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The variability of Indian Ocean surface meteorological fields during summer monsoon in EL Nino/La Nina years

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In the present study, the possible linkages between Indian summer monsoon rainfall and surface meteorological fields (basic fields and heat budget components) were investigated during El Nino years and La Nina years. For this purpose, monthly surface meteorological fields in pre-monsoon month of May and summer monsoon season (June to September) were analyzed using reanalysis data of NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research). The statistical significance of the anomaly (difference) between the El Nino years and La Nina years in the surface meteorological fields was also examined. The significant negative precipitation anomalies over Indian landmass show that monsoon activity increases considerably during La Nina years. Significant positive anomalies of mean sea level pressure are observed over India during, Arabian Sea and Arabia in pre-monsoon month of May and monsoon season during El Nino years. Weaker westerlies develop in the west Arabian Sea in the month of may during El Nino years. The stronger southerlies in the monsoon months of La Nina years indicate higher northward transport of moisture. In the month of May, significant negative anomalies of cloud amount are observed over Somali coast, north Bay of Bengal and adjoining West Bengal and Bangladesh. During monsoon season, cloud amount shows negative anomalies over northwest India and Arabian Sea. There is overall reduction in the incoming shortwave radiation flux over northwest India, Arabia and north Arabian Sea during La Nina years. A significant higher magnitude of latent heat flux was also found over northwest India, central India and south Indian Ocean during La Nina years during monsoon season. The distribution of net heat flux is predominantly positive over northwest India and adjoining region, south Indian Ocean during monsoon season.

[Key words: Surface meteorological fields, monsoon, El Nino, La Nina, ENSO, Precipitation, Pressure, cloud cover, SST, wind, temperature, radiation flux, heat flux]

1 Introduction

The Indian summer monsoon (June to September) contributes 80% of the annual rainfall of the country. The Indian summer monsoon rainfall shows large annual variability. It is well known that the tropical seas/ocean act as main reservoir of heat and moisture. It provides the necessary energy to drive the large-scale summer monsoon circulation and the associated rainfall over Indian sub-continent. Therefore, it is important to understand the air-sea interaction processes over the tropical ocean and its association with Indian summer monsoon activity. The experiments such as Indian Ocean Experiment (IIOE 1964-1965), Indo Soviet Monsoon Experiment (ISMEX 1973), MONSOON-77 (1977) and Monsoon Experiment (MONEX 1979) were organized to examine the role of the ocean in the variability of Indian summer monsoon. In recent years, Indian Ocean Experiment (INDOEX, 1998-1999), Bay of Bengal Monsoon Experiment (BOBMEX 1999) and Arabian Sea Monsoon Experiment (ARMEX 2002-2003) were also organized to study the dynamics of atmosphere-ocean interaction.

Studies by many workers over the past decade or so have shown that interannual variation in rainfall over many parts of the world and ENSO (El Nino Southern Oscillation) events (warm events) in the tropics are generally related. For example droughts in Australia, Indonesia, India and parts of Africa and heavy rain and floods in the Pacific Coast of South America[1, 2] were some of the specific related events. During an anti ENSO or the cold event the pattern of climatic anomalies is broadly the reverse of that experienced during an ENSO event[3-6]. As already mentioned, there are several studies relating to Indian monsoon rainfall and ENSO/anti ENSO events[7-10].

Although most studies suggest some link between ENSO (anti ENSO) events and deficient (excess) summer monsoon rainfall over India, the relationship is far from universal. Moreover, different authors selected the ENSO/anti ENSO events based on a number of factors e.g. sea surface temperature (SST) anomaly over eastern equatorial Pacific Ocean[11, 12], southern oscillation index[13] and several other atmospheric and oceanographic parameters like disruption of fishery and marine bird life off the coasts of Peru and Ecuador. In view of this ambiguity in the definition of ENSO/anti ENSO years, disagreement prevails among scientists about the listing of the above years. Moreover, ENSO/anti ENSO events sometimes continue for two years. The importance of the energy fluxes on summer monsoon activity over India during different epochs of the summer monsoon was also studied[14-19].

The aim of the present study is to examine the linkage of surface meteorological fields (basic fields and heat budget components) with summer monsoon activity over India during El Nino and La Nina years for a recent period of 40 years (1958-1990) using NCEP/NCAR reanalysis data set.

2. Data and Analysis

One of the reliable and homogenous global data set recently available from NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research, USA) reanalysis data set has been used in the present study. This data set is a result of the joint efforts of the NCEP, formerly known as NMC (National Meteorological Center) and the NCAR, to produce a 40 years (1958-1997) record of global analysis of the atmospheric fields. The effort involves the recovery of land surface, ship, rawinsonde, aircraft, satellite data and delayed mode GTS data, its quality control and assimilation with four dimensioned data assimilation system that is kept unchanged over the entire period[20].

