

Northeast monsoon rainfall variability over south peninsular India and its teleconnections

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Abstract Rainfall over south peninsular India during the northeast (NE) monsoon season (Oct–Dec) shows significant interannual variation. In the present study, we relate the northeast monsoon rainfall (NEMR) over south peninsular India with the major oscillations like El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Equatorial Indian Ocean Oscillation (EQUINOO) in the Indian and Pacific Oceans. For establishing the teleconnections, sea surface temperature, outgoing long wave radiation, and circulation data have been used. The present study reveals that the positive phase of ENSO, IOD, and EQUINOO favor the NEMR to be normal or above normal over southern peninsular India. The study reveals that the variability of NEMR over south peninsula can be well explained by its relationship with positive phase of ENSO, IOD, and EQUINOO.

1 Introduction

The season, October to December is considered as northeast monsoon season in India, which is actually representing the withdrawal phase of southwest monsoon. During this season, low-level winds over India reverse their direction from southwesterly to northeasterly during the second or third week of October. Northeast (NE) monsoon is a part of northeast trades and is dry, stable, and has less vertical

extent compared to southwest monsoon. Usually during the first of October, a trough of low pressure gets established over the south Bay of Bengal. Depressions and cyclonic storms occasionally form in this trough giving widespread rainfall over South India. For a comprehensive examination of variability of the northeast monsoon rainfall of India, the region south peninsula demarcated by the Indian peninsula south of 15° N, as proposed by Singh and Sontakke (1996) is the most appropriate. This region consists of six meteorological subdivisions viz., Coastal Andhra Pradesh, Rayalseema, South interior Karnataka, coastal Karnataka, Tamil Nadu, and Kerala. During the NE monsoon season, India receives about 11% of its annual rainfall, while many of the above mentioned subdivisions receive 17–49% of their annual rainfall. There is a good influence of NE monsoon rainfall (NEMR) on agricultural production over south peninsular India. During the years of deficient monsoon years, it has been noted that there is a considerable decrease in agricultural production over south peninsular India (Rao Krishna and Jganathan 1953).

The NEMR is highly variable both in spatially and temporally. It is observed that NEMR is more variable (28%) than southwest monsoon rainfall (11%) (Nageswara Rao 1999). In spite of its importance, studies on NEMR variability are very limited (Rao and Raghavendra 1971; Ramaswamy 1972; Dhar and Rakkecha 1983; Sridharan and Muthuswamy 1990; Singh and Sontakke 1999; Kumar et al. 2003). Earlier studies related NEMR variability with ocean–atmosphere phenomenon like El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD; Bhanu Kumar et al. 2004; Kripalani and Kumar 2004). Some recent studies have shown that inter-annual variability of NEMR is significantly influenced by ENSO and this relationship has been strengthened during the recent years. Pankaj Kumar et al. (2007) have shown that the recent strengthening in the relationship between ENSO and NEMR over South Asia is due to the stronger easterly wind anomalies and anomalous

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low-level moisture convergence. Bhanu Kumar et al. (2004) also showed similar kind of strengthening in the relationship between ENSO September month Southern Oscillation Index and NEMR over Andhra Pradesh. De and Mukhopadhyay (1999) have studied the effect of ENSO on northeast monsoon (NEM) over five meteorological divisions of India in south peninsular India for the period 1901–1997. Rao (1999) has shown that during the low SO index years, the all-Indian summer and winter monsoon rainfalls are 3% and 21% more, while during high SO index years, they are 6% lesser than their corresponding means during the normal years. Kripalani and Kumar (2004) have shown that the NEMR over south peninsula and Indian Ocean Dipole Mode are directly related, suggesting that the positive (negative) phase enhances (suppresses) the northeast monsoon activity. Gadgil et al. (2004) suggested that during the positive phase of IOD, anomalous positive sea surface temperature (SST) anomalies and enhancement of convection are observed over western part (50–70° E, 10° S–10° N) of Indian Ocean and anomalous negative SST anomalies and suppression of convection are observed over the eastern (90–110° E, 0–10° S) part of Indian Ocean. This is in turn associated with easterly anomalies in the equatorial zonal wind. In the same way, the negative phase of IOD is characterized by enhanced convection over Eastern Indian Ocean (IO) and suppressed convection over western IO is associated with westerly

anomalies of the zonal wind at equator. The oscillation between these two states is Equatorial Indian Ocean Oscillation (EQUINOO). The studies on EQUINOO with NEMR variability can lead to the better understanding and better prediction of NEMR. Till now, there are no studies in understanding the EQUINOO–NEMR relationship.

To understand the inter-annual variability of NEMR, it is essential to understand associated circulation anomalies and their physical mechanisms. Thus, in this present study, we have examined the variability of NEMR and its relation with major oscillations of tropical Pacific and Indian Oceans like ENSO, IOD, and EQUINOO by analyzing outgoing long wave radiation (OLR), SST, and large-scale circulation anomalies using long time series of climatic datasets.

2 Data

The main dataset used for the present study is the high resolution (1°×1° lat/lon) gridded daily rainfall dataset (Rajeevan et al. 2006) for 54 years (1951–2004) over the Indian region. The comparison of this rainfall dataset with similar global gridded rainfall datasets revealed that the present rainfall analysis is better in accurate representation of spatial rainfall variation. The geographical area, 66.5–101.5° E, 6.5–37.5° N was considered for the calculation of

Fig. 1 The spatial distribution of seasonal mean rainfall (Oct–Dec) in millimeter for a period of 54 years (1951–2004)

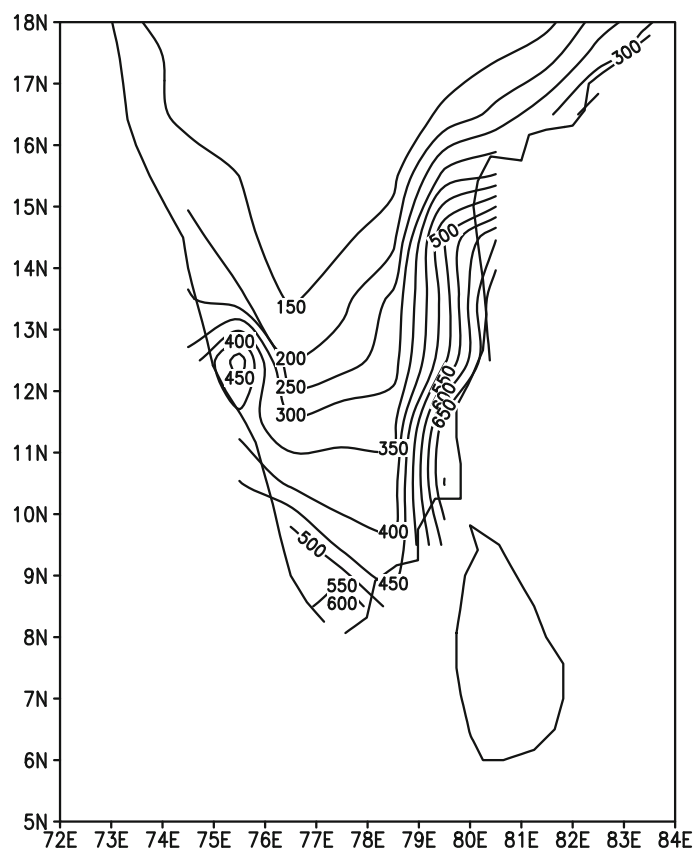


Fig. 2 Inter-annual variation of NEM rainfall over south peninsular India during 1951–2004



