is out of phase. In this paper we have studied the spatial and temporal variability of winter-time temperature field over Europe, Arabian Sea and Bay of Bengal during contrasting phases of ESI tendency. The study reveals that during positive (negative) ESI tendency, smaller (larger) region of Europe is showing significant winter-time cooling (warming) at surface. The relationship between winter-time surface temperature over above regions and Indian summer monsoon rainfall (ISMR) also shows spatial and temporal variability. The probable explanation for this change in the relationship is discussed in the paper. Two sets of temperature parameters for two different phases of ESI tendency are found out. Multiple regression equations are developed for the prediction of ISMR in each phase of ESI tendency. The performance of these equations is also discussed in this paper.

1. Introduction

Asian summer monsoon is a thermally driven phenomenon and hence Indian summer monsoon rainfall (ISMR) depends upon temperature fields over different parts of the world. Many earlier studies pointed out the relationships between surface temperature over different regions and ISMR. In this paper, we are mainly highlighting the influence of sea surface temperatures (SST) over Arabian Sea, Bay of Bengal and surface temperature over Europe on ISMR. Shukla [1], Shukla and Mooley [2], Kothawale et al. [3], and others studied the significant impact of SSTs over the Arabian Sea and Bay of Bengal on ISMR. Shukla [1] suggested that western Arabian Sea SST anomaly is inversely associated with ISMR. Rao and Goswami [4] found that March-April SST anomaly over southeastern Arabian Sea is directly associated with ISMR. Clark et al. [5] also showed the direct and significant association between Arabian Sea SST and ISMR. Wang et al. [6] pointed out that the relationship between Arabian Sea SST and Indian summer monsoon rainfall (ISMR) is negative (positive) when the ENSO influence on Arabian Sea is considered (not considered). Kothawale et al. [3] also pointed out that the positive relationship between winter SST (spring SST) and ISMR is significant (insignificant) and is independent (dependent) of ENSO effect. They further showed that after removing the ENSO effect the positive relationship between spring SST and ISMR become significant.

The interaction between European temperature and ISMR is the evidence of impact of Eurasian snow on ISMR. Hahn and Shukla 1976; Dickson 1984; Bhanu Kumar 1988; Yang 1996; Harzallah and Sodourny 1997; Bamzai and Kinter 1997 [7–12] studied the influence of Eurasian snow on ISMR. Kripalani and Kulkarni [13] pointed out that the winter-time snow depth over western Eurasia surrounding Moscow (eastern Eurasia in central Siberia) is showing significant inverse (direct) relationship with subsequent ISMR. Many recent studies by Liu and Yanai 2001, Robinson et al 2001, Ye and Bao 2001, Zhao and Chen 2001, Rajeevan M 2002, Robock et al. 2003, Wu and Qian 2003, Fasullo 2004 [14–21], and others have also pointed out the relationship between surface

pressure/temperature over Eurasia and ISMR. Thus influence of temperature field over Europe, Arabian Sea, and Bay of Bengal on ISMR is well known but there is a temporal and spatial variability in the relationship between winter-time temperature and ISMR. In this paper an attempt has been made to understand the probable mechanism for the temporal and spatial variability in the relationship between temperature and ISMR.

Kakade and Dugam [22] have defined an index called Effective Strength Index (ESI) on the basis of monthly indices of NAO and SO. They have also shown that during excess (deficient) monsoon years the ESI decreases (increases) from January to April. ESI tendency is the difference between April and January ESI values. ESI tendency represents the simultaneous evolution of NAO and SO from winter to spring. Kakade and Dugam [23] pointed out that ESI tendency can be used as one of the predictors for the prediction of ISMR. The interannual variability of ESI tendency suggests that during contrasting phases of ESI tendency, evolution of both the oscillations from winter to spring differs and hence their impact on thermal field over different parts and the influence on Indian summer monsoon rainfall activity may change so as to keep thermal balance. In this paper, we are mainly emphasizing the variability in the relationship between ESI tendency and ISMR during contrasting phases of ESI tendency. Since NAO and SO and hence ESI tendency represent the global teleconnection pattern, the study is further extended to understand the influence of thermal field over Arabian Sea, Bay of Bengal, Europe, and Nino3 region on ISMR during contrasting phases of ESI tendency. An attempt has also been made to understand when ENSO influences the Arabian Sea temperature field by considering Nino3 SST anomaly and 1000-hPa winter temperature anomaly over Arabian Sea. This study may lead us to understand the positive and negative relationship between winter temperature over different regions over Arabian Sea and ISMR.

