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Indian Ocean moisture flux variations during summer monsoon and its relation with Indian rainfall

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In this article, we discussed about the variations of moisture flux (MF) over the Indian Ocean (IO) and successive Indian summer monsoon rainfall (ISMR). MF calculated over 1000-850 mb levels at five different sub regions over the IO during 2006-2014. In monsoons months (June through September), moisture transported from the southern IO through Arabian Sea (AS) via a low-level jet produces rainfall in Indian subcontinent. MF commences in May then increases through August and then decreases by September. We verified the relation of five sub regions MF with ISMR and found northwest IO (NWIO), Arabian Sea (AS) have positive relation. However, the Bay of Bengal (BOB) and the central IO (CIO) indicated negative relation. Strong positive relation observed with correlation coefficients (CC) of 0.81 and 0.72 between MF and ISMR over NWIO and AS respectively, however BOB and CIO reveal an inverse relation (CC of –0.34 and -0.7). During an El Nino year, MF deviations are negative over the NWIO and AS, indicating lower moisture transport to India and consecutive ISMR is low. MF during El Nino/La Nina/normal monsoon season over the NWIO and AS areas are important for ISMR.

[**Keywords:** El Nino; Indian Ocean; Indian summer monsoon rainfall; Moisture Flux]

Introduction

Indian monsoon is one of the main components of the climate system, both in regards to its strong interaction and variability[1-3] as well as its enormous socioeconomic impacts[4-6]. The link between atmospheric hydrology in the Pacific Ocean and the monsoonal moisture budget is more complex than originally portrayed in early studies of monsoon–El Niño Southern Oscillation (ENSO) coupling[7]. The meridional and zonal heating gradients that drive the large-scale atmospheric and oceanic monsoon circulations and hydrologic processes exist as a key component of the monsoon's intraseasonal, seasonal, and interannual variability[7-10]. Seasonal hydrologic variations include the sustained enhancement of rainfall, winds, and surface evaporation in India. Neighbouring subsident environments such as the Arabian Sea (AS) and southern Indian Ocean (IO) enhance MF due to surface evaporation and divergent winds during summer. The variations compose the globe's most intense seasonal inter-hemispheric mass and moisture exchange and links the Southeast Asia, AS, and southern IO regions[11-13]. Transport of moisture into a region where it can be trained into aprecipitating weather system depends on the atmospheric dynamics as well as the sources of moisture from other parts of the globe. Heavy rainfall results from the moisture fluxes (MFs) that originate from various sources during the summer monsoon over India. Moisture resources are critically important to the study of monsoon rainfall. During the summer monsoon season in India, moisture is transporting from IO to AS. Moist low-level winds bring moisture from the AS and the Bay of Bengal (BOB) into the warm subcontinent during the summer monsoon[2,14,15]. MF is transporting from southern IO to BOB through AS and producing rainfall over India.

The teleconnection between the El Nino/ENSO and rainfall has been studied[16-20] and the studies indicated that there is a strong inverse relation. A strong relation found between ISMR and ENSO as well as a composite index based on indices of ENSO and EQUINOO[21]. However, IOD and El Niño/Southern Oscillation (ENSO) are having complementary affect on the ISMR[22]. The study area was sub divided in to five areas (details of areas are given in data and methodology) to check which area was having prominent affect on Indian summer monsoon rainfall

(ISMR). During the study period, variations between MF and ISMR and their relation to El Nino/ La Nina events were discussed.

Materials and Methods

Monthly mean data of wind components and specific humidity obtained for this study is from the US National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis[23,24]. Monthly rainfall data obtained from the Indian Institute of Tropical Meteorology (IITM) website and homogeneous all India rainfall[25] were used for this analysis. Several studies have been carried out with the column integrated MF from the surface to 300 mb level[26,27]. Strong low-level jet was observed at 850 mb level during the monsoon period[11, 28,29]. We chose the column over 1000-850 mb level and calculated MF to verify the relation with monsoon rainfall. MF calculated over the five areas is given in Figure 1 (Area 1- the Southeast IO (0-10°S; 90-100°E), Area 2–the central IO (5°S-5°N; 70-80°E), Area 3–the Northwest IO (NWIO) (0-10°N;50-60°E), Area 4- the AS (5-20°N; 60-75°E) and Area 5-over the BOB (5-15°N; 85-95°E)). MF was calculated for five areas and evaluated the relation with ISMR. Using Oceanic Nino index done with 3 months running mean of Nino 3.4 region SST (ONI), El Nino and La Nina years were identified by climate prediction center (CPC) (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The El Nino and La Nina years from CPC with ONI criteria used for this study period suggested two El Nino years (2006 and 2009), three La Nina years (2007, 2010-11) and other four years as normal years. Identified area that is more prominent for the rainfall over India and the correlation coefficients (CC) between MF-ISMR and MF-Nino 3.4 SST (ONI) over all five areas is being presented and discussed in this paper. The low level moisture over the Arabian Sea is increasing from the surface up to the 925 hPa and decreasing above it[30]. We checked the moisture flux level at different levels (not given) and found that the MF over the pressure levels between 1000 and 850 mb are more dominant due to the low level jet mainly concentrated over 1000-850 mb level, so we calculated the MF over the levels between 1000 and 850 mb as per the equation given below:

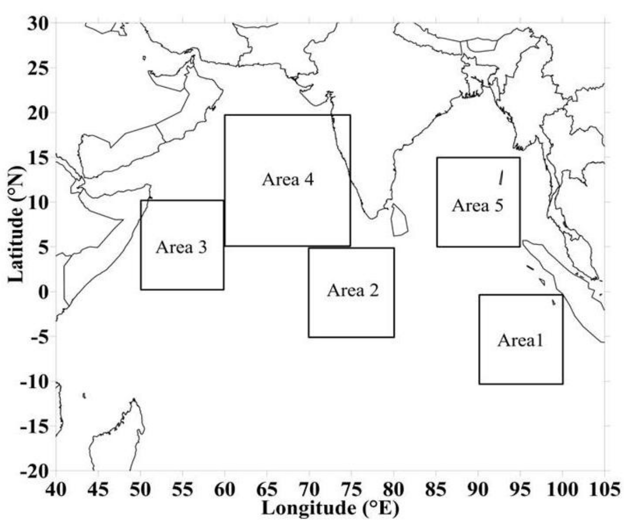

Fig. 1 — Areas of study area

$$MF = \frac{1}{g}\int_{1000}^{850} q\, V\, dp$$

where, q is the specific humidity, V is the wind vector, and g is the acceleration due to gravity.

Results and Discussions

MF variations

Moisture transportation occurs over the ocean throughout the year; however, the variations, distribution, intensities and orientations are different. Previous studies indicate that the moisture transport is from the southern IO to India[19,27,28]. In summer monsoon months (June through September) wind changes its direction to southwest and wind intensity mainly confined at 850 mb (i.e., lowlevel jet (LLJ)), which transport moisture from the southern IO via AS and India experiences rainfall[29]. MF is following LLJ over the AS, which carries moisture to Indian subcontinent to produce rainfall. Figure 2 depicts the vector representation of MF in monsoon months and reveals that the moisture is transporting from the southern IO, crossing the equator, moves to AS and continues to the BOB. India experience rainfall with the advent of monsoon in June and follows until September with peak rainfall in July, which depends on MF intensities. This analysis of moisture transport agreed well with the study of Trenberth and Guillemot[31], in which they found a strong northward moisture flow from the Southern Hemisphere via the Somali jet into India during the summer monsoon season. Fasullo and Webster[26] described in detail that the vertically integrated moisture transport is directly associated with the primary monsoon driving force. In addition, they indicated that deep convection over the

