large negative (positive). However, over the north Bay of Bengal, positive (negative) anomalies are observed during the active (weak) spell days.

Fig. 6.11 shows the similar composite plots, but for the OLR anomalies. The results are consistent with the rainfall anomaly plots. During the active (weak) spell days, OLR anomalies are large negative (positive) over the Indian sub-continent suggesting enhanced (suppressed) rainfall activity. The drastic difference between these two cases is observd over the west Pacific Ocean and China and adjoining area. During the active (weak) phase of the monsoon, convection over the west pacific is suppressed (enmhanced). The enhanced convection over the west Pacific could cause anomalous descending motion over the Indian region and thus reduce the NE monsoon activity.

Fig. 6.12 shows the 850 hPa wind anomalies during the active and weak spells of NE monsoon. The most striking feature of the wind anomalies is observed over the Indian region. The active (weak) phase of the NE monsoon is associated with cyclonic (anti-cyclonic) circulation anomalies over the Indian region, which is consistent with the observed rainfall anomalies. The other significant anomalies are observed over the west Pacific and adjoining eastern parts of China. During the active (weak) phase, an anomalous anticyclonic (cyclonic) circulation is observed over the region, suggesting below (above) normal convection over the region. This is consistent with the OLR anomalies discussed above.

6.3. **Interannual variation of NE monsoon rainfall (NEMR)**

In this section, the inter-annual variability of NE monsoon rainfall is discussed. There are not adequate studies examining the inter-annual variability of NE monsoon rainfall except the studies by De and Mukhopadhyay, 1999; Kripalani and Kumar, 2004; Raj and Geetha, 2008; Zubair and Ropelewski, 2006; Kumar et al., 2007; Sreekala et al., 2012, Rajeevan et al., 2012.

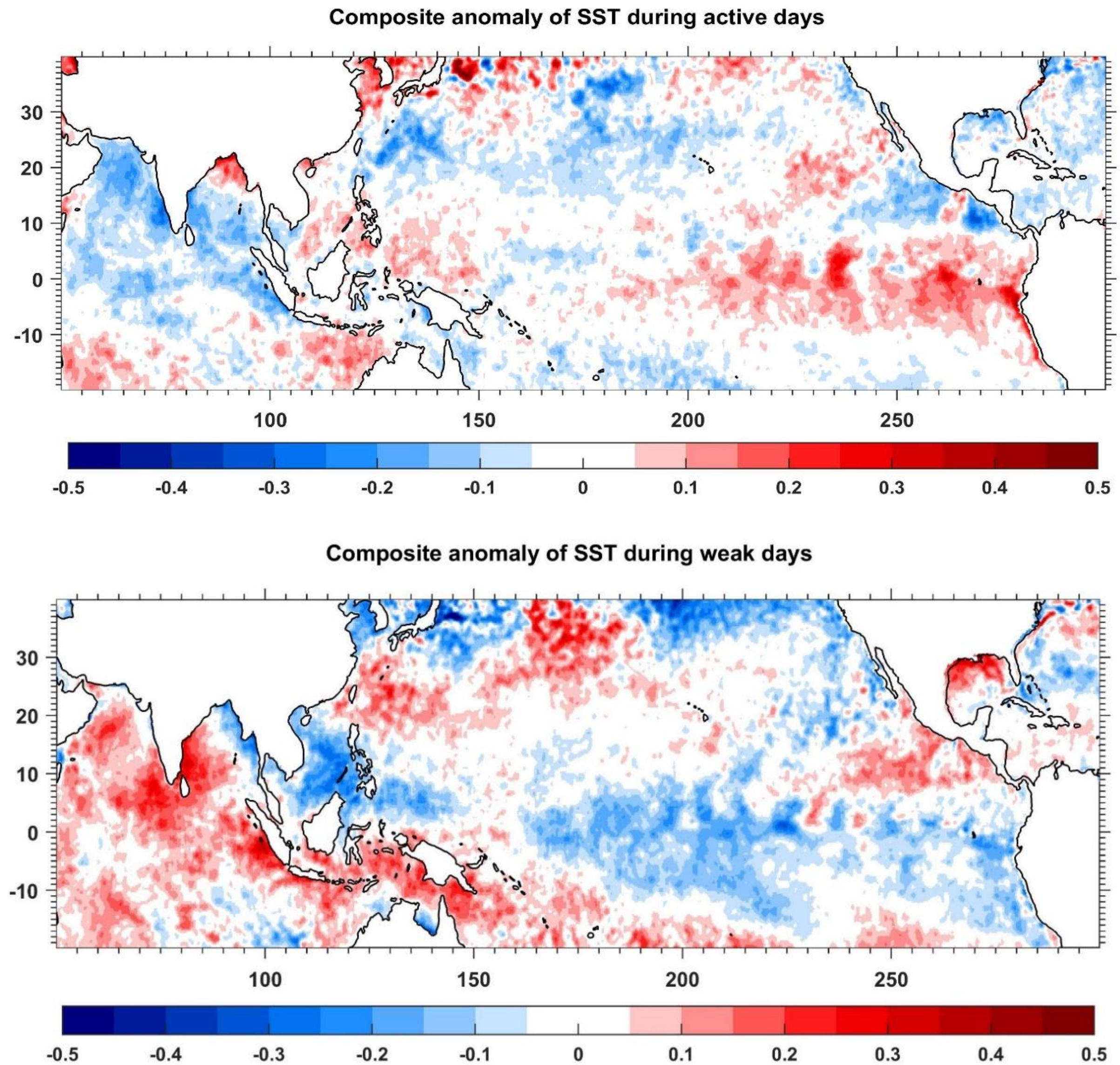
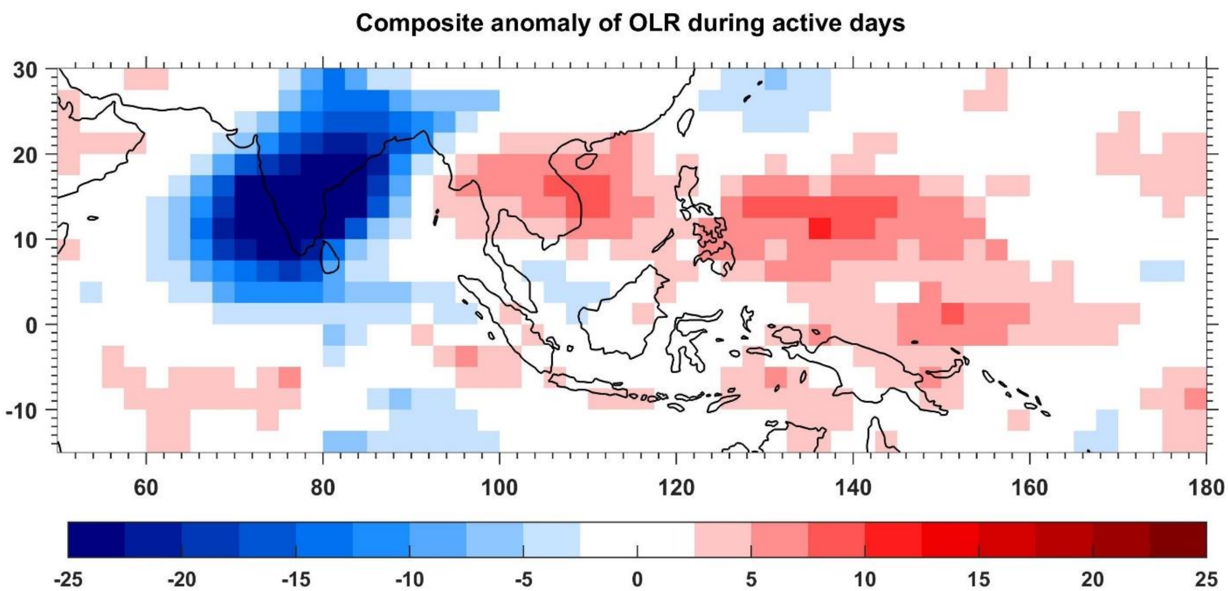