2. Data Used

In this study, the following data for the period 1951–2007 have been used.

(1) The summer monsoon rainfall (June–September) data for India as a whole have been taken from the web site http://www.tropmet.res.in/. The percentage departure from long-term mean is calculated and these indices are used for further analysis.

(2) 1000-hPa temperature (in degrees Kelvin) over Arabian Sea(40°–77.5°E, 5°–25°N), Bay of Bengal (5°–25°N, 80°–90°E), and Europe (45°–65°N, 25°W–60°E) have been obtained from the web site http://www.cru.uea.ac.uk/cru/data/ncep/qs_eurasia/.

(3) Nino3 (5°S–5°N, 150°–90°W) sea surface temperature anomaly data have been obtained from the web site http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices.

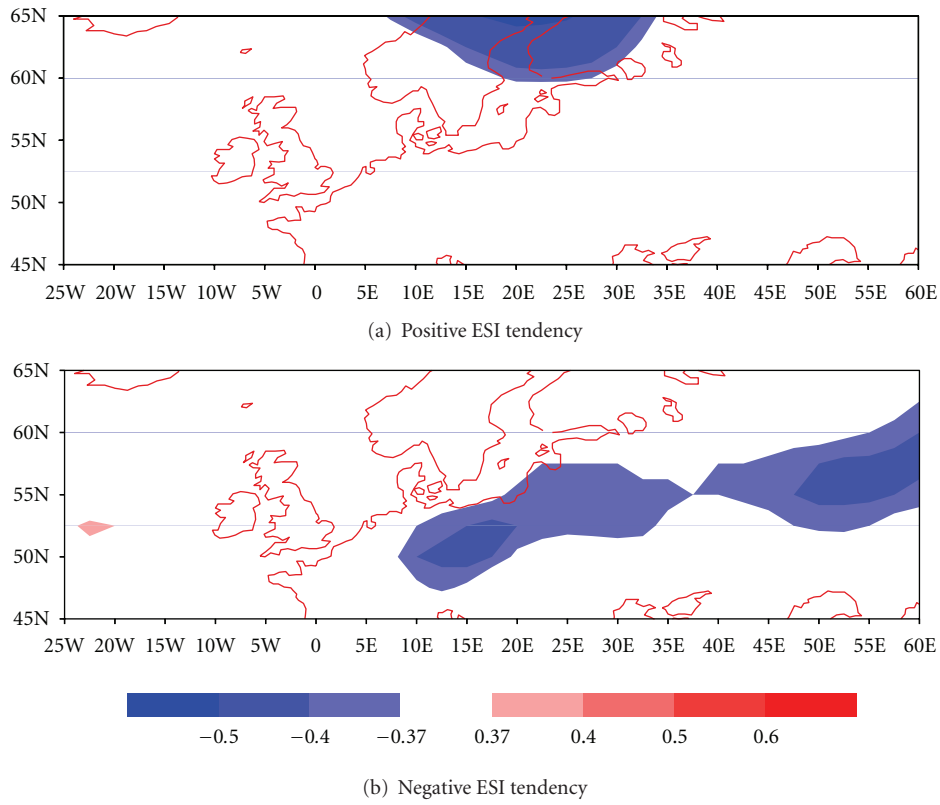
(4) Oceanic Nino Index (ONI) data have been obtained from the web site http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

(5) North Atlantic Oscillation (NAO) and Southern Oscillation (SO) data have been taken from http://www.cpc.ncep.noaa.gov/.