gridded rainfall dataset. In addition, the subdivisional rainfall dataset for 1901–2010 has been also used for understanding the climatology of northeast monsoon. The five meteorological subdivisions considered for the present study are Coastal Andhra Pradesh (normal rainfall is 326.6 mm), Rayalseema (212.2), Tamil Nadu (429.6), South Interior Karnatka (200.6), and Kerala (498.1). The subdivisional rainfall dataset was obtained from the records of the India Meteorological Department.

The other datasets used here for studying the relationship of NEMR over south peninsula with ENSO, IOD, and EQUINOO are as follows.

1. National Oceanic and Atmospheric Administration’s Climate Prediction Center declares the onset of an El

Niño episode when the 3-month average sea-surface temperature departure exceeds 0.5°C in the east-central equatorial Pacific [between 5° N–5° S and 170–120° W]. For our analysis, we used the Nino3.4 SST data. Monthly mean Nino3.4 SST datasets for the period of 1951–2004 have been downloaded from the site: www.cgd.ucar.edu.

2. The Indian Ocean dipole is a coupled ocean–atmosphere phenomenon observed in the IO in the form of an east–west dipole in the SST anomalies. A positive IOD year is characterized by cooler-than-normal water in the tropical eastern Indian Ocean, near Indonesia and warmer-than-normal water in the tropical western Indian Ocean, near Africa. An index to quantify IOD has been identified (Saji et al. 1999) as the SST difference between the tropical western Indian Ocean

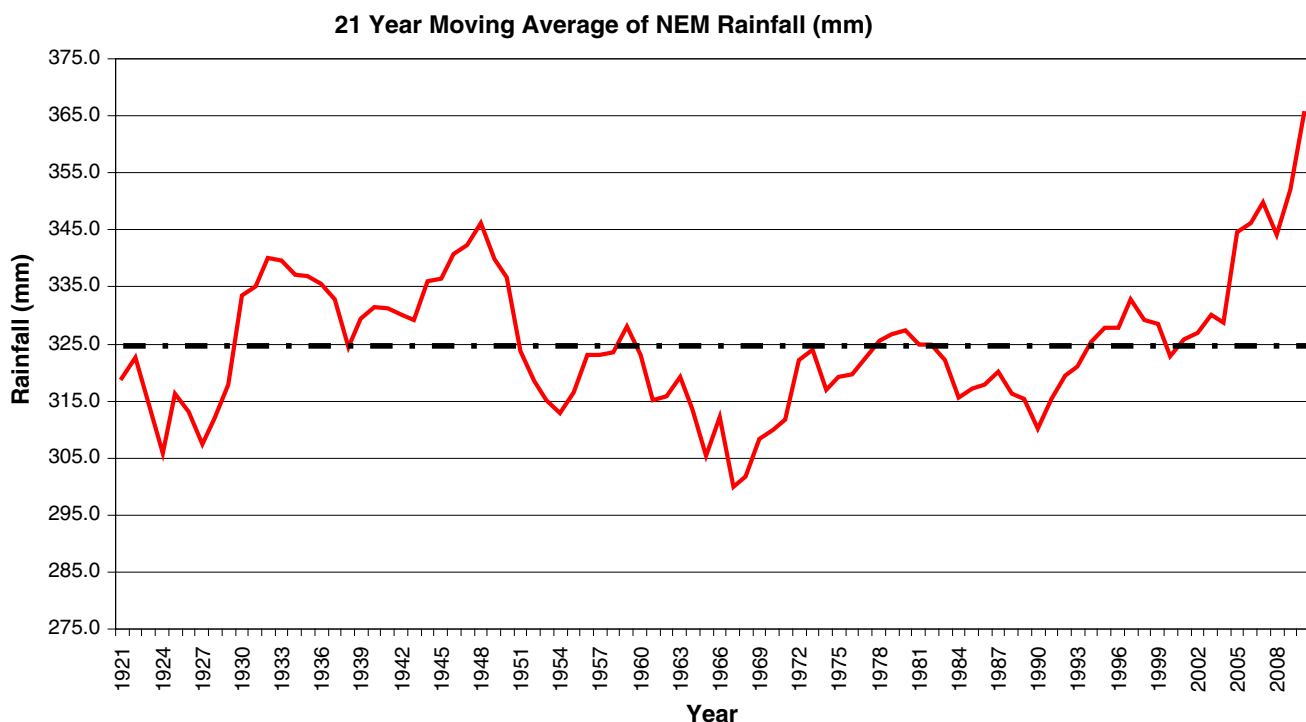


Fig. 3 Twenty one-year moving average of NEM rainfall for using subdivisional rainfall data for 110 years (1901–2010)

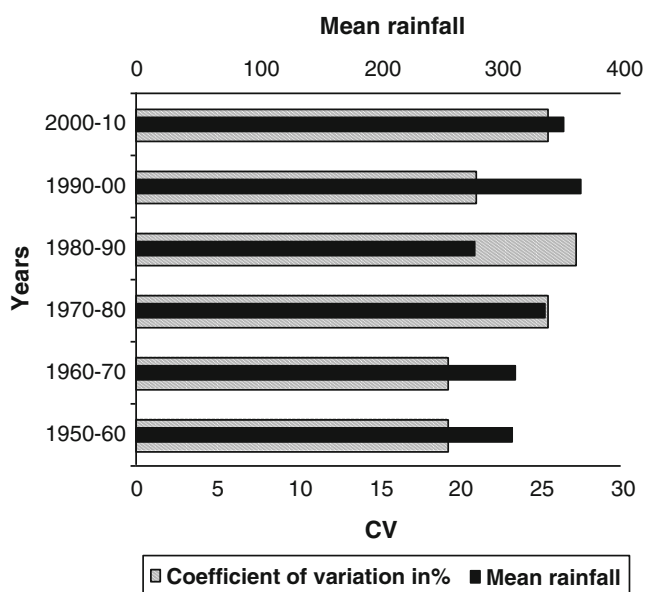


Fig. 4 The mean and coefficient of variation (CV in%) of northeast monsoon rainfall during the past six decades (1950–2010)

(50–70° E, 10° S–10° N) and the tropical southeastern Ocean (90–110° E, 10° S equator). The index is known as Indian Ocean Dipole Mode Index. The DMI data has been derived from monthly Geographical Information Systems Services and Training data (Reyner et al. 1996) for the period 1951–1997.