Fig. 6.10. Composite Sea Surface Temperature (SST) (°C) anomalies during the active spell days (above) and weak spell days (below) for the period 1981-2021.



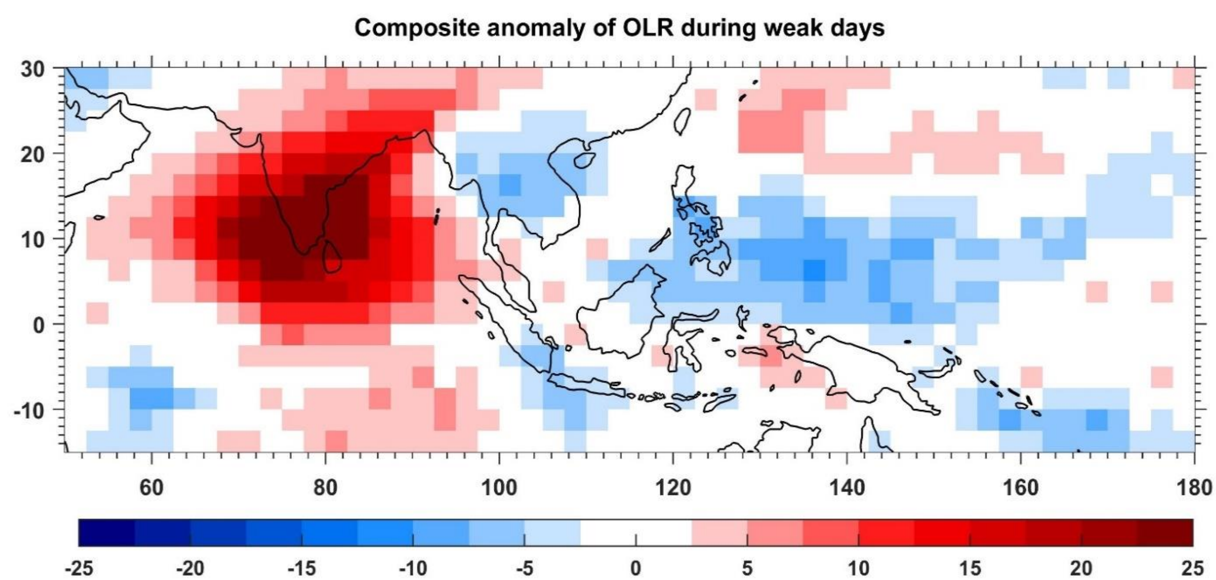


Fig. 6.11. Composite OLR anomalies (Wm^{-2}) during the active spell days (above) and weak spell days (below) during the period 1981-2021.