(6) Effective Strength Index (ESI) is defined as the algebraic difference between monthly indices of NAO and SO. The anomalies from the annual mean have been calculated for each month and these anomaly series are then divided by the standard deviation. These series are called as effective strength index (ESI) series of respective month. Seasonal means for all the above parameters are computed by averaging over the seasons as Winter (December–January–February), Spring (March–April–May), Summer (June–July–August), and Autumn (September–October–November).

3. Results and Discussion

Kakade and Kulkarni [24] pointed out the variability in surface temperature over Europe during contrasting phases of ESI tendency and hence change in the relationship between winter-time European temperature and ISMR. The study further concludes that winter-time temperature over northwest Europe can be used as predictor for predicting ISMR during negative ESI tendency only. The same paper also suggests that during positive (negative) ESI tendency, winter phases of NAO and SO are negative (positive) and positive (negative), respectively. It also indicates that during positive (negative) ESI tendency, NAO restores positive (negative) phase and SO restores negative (positive) phase before the beginning of summer season. Thus during contrasting phases of ESI tendency, the evolution of NAO and SO is out of phase. In order to understand why only negative ESI tendency has association with ISMR, we have computed the correlation coefficients between ESI tendency and 1000 hPa winter temperature anomaly for each $2.5^\circ \times 2.5^\circ$ grid point over Europe during contrasting phases of ESI tendency (as shown in Figure 1). It is observed that during positive (negative) ESI tendency, smaller (larger) region of Europe is showing significant winter-time cooling (warming). It may be due to the negative (positive) winter phase of NAO during positive (negative) ESI tendency. During negative phase of ESI tendency, the positive phase of winter NAO makes larger area of Europe anomalously warm in winter season. This anomalous warming may melt the Eurasian snow which creates more snow-free surface area over Eurasia and hence reducing the reflection of solar radiation back into the atmosphere due to albedo effect. It involves relatively more solar energy in land-atmosphere system which is again utilized for snow melting and due to this natural feedback process European temperature rises. During positive phase of ESI tendency, smaller area of Europe is anomalously cool in winter season and natural feedback process may be very weak during anomalous cooling over the same region. Therefore cooling effect during positive phase of ESI tendency is not that much



(a) Positive ESI tendency

(b) Negative ESI tendency

Figure 1: The correlation coefficients between ESI tendency and Winter temperature anomaly over Europe (45°–65°N, 25°W–60°E) during (a) positive (29 years) and (b) negative (28 years) ESI tendency.

prominent as the warming effect during negative phase of ESI tendency. This may be the probable reason for significant relationship between ESI tendency and ISMR during negative phase of ESI tendency only.

3.1. ISMR and 1000-hPa Winter Temperature Anomaly over Arabian Sea and Bay of Bengal. Figure 2 shows correlation coefficients between ISMR and 1000-hPa winter temperature anomaly for each 2.5°× 2.5° grid point over Arabian Sea and Bay of Bengal during contrasting phases of ESI tendency. It is observed that during positive (negative) phase of ESI tendency, 1000-hPa winter temperature anomaly over larger area of northeastern Arabian Sea (smaller area of southeastern Arabian Sea) is showing positive (negative) relationship with ISMR. It further suggests that 1000-hPa winter temperature anomaly over southeastern region of Bay of Bengal is showing an inverse and significant relationship with ISMR during negative ESI tendency only.

The time series of 1000-hPa winter temperature anomaly over northeastern Arabian Sea (Win-NEAS), southeastern Arabian Sea (Win-SEAS), southeastern Bay of Bengal (Win-SEBB), and Europe (Win-Europe) are prepared by averaging the corresponding temperature anomalies over selected grid points of significant correlations in respective regions. The correlation coefficient between Win-NEAS and ISMR is 0.49, during 29 years of positive ESI tendency. Moreover, the correlation coefficient between Win-SEAS and ISMR is −0.4 and between Win-Europe and ISMR is 0.51, during 28 years of negative ESI tendency. These correlation coefficients are significant at 5% level.