3. EQUINO has been considered as the atmospheric component of coupled Indian Ocean dipole. EQUINO index (EQWIN) is based on anomaly of zonal component of surface wind at equator (60–90° E, 2.5° S–2.5° N), which is highly correlated with the difference between OLR of Western Indian Ocean and Eastern Indian Ocean (Gadgil et al. 2007). Here, we used EQWIN as anomaly of zonal component of surface wind over the box 60–90° E, 0–5° S. EQWIN was derived from monthly zonal surface wind downloaded from the website www.cdc.noaa.
4. For examining the circulation features, National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis

Table 1 The probability of El Niño and La Niña years to be excess, normal/excess and deficient

El Niño	Probability of excess	0.407
	Probability of nor/excess	0.778
	Probability of deficient	0.222
La Niña	Probability of excess	0.125
	Probability of nor/excess	0.594
	Probability of deficient	0.406

data (Kalnay et al. 1996) for surface, 850 and 200 mb vector wind anomaly data has been used. For studying the synoptic features during the NE season over tropical region (15° S–15° N, 40–160° E), SST, OLR, and sea level pressure (SLP) anomaly data have been downloaded from the website www.cdc.noaa.gov

3 Interannual variability of NEMR over south peninsular India

The spatial distribution of mean seasonal (Oct–Dec) rainfall averaged over 54 years (1951–2004) over India is shown in Fig. 1. The southeastern part of the country receives (~450 mm) maximum rainfall during the season. The Southern Peninsular Indian region (8.5°–15.5° N, 75.5°–80.5° E) is considered for calculating NEMR for the present study. The south peninsular India receives a mean rainfall of 373 mm with a standard deviation of 97.33 mm. The coefficient of variation of NEMR over south peninsula is 26.11%.

The standardized NE monsoon seasonal rainfall averaged over the south peninsular region was calculated by averaging rainfall over the southern peninsular India and the time series for the period 1951–2004 is shown in Fig. 2. There is no significant trend observed in the time series. Out of 54 years, 24 years are above-normal rainfall years. There have been continuously above-normal rainfall during the recent decades, 1975–1979 and 1990–1995. The years 1977, 1991, and 1994 were the El Niño years. All positive ENSO/IOD years (1957, 1963, 1972, 1977, 1982, 1994, and 1997) are normal or above-normal rainfall years except the year 1982.

Figure 3 shows the 21-year moving average of NEM rainfall calculated using 110 years of NEM rainfall data (1901–2010). NEM rainfall shows significant multidecadal variations. NEM rainfall during the recent years has been above normal. An increasing trend in the NEM rainfall during the recent years can be noted.

Figure 4 shows the decadal variability of mean and CV of NEMR for the last six decades (1950–2010) using sub-divisional rainfall data. It shows that the mean has increased during the recent two recent decades and CV has increased in the last decade (2000–2010) which makes that decade more vulnerable to large variability.

The probability calculations shows that the probability of an El Niño year to be a deficient monsoon year is small (0.22) compared to the year to be an excess (0.41) monsoon year. Table 1 shows the probability of El Niño and La Niña years to be excess and deficient. The probability of a positive IOD year to be a deficient monsoon year is small (0.18) compared to be an excess monsoon year (0.45). The probability of the positive ENSO/IOD year to be a deficient year is 0.12 while for the excess year, it is 0.62. The

probability of a positive EQUINOO year to be a deficient monsoon year is small (0.22) compared to be normal or above-normal monsoon year (0.78). And the probability of the positive ENSO/EQUINOO year to be a deficient year is 0.22 while for the excess year, it is 0.44. Therefore, positive phase of ENSO, IOD, and EQUINOO is favorable for an excess monsoon year over south peninsula.

4 Composite OLR, wind, and SST anomalies associated with extreme phases

The teleconnections such as ENSO, IOD, and EQUINOO in relation with NEMR can be further explored by considering the composite spatial pattern of OLR, wind, and SST anomalies over tropical Indian and Pacific Ocean regions (15° S to 20° N, 40° E to 160° W) for the extreme NEMR phases. To examine the composite anomalies, we have selected 13 excess monsoon years (1956, 1966, 1969, 1972, 1977, 1978, 1979, 1987, 1991, 1993, 1996, 1997, and 1998) having standardized rainfall more than 0.75 and 12 deficient monsoon (1951, 1952, 1959, 1961, 1968, 1974, 1982, 1986, 1988, 1989, 1995, and 2000) years having the standardized rainfall less than -0.75 mm from the entire study period of 54 years (1951–2004). The composites of all the above

mentioned anomalies during the excess and deficient monsoon phases and their differences have been studied in detail. The OLR and circulation anomalies over India and its surroundings composed for the extreme phases of NEMR will give us better understanding on the physical mechanisms responsible for the NEMR variability.

Figure 5 shows the composite OLR anomalies for the excess and deficient monsoon years. Positive OLR anomalies are observed over central Pacific Ocean and south India during deficient monsoon years, which suggests the suppressed convective activity over these two regions. During the excess monsoon years, negative OLR anomalies are observed over Central Pacific Ocean, south peninsular India, and northwestern Indian Ocean. Thus, the above-normal convection over Central Pacific Ocean and suppressed convection over warm pool region and southeastern Indian Ocean is associated with good NEM rainfall activity.

The composite wind anomalies associated with NEM rainfall extremes are shown in Fig. 6. The southerly and southeasterly wind at the 1,000 and 850 hPa levels over the Indian region and surroundings are associated with the enhanced convection over the subcontinent and suppressed convection over south Indian Ocean during the excess monsoon years (Fig. 6c and d). During the excess monsoon period, south easterlies, blowing from Bay of Bengal and