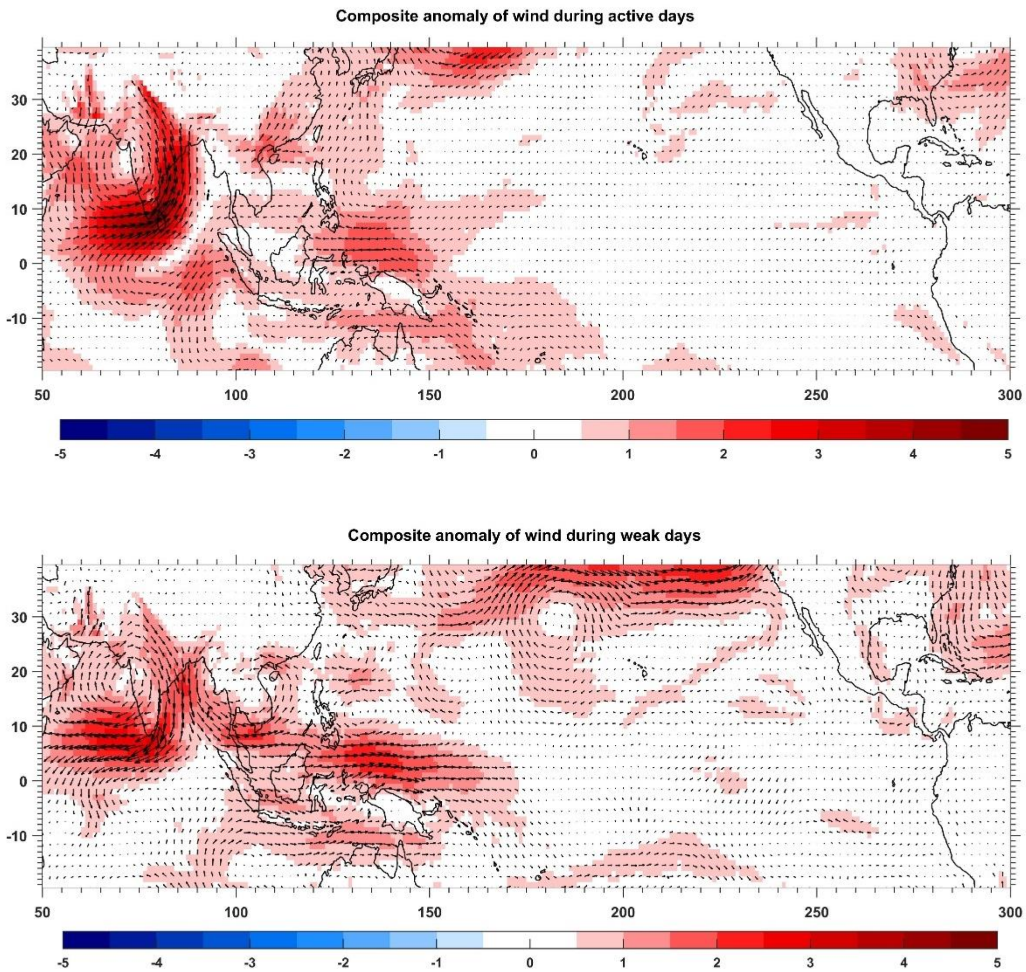


Fig. 6.12. Composite OLR anomalies (Wm^{-2}) during the active spell days (above) and weak spell days (below) during the period 1981-2021.

The inter-annual variability of the NEMR is calculated using the sub-divisional rainfall data for the period 1901–2021. During the northeast monsoon season, south peninsular India receives a mean rainfall of 338.4 mm with a coefficient of variation of about 25%. It may be noted that the coefficient of variation during the NE monsoon season is much more than that of SW monsoon rainfall (June to September) for the whole country which is around 10%.

Fig. 6.13 a shows the interannual variation of the NEMR as expressed as percent departure of the seasonal rainfall. No long-term trend in the NEMR is noticed, but there are years with large rainfall departures, even exceeding 40%. The years with more (less) than 1 Standard Deviation (25%) are termed as excess (deficient) years. If the departure is more than -25% but less than 25%, then those years are termed as normal years. Out of 121 years (1901-2021), there were 78 normal years, 23 excess years and 20 deficient years. Among these years, the 2021 monsoon season has the highest positive departure (73%). The year 2016 was the worst deficient year with a deficiency of 65%. The other two notable excess years are 2010 and 2015. The other two notable deficient years are 1938 and 1988. Recently, three consecutive years 2016-2018 experienced below normal rainfall with large negative rainfall departures. However, the subsequent three years witnessed above normal monsoon rainfall with positive departures. Fig. 6.13 b shows the 21-year moving average of the NEMR during the period 1901–2021. It clearly shows the multi-decadal variations of the NEMR with epochs of above normal and below normal rainfall. An increasing trend in the NEMR during the recent years is observed.

