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Relation between outgoing longwave radiation and findlater jet over Arabian Sea during summer monsoon and influence on Indian monsoon rainfall

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This work analyses the relationship between outgoing Longwave radiation (OLR) and Findlater jet (FLJ) intensities at 850 hPa pressure level and also their relation with Indian summer monsoon rainfall (ISMR; June-September) for a period of 1997-2010 over Arabian Sea and India. FLJ is a low-level jet (LLJ) which can be observed during southwest monsoon months. This LLJ generally supports the large-scale moisture and momentum transport from ocean to atmosphere, which results in rainfall over India. FLJ and OLR are associated during the monsoon months. However FLJ (positively) and OLR (negatively) are related with ISMR. Monthly and seasonal correlation coefficients among FLJ, OLR and ISMR presented and the deviations during El Nino/La Nina are discussed. Based on this analysis we recommend that the variations in FLJ should include interannual variability in atmospheric dynamics.

[**Keywords**: Findlater jet, Outgoing Long wave Radiation, Rainfall]

Introduction

Monsoon is a system of winds characterized by a seasonal reversal of its direction. During the summer monsoon, the winds cross the equator and deviates towards Indian sub-continent with the change in wind direction as south-westerly. During the Southwest Monsoon (SWM), wind blows with consistency and regularity during a part of the year. Such seasonal changes of wind are the result of differences in the quantity of heat received from the sun at different parts of the earth. The rainfall occurring during the summer monsoon is important because the main cultivation with the monsoon begins. SWM rainfall is important for Indian sub-continent, as it influences the economy and summer monsoon. Gradual formation of a low-level jet (LLJ) is a remarkable feature of the summer monsoon over the Indian Ocean (IO)[1] especially at the western Indian Ocean. The presence of LLJ off Somalia was first reported by Bunker[2] in a preliminary analysis of the International Indian Ocean Expedition (IIOE, during 1962–66). The existence of similar LLJs with a core speed of 20–30 m/s about 1.5 km above sea level during July over peninsular India has been reported[3]. Findlater[1,4] have explained the importance of LLJ in the monsoonal activity. The mean monthly air flow (at 1.0-1.5 km height) over western IO, which found to appear at Kenyan highlands as western boundary low-level air current[4,5]. Stommel and Fieux[6] found the linkage between the mean June rainfall data over West coast of India and onset near Somali coast in May.

OLR data can be used for large-scale monsoon circulation with associated cloudiness and rainfall over the Indian regions[7]. Over the tropical ocean, OLR variations are almost entirely owing to changes in the distribution of cloudiness hence can be related to precipitation[8]. Muthuvel and Arkin[9] have examined the interannual and long-term climatic variations in the tropics using OLR data. A new technique to estimate monthly precipitation for the entire globe has been developed to investigate the relationship between precipitation and OLR[10,11]. Long-range prediction of the Indian summer monsoon rainfall (ISMR) is also done with OLR in the IO[12]. There is a significant relation found between the interannual variation of ISMR and OLR in west-central IO. However, south equatorial IO indicates inverse relation. Hence, low OLR (or high convective activity) of the regions represents high ISMR and vice versa. OLR appears to be modulated by the variation of Sea Surface Temperature (SST). As OLR reveals the clouding over the Arabian Sea, the FLJ plays an important role to transport the cloud to Indian sub-continent, which produces the rainfall. The present study is an attempt to understand FLJ in relation to OLR during monsoon activity and to understand the possible mechanism of the monsoon processes on intraseasonal and seasonal scales.