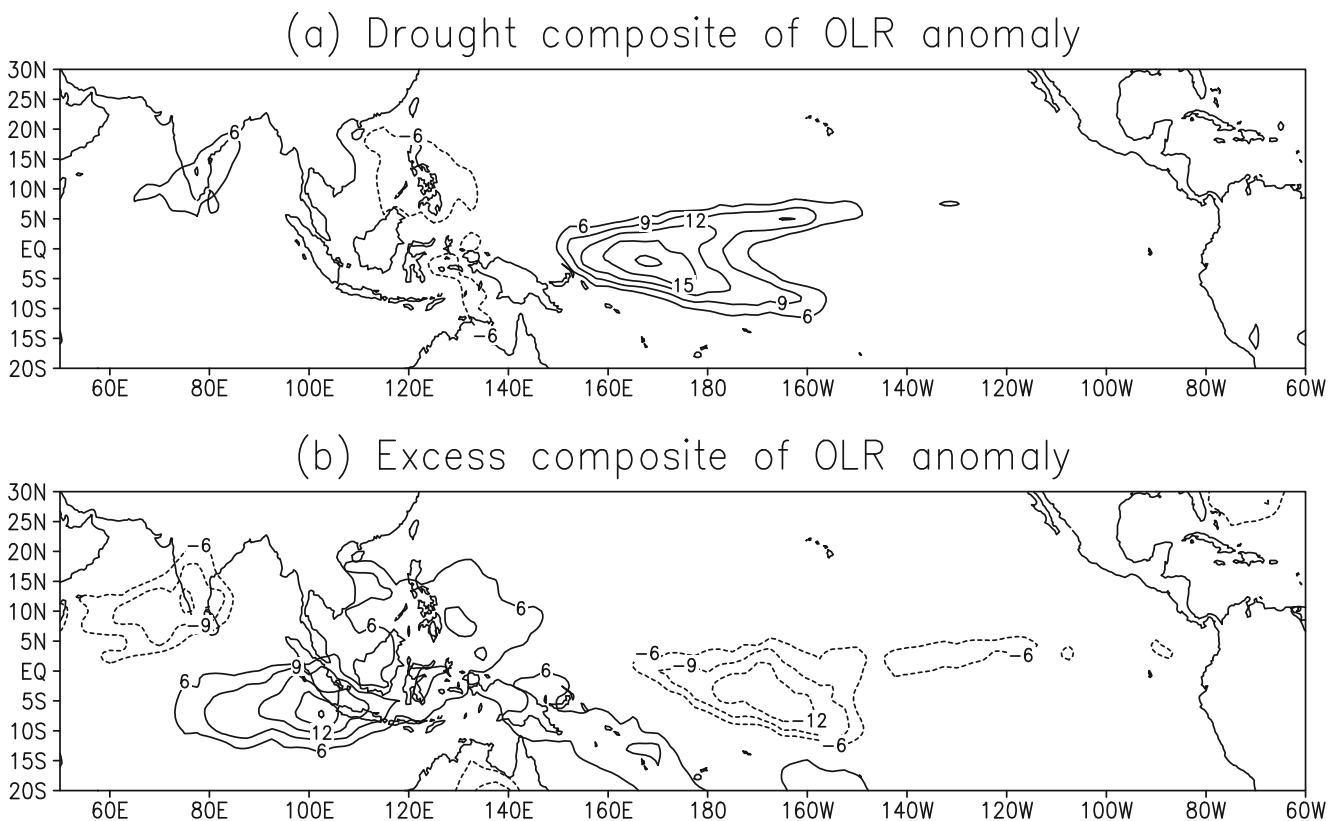


Fig. 5 Composite seasonal (Oct–Dec) OLR anomalies for excess and deficient northeast monsoon years

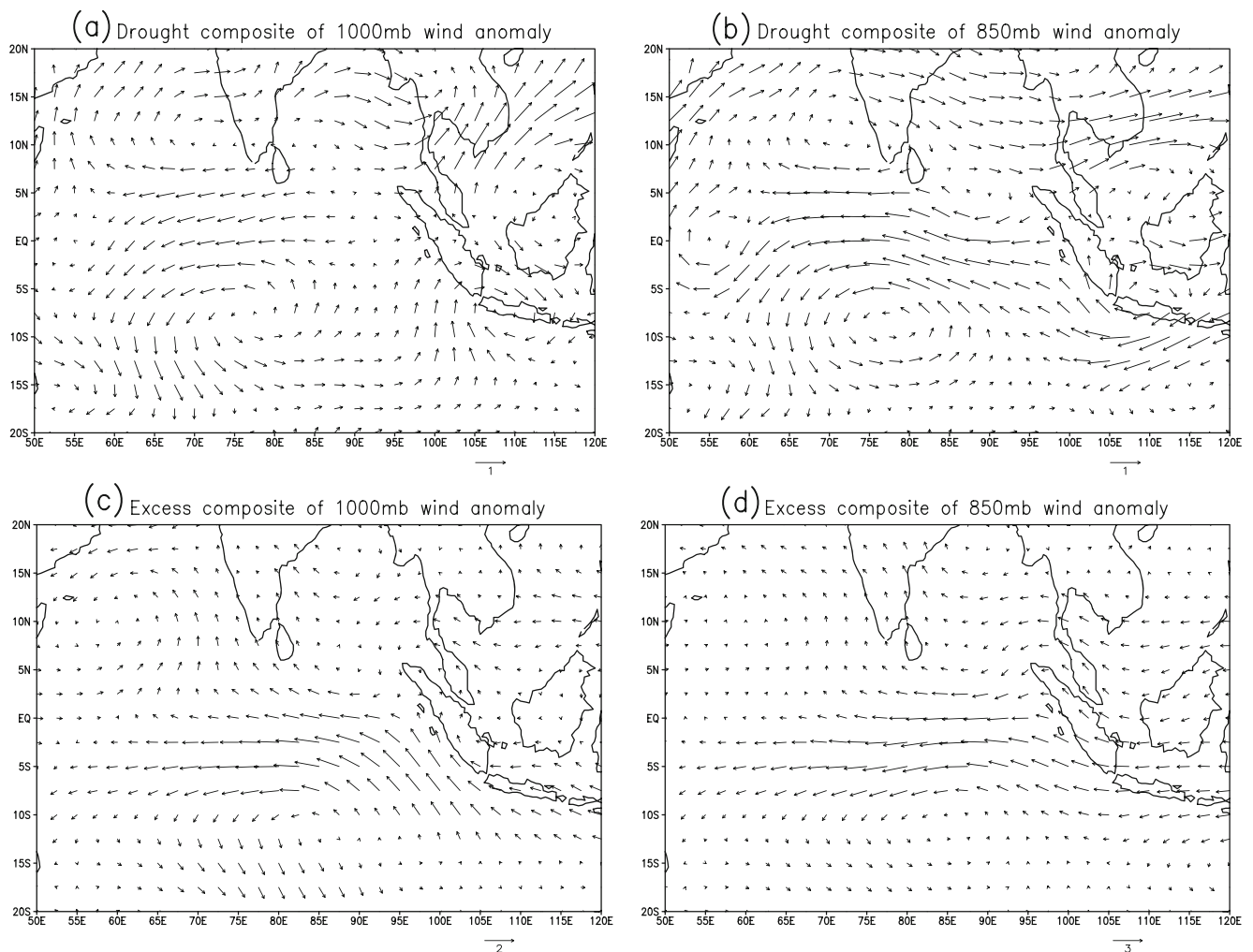


Fig. 6 Composite seasonal (Oct–Dec) 1,000 and 850 mb wind anomalies for excess and deficient northeast monsoon years

Indian Ocean region to the Indian subcontinent bring more moisture towards the south peninsular India and thus enhances the amount of rainfall over this region. Anomalous easterlies over the equatorial Indian Ocean is also associated with excess monsoon years. During the deficient monsoon years, anomalous anticyclonic flow at the 1,000 and 850 hpa is observed over North Indian Ocean (Fig. 6a and b). This suggests the weaker/absence of intertropical convergence zone (ITCZ) during the drought years. The moisture transport towards the Peninsular India by the southeasterly wind anomalies is found to be absent during the deficient monsoon seasons.