In order to understand this positive and negative relationship between ISMR and winter-time temperature anomaly over different locations of Arabian Sea, we must study the ENSO influence on Arabian Sea because Wang et al. [6] have pointed out that the relationship between winter Arabian Sea temperature and ISMR is positive when ENSO effect on Arabian Sea is not considered and is negative when ENSO effect on Arabian Sea is considered. ENSO effect is represented by winter Nino3 SST anomaly and its influence on seasonal Arabian Sea temperature during contrasting phases of ESI tendency is studied by the composite and correlation analysis.

3.2. Nino3 SST, 1000-hPa Winter Temperature over Arabian Sea and ISMR. The composite seasonal mean Nino3 SST anomaly during contrasting phases of ESI tendency is shown in Figure 3. The figure indicates that during positive ESI tendency, winter Nino3 SST is below normal and then it warms as season progress while during negative ESI tendency the winter Nino3 SST is above normal and it cools as season progresses. Moreover, probability of warm (cold) annual Nino3 SST during positive (negative) phase of ESI tendency is 0.66 (0.71). Thus during positive (negative) ESI tendency, Nino3 region shows warming (cooling) from winter through

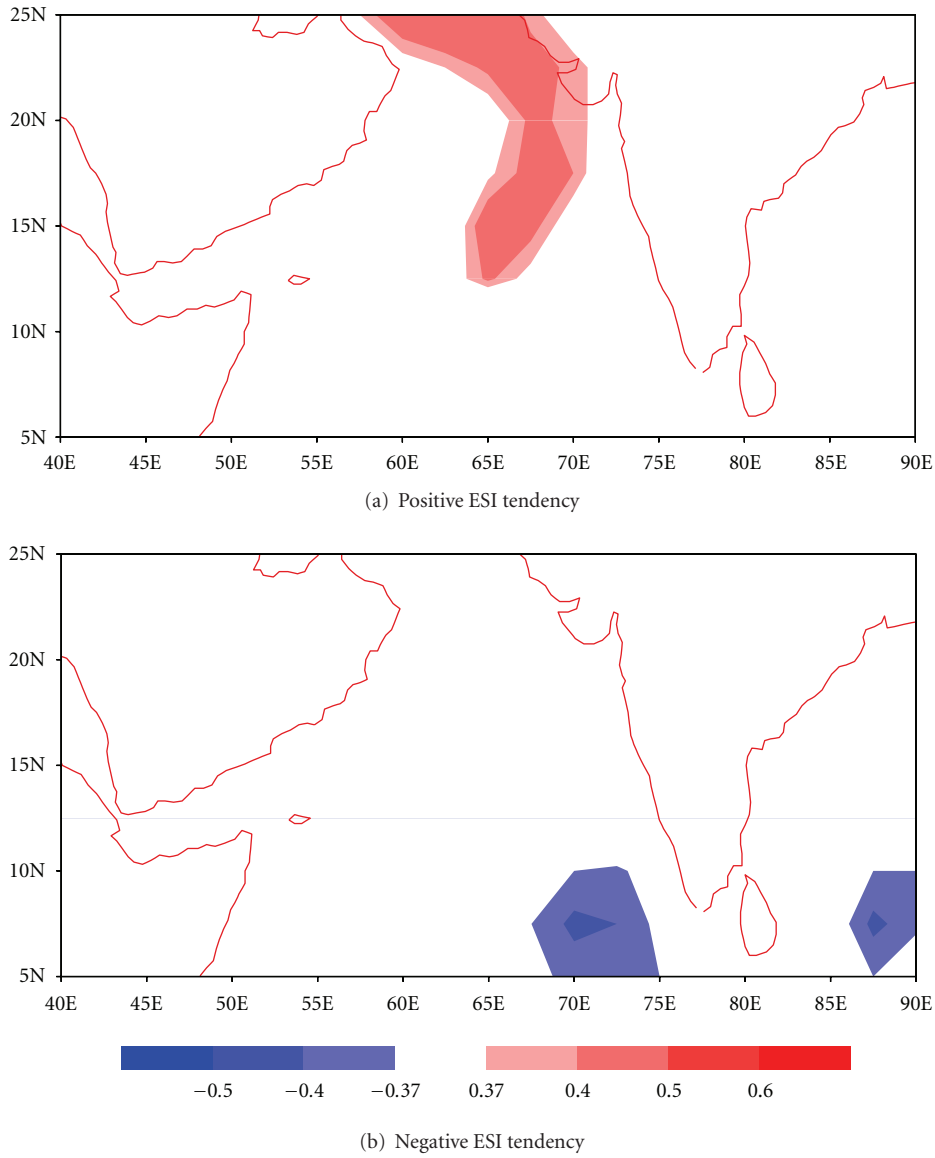