ENSO events are categorized to one of three phases of ENSO: El Nino (warm SST anomalies in the Pacific), La Nina (cool SST anomalies) and neutral based on an index derived from observed SST anomalies. The El Nino and La Nina events chosen in the present study are from the Japan Meteorological Agency (JMA). The index is a 5-month running mean of spatially averaged SST anomalies over the tropical Pacific: 4°S-4°N, 150°W-90°W. If index values are 0.5°C or greater for 6 consecutive months (including October, November, December), the ENSO year of October through the following September is categorized as El Niño, La Nina (index values equal or exceed -0.5°C) or neutral (all other values) (Table 1). Thus, in the 40 years period (1958-1997), there have been 8 El Nino years, 10 La Nina years and the remaining as normal.

The domain examined in the present study extends from 30°S to 30°N and 30°E to 120°E (Fig. 1), which consists of the major oceanic and land regions under the influence of monsoon regime. The daily average of surface meteorological fields i.e basic fields (mean sea level pressure, zonal and meridional wind, surface and air temperature, cloud amount, outgoing longwave radiation flux) and heat budget components (shortwave radiation flux, longwave radiation flux, sensible heat flux, latent heat flux, net heat flux) for El Nino years and La Nina years were computed for the month of May as well as the following monsoon season. The composite of anomalies (difference) of

Table 1 — El Nino and La Nina years for the period 1958-1997

EL Nino Years	La Nina Years
1963	1964
1965	1967
1969	1970
1972	1971
1976	1973
1982	1975
1986	1988
1987	1998
1991	
1997	

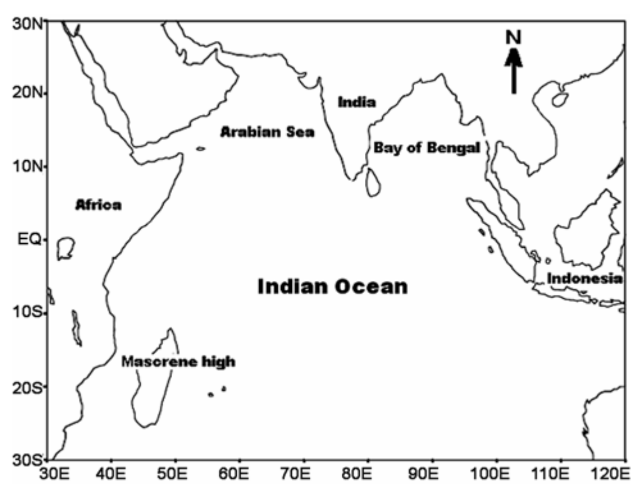

Fig. 1—Map showing the important regions of study.

surface meteorological fields between the two categories of the monsoon (El Nino and La Nina years) have been tested for their significance using Students' *t*-test. The anomalies with 95% level of confidence are shaded in all anomalies results.

To compute the net balance of the radiative and turbulent fluxes of heat and moisture at the air-sea interface, the net heat budget equation (Wm^{-2}) can be written as

$$Q_N=Q_R-Q_B-Q_H-Q_E$$

where Q_N is the net heat flux (Wm^{-2}), Q_R is the incoming shortwave radiation flux (Wm^{-2}), Q_B is the effective outgoing longwave radiation flux (Wm^{-2}), Q_H is the sensible heat flux (Wm^{-2}), and Q_E is the latent heat flux (Wm^{-2}). In this quation, Q_R contributes significantly to the oceanic heat gain whereas the other terms contribute towards the heat loss from tropical oceanic surfaces. In the present study, daily values of Q_R, Q_B, Q_H and Q_E at 00, 06, 12, 18 UTC (Universal Time Coordinate) for each grid point are directly taken from the NCEP/NCAR reanalysis and averages computed for each month and season.

3. Results and Discussion

In order to investigate the influence of ENSO on Indian summer monsoon, the anomalies of surface meteorological fields were examined for the pre-monsoon month of May as well as summer monsoon season (June-September). The effective longwave radiation flux and sensible heat flux showed no significant variations in the month of May as well as in the following monsoon season for El Nino and La Nina years. Therefore, the variations of longwave radiation flux and sensible heat flux in the present study have not been discussed. The anomalies in respect of other fields were discussed below.

3.1 Variation of the surface meteorological fields

Figure 2 A, D show the distribution of precipitation rate (mm day^{-1}) anomalies with *t*-test of significance at 95% confidence level (shaded region) for the month of May and summer monsoon season (June-September) respectively. Significant negative anomalies were observed over southwest Arabian Sea, northeast Bay of Bengal and its adjoining northeastern states of India and parts of south equatorial Indian Ocean indicating higher premonsoon activity during La Nina years (Fig. 2A). Significant positive anomalies were observed over western Indonesian region. However, during monsoon months June-September (JJAS) the significant negative anomalies covers most of the Indian landmass except northeastern states indicating decreased monsoon activity during El Nino years (Fig. 2D). Negative anomalies were also noticed over eastern Indonesia and Malaysia.