Materials and Methods

Indian Ocean is a tremendous storage house of thermodynamic energy, which drives the monsoonal circulation due to differential heating between land and sea. During summer monsoon months, wind increases rapidly over the Arabian Sea and brings the moisture to Indian sub-continent as rainfall. The domain investigated covers a major portion of Arabian Sea at 850 hPa during the SWM i.e. 10º S – 30º N and 50º E – 75º E. It is important to study the wind pattern especially at FLJ area and OLR, which reveals the clouding over the Arabian Sea further as rainfall over Indian Sub-continent. The major dataset used for this work are OLR, wind and rainfall. The daily averages of OLR with a spatial grid resolution of 2.5º with diurnal temporal resolution obtained from the National Oceanic and Atmospheric Administration (NOAA). The daily OLR data averaged for June through September at each of the grid points. The monthly OLR data analysed in this study are from 1997 to 2010 at 2.5° degree grids over Arabian Sea. Daily wind data is obtained from National Center for Environmental Prediction (NCEP) II reanalysis[13] to study the wind pattern and wind intensities at a pressure level of 850 hPa. In this study, we analysed the intensities of FLJ over the core area (5° N - 20° N and 50° E - 75° E). Monthly mean time series has been obtained from daily values. To study variations of rainfall, daily precipitation data has been taken from Global precipitation climatology project (GPCP) from 1997-2010. One of the major goals of GPCP is to develop a more complete understanding of the spatial and temporal patterns of global precipitation. Data from over 6,000 rain gauge stations, and satellite geostationary and low-orbit infrared, passive microwave and sounding observations have been merged to estimate monthly rainfall on a 1-degree global grid from 1979 to 2010. These FLJ, OLR and ISMR data are analysed for the study of their concurrent relationship.

Results

Relation between OLR and FLJ

The composite variations of OLR with FLJ intensities over the Arabian Sea for the study period are given in Figure 1. During the study period, it is observed that with the decrease of OLR there is an increase in FLJ intensities. Clouding over Arabian Sea reduces OLR and reduces SST as the insolation is reduced as a part of the incoming solar radiation over the sea. This leads to large temperature gradients and therefore the FLJ intensities increase. Thus, OLR and FLJ are inversely associated. The theoretical consideration is having good agreement with the observed data. Whenever FLJ intensities increase there is a corresponding OLR decrease. In general, OLR is high in the month of May and decreases with the advent of SWM. As the clouding increases in June and July, the OLR decreases and consequently there is an increase in FLJ intensity. However, in August and September OLR increases, which is perhaps because the intensity and frequency of clouding over is low. Thus, during the period of study FLJ intensities are higher with decrease in OLR (Fig. 2).

The correlation coefficients with significant level of 95 % between OLR and FLJ are given in Table 1. Negative correlations observed in June and July. We can observe a positive correlation between FLJ and OLR in 1997 and 2003. The year 1997 is a Strong El Nino, which affected all over the world, but over Indian sub-continent, there is a normal rainfall. The year 2003 is a normal year, but it is one year after strong drought condition prevailed (2002) over Indian sub-continent. During August, both negative and positive correlations (1999, 2007, 2009 and 2010) can be observed. Only year 2009, have a correlation of 0.4, in other years the correlation is small indicating no relation between FLJ and OLR. During September 1999, a high positive correlation of 0.67 is found. The correlation in the month of September 2007 is -0.8, which is a La Nina year. The year 2008 [one year before the moderate El Nino (2009)], the correlation is positive and higher (0.65), which affected Indian sub-continent with drought condition. La Nina year (1998) which is one year after the strong El Nino year 1997 also indicated a significant negative correlation (-0.61).

Variations of Outgoing Longwave Radiation with Findlater Jet intensities during El Nino, La Nina and Normal years

Overall examination of OLR and FLJ intensities in El Nino years indicates that OLR is higher and FLJ