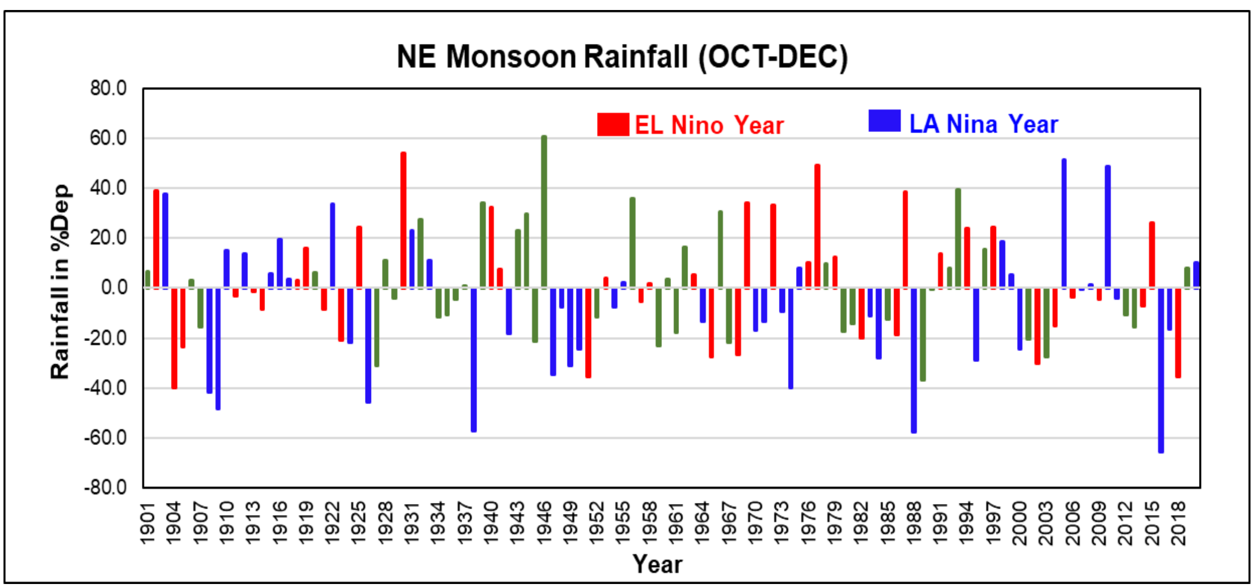


Fig. 6.13 a. Time series of NE monsoon seasonal rainfall as % Departure from 1901-2020. El Nino year is shown as red and La Nina year is shown as blue lines.

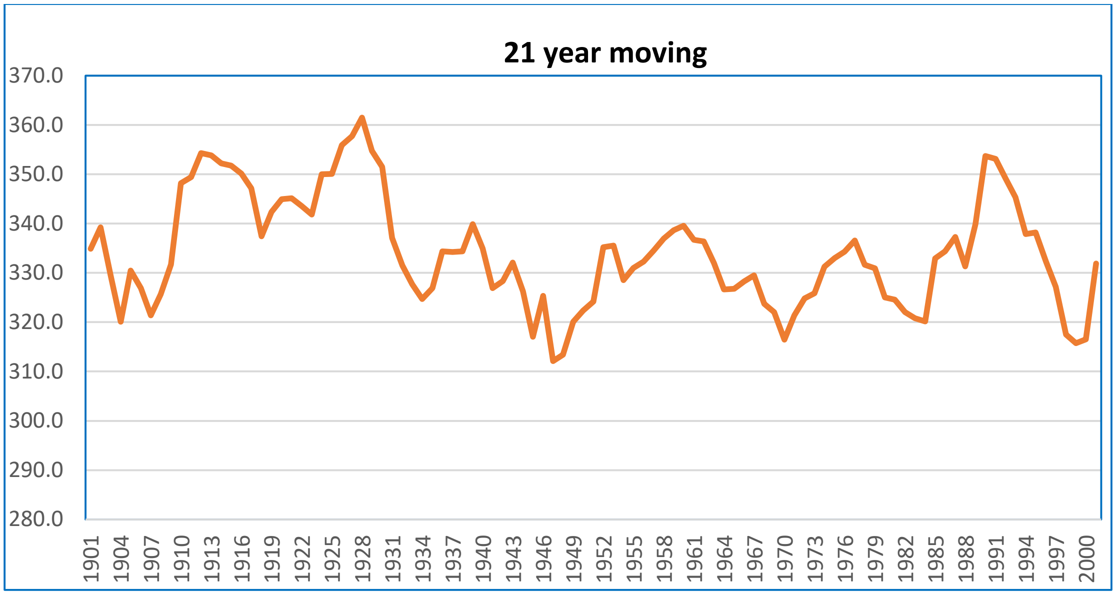


Fig. 6.13 b. The 21 year moving mean of NE monsoon seasonal rainfall (Oct-Dec) in mm, showing multi-decadal variations of NE monsoon rainfall.

Fig. 6.14 a shows the periodogram of NE Monsoon seasonal rainfall for the period 1901-2021. Even though many periodicities of shorter duration are seen, the periodicity of about 16 years is close to the significant (90% significance) level. Fig. 6.14 b shows the wavelet spectrum of NE monsoon seasonal rainfall for the same period 1901-2021. It clearly shows the periodicity of about 16 years, which is statistically significant. This periodicity, however, was not uniformly active during the whole period. It was active till about 1950. Then, it became active from 1980s till date. Raj (2012) also suggested the periodicity of similar periods for NE monsoon rainfall. This periodicity is also apparent in the 21-year running mean shown in Fig. 6.13 b. The periodicity of 2-3 years (quasi biennial) is observed during 1920s to 1970s. Kripalani and Kumar (2004) also suggested the NE monsoon rainfall undergoes different epochs of above and below normal rainfall. These epochs last about a decade or two. More studies are required to understand the decadal variations of NE monsoon rainfall using long term data.