The distribution of mean sea level pressure anomalies shows significantly higher pressure of 1 hPa to 2 hPa covering India, Arabian Sea, parts of Arabia and part of southeast equatorial Indian Ocean (Fig. 2D) during El Nino years as compared to La Nina years. In the monsoon months significant positive anomalies of 0.8 to 1.6 hPa were observed over most of the domain of southwest monsoon (Fig. 2E). Thus, the mean sea level pressure in El Nino years is significantly higher in the pre-monsoon month of May as well as the monsoon season by 1 hPa to 2 hPa as compared to La Nina years. The maximum rise was noticed over north Arabian Sea and the usual region of monsoon heat low. The pressure change in Mascrene region is not significant. Thus, during El Nino years the pressure gradient between monsoon low and the Mascrene's high pressure during southwest monsoon months will be less as compared to La Nina years resulting in less vigorous cross equatorial flow and relatively weaker wind field close to the surface.

The distribution of total cloud cover (Fig. 2C, F) shows significant negative anomaly of cloud amount during May in the western Arabian Sea off Somali coast, north Bay of Bengal adjoining parts of West Bengal, Bangladesh and part of the southern Indian Ocean (Fig. 2C). In the monsoon months significant negative anomalies were observed along the belt extending from southwest equatorial Indian Ocean across Somalia, Kenya, Arabian Peninsula, Arabian Sea to most parts of Indian landmass west of 85^{o}E (Fig. 2F). The negative anomalies during southwest monsoon season indicates less vertical upward motion and lower availability of moisture that results in lower cloud amount during El Nino years. In other words, southeast trade winds in the southern hemisphere are stronger in the La Nina years and higher cross equatorial flow results in higher cloudiness north of equator and west of 85^{o}E. Indonesia and Malaysia and southeast equatorial Indian Ocean also show less cloudiness during El Nino years. Significant lower precipitation rate and cloudiness in the southwest equatorial Indian Ocean, significant higher pressure over the Indian landmass particularly over the monsoon heat-low region in the month of May of El Nino years indicate less than normal precipitation over the Indian region west of 85^{o}E and eastern