The wind pattern over south peninsular India during the El Niño composites are also found to be south easterlies (Kumar et al. 2007) which is similar to the wind pattern observed during the excess monsoon phase revealed in the present study. This highlights the role of El Niño events in causing excess rainfall during the NE monsoon season. In the surface

wind anomaly pattern, strong easterlies are observed over the eastern equatorial Indian Ocean which suggests the link between excess NEMR and positive phase of EQUINO.

Figure 7 shows the composite SST anomalies during the drought and excess monsoon years. Positive SST anomalies are observed over the central equatorial Pacific and North Indian Ocean during the excess monsoon years, suggesting the influence of warm phase of ENSO on NEMR. During the deficient monsoon years, large negative anomalies are observed over the central Pacific Ocean. Thus, large differences in SST anomalies are observed over the central Pacific and North Indian Ocean in drought and excess monsoon years.

Similar composite patterns for the sea level pressure anomaly are shown in Fig. 8. Below-normal pressure over the East Asia is associated with deficient monsoon and positive SLP anomalies over the west Pacific Ocean are associated with above-normal rainfall activity.

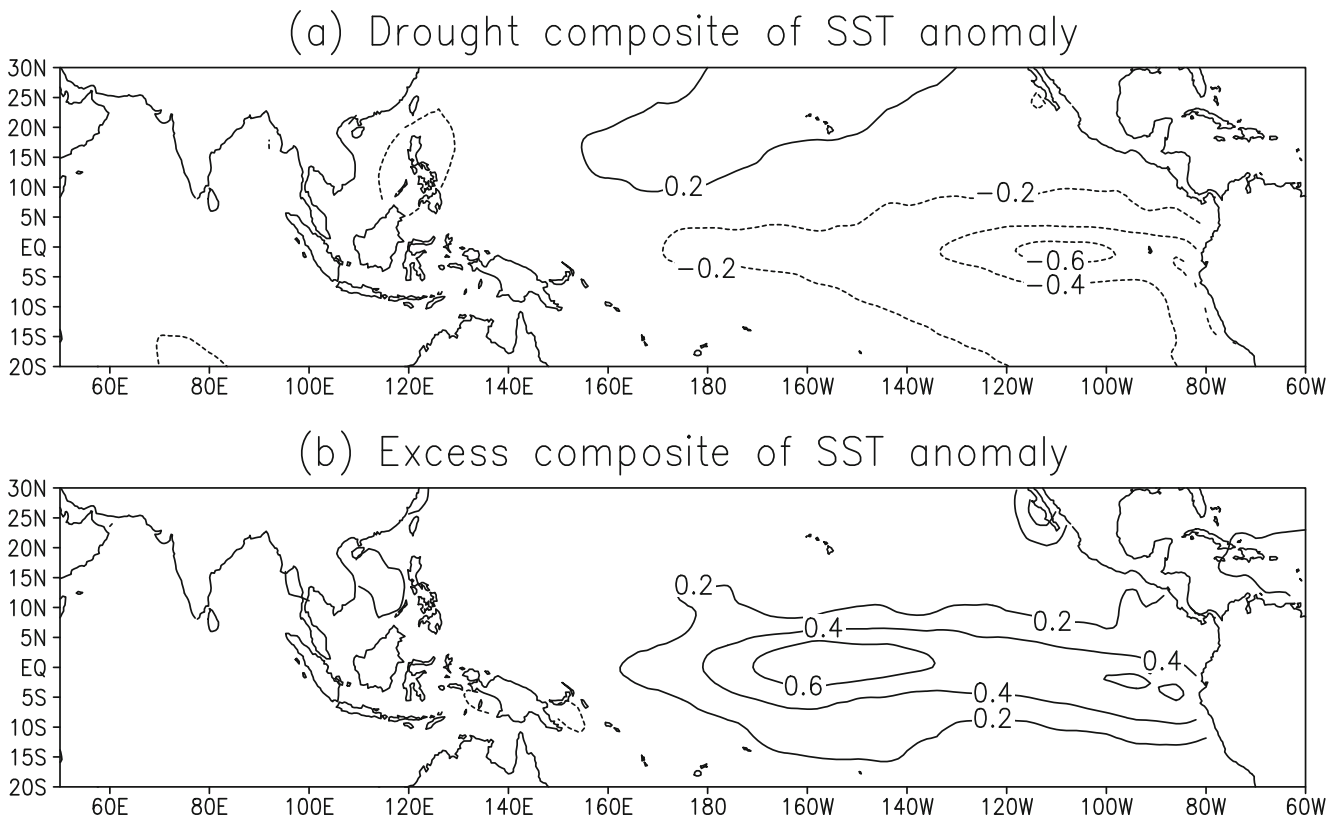


Fig. 7 Composite seasonal (Oct-Dec) SST anomalies for excess and deficient northeast monsoon years