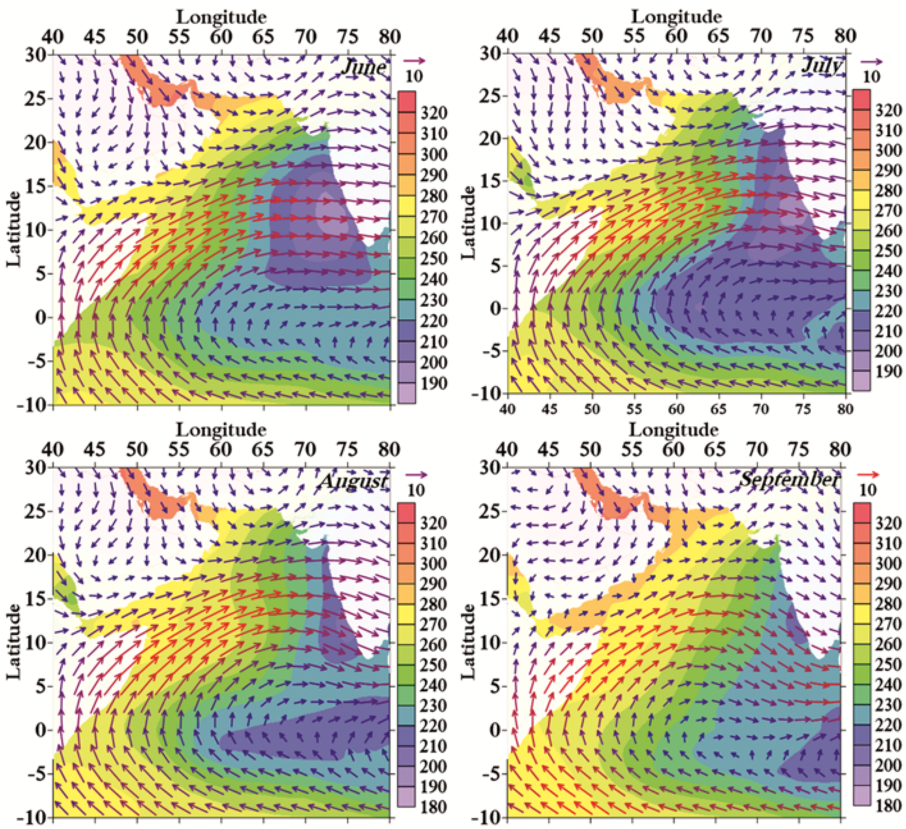

Fig. 1 — Composite variation of wind at 850 mb level (Findlater jet) in vectors and Outgoing Longwave Radiation (OLR) in contours for the period of 1997-2010 during monsoon months from June through September

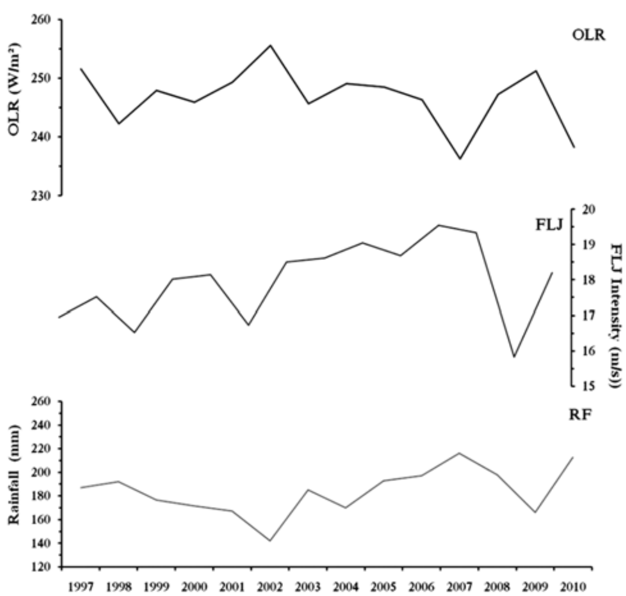

Fig. 2 — Seasonal (JJAS) variation of OLR, FLJ intensities and all India summer monsoon rainfall (ISMR) during 1997-2010

intensities are lower. During El Nino years, OLR is high in the month of June and July, and an increase is observed in the month of August. Here, it should be mentioned that OLR is more in 2002 July compared to 1997. The monthly averages of OLR for the month of June varied from 239.60 W/m^2 to 252.61 W/m^2 and FLJ intensities varied from 12.3 m/s to 19.96 m/s. In July, OLR is varied from 236.58 W/m^2 to 260.07 W/m^2 and FLJ intensities are varied from 18.06 m/s to 22.35 m/s. In August, OLR is varied from 248.44 W/m^2 to 257.37 W/m^2 and FLJ intensities varied from 17.16 m/s to 20.61 m/s. In September, the OLR jumbled from 248.23 W/m^2 to 269.69 W/m^2 and FLJ intensities varied from 10.4 m/s to 14.2 m/s during the years 1997, 2002, 2004, 2006 and 2009, respectively.