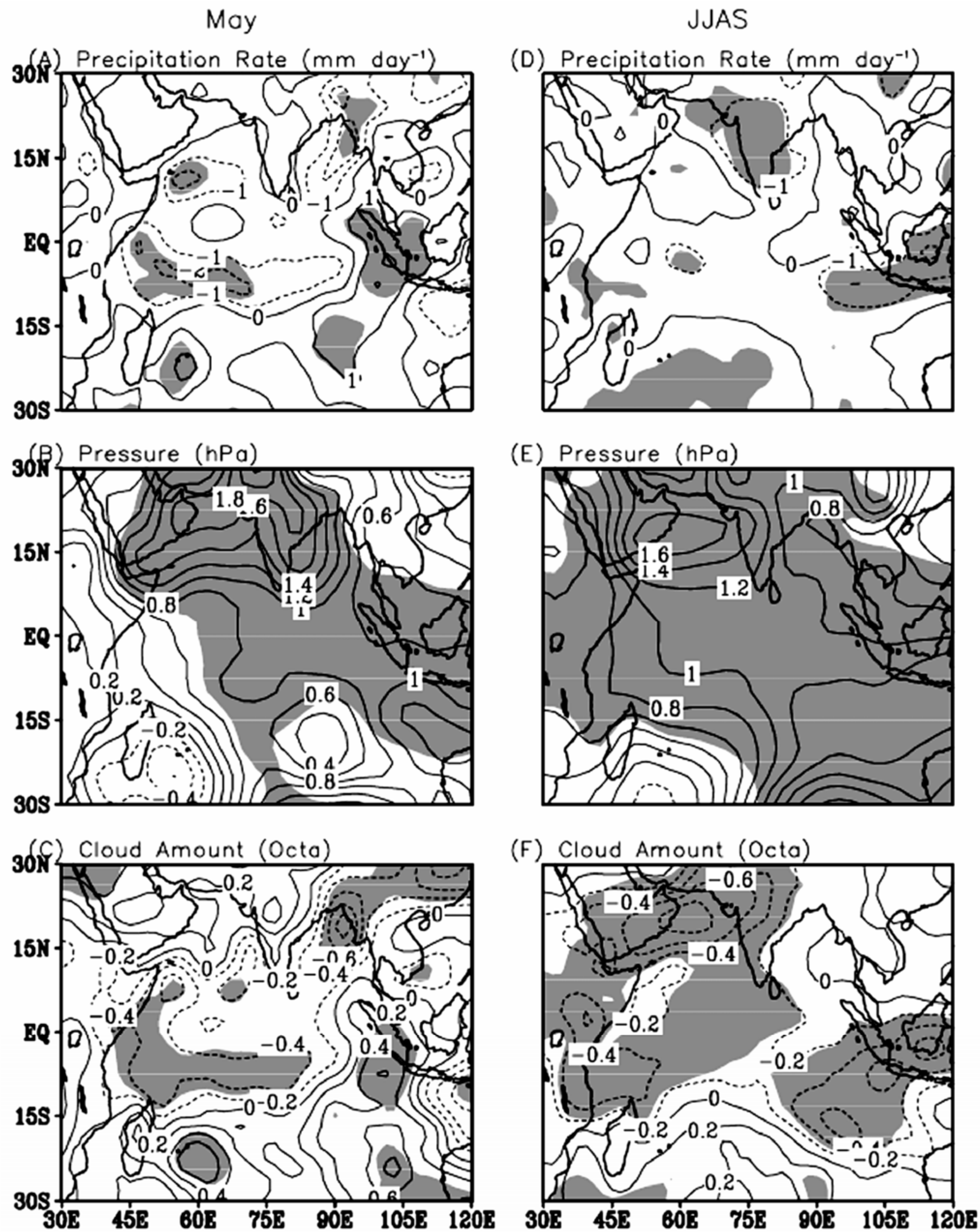

Fig. 2—Distributions of anomaly of (A) precipitation rate (mm day^{-1}) (B) mean sea level pressure (hPa) (C) total cloud cover (Octa) during May and D, E and F are same as A, B and C but for monsoon season (JJAS) with confidence limit above 95% (shaded).

Indonesia and Malaysia in the following monsoon season.

The zonal wind (m s^{-1}) anomaly distribution for the month of May and monsoon season along with *t*-test of significance are shown in the Fig. 3A, D respectively. During May, the zonal wind anomalies off Somali coast and southwest Arabian Sea are negative and significant (Fig. 3A). It indicates that weaker westerlies develop at the west Arabian Sea during May during El Nino years. Significant positive anomalies of 0.6 to 1.2 ms^{-1} were observed over northeast Bay of Bengal and parts of south Indian Ocean (Fig. 3A). Positive anomalies over northeast Bay of Bengal indicate late establishment of monsoon trough line in May. Negative anomalies in May were also noticed over eastern Indonesia and Malaysia. During monsoon season, significant negative anomalies 0.2 to 1 ms^{-1} extend from Somali coast to west coast of India associated with stronger Somali jet during La Nina years. Significant positive anomalies are also observed over southwest Indian Ocean and Indo-Gangetic plain (Fig. 3D). The positive anomalies over Indian Ocean are due to stronger southeast trade winds in monsoon months in the La Nina years. Similarly, persistence of positive anomalies over the Indo-Gangetic plain in monsoon season indicates the greater strength and persitence of monsoon trough line in the La Nina years.

The month of May showed significant negative anomaly of Meridional wind between 0.6 to 1.5 ms^{-1} extending from Madagascar Island and proceeding along the Somali coast. Significant negative anomalies of 0.6 to 1.5 ms^{-1} were also observed in the Bay of Bengal extending from Srilanka to northeast Bay (Fig. 3B). Significant southerlies at surface during May indicate prevalence of northward transport, which in the present case could also mean higher moisture transport in May during La Nina years. In the monsoon months the significant southerly anomalies were observed over southwest Indian Ocean adjoining Madagascar, north Arabian Sea and central India (Fig. 3E). The stronger southerlies in monsoon months of La Nina years indicate higher northward transport of air in the Arabian Sea from equatorial southwest Indian Ocean. In southeast Indian Ocean and adjoining Indonesia and Malaysia, there is significant less northward transport during La Nina years. Thus, whatever we observed in southwest Indian Ocean and Arabian Sea in May was maintained during monsoon months. But in the Bay of Bengal, southerlies in the month of May are replaced by northerlies in monsoon months.

The precipitable water content (kg m^{-2}) anomaly distribution showed significant negative anomalies was observed over northeast Bay, northeastern states of India, southeast China, south equatorial Indian Ocean and western Arabian Sea off Somali Coast in the month of May (Fig. 3C). However, during monsoon season the significant negative anomalies of 2 to 5 kg m^{-2} are found over Arabian Sea and most of the Indian landmass (Fig. 3F). Significant negative anomalies of 2 to 3 kg m^{-2} were also noticed over equatorial southeast Indian Ocean indicating higher precipitable water content during La Nina years. The reduction in the total precipitable water content during the El Nino years could be due to less transport as was indicated by meridional wind and lower magnitude of flux convergence of moisture.

In the month of May warmer temperature was observed over complete northwest India (Fig. 4A). The negative anomaly of surface temperature over major western part of India and extending westwards up to Arabian Peninsula is due to lower surface temperatures during El Nino years. This could possibly be due to prolonged winter or incursion of colder air from northern latitudes due to the passage of eastward moving western disturbances or troughs in the westerlies. The northeastern Indian region shows cooler temperature during La Nina years. The negative anomaly over northwest India is due to excess heating and the positive anomaly over northeast India is due to excess clouding and possibly precipitation due to pre-monsoon thunderstorm activity over the region during La Nina years. In the monsoon season significant positive anomalies were observed over the complete Indo-Gangetic plain indicating less insolation possibly due to lower clouding and precipitation in El Nino years (Fig. 4D). Distribution of air temperature for the month of May and monsoon season shows similar pattern as in surface temperature (Fig. 4B, E).