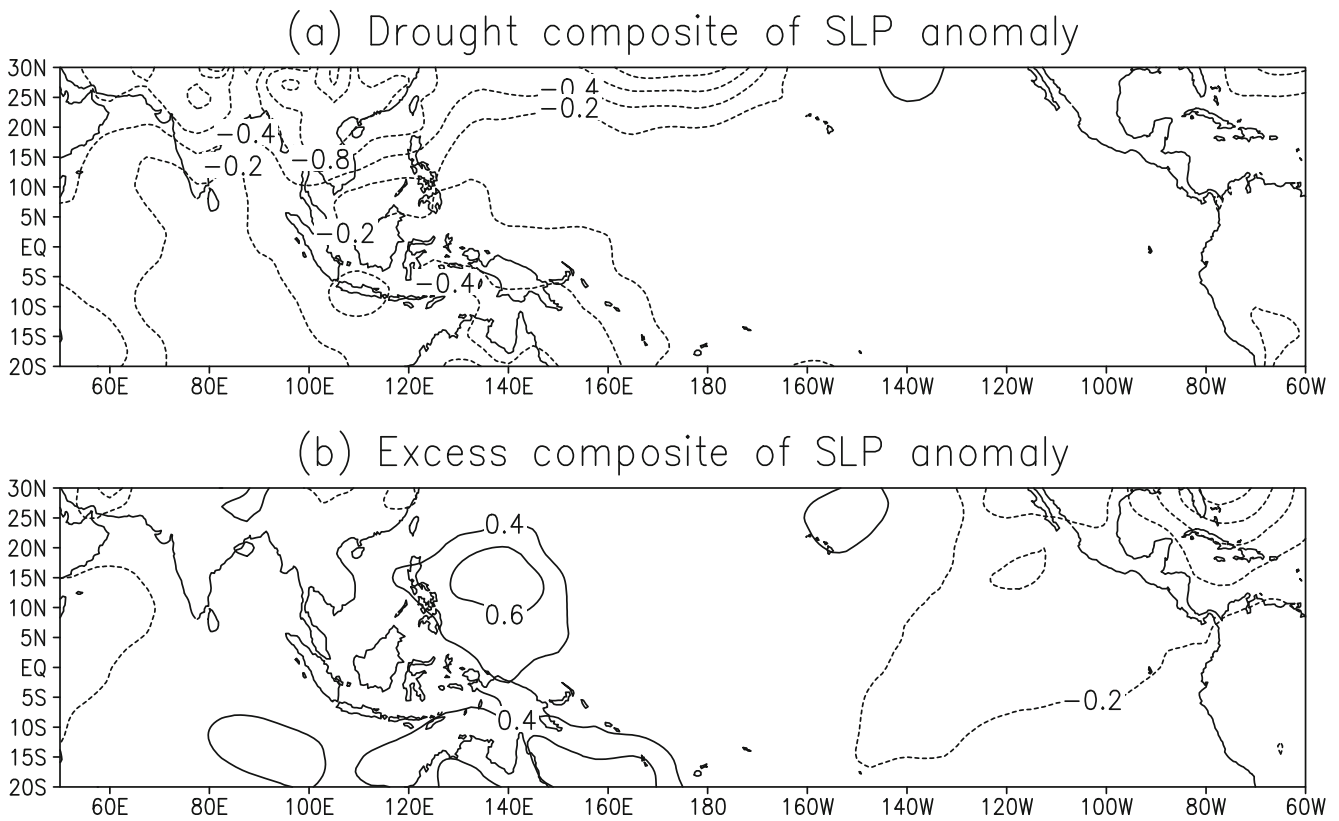


Fig. 8 Composite seasonal (Oct-Dec) sea level pressure (SLP) anomalies for excess and deficient northeast monsoon years

5 Spatial correlation between NEMR with SST, OLR, SLP, and wind anomalies

The spatial correlation patterns between NEMR and SST, OLR, and wind anomalies have been examined to further establish the teleconnection links with ENSO, IOD, and EQUINOO.

Figure 9 shows the spatial pattern of the correlation coefficient (CC) between NEMR and OLR anomalies during NEM season. The CC between NEMR and OLR anomalies is negative and high (-0.2 to -0.7) over northwestern IO and the Indian land mass region and it is positively correlated with southeastern IO. The negative OLR anomalies indicate the enhancement of convection. Thus, the NEMR is positively correlated with convection over northwestern IO and Indian land mass and negatively correlated with the convection over southeastern IO. The EQWIN is highly correlated with the difference between OLR of western equatorial IO and eastern equatorial IO. In the same way, NEMR is also highly correlated with OLR over the same regions, which suggests the relation between NEMR and EQUINOO.

The CC pattern between zonal wind anomalies at surface and 850 hPa and NEMR over south peninsula is shown in Fig. 10a and b. The significant negative correlation between zonal wind over southeastern IO and NEMR is observed emphasizing the positive relation of EQUINOO with NEMR. Easterlies over south peninsular India and its

surrounding IO are positively correlated with NEMR. Similarly, westerlies over Western Equatorial IO and easterlies over South Eastern IO are also positively correlated with NEMR. Figure 10c, d shows the correlations of meridional wind anomaly with NEMR. It is observed that the NEMR is positively correlated with southerlies over Indian peninsula and surrounding southwestern part of the Indian Ocean both at surface and 850 hPa level. Even though northeasterlies are prominent over south peninsular India and its surrounding Indian Ocean during the NE monsoon season, the NEMR over the south peninsula is more positively correlated with southeasterly wind anomalies over the same region.

From the correlations, one can deduce that suppressed convective activity over south East Indian Ocean and thus divergent circulation helps in more moisture transport from southeast Indian Ocean to South peninsular India and enhancing the rainfall activity.

NEMR is also positively correlated with SST anomalies over the western Indian Ocean ($CC=0.2$) and the Central Pacific Ocean ($CC=0.3$) during NEM season as shown in Fig. 11. NEMR is negatively correlated with SST anomalies over Western Pacific Ocean. Thus, the warming over central Pacific Ocean and cooling over the western Pacific Ocean is responsible for the excess monsoon over south peninsular India. The warming over western IO is also causing more rainfall over the same region. These observational features emphasize the relationship between NEMR with ENSO and IOD.

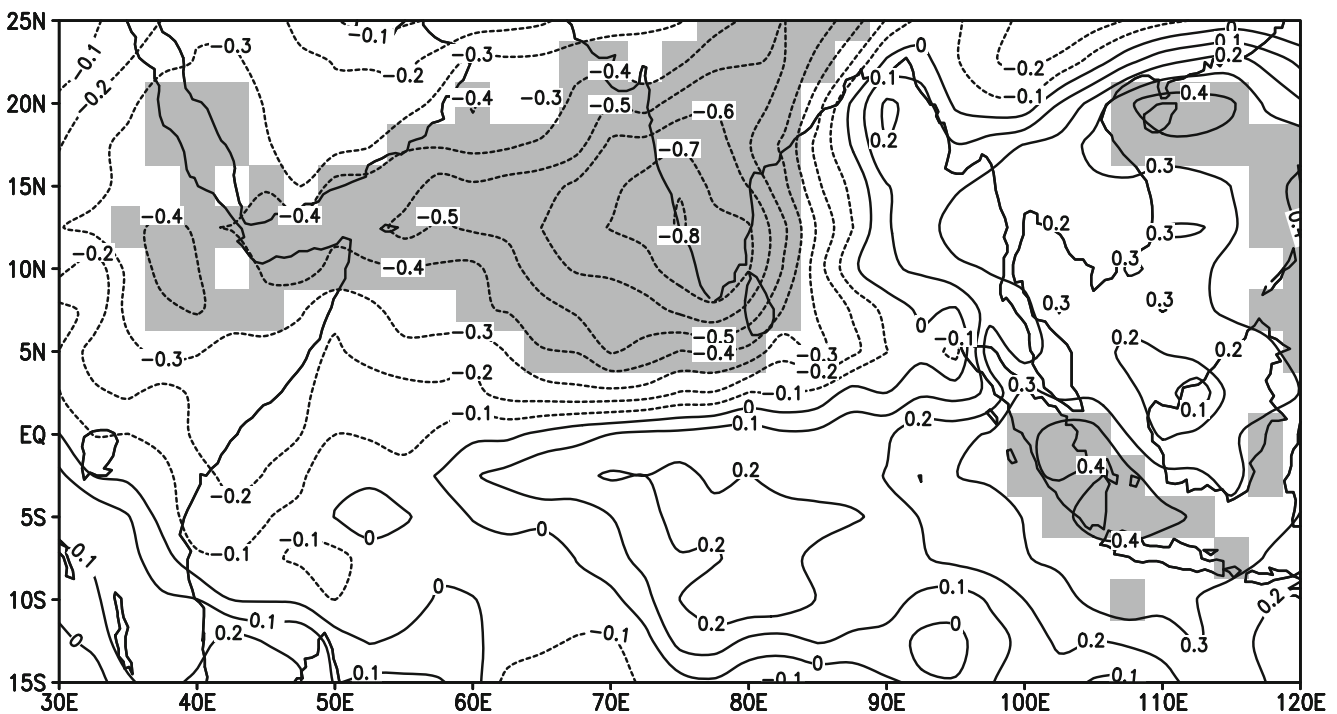


Fig. 9 Spatial correlation between NEMR over south peninsula and OLR anomalies during NEM season (Oct–Dec) for the period 1974–2004 with shaded portion as significant at 5% level