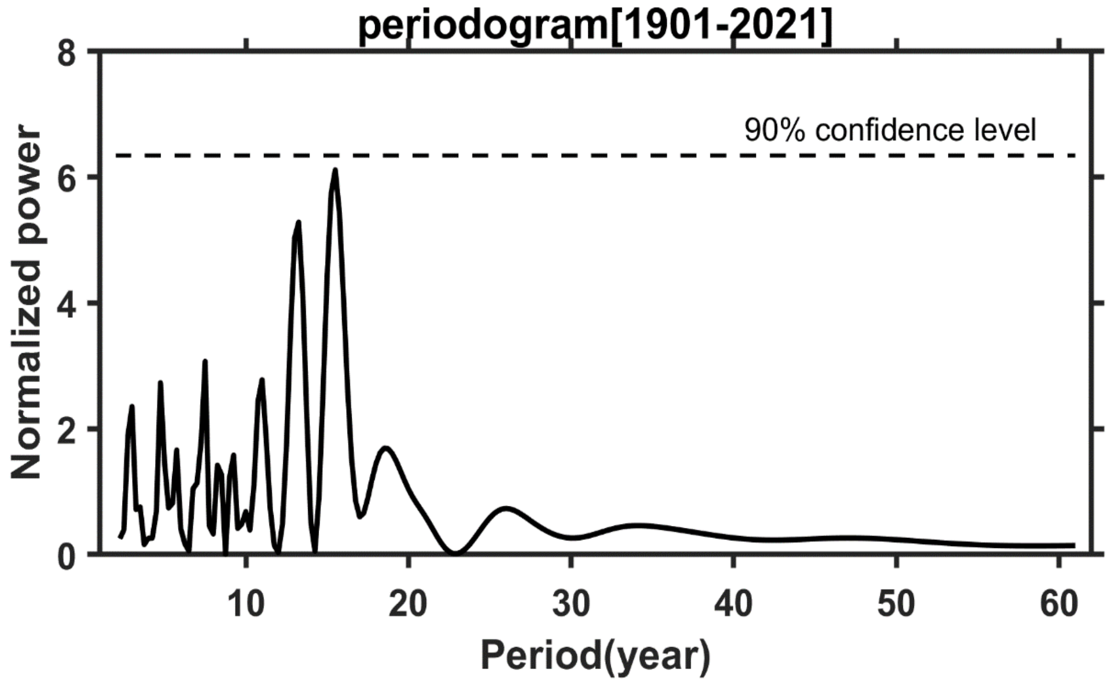


Fig. 6.14 a. Periodogram of NE Monsoon seasonal rainfall (1901-2021). The peak around 16 years is close to significance level at 90%.

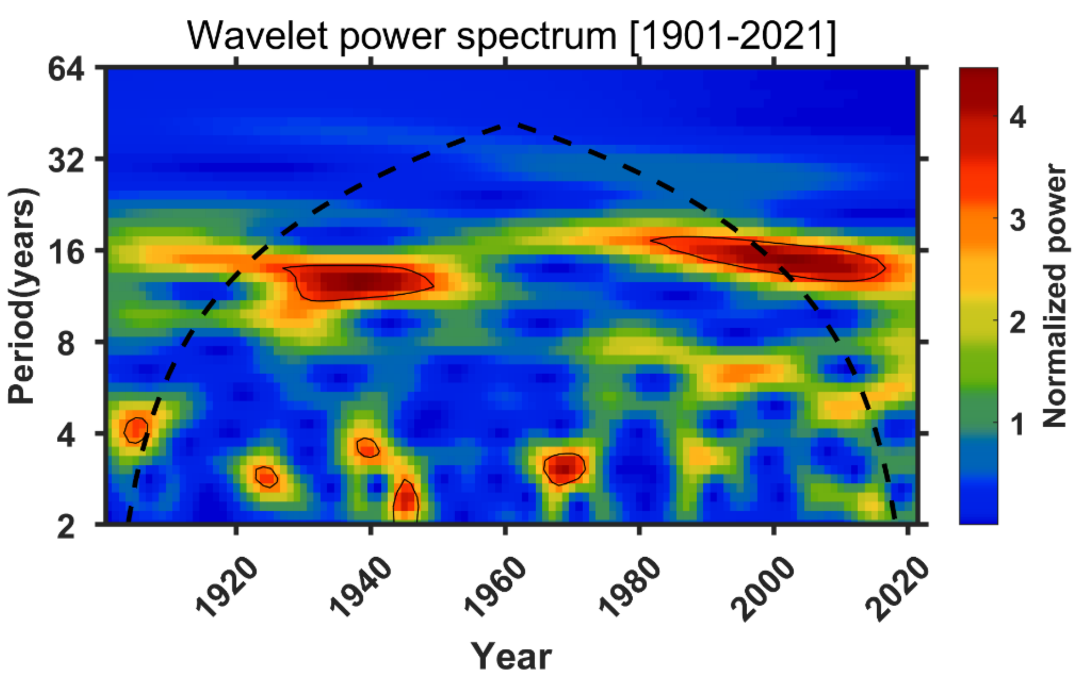


Fig. 6.14 b. Wavelet power spectrum (1901-2021) of NE monsoon seasonal rainfall. The periodicity close to 16 years is statistically significant.

The inter-annual variability of the NEMR is linked to the El Nino/Southern Oscillation (ENSO), the Indian Ocean Dipole and the EQUINOO (De and Mukhopadhyay, 1999; Kripalani and Kumar, 2004; Raj and Geetha, 2008; Jayanthi and Govindachari 1999; Zubair and Ropelewski, 2006; Kumar et al. 2007; Sreekala et al. 2012, Rajeevan et al. 2012). ENSO is an irregular periodic variation in Sea surface temperatures and winds over the equatorial Pacific Ocean. ENSO influences the climate of much of the tropics and subtropics. ENSO is a coupled process in which the equatorial Pacific and atmosphere interact. The warming phase of the sea surface temperature is known as El Nino and the cooling phase as La Nina. The Southern Oscillation is the accompanying atmospheric component, coupled with the changes in SST.

The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature between two areas – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia. The IOD affects the climate of Australia and other countries surrounding the Indian Ocean Basin, and is a significant contributor to rainfall variability in this region. Positive Dipole events are characterized by positive (negative) SST anomalies over the west (east) equatorial Indian Ocean. Conversely, the negative phase is characterized by negative (positive) SST anomalies over the west (east) equatorial Indian Ocean.