The difference of outgoing long wave radiation (OLR) between composite of El Nino and La Nina years shows positive OLR over equatorial Indian Ocean with maximum in western sector along Somali Coast, northeast Bay of Bengal and adjoining parts of West Bengal, Bangladesh during the month of May (Fig. 4C). These regions are statistically significant at 95% confidence level. It indicates that these regions observed low OLR values during La Nina monsoon years. Further, the zones of low OLR values are in good agreement with region of excess cloudiness (Fig. 2C). In the monsoon month’s significant positive anomalies were observed extending from south Indian

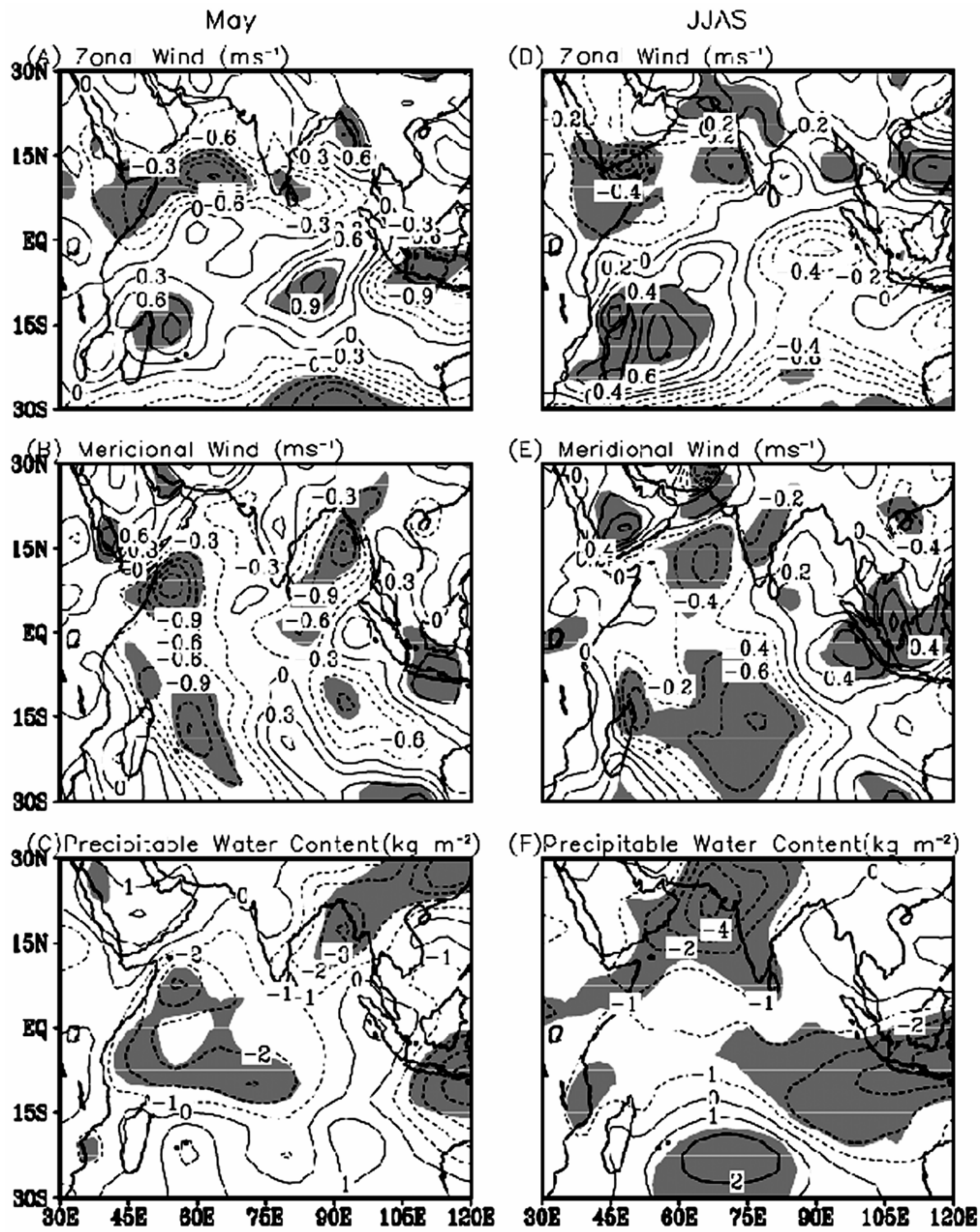

Fig. 3—Distributions of anomaly of (A) zonal wind (ms^{-1}) (B) meridional wind (ms^{-1}) (C) precipitable water content ($kg\ m^{-2}$) during May and D, E and F are same as A, B and C but for monsoon season (JJAS) with confidence limit above 95% (shaded).