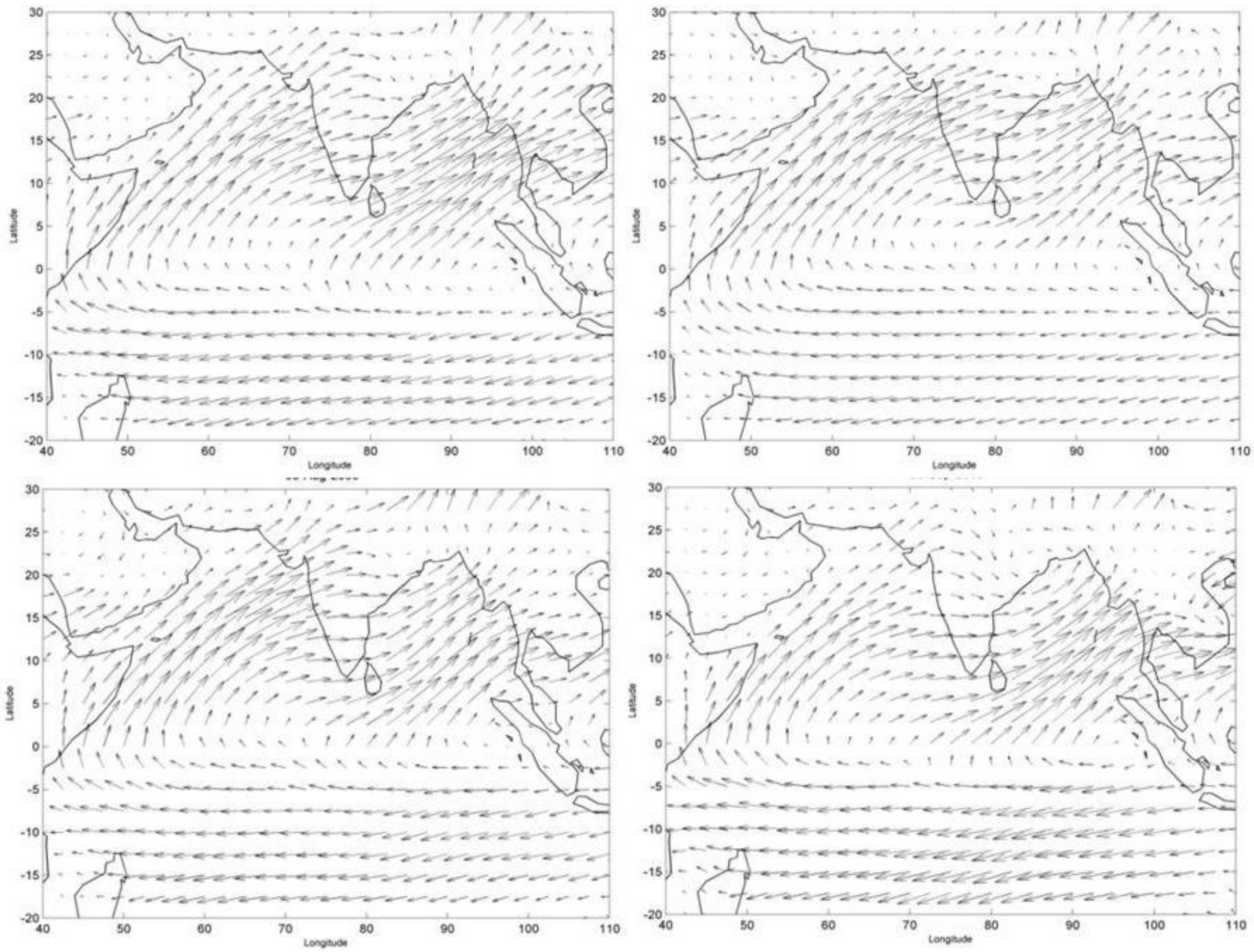

Fig. 2 — Composite spatial variation of moisture flux during the mansoon months for the Study period (2006-2014)

Central AS and BOB supply moisture, which transported from the divergent regions of the southern IO and AS.

Figure 3 represent the variation of MF during monsoon months and Figure 4 depicts the seasonal deviations with respect to the mean during the study period over given five areas. Area 1 is the eastern pole of the Indian Ocean Dipole (IOD), which has a linkage with the western Pacific Ocean and playing an important role in onset and development of IOD[32]. The IOD is playing an important role as a modulator of the Indian monsoon rainfall, and has a significant negative partial correlation with Australian rainfall[33,34]. Magnitude and direction of MF in the months of January to May can indicate about moisture transporting to Australia. However, higher MF depicted in the months from June to September has an association with Indian monsoon. Interannual variations over Area 1 can be clearly seen in MF and ISMR. Area 2 is at the central IO serves as a haulier for moisture transport from the East and West IO and between the AS and BOB. Figure 3 clearly indicates that MF was increasing during monsoon months in 2006 and 2009, however its intensities were different. Similar variations were observed in 2007 and 2010-11 years. In normal years, MF intensities were dissimilar and did not have relation with ISMR.