Figure 2: The correlation coefficients between ISMR and Winter temperature anomaly over Arabian sea and Bay of Bengal (5°–25°N, 40°–90°E) during (a) positive (29 years) and (b) negative (28 years) ESI tendency.

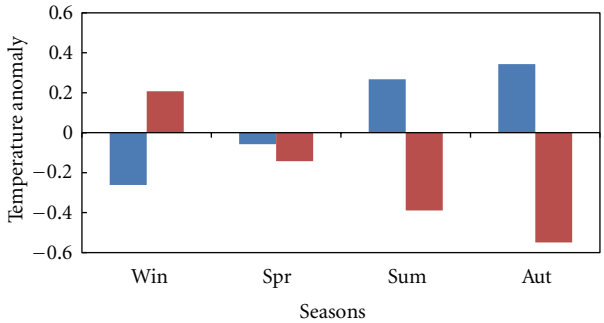


Figure 3: Composite seasonal mean Nino-3 SST anomaly during positive (blue column) and negative (red column) phases of ESI tendency.

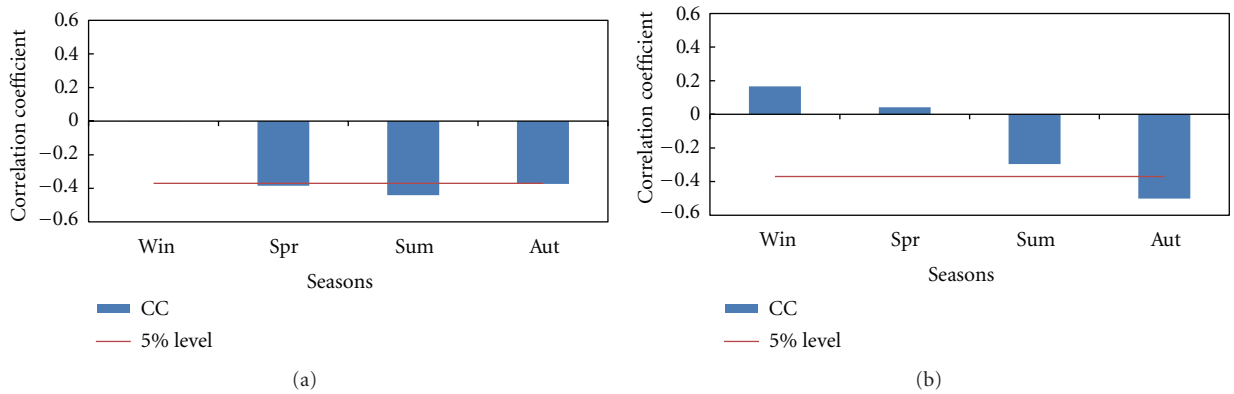


Figure 4: Relationship between seasonal mean Nino-3 SST anomaly and ISMR during (a) positive and (b) negative ESI tendency.

autumn. Most of the El Nino and La Nina years, based on Oceanic Nino Index (ONI), are observed to have positive ESI tendency (except 1968, a weak and 1986, a moderate El Nino years) and negative ESI tendency (except 1962, 1967 and 1972 weak years, 1954, a moderate and 1955, a strong La Nina years), respectively. Figure 4 depicts the correlation coefficients between seasonal mean Nino3 SST anomaly and ISMR during contrasting phases of ESI tendency. It suggests that Nino3 SST anomaly from spring to autumn is showing significant inverse relationship with ISMR during positive ESI tendency only. During positive phase of ESI tendency, the correlation coefficient between Spring Nino3 SST anomaly and ISMR is −0.38, which is significant at 5% level. The variance explained by spring Nino3 SST anomaly is 14% during positive ESI tendency.