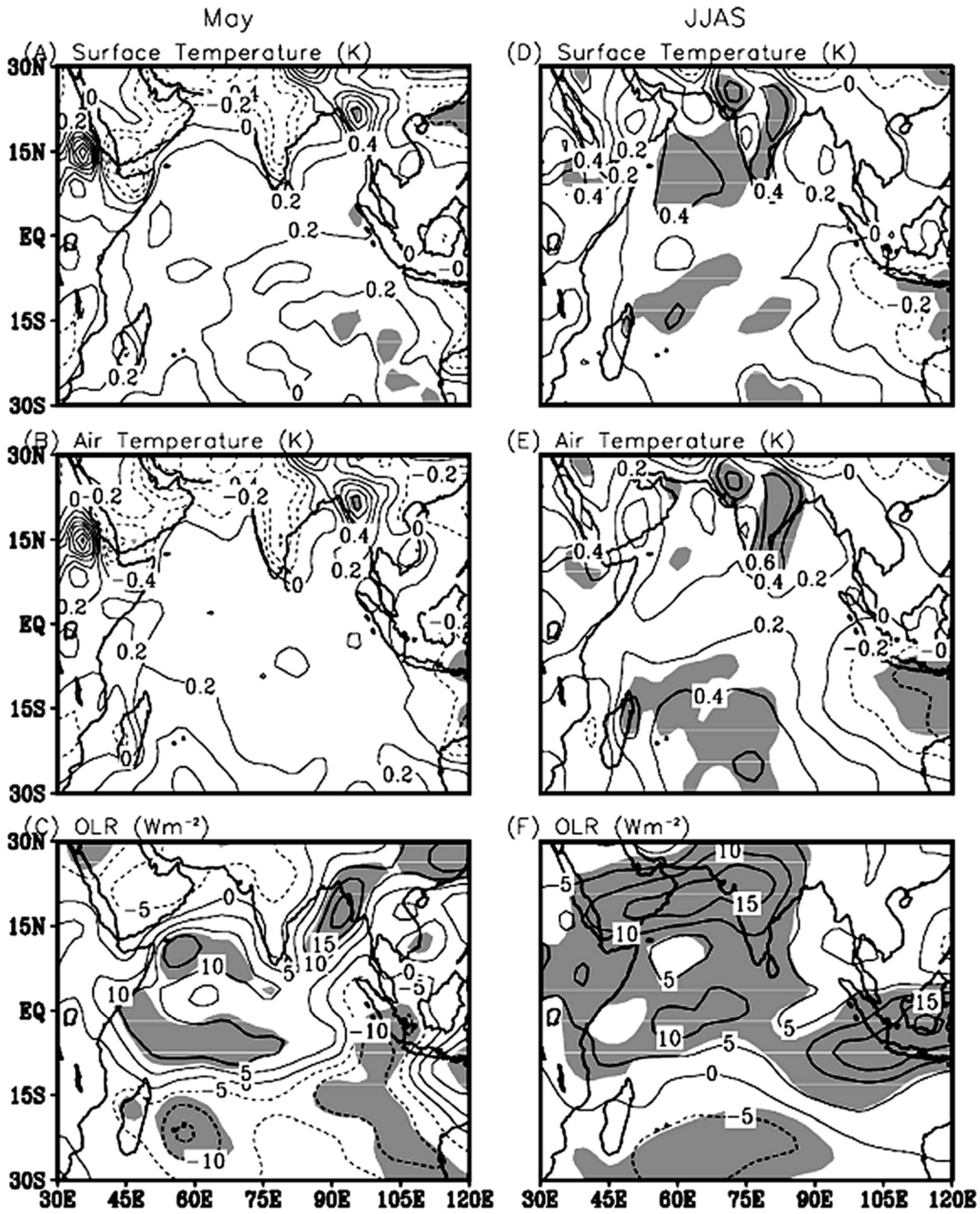

Fig. 4—Distributions of anomaly of (A) surface temperature (K) (B) air temperature (K) (C) Outgoing longwave radiation flux (Wm^{-2}) during May and D, E and F are same as A, B and C but for monsoon season (JJAS) with confidence limit above 95% (shaded).