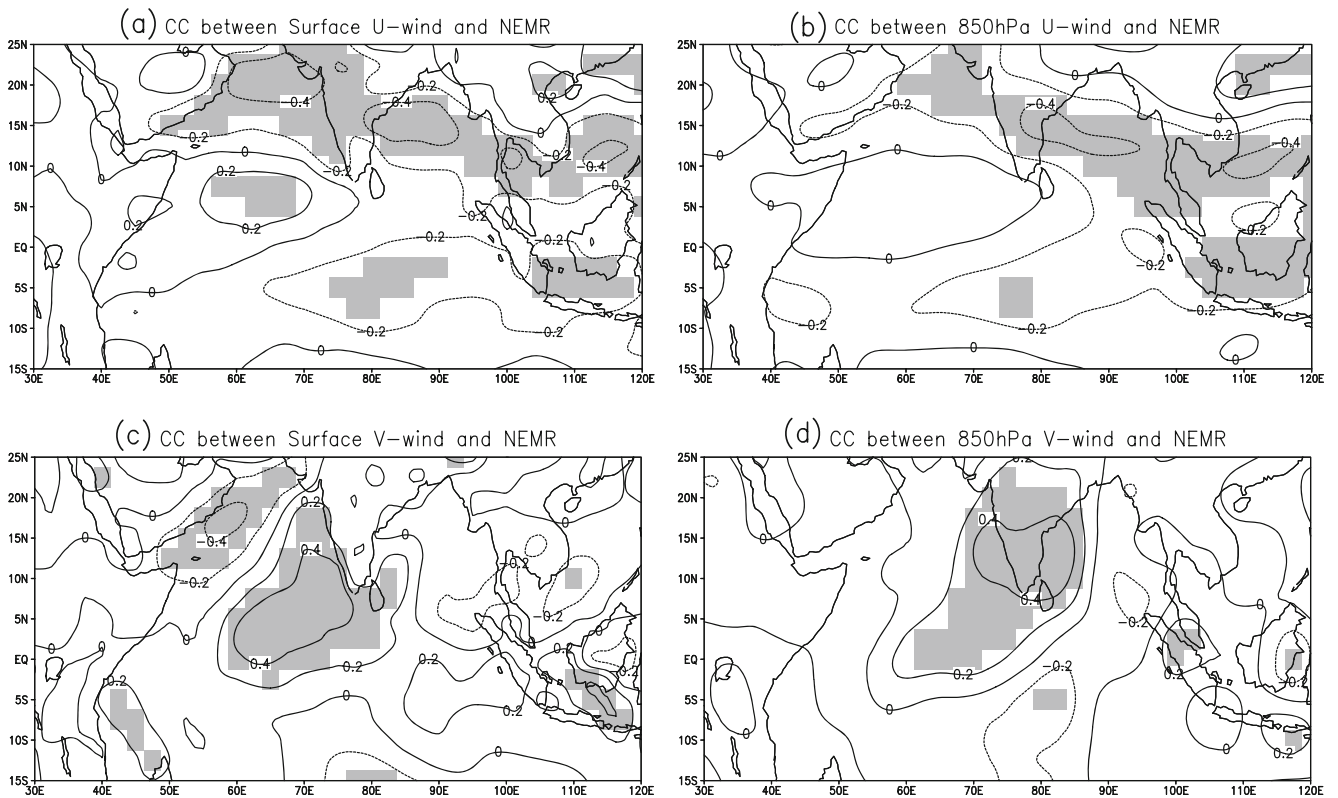


Fig. 10 Spatial correlation between NEMR over south peninsula and wind anomalies during NEM season (Oct–Dec) for the period 1951–2004 with shaded portion as significant at 5% level

Table 2 shows the CC of seasonal NEMR with monthly values of Nino3.4 SST, EQWIN (CC for 54 years (1951–2004)) and with DMI (for 46 years (1951–1997)) for August to December and the NEM season. The correlation of NEMR with Nino3.4 SST in all the months from August to December is found to be positive and significant and the correlation is highest in the month of October. The NEMR is positively correlated with DMI and EQWIN. The correlation with DMI is highest in the month of September and the correlation with EQWIN is highest in the month of October.

6 Summary

The present study has examined the NEMR variability over south peninsular India and its relation with different ocean–atmospheric phenomenon (ENSO, IOD, and recently established EQUINOO) using 54 years (1951–2004) data. The spatial pattern of OLR, wind, SST, and SLP anomalies during drought and excess monsoon years has been studied in detail to understand the physical mechanisms involved in the teleconnections. The spatial correlation of NEMR rainfall with SST, OLR, and wind

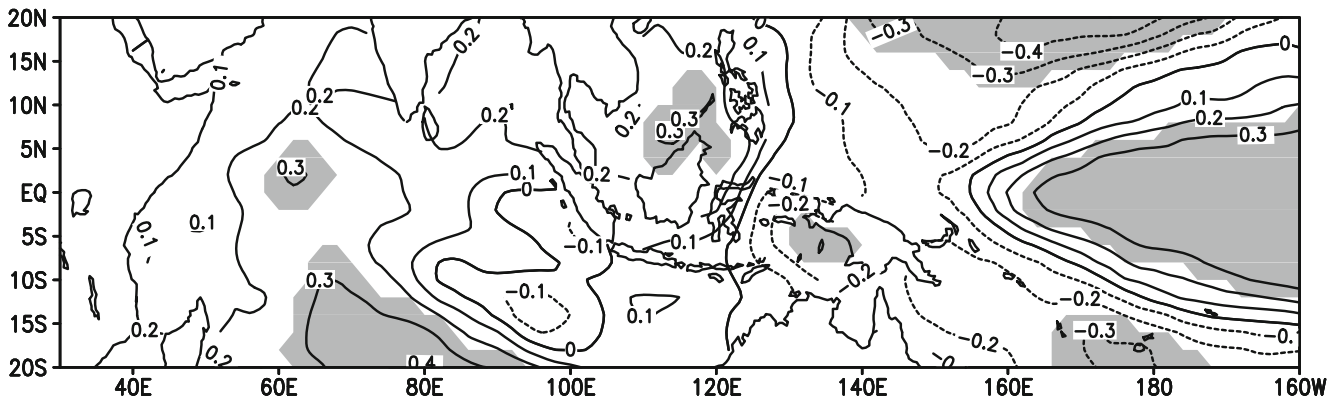


Fig. 11 Spatial correlation between NEMR over south peninsula and SST anomalies during NEM season (Oct–Dec) for the period 1951–2004 with shaded portion as significant at 5% level