During La Nina years, in 2000 May the OLR is high i.e. there is no clouding. OLR is low which indicates the monsoon activity in the month of June. The same is observed in July and August. In monthly comparison, a high OLR is observed in 1999 June and in August compared with other years of La Nina. In the month of July only in 2000, the OLR is high. A daily value of OLR shows a decrease in June and August in 1998. In 2007, decrease in OLR is observed in June however, July and September indicated a

Table 1. Correlation coefficients (95% significant) between Outgoing Longwave Radiation (OLR), Findlater jet (FLJ) intensities and All India Rainfall (AIRF) for individual monsoon months and Southwest Monsoon season (SWM) over 1997-2010.

	Correlation coefficients between OLR and FLJ					Correlation coefficients between AIRF and FLJ					Correlation coefficients between AIRF and OLR				
year	Jun	Jul	Aug	Sep	SWM	Jun	Jul	Aug	Sep	SWM	Jun	Jul	Aug	Sep	SWM
1997	-0.70	0.11	-0.07	-0.36	-0.47	0.43	0.34	0.28	0.07	0.46	-0.17	-0.30	-0.43	-0.67	-0.20
1998	-0.62	-0.46	-0.39	-0.09	-0.61	0.41	0.36	0.03	0.14	0.17	-0.25	-0.57	-0.40	-0.23	-0.27
1999	-0.79	-0.34	0.06	0.67	-0.51	0.76	0.18	-0.22	0.17	0.36	-0.81	-0.34	-0.21	0.05	-0.46
2000	-0.69	-0.52	-0.33	0.21	-0.42	0.36	0.63	0.04	0.09	0.52	-0.64	-0.64	-0.34	0.08	-0.41
2001	-0.59	-0.28	-0.52	0.02	-0.36	0.21	0.25	0.20	0.11	0.47	-0.53	-0.33	-0.23	-0.06	-0.43
2002	-0.62	-0.12	-0.13	0.29	-0.50	0.46	0.08	0.03	0.59	0.32	-0.21	-0.43	-0.61	0.00	-0.32
2003	-0.44	0.21	-0.50	0.17	-0.48	0.59	0.24	0.05	-0.17	0.39	-0.02	-0.09	-0.26	-0.58	-0.15
2004	-0.47	-0.71	-0.80	0.24	-0.32	0.44	0.36	0.75	-0.35	0.49	-0.65	-0.62	-0.81	-0.43	-0.54
2005	-0.47	-0.32	-0.54	-0.67	-0.54	0.64	0.37	0.33	0.66	0.46	-0.22	-0.51	-0.50	-0.81	-0.47
2006	-0.88	-0.38	-0.63	-0.61	-0.59	0.82	0.08	0.30	0.63	0.53	-0.75	-0.45	-0.71	-0.38	-0.47
2007	-0.46	-0.12	0.08	-0.80	-0.48	0.14	-0.26	-0.09	0.35	0.06	-0.17	-0.33	-0.68	-0.28	-0.08
2008	-0.40	-0.53	-0.51	-0.72	-0.65	0.28	0.45	0.63	0.84	0.52	0.09	-0.49	-0.35	-0.62	-0.31
2009	-0.52	-0.47	0.40	-0.47	-0.47	0.36	0.19	-0.22	0.68	0.52	-0.43	-0.57	-0.52	-0.83	-0.58
2010	-0.72	-0.74	0.05	0.36	-0.48	-0.15	0.40	-0.33	0.66	0.35	-0.17	-0.35	-0.24	0.27	-0.24

smaller decrease in OLR. In 1999, decrease was observed in June and twice in July. In 2000, a similar decrement of OLR was observed in June, 1st week of July and twice in August. The monthly averages of OLR for the month of June varied from 215.74 W/m^2 to 251.84 W/m^2 and monthly averages of FLJ intensities varied from 16.1 m/s to 21.3 m/s. In July, OLR monthly averages varied from 226.08 W/m^2 to 245.58 W/m^2 and FLJ intensities varied from 20.41 m/s to 21.12 m/s. In August, OLR varied from 239.07 W/m^2 to 250.17 W/m^2 and FLJ intensities varied from 15.96 m/s to 19.54 m/s. In September, OLR varied from 243.86 W/m^2 to 256.24 W/m^2 and FLJ intensities varied from 12.73 m/s to 16.83 m/s in the La Nina years.