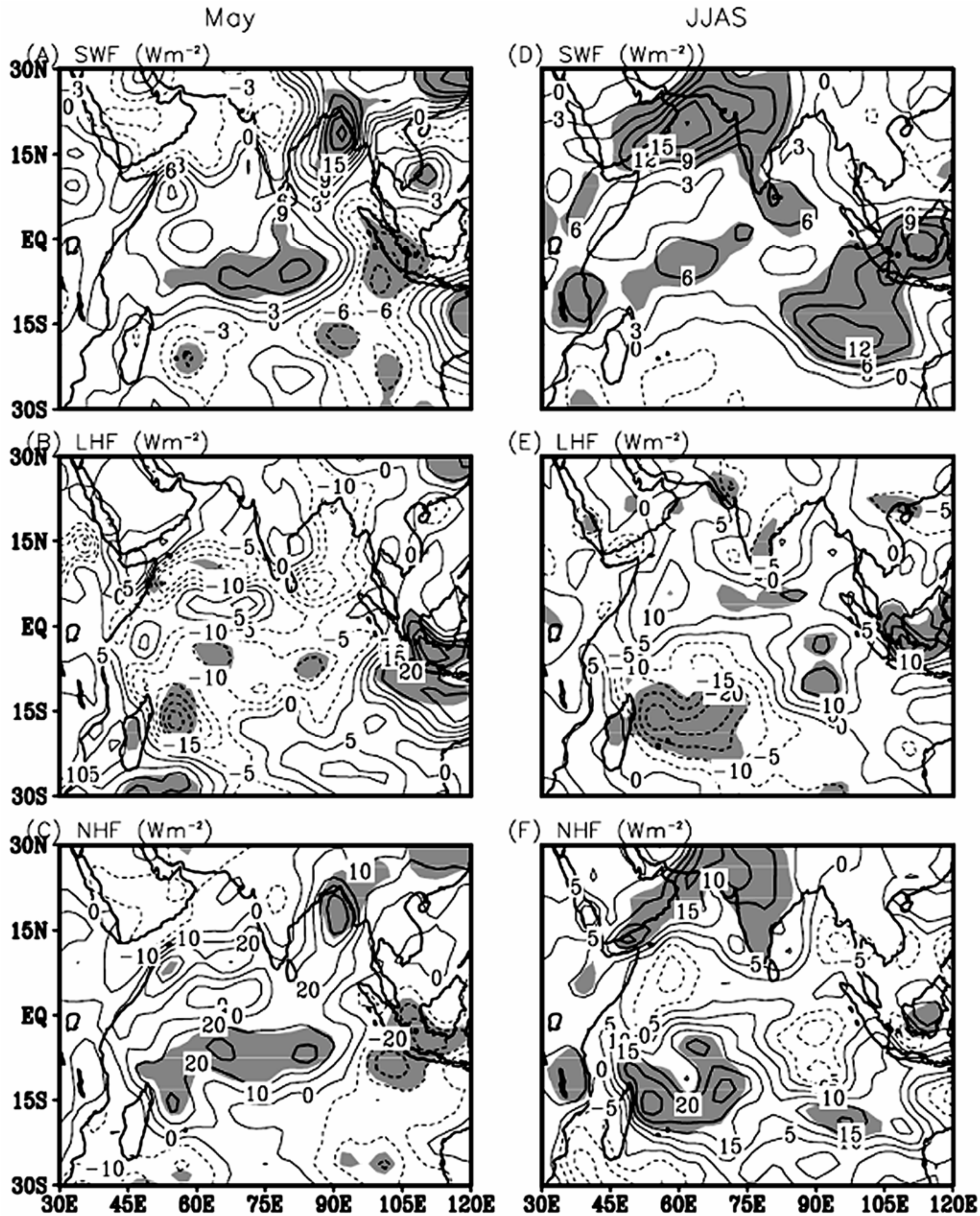

Fig. 5—Distributions of anomaly of (A) shortwave radiation flux (Wm^{-2}) (B) latent heat flux (Wm^{-2}) (C) net heat flux (Wm^{-2}) during May and D, E and F are same as A, B and C but for monsoon season (JJAS) with confidence limit above 95% (shaded).

Ocean across Somalia, Kenya, Arabian Peninsula and north Arabian Sea to northwestern parts of India (Fig. 4F). Maximum anomalies (10-15 Wm^{-2}) were noticed over north Arabian Sea and adjoining western India and equatorial southeast Indian Ocean, Indonesia and Malaysia. This is due to the fact that during summer monsoon season, the lower OLR associated with higher convective cloudiness and hence the precipitation.

3.2 *Variation of the heat budget components*

The distribution of average of incoming short-wave radiation flux at surface (SWF) anomalies during May and monsoon season are shown in Fig. 5A, D respectively. Significant positive anomaly of 10-18 Wm^{-2} were seen over the north Bay of Bengal and adjoining regions of Bangladesh, Myanmar, northeast India and part of equatorial south Indian Ocean (Fig. 5A). The significant positive anomalies were in consonance with the total cloud cover observed in Fig. 2C. In the monsoon season the significant positive anomaly of SWF (Fig. 5D) was observed in the NE-SW oriented band extending from Gangetic West Bengal to northwest India to Arabia through north Arabian Sea. Maximum positive anomalies of 15 Wm^{-2} were observed over north Arabian Sea. Significant positive anomaly of 12 Wm^{-2} was also observed over southeast Indian Ocean extending northeastwards across Indonesia and Malaysia. The positive anomaly is due to higher prevalence of cloud cover in the La Nina years as is evident from Fig. 2F. Smaller magnitude of positive anomaly was also noticed in southwest equatorial Indian Ocean.