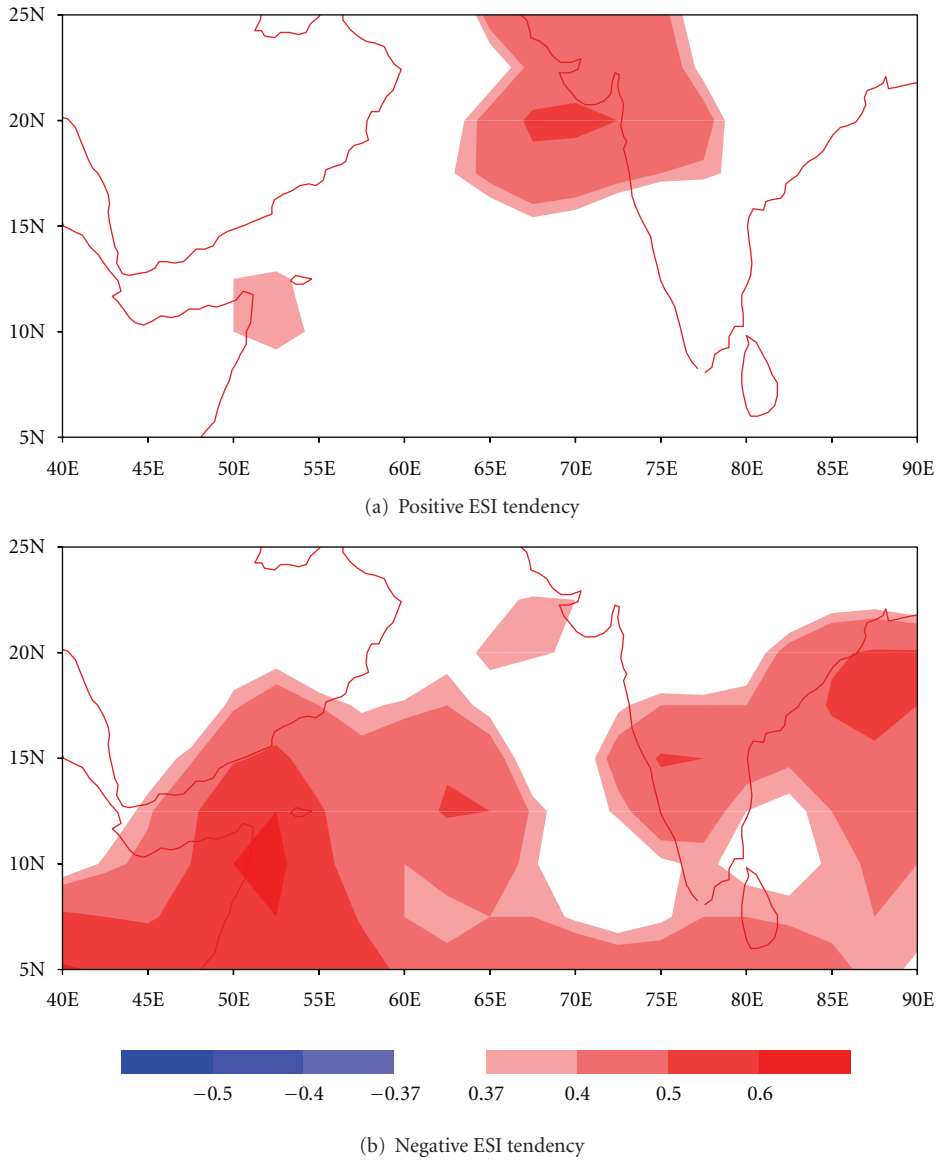
In order to understand the variability in the relationship of winter temperature anomaly over Arabian Sea and Bay of Bengal with ISMR during contrasting phases of ESI tendency, the correlation coefficients (CCs) between winter Nino3 SST anomaly time series and 1000-hPa annual temperature anomaly over each $2.5^\circ \times 2.5^\circ$ grid box over Arabian Sea and Bay of Bengal are computed for both the contrasting phases of ESI tendency and the CCs are shown in Figure 5. It is observed that during positive phase of ESI tendency the spatial extent of significant impact of winter Nino3 SST is reduced while during negative phase it is enlarged. It further suggests that winter Nino3 SST anomaly is not influencing annual 1000-hPa temperature over Bay of Bengal during positive phase of ESI tendency, whereas it influences during negative phase of ESI tendency. As the positive phase of SO is quickly restored during negative phase of ESI tendency rather than that of positive phase of ESI tendency and that is why during positive ESI tendency, winter Nino3 SST anomaly is not influencing the 1000-hPa temperature anomaly over Bay of Bengal and Arabian Sea.