Years other than El Nino and La Nina are 2001, 2003, 2005 and 2008 considered as Normal years. One can observe during all Normal years that OLR illustrating lower values in June and July. The monthly averages of OLR for June varied from 228.45 W/m^2 to 247.97 W/m^2 and FLJ intensities varied from 17.93 m/s to 20.7 m/s. In July, OLR varied from 232.73 W/m^2 to 242.07 W/m^2 and FLJ intensities varied from 21.96 m/s to 23.80 m/s. During August, OLR varied from 248.05 W/m^2 to 257.56 W/m^2 and FLJ intensities varied from 18.38 m/s to 20.51 m/s. In September, OLR varied from 254.09 W/m^2 to 266.23 W/m^2 and FLJ intensities varied from 10.83 m/s to 15.06 m/s. A lower OLR is also observed in August but higher when compared with June and July.

This study may infer that OLR in normal years is low in June and July and increased in August, which indicates lower cloud cluster. OLR is not only an indication of radiation intensity going out but also indicates whether there are cloud clusters or bright sunshine. Careful examination of OLR intensity for La Nina illustrate lower, and higher in El Nino. Surprisingly, 1997 though strong El Nino year resulted in near normal rainfall and 2002 a moderate El Nino year as it is in phase with Indian Ocean Dipole (IOD) resulted in very much deficit rainfall. This also reflected by the OLR values. In 2002, OLR is above normal, which reflects less clouding and less rainfall. The detailed study has been given in the next section as special case of FLJ and OLR variations during 1997 and 2002.

Variations of OLR and FLJ intensities: Special case of 1997, 2002 and 2009

As it is mentioned earlier that 1997 is a strong El Nino year with normal rainfall and 2002 is a moderate El Nino year but with deficit in rainfall, it is interesting to find the variations of OLR with FLJ intensities during monsoon months. The daily variations of OLR and FLJ intensities are given in Figure 3a, b and c. It is observed that in 1997 there is a sharp decrease on 16th June with 200 W/m^2 with FLJ intensity as 22 m/s. Similarly, OLR decreased on July 24th and August 21st. However, this decrease is not that much as compared to decrease observed in June. In 2002, there is a sharp decrease on 13th June with 194 W/m^2 and FLJ intensity as 22 m/s. In 2009, decrease in OLR is observed on 29th June, clearly indicating that there is a delay. However, FLJ and rainfall increased after 29th June. The march of OLR during the entire season indicates that in both 1997 and 2002 the OLR intensities were fluctuating which indicates clouding over the Arabian Sea. In 2009,