Fig. 6.15 a shows the spatial pattern of correlations between Oct-Dec SST and NE monsoon rainfall during two 30-year periods, 1961-1990 and 1991-2020. The plot for the period 1961-1990 clearly shows that positive SST anomalies over the equatorial Pacific Ocean (El Nino) are associated with normal or above normal rainfall. However, during the recent 30-year period, the positive correlations over the equatorial Pacific have weakened. Another interesting area of strong correlation is over the North Atlantic. During the period 1961-1990, strong positive correlations are observed, which are replaced by weak negative correlations during the period 1991-2020.

Raj and Geetha (2008) analyzed the relationship between Southern Oscillation Index (SOI) and NE monsoon rainfall in antecedent and concurrent mode and found there is a negative relationship. The relationship in antecedent mode is stronger. Sengupta and Nigam (2019) studied the aspects of ENSO impact on NE monsoon rainfall. Their study suggested stronger NE monsoon rainfall over south peninsula and Sri Lanka during El Nino events. The impact varies sub-seasonally, being weak in October and strong in November. The positive anomalies over the south peninsula are generated by anomalous anticyclonic flow centered over the Bay of Bengal, which is forced by an El Nino-related reduction in deep convection over the Maritime continent.

In fact, the correlation between NE monsoon rainfall and Nino 3.4 changes its sign by middle of October. Till middle of October, the correlation is negative and it changes to positive correlation by November. Fig. 6.15 b clearly suggests this shift in the sign of correlation between Nino 3.4 and NE monsoon rainfall by October end.

However, the relationship between NE monsoon and ENSO is not very stable. It was weakened during the recent epoch (1991-2020) (Fig. 6.15 c). Another interesting aspect to be noticed is the positive correlation of SSTs over the north Bay of Bengal with the NE monsoon rainfall, suggesting a warmer Bay of Bengal could be related to better performance of NE monsoon rainfall. It may be interesting to examine long term data to understand why the relationship between ENSO and NE Monsoon rainfall undergoes secular variations.

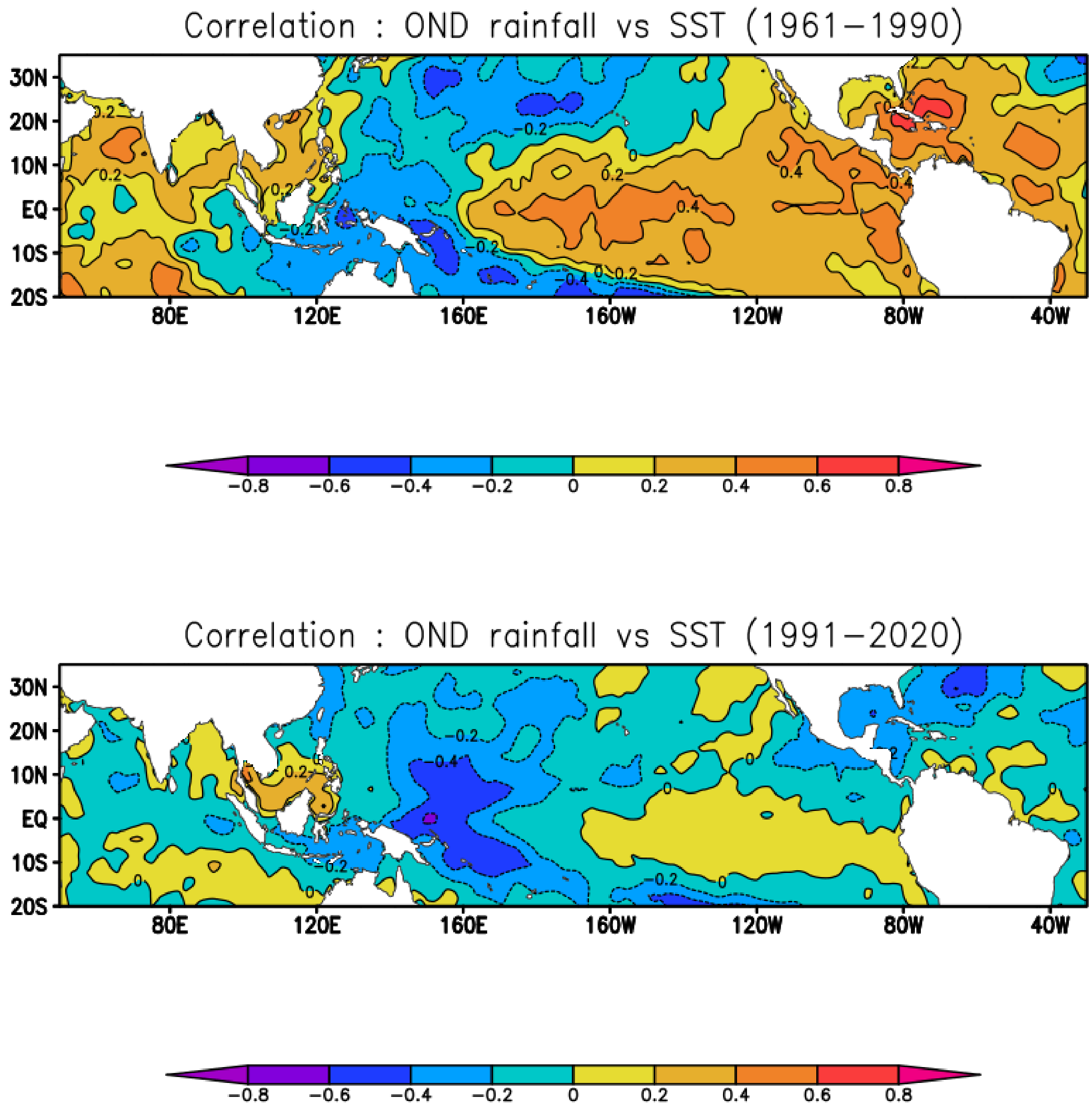


Fig. 6.15 a. Spatial Pattern pf correlation between Sea Surface Temperature (SST) and NE Monsoon seasonal rainfall during the period 1961-1990 (above) and 1991-2020 (below).