Therefore, when ESI tendency is positive then the ENSO influence on the SSTs over Arabian Sea is very negligible and hence should not be considered and so the Arabian Sea temperature correlates positively with ISMR. When ESI tendency is negative then ENSO influences the Arabian Sea temperature substantially and hence the ENSO influence on Arabian Sea has to be considered and so the correlation becomes negative [6].

3.3. Multiple Regression Equation. The discussion in earlier sections suggests that evolution of temperature from winter to spring season during contrasting phases of ESI tendency differs drastically. Therefore the performance of temperature parameters used for predicting ISMR will be different in positive and negative phases of ESI tendency. Since the phase of ESI tendency can be known well in advance (in May), we select different temperature parameters in different phases of ESI tendency. In this section we frame two sets of different predictors (one set for each phase of ESI tendency) and develop multiple regression equations based on positive and negative ESI tendency.

During positive phase of ESI tendency, two predictors (set-1), namely, Win-NEAS and spring Nino3 SST anomaly (Spr-NINO3) explain 24% and 14% variance in ISMR respectively. Similarly during negative phase of ESI tendency, three predictors (set-2), namely, winter Europe temperature (Win-Europe), Win-SEAS and ESI tendency (ESIT) explain 26%, 16%, and 15% of ISMR variance, respectively. In order to understand which integral power of a particular predictor is strongly associated with ISMR, the correlation coefficients (CCs) between ISMR and different integral powers of respective predictor are computed.

The correlation coefficient (CC) between ISMR and Win-Europe temperature is significant at 1% level (CC = 0.51) during 28 years of negative ESI tendency only. It is observed that the relationship is not significant for any negative power, whereas it is significant for all positive powers. All odd (even) positive powers show significant direct (inverse) correlation coefficients. All odd positive powers retain the sign but rises the magnitude of winter temperature anomaly as that of original temperature anomaly series (Power = 1) and hence these are directly associated with ISMR. Whereas even positive powers will raise the magnitude and make all of them greater than zero, which changes the CC drastically. Magnitude wise, fifth power of winter-time NWEU temperature anomaly is showing highest correlation coefficient with ISMR (= 0.72). Therefore fifth power of winter-time NWEU temperature anomaly is used as one of the predictors for predicting ISMR in negative ESI tendency. Similarly powers of different predictors in set-1 and set-2 are decided. First power of Win-SEAS temperature anomaly and



(a) Positive ESI tendency

(b) Negative ESI tendency

Figure 5: The correlation coefficients between winter Nino3 SST anomaly and annual 1000-hPa temperature anomaly over Arabian sea and Bay of Bengal (5°–25°N, 40°–90°E) during (a) positive and (b) negative ESI tendency.

ESIT of set-2 are showing stronger association with ISMR. The powers of two predictors of set-1, namely, Win-NEAS temperature anomaly and Spr-NINO3 SST anomaly are 3 and 1, respectively.