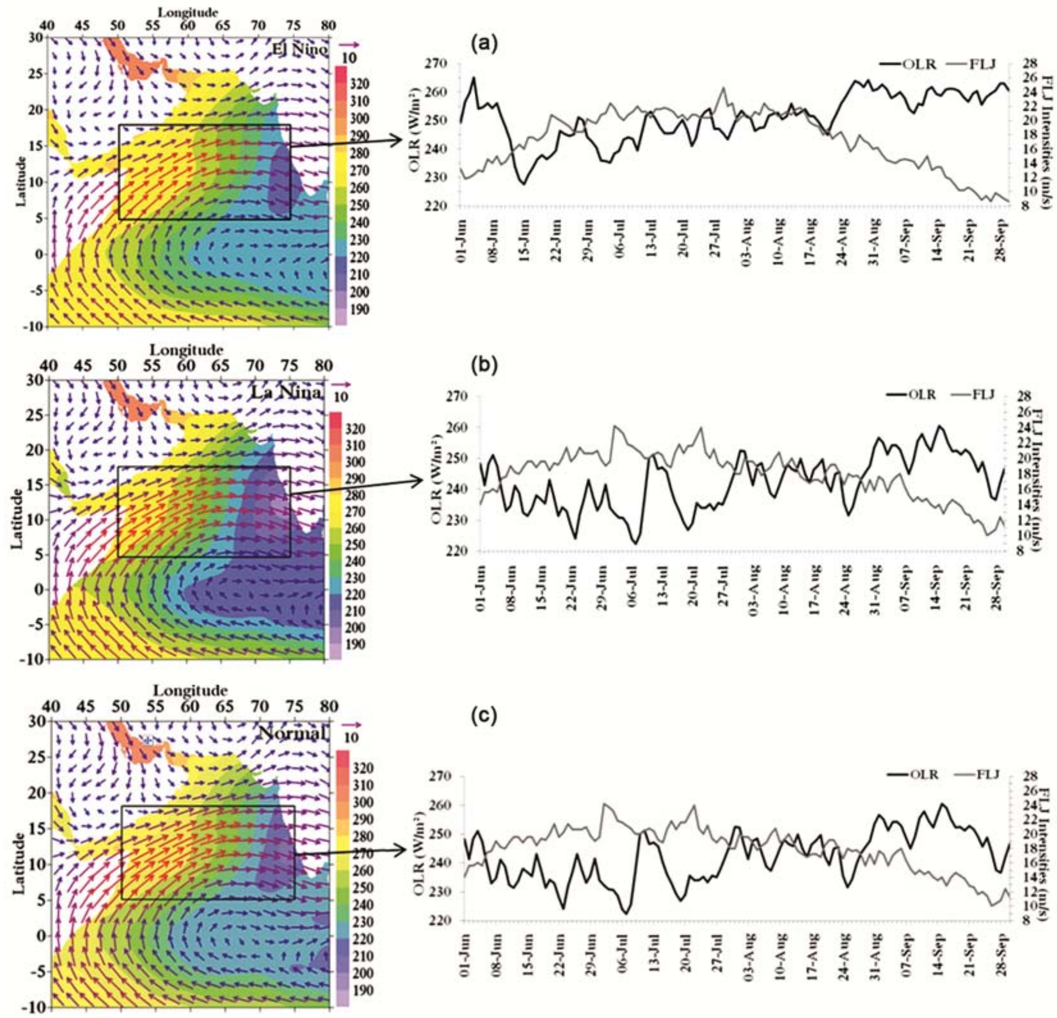

Fig. 3 — Composite seasonal variations of OLR with FLJ intensities during a) in El Nino years, b) in La Nina Years, and c) in normal years

fluctuations of OLR were more predominant and lower OLR can be observed on 20th August. At the same FLJ does not change much, however, there is an increase in rainfall. The FLJ intensities have also showed a corresponding variation. However, the contrasting feature is in July and August. In 2002, there is a sharp increase in OLR and a consistent decrease in FLJ intensities. During 2009, the break monsoon can be identified very clearly.

ISMR in relation with FLJ and OLR:

The JJAS months and seasonal correlation coefficients between ISMR and FLJ are given in the Table 1. There is a positive correlation between (All India Rainfall) AIRF and FLJ. Correlations, which are higher than 0.5 are given in bold. During June, a high correlation of 0.82 can be seen in the year 2006 and the higher correlations of 0.76 and 0.59 can also be observed in the years 1999, 2003. In the year 2000, except in July (correlation of 0.63) all the remaining months of SWM have a correlation less than 0.5. In the month of August a higher correlation of 0.75 and 0.63 in 2004 and 2008 are observed. Highest correlation of 0.84 between ISMR and FLJ is observed during September 2008. Correlations more than a value of 0.5 can be observed during 2002 (0.59), 2005 (0.66), 2006 (0.63), 2009 (0.68) and 2010 (0.66). When we checked the correlation between the seasonal rainfalls with FLJ, the years 2000, 2006, 2008 and 2009 were having higher correlation of 0.52, 0.53, 0.52 and 0.52, respectively. Some negative low correlations were also observed. This revealed that the ISMR was more than normal rainfall but FLJ was lower than normal.