Area 3 is in the western IO in the northern hemisphere. The importance of this area is that cross equatorial wind brings the moisture from the southern IO during the monsoon months and produce rainfall for India. The year 2009 is a delayed El Nino year, maximum MF attains in July, which affected the ISMR and India faced drought condition. All years MF indicated normal and positive in monsoon months, except in 2009. Area 4 was at central AS where the strong low-level jet flows and transports moisture to India. MF at area 4 was higher than area 3

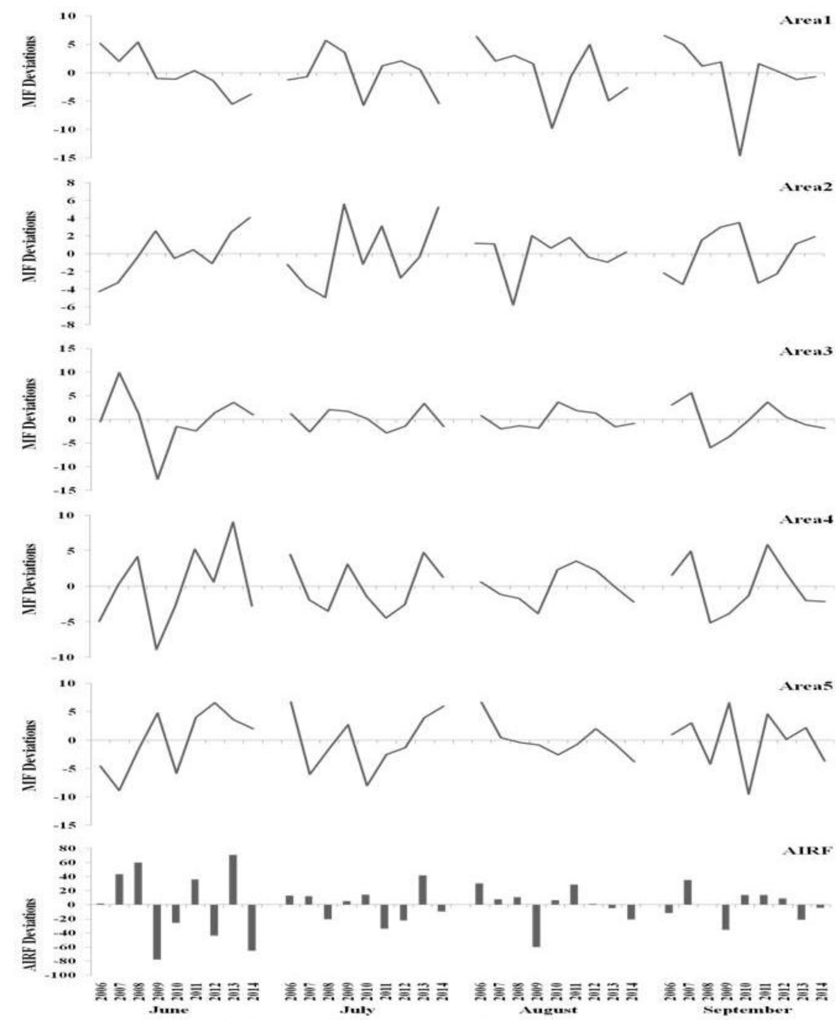

Fig. 3 — Monthly variations of (monsoon season) moisture flux at areas 1-5 and all India rainfall (AIRF)

with the additional contribution of moisture in the AS to MF from the area 3 by LLJ. MF at area 4 was indicated higher values confined to the monsoon months only, which was important for the rainfall over India. The MF from the AS plays a dominant role in monsoon rainfall[20]. However, the MF spitted into two parts; one towards north and another towards east, which was pointed to India. Area 5 was in BOB, MF was deviated from the AS and transported below Indian subcontinent to the BOB and over the northern part of central IO (area 2). Warm pool over the BOB produced moisture, which added to the moisture transported from the AS. Area 5 revealed higher positive anomalies of MF during the monsoon months. However, MF was having an inverse relation with ISMR.

Table 1 illustrate the correlation coefficients (CC) of MF (five areas) with ISMR and Nino 3.4 SST index (ONI) for summer monsoon (June to September and monsoon season). From Table 1, it could be deduced that area 1 MF and ISMR was having an inverse relation in July with CC of -0.31, however ONI and MF was having a positive relation with CC of 0.46, 0.72 and 0.58 in July, August and September, respectively. Area 2 indicated an inverse relation between MF and ISMR (CC=-0.70), however ONI and MF revealed positive relation (0.24). Area 3 is indicated a good relationship between MF and ISMR during monsoon months and seasonal (CC = 0.81), which revealed that seasonal variations over area 3 is prominent than area 4 (CC=0.72). ONI and MF indicated an inverse relation (CC=-0.51) during monsoon months as well as in the monsoon season over area 3. Area 4 was having positive and good CC with ISMR in monsoon months as well as in monsoon season. In September, MF reduced as the summer