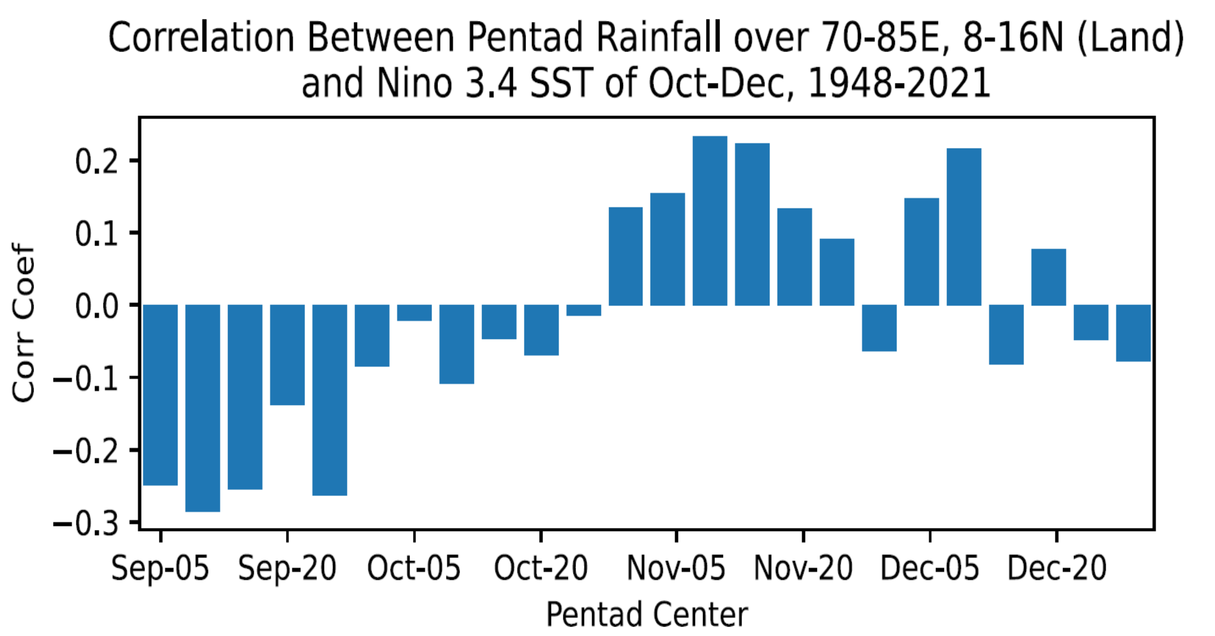


Fig. 6.15 b. Correlation between pentad rainfall averaged over south peninsula and Nino 3.4 SST index. The period 1948-2021 is considered for the analysis.

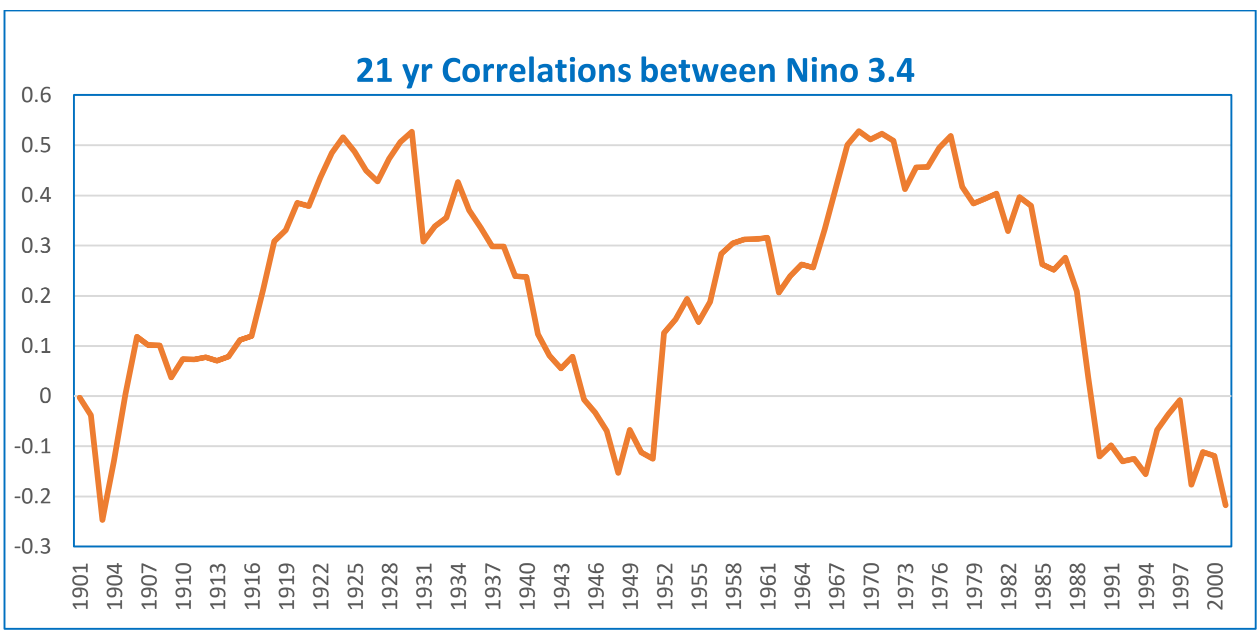


Fig. 6.15 c. The 21 year moving correlations between Nino 3.4 index during OND and NE Monsoon seasonal rainfall (OND) suggesting multi-decadal variation of relationship between NE monsoon rainfall and El Nino.