Correlations between ISMR and OLR are given in Table 1. There is a negative correlation between rainfall over India and OLR. Decrease in OLR signifies that there is clouding over Arabian Sea, which is transported to Indian sub-continent by FLJ. If the FLJ is higher, cloud over Arabian Sea is carried to Indian sub-continent faster and turns out to be rainfall. Table 1 discloses correlations for individual months of SWM and seasonal. The seasonal monsoon rainfall shows negative correlations with OLR.

Seasonal values of ISMR, FLJ and OLR are shown in Figure 4. During 1997, the OLR is higher, which reveals the radiation is higher and low clouding over the Arabian Sea. FLJ is normal and also rainfall is normal. Figure 4 reveals a low rainfall, high OLR and normal FLJ during 2002, which is a moderate El Nino year, but there is a drought condition over Indian sub-continent. The year 2009 showed lower rainfall, and higher OLR; however, there was a lower FLJ. We can observe a decrease in rainfall from 1998 to 2002.

Discussion

The OLR can be used as a good proxy for rainfall activity associated with tropical convection. Long-term averaged OLR data can be considered as a good surrogate for the rainfall. With decrease of OLR, there is an increase in FLJ intensities. This is because decrease in OLR is mainly due to clouding, the clouding reduces the insolation, part of the incoming solar radiation reflected from the cloud tops. This leads to large temperature gradients and therefore FLJ intensities increase. Halpen and Woiceshyn[14] have explained that eastward expansion of the FLJ and raise in the intensity of surface wind convergence leading to increase in the amount of integrated cloud liquid water in the Eastern Arabian Sea, which presumably influences the rainfall of the west coast of India. LLJ at 850 hPa plays a vital role in maintaining