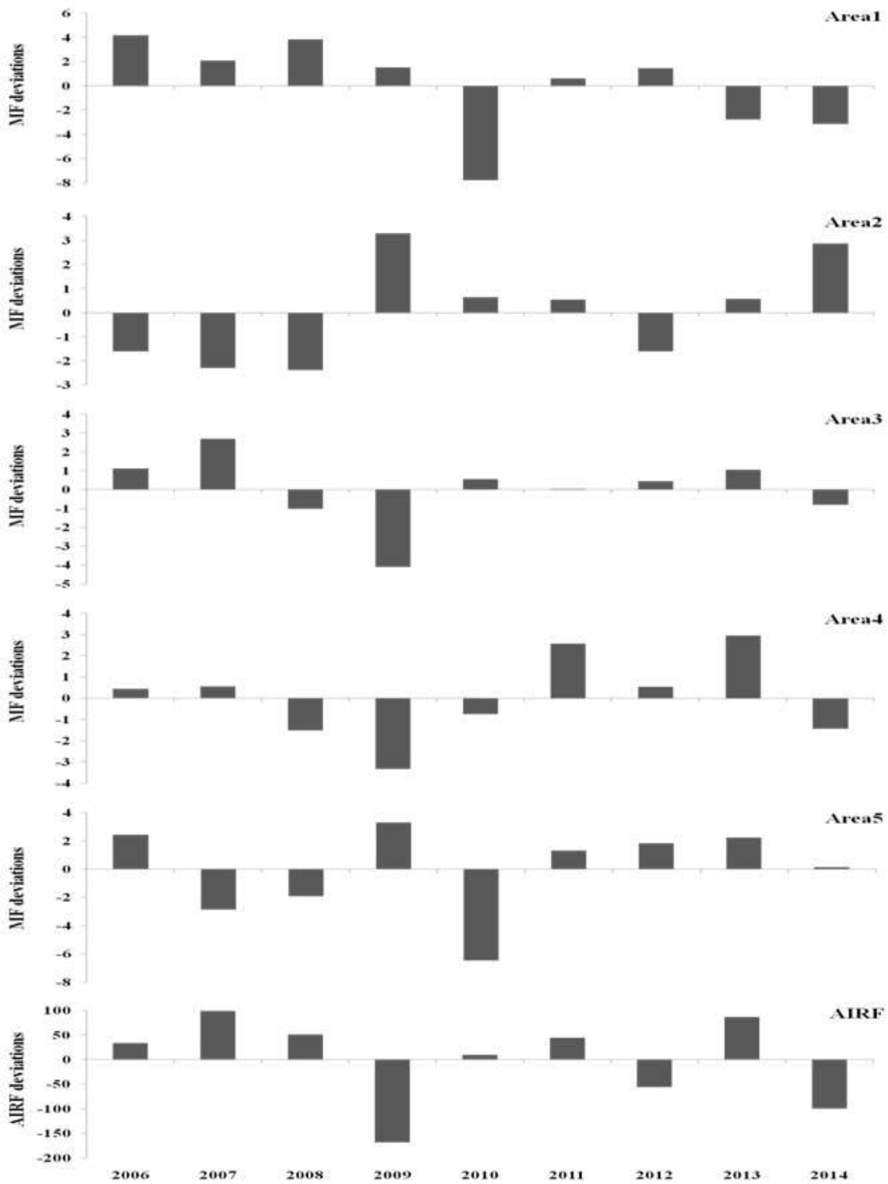

Fig. 4 — Monsoon seasonal variation (June through September) of Moisture flux at areas 1-5 and all India rainfall over the study period (2006-2014)

monsoon retrieved; CC (0.65) was lower than other months. ONI and MF indicated inverse relation in the monsoon month except in the month of July, which revealed positive relation (0.41). Area 5 seasonal MF and ISMR was having an inverse relation (CC= -0.34), however august month indicted a positive relation (CC= 0.45). ONI and MF are showed a positive relation in the monsoon months also seasonal (CC=0.86). This study revealed CCs in area 3 and 4 area having a positive relation between MF and ISMR and inverse relation between ONI and MF. However, the seasonal CCs revealed that area 3 MF was having higher positive (negative) relation with ISMR (ONI) than area 4. From the table 1, ONI indicated an inverse relation with area 3 and 4, and strong positive relation with area 1 and 5. An inverse relation between MF and ISMR over area 5 indicated that moisture transport varied its direction towards the eastern countries to bring rainfall; this may be due to northern part of the BOB having higher river discharge with lower SSTs.