Table 6.2 below shows El Nino/La Nina's relationship with NE monsoon rainfall.

Table 6.2
Relationship between ENSO and NE Monsoon Rainfall
Period: 1940-2021

El Nino Years (39)			La Nina Year (42)		
Excess >25%	Normal -25% to 25%	Deficient < -25%	Excess >25%	Normal -25% to 25%	Deficient < -25%
11	22	6	6	23	13
28%	57%	15%	14%	55%	31%

The analysis shows that the probability of an El Nino year being an excess NEMR year is higher (28%) compared to the year being a deficient (15%) monsoon year. However, the probability of a La Nina year being an excess monsoon year (14%) is smaller compared to an excess (31%) monsoon year. Therefore, more confidence in excess or deficient monsoons may be obtained with the additional information on IOD. However, compared to the Southwest monsoon, the NE monsoon is not very strongly related to ENSO or IOD.

An analysis was carried out by Prasanna et al. (2019) of two successive La Niña years, referred to as the first and second year during the period 1900–2010 to see the impact on NE monsoon rainfall. Observations show that despite noticeable weakening in the equatorial Pacific cooling from the first year to the second year, strong La Niña teleconnections and the rainfall deficiency over the region remains the same in most of the multiyear-La Niña events (70%).

Even though, there is a high probability for NE monsoon to be on lower side of the normal during the La Nina years, there have been three major exceptions to be examined in detail. These years occurred recently, 2010 and 2021, when the ENSO-NE monsoon rainfall relationship was weaker. The NE monsoon rainfall percent departure during these three seasons was 49% and 73% respectively. The year 2021 was truly an exception.

Kripalani and Kumar (2004) documented the NEMR and IOD relationship. They suggested that the NEMR variability is enhanced during the decades when the IOD exhibits its active phase, and is suppressed during the decades when the IOD is inactive. This relationship suggests that the positive (negative) phase enhances (suppresses) the northeast monsoon activity. During the positive phase, the anomalous flow pattern shows winds converging and suggesting moisture transport from the southeast Indian Ocean and the Bay of Bengal towards south peninsular India. In contrast, the negative phase reveals winds diverging and transporting moisture away from the south Indian region. These results show the direct influence of the IOD phenomenon on the interannual NE monsoon rainfall variability over south India.

Balachandran et al. (2006) examined the local and teleconnective association between Northeast Monsoon Rainfall over Tamil Nadu and global surface temperature anomalies (STA) using the monthly gridded STA data for the period 1901–2004. It is observed that the meridional gradient in surface air temperature anomalies between Europe and north Africa, in the month of September is directed from the subtropics (higher latitudes) to higher latitudes (subtropics). It is also observed that North Atlantic Oscillation (NAO) during September influences the surface air temperature distribution over north Africa and Europe. Also, the NAO index in January shows significant inverse relationship with the NE monsoon rainfall since recent times. The central and eastern equatorial Pacific oceanic regions have significant and consistent positive correlation with NE monsoon rainfall while the western equatorial region has significant negative correlation with Northeast monsoon rainfall. A zonal temperature anomaly gradient index (ZTAGI) defined between eastern equatorial Pacific and western equatorial Pacific shows stable significant inverse relationship with Northeast monsoon rainfall.

The unusual excess year of the 2021 NE monsoon season is discussed below.

6.4. **The unusual NE monsoon during the year 2021**

During the year 2021, the southwest monsoon withdrew from the Indian region on 25th October. Simultaneously, the Northeast monsoon (NEM) of 2021 commenced over the southeastern parts of peninsular India on 25th October against the normal date of 20th October. Excepting Coastal Andhra Pradesh (CAP), which received normal rainfall during the season, the other four sub-divisions [Tamil Nadu (TN (including Puducherry & Karaikal), Kerala (KER), Rayalaseema (RYS) and South Interior Karnataka (SIK)] benefitted from the NE monsoon. These sub-divisions received excess to large excess rainfall during the NEM season (October-December) with KER, SIK, RYS recording more than 100% excess (large excess) rainfall. During the season, there were 30 days of active to vigorous monsoon conditions over Tamil Nadu and Kerala. There were 65 days of isolated heavy rainfall activity with 33 days of isolated very heavy rain, including 09 days of isolated extremely heavy rainfall activity over Tamil Nadu. Two Depressions formed over the North Indian Ocean during November contributed significantly to NEM rainfall over the peninsular India. Cyclonic Storm (CS) Jawad over the Bay of Bengal (BOB) during 02-06 December tracked northwards towards West Bengal- Bangladesh coasts and did not contribute towards NEM seasonal rainfall. However, two days of extremely heavy rainfall occurred over Chennai (i) 06th November night & (ii) 30th December 2021. Recurrent heavy rainfall over the coastal and adjoining districts from the last week of October to November led to the filling up of water bodies, and inland and riverine flooding occurred over several areas of Tamil Nadu and Rayalaseema. As a result, NE monsoon 2021 was extended into January 2022 and cessation of NEM 2021 rainfall over peninsular India was declared on 22nd January 2022 (Geetha et al., 2022). A more detailed report on 2021 NE monsoon is available for reference (Geetha et al., 2022).

The Table 6.3 presents the frequency of active and vigorous monsoon days and heavy rainfall days during the 2021 NE monsoon season (after Geetha et al., 2022).