Table 2 The correlation coefficient (CC) of seasonal NEMR with the monthly values of Nino3.4 SST, DMI, and EQWIN

The Correlation coefficient of NEMR with Nino3.4 SST (1951–2004), EQWIN (1951–2004) and DMI (1951–1997)

	Nino3.4 SST	EQWIN	DMI
August	<i>0.31</i>	0.01	0.23
September	<i>0.32</i>	−0.08	0.24
October	<i>0.35</i>	<i>0.32</i>	0.20
November	<i>0.32</i>	<i>0.28</i>	0.15
December	<i>0.30</i>	0.01	0.11
Season (Oct–Dec)	<i>0.32</i>	0.25	0.16

Values in italics are significant at 95% level. The CC between NEMR and Nino 3.4 SST and EQWIN is calculated for 54 years and CC between NEMR and DMI is calculated for 46 years

has also been examined in detail for further understanding in the teleconnections.

The major findings of the present study are:

1. The NEMR is directly related with the above mentioned ocean–atmospheric phenomenon, ENSO, IOD and EQUINOO.
2. The correlation analysis revealed that NEMR is positively correlated with Nino3.4 SST in the months of August to December which is significant at 95% level. The DMI is also positively correlated with NEMR, the correlation is high in the month of September (CC=0.24). Significant positive correlation is observed in between NEMR and EQWIN in the month of October and November
3. The spatial distribution of OLR anomalies reveals that the above-normal convection over Central Pacific Ocean and suppressed convection over warm pool region and southeastern Indian Ocean is associated with good NEM rainfall activity. During the deficient monsoon years, anomalous anticyclonic flow at the 1,000 and 850 hpa is observed over North Indian Ocean. This suggests the weaker/absence of ITCZ during the drought years.
4. Strong easterlies observed in the surface wind pattern over the eastern equatorial Indian Ocean suggests the link between excess NEMR and positive phase of EQUINOO.
5. Positive SST anomalies are observed over the central equatorial Pacific and North Indian Ocean during the excess monsoon years, suggesting the influence of warm phase of ENSO on NEMR. During the deficient monsoon years, large negative anomalies are observed over the central Pacific Ocean.
6. As the EQWIN is highly correlated with the difference between OLR of western equatorial IO and eastern equatorial IO, NEMR is also found to be highly correlated with the OLR over the same regions. Negative correlation of NEMR with zonal wind over

southeastern IO is observed. These emphasize the positive relationship between EQWIN and NEMR.

7. The suppressed convective activity over southeast Indian Ocean and thus divergent circulation helps in more moisture transport from southeast Indian Ocean to South peninsular India and enhancing the rainfall activity during the excess monsoon years.

Thus, the positive relationship of NEMR with the major ocean–atmospheric oscillations, ENSO, IOD, and EQUINOO is clearly established in the present study.

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References

- Bhanu Kumar OSRU, Naidu CV, Rao SRL (2004) Influence of Southern Oscillation and SSTs over Nino-3.4 region on the winter monsoon rainfall over coastal Andhra Pradesh. *Proc Indian Acad Sci* 113:313–319
- De US, Mukhopadhyay RK (1999) The effect of ENSO/Anti ENSO on northeast monsoon rainfall. *Mausam* 50:343–354
- Dhar ON, Rakhecha PR (1983) Forecasting northeast monsoon rainfall over Tamil Nadu, India. *Mon Wea Rev* 111:109–112
- Gadgil S, Vinayachandran PN, Francis PA, Gadgil S (2004) Extremes of Indian summer monsoon rainfall, ENSO, equatorial Indian Ocean Oscillation. *Geophys Res Lett* 31. doi:10.1029/2004GL019733
- Kalnay E et al (1996) The NCEP/NCAR reanalysis projects. *Bull Am Meteor Soc* 7:437–471
- Kripalani RH, Kumar P (2004) Northeast monsoon rainfall variability over south peninsular India vis-a-vis Indian Ocean Dipole mode. *Int J Climatol* 24:1267–1282
- Kumar P, Kumar KR, Rajeevan M, Munot AA (2003) Interannual variability of northeast monsoon rainfall over south peninsular India: teleconnections and long range forecasting. In: Conference on monsoon environments: agricultural and hydrological impacts of seasonal variability and climate change. ICTP, Trieste, 24–28 March, 2003

- Pankaj K, Rupa Kumar K, Rajeevan M (2007) On the recent strengthening of the relationship between ENSO and northeast monsoon rainfall over South Asia. *Clim Dyn* 28:649–660
- Rajeevan M, Jyothi B, Kale JD, Lal B (2006) Development of a high resolution daily gridded rainfall data for Indian Region. National Climate Centre, IMD, Pune
- Ramaswamy C (1972) The severe drought over Tamil Nadu during the retreating monsoon period of 1968 and its association with anomalies in the upper level flow pattern over the Northern Hemisphere. *Indian J Meteorol Geophys* 23:303–316
- Rao GN (1999) Variations of the SO relationship with summer and winter monsoon rainfall over India: 1872–1993. *J Clim* 12:3486–3495
- Rao Krishna PR, Jganathan P (1953) A study of the northeast monsoon rainfall of Tamilnadu. *Indian J Meteor Geophys* 4:22–43
- Rao KN, Raghavendra VK (1971) Time series analysis of 158 years rainfall of Madras (India) (period 1813–1970). Pre-published scientific report no.163. Meteorological Office, Poona, India
- Reyner NA, Horton EB, Parker DE, Folland CK, Hackett RB (1996) Version 2.2 of the global sea ice and surface temperature data set, 1903–1994. Climate Research technical note 74. Hadley Center for Climate Prediction and Research: Meteorological Office, Bracknell
- Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian ocean. *Nature* 401:360–363
- Singh N, Sontakke NA (1996) The instrumental period rainfall series of the Indian region. A documentation research report no. RR-067. Indian Institute of Tropical Meteorology: Pune. pp 79.
- Singh N, Sontakke NA (1999) On the variability and prediction of post-monsoon season rainfall over India. *Int J Climatol* 19:309–339
- Sridharan S, Muthuswamy A (1990) Northeast monsoon rainfall in relation to El Niño, QBO and Atlantic hurricane frequency. *Vayu Mandal* 20:108–111
- Sulochana G, Rajeevan M, Francis PA (2007) Monsoon variability: links to major oscillations over the equatorial Pacific and Indian Oceans. *Curr Sci* 93:2