Table 1 — Correlation coefficients of MF with AIRF and ONI over five study areas

MF Vs. AIRF	Area1	Area 2	Area 3	Area 4	Area 5
June	0.28	-0.33	**0.59**	**0.81**	-0.30
July	-0.31	-0.08	**0.56**	**0.75**	0.17
August	0.14	-0.16	0.47	**0.73**	**0.45**
September	-0.12	**-0.54**	**0.60**	**0.65**	-0.28
Seasonal *	0.08	**-0.70**	**0.81**	**0.72**	**-0.34**
Nino 3.4 SST (ONI) Vs. MF					
June	-0.10	0.13	**-0.56**	**-0.66**	0.33
July	0.46	**0.45**	0.13	0.41	**0.66**
August	**0.72**	0.02	**-0.48**	**-0.48**	**0.47**
September	**0.58**	-0.01	-0.30	-0.30	0.42
Seasonal *	**0.56**	0.24	**-0.51**	-0.32	**0.86**

* Seasonal is the mean of monsoon months (June through September) correlation of MF with AIRF and ONI

Variation of seasonal MF in relation with India rainfall

Figure 4 illustrates the variations of seasonal deviations of MF and ISMR during the study period. MF deviations of all the five areas represented the variations with respect to El Nino/La Nina/Normal years. Year 2006 was a weak El Nino year. All the five areas demonstrated positive deviations; however, in areas 1, 2, and 5 MF was higher than in areas 3 and 4. Lower MF clearly indicated at areas 3 and 4 during El Nino years. MF was lower and the transportation of moisture was less, which revealed in rainfall over India was normal. Year 2007 was a La Nina year (moderate), areas 3 and 4 illustrated positive MF anomalies and rainfall was higher over India. Year 2008 was a normal year and depicted higher positive deviations of MF over area 1. However, other areas had negative deviations and area 2 indicated stronger negative anomaly than other areas. ISMR revealed positive deviations, but lower than in 2007. This specifies that La Nina produced higher rainfall than normal year. Delayed El Nino event occurred in the year 2009 and India experienced a drought condition as revealed in ISMR. Negative deviations of MF can be observed in the areas 1, 3 and 4. However, areas 2 and 5 depicted positive deviations. In the year 2009, lower MF over areas 3 and 4 revealed that the moisture transport was lower than normal and leads to lower ISMR. Year 2010, illustrated negative MF deviations in areas 1 and 5 and positive deviations in other areas, however India experienced normal rainfall. The El Nino 2009 had delayed affect on 2010 rainfall over India. Delay in rainfall could be observed in 2010, even though onset of monsoon occurred, rainfall occurred in July and extended up to October. Year 2012 indicated lower than normal rainfall due to MF at areas 3 and 4. Year 2013 rainfall was more than normal, which revealed positive deviations of MF over all the areas. Mean seasonal variations clearly indicated that areas 3 and 4 were having higher influence on mean ISMR with a strong CC of 0.81 and 0.72, respectively. However, areas 2 and 5 seasonal MF were having an inverse relation with mean seasonal ISMR CC of -0.70 and -0.34, respectively.

This study signified that ISMR was having a positive relation in areas 3 and 4 and inverse relation in areas 2 and 5. During El Nino, areas 3 and 4 MF demonstrated lower values and the rainfall extended to October and also affects subsequent year's rainfall[35]. In the study period, year 2009 was a peculiar case of El Nino. Areas 3 and 4 indicated positive MF in July month and ISMR showed positive. Area 5 MF showed positive in June and decreased in July and attained negative in August. However, rainfall was lower than normal in June and became normal in July and further decreased in August and September.

Conclusion

MF is having relation with ISMR explicitly and clearly indicates that areas 3 and 4 is having momentous relation with ISMR, however area 5 MF has an inverse relation with ISMR. ONI is having an inverse (positive) relation with MF over areas 3 and 4 (areas 1 and 5). ONI is having an inverse relation with the ISMR and reduction in MF in areas 3 and 4 during El Nino years reduces rainfall over India. However, in La Nina higher rainfall confined to June to September months, and areas 3 and 4 indicating higher MF.

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