The distribution of average latent heat flux (LHF) anomaly shows a region of significant negative anomaly over the southwestern sector of the Arabian Sea off Somali coast (Fig. 5B). The significant negative anomaly of LHF in May over southwest Arabian Sea is expected due to higher surface wind and higher air-sea temperature contrast in those areas. Significant negative anomalies of LHF were noticed in the equatorial southwest Indian Ocean off Madagascar. Significant positive anomalies of 15-20 Wm^{-2} were observed over equatorial southeast Indian Ocean. Since low level wind strength is an important parameter in LHF, it is quite probable that location and depth of Mascrene’s high and the associated cross equatorial wind are responsible for the variations in LHF during pre-monsoon month of May of El Nino and La Nina years. During the summer monsoon season, the LHF anomaly shows significant negative anomaly over parts of central and northwest India. Another region of significant negative anomaly was found in the southwest Indian Ocean, particularly over and to the east of Madagascar (Fig. 5E). Stronger southeast trade winds in the southern hemisphere during monsoon months appear to be associated with the negative anomalies in the southwest Indian Ocean. Significant but positive anomalies are noticed over Indonesia and Malaysia.

The geographical distribution of average net heat flux (NHF) anomaly showed that during May (Fig. 4C) significant positive anomalies (heat gain) were found in the equatorial southwest Indian Ocean, Arabian Sea off Somali coast, north Bay of Bengal and some areas of Bangladesh during El Nino years. The positive anomalies (oceanic heat gain) were mainly attributed to weaker low level wind and reduced evaporation, leading to downwelling, warming of sea surface and reduced pre-monsoon convective activity with less cloud cover and enhancement of incoming short-wave radiation. The results in pre-monsoon month of May confirm an earlier study[19] and serve as a useful predictor for the subsequent monsoon season rainfall activity.

Positive NHF anomaly was observed over the western sector of Arabian Sea, most parts of the Indian subcontinent and equatorial southwest Indian Ocean (Fig. 5F) during monsoon season. The possible reason could be increase in SWF together with reduced LHF during the summer monsoon season leading to the development of significant heat gain region during El Nino years. It clearly shows that La Nina year are associated with larger heat loss from the ocean to atmosphere and lower heat loss in El Nino years over the Arabian Sea and equatorial southwest Indian Ocean.

4. Summary

The results of present study clearly demonstrate that large and statistically significant changes in surface meteorological parameters and energy flux are observed during El Nino years over Indian landmass, Indonesia and equatorial Indian Ocean indicating decrease of strength of monsoon and convective activity. There are significant changes observed in the precipitation rate, zonal wind, meridional wind, precipitable water content, total cloud amount, pressure, LHF, OLR, SWF and NHF over parts of India, Arabian Sea, Arabia and part of north Africa, Somalia and Indonesian region.

The negative anomalies of cloud amount over and northwestern parts of India indicate that southeast trades in the southern hemisphere are stronger in the La Nina years and after crossing equator maintain their strength and vigor. Positive anomalies over Gangetic West Bengal indicate the establishment of deeper monsoon trough line in May. Persistence of positive anomalies over the Indo-Gangetic plain in monsoon season indicates the greater strength and persistence of monsoon trough line in the La Nina years. Significant southerlies at surface in the month of May indicate prevalence of northward transport, which in the present case could mean higher northward transport of moisture. The stronger southerlies in monsoon months of La Nina years indicate higher northward transport of moisture. Significant positive anomalies are observed over the complete Indo-Gangetic plain indicating less insolation mainly due to excess clouding and precipitation during monsoon season. Significant negative anomalies of the surface temperature and air temperature in the month of May are observed over North India and adjoining Pakistan and Afghanistan region. During monsoon season this region is replaced by significant positive anomalies.

In the monsoon season, there is a NE-SW oriented band extending from Gangetic West Bengal across northwest India to Arabia through north Arabian Sea, where significant rise in SWF is observed during El Nino years. Significant regions of lower LHF located over northwest India, Central India and south Indian Ocean off Madagascar during La Nina years for monsoon season. The NHF in the month of May is significantly positive in the south Indian Ocean off Madagascar and north Bay of Bengal. There is significant region of NHF gain located over northwest India and adjoining Indian region and south Indian Ocean during La Nina years for the monsoon season.

Significant variations in the anomalies in the month of May, particularly surface pressure, zonal and meridional wind at surface, precipitable water content, OLR and NHF during El Nino and La Nina years over equatorial southwest Indian Ocean, Arabian Sea off Somali coast, north Bay of Bengal and some areas of Bangladesh give indications to the behavior of the forthcoming summer monsoon during the months of June to September.

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