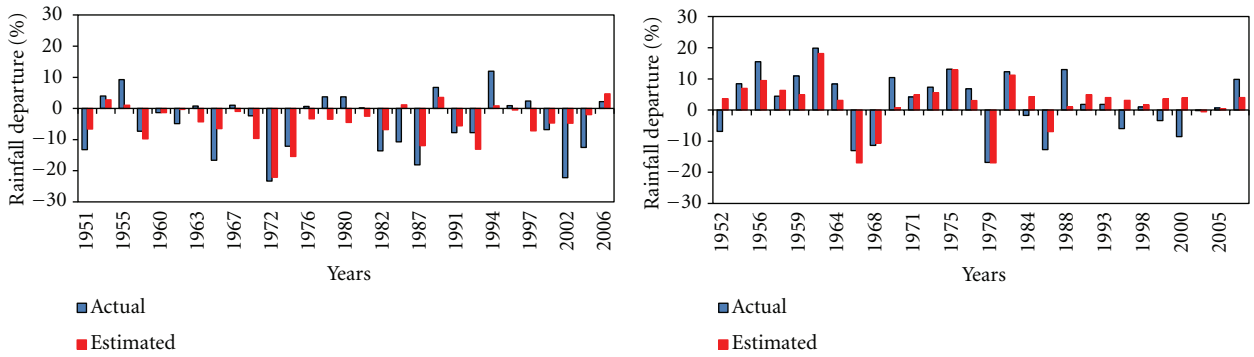
The interrelationship between the predictors of a particular set is found to be insignificant, which indicates that both the sets have independent predictors. The multiple regression equations are developed for predicting ISMR using predictors with corresponding powers from set-1 and set-2 during positive and negative phases of ESI tendency, respectively. The multiple regression equation for positive ESI tendency is

$$\text{Rainfall (\%dep.)} = 20.25\ (\text{Win-NEAS})^3 - 6.32\ (\text{Spr-NINO3}) - 4.85. \quad (1)$$

The multiple regression equation for negative ESI tendency is

$$\text{Rainfall (\%dep.)} = 1.05\ (\text{NWEU})^5 - 1.5\ (\text{ESIT}) - 5.92\ (\text{Win-SEAS}) + 2.47. \quad (2)$$

The actual and estimated rainfall departures (%) during contrasting phases of ESI tendency are depicted in Figure 6. The multiple correlation coefficients are 0.65 and 0.80 for positive and negative ESI tendency, respectively. During positive (negative) ESI tendency, the Heidke Skill Score is 0.34 (0.56). It suggests that the predictive skill during negative phase of ESI tendency is far better than that of during positive ESI tendency.



(a) Positive ESI tendency

(b) Negative ESI tendency

Figure 6: Actual and estimated % rainfall departure of all India during (a) positive and (b) negative phase of ESI tendency.

4. Conclusions

Following conclusions can be drawn on the basis of present study.

(1) The relationship between ESI tendency and ISMR is significantly different during contrasting phases of ESI tendency. This difference is mainly due to the out-of-phase evolution of two large-scale atmospheric oscillations NAO and SO from winter to spring.

(2) The influence of winter-time Nino3 SST anomalies (ENSO effect) on temperature anomalies over Arabian Sea and Bay of Bengal depends upon the phase of ESI tendency. When ESI tendency is positive (negative) then ENSO effect on Arabian Sea and Bay of Bengal temperature is insignificant (significant).

(3) During contrasting phases of ESI tendency, 1000-hPa winter-time temperature anomalies over different regions of Arabian Sea show variations in the significant relationship with ISMR because of the significant and insignificant ENSO effect on it. Therefore, with respect to the phase of ESI tendency if we select the winter-time temperature anomalies over the respective regions of Arabian Sea then the prediction may improve.

(4) During positive phase of ESI tendency, if warming over Nino3 region persists in spring season also then it reduces the rainfall activity over India.

(5) During negative ESI tendency, there is anomalous winter-time warming over Europe and hence the rainfall activity over India is increased.

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