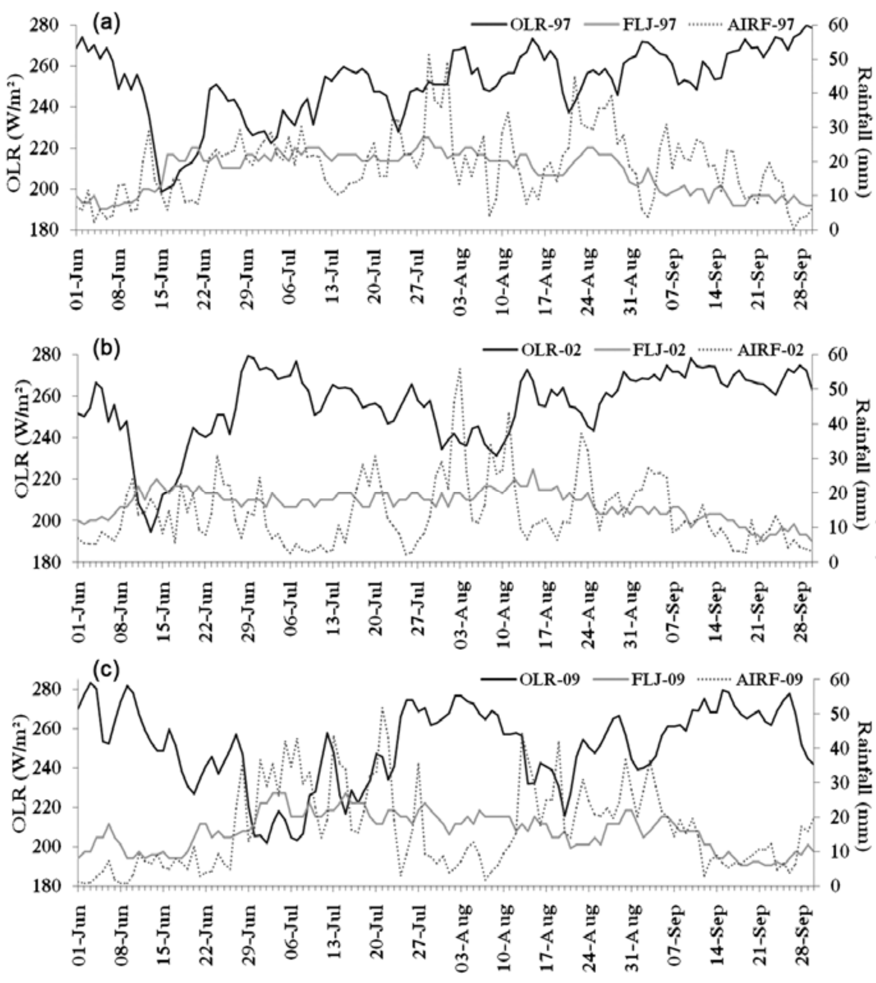

Fig. 4 — Variations of daily OLR, FLJ intensities and all India rainfall during 1997, 2002 and 2009 monsoon months

and controlling the Indian Summer Monsoon[15]. This theoretical consideration is corroborated well with the observed data. A linkage between SWM winds over the Arabian Sea and rainfall over India has been indicated[1]. The relation between the strength of cross equatorial flow and ISMR during monsoon is well established[1,16]. However, rainfall of parts of western India is also correlated with intensity of low-level equatorial winds over Kenya[17]. Some researchers found that even in the good monsoon, there is a strong cross-equatorial wind than a bad monsoon[18]. In general, OLR is higher in the month of May with the advent of SWM, the clouding increases leading to decrease in OLR during June and July. However, in August and September there is an increase in OLR which is perhaps because the intensity and frequency of clouding decreases and FLJ also decrease.

OLR intensity for La Nina conditions showed lower values and higher values for El Nino conditions, however during normal conditions OLR is lower during June and July and higher in August and September. OLR intensity variations over the Arabian Sea during the entire season indicate cloud clusters are different in 1997 and 2002. However, the FLJ intensities also showed a corresponding variation. However, there is a contrasting feature observed in 2002 in July and August, indicating a sharp increase in OLR and a consistent decrease in FLJ intensities.

The cross equatorial winds carry much of the moisture that sustains the monsoon rainfall and this moisture may be accounted for 60 % - 80 % of the rainfall by fluxes across the equator[19,20]. The importance of low level cross-equatorial flow has been studied in the several modelling studies[21-25]. It is well known that the LLJ or FLJ is carrying the moisture from the Southern hemisphere to Indian sub-continent as rainfall during SWM. The ISMR depends on the OLR over the Arabian Sea and moisture carried by FLJ. The active phase of the monsoon begins; the cloud band formed (reducing OLR) and LLJ strengthened[26]. From the observation of FLJ intensities, OLR and its relation to precipitation clearly indicates the relation with rainfall. It is emphasised that the rainfall is normal in a strong El Nino year 1997, however 2002 moderate El Nino year experienced much below normal rainfall. Subrahmanyam[27] has explained earlier that IOD decides El Nino; an important factor in determining the rainfall. In 2002, El Nino and IOD are in phase, in other words the effect is synergistic. Both IOD and El Nino played their role in reducing rainfall. In 1997 even though it is a strong El Nino year as there is no support from IOD leading to normal rainfall. Year 2009 is a delayed El Nino; occurrence of rainfall also delayed resulting below normal rainfall during the monsoon season. It is seen here that OLR and FLJ intensities are also reflecting this hypothesis. The OLR is relatively high in 2002 followed by low FLJ intensities resulting in a prolonged break spell in monsoon and the cumulative effect is deficit in rainfall.

Conclusion

With the advent of SWM, in June and July OLR decreases and FLJ increases. However, in August and September, OLR increases and there is a decrease in FLJ. This reveals FLJ and OLR are inversely correlated. OLR is higher (lower) during El Nino (La Nina) conditions. In normal conditions, OLR is low during June and July and an increase in August and September is observed. A strong El Nino year (1997) resulting in normal rainfall and moderate El Nino year (2002) resulting in deficit in rainfall are due to changes in OLR and FLJ.

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