Relationship between the position and intensity of Low-Level Jet stream and Indian summer monsoon rainfall

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Abstract

A strong equatorial Low-Level Jet (LLJ) exists over the Indian Ocean plays a crucial role in modulating the Indian Summer Monsoon Rainfall (ISMR). The variation in strength and height of Monsoon LLJ (MLLJ) can provide an important lead in predicting the variations in ISMR. The variability of MLLJ is examined using the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis ERA-5, National Centers for Environmental Prediction-Climate Forecast System Reanalysis (NCEP-CFSR) / Climate Forecast System, version 2 (CFSv2) and the Modern-Era Retrospective Analysis for Research and Application, version-2 (MERRA-2) during 40 years period (1979–2018). The results suggest that there is an increasing trend in MLLJ strength during July and September, but a decreasing trend during August. The MLLJ level showed an upward trend (increase in height from the surface level) in all the reanalysis data sets. The ISM rainfall over Western Ghats region and central India showed strong positive (and negative) correlation with the MLLJ strength (and height) except during August. It is noted that the influence of the MLLJ on rainfall over the Indian subcontinent is stronger during the onset and withdrawal phases of monsoon. The increasing trend in MLLJ height indicated the possibility of increase in rainfall over many regions in India especially Western Ghat and Central India. The relationship between MLLJ strength and level with ISMR is strongest during the month of September. Our analysis also showed that lag correlation between MLLJ and ISMR is relatively weaker when compared to zero lag correlations.

1. Introduction

The Indian summer monsoon rainfall (ISMR) accounts for nearly 70–90% of the annual precipitation of India, which is highly interlinked with the socio-economic life of Indian people in many ways (Webster et al. 1998; Zimmermann 1987, Shukla and Huang, 2016). The winds from Arabian Sea bring great amount of moisture and rainfall over the Indian region during June-September (JJAS) months. Due to vagaries of the monsoon, the variations in the intensity and amount of rainfall may cause droughts or sometimes instant excessive floods in different regions of India; consequently it may cause major socio-economic impacts (Mohapatra et al. 2021). The Asian summer monsoon circulation during JJAS is prominently controlled by the two components, the monsoon low-level jet (MLLJ) and the tropical easterly jet (TEJ), which govern the large-scale spatio-temporal distribution and variability of the ISMR. A strong cross equatorial low level jet stream governs the variability in ISMR over India, which prevails over the Indian Ocean of South Asia with its core close to 850 hPa. This cross-equatorial flow brings the evaporative flux from the Arabian Sea and the moisture generated by the trade winds over the south Indian Ocean and adjoining south Asia, known as MLLJ or Somali Jet or Findlater jet (Findlater, 1969, Naidu et al. 2011). It develops during the onset phase of the summer monsoon and its strength and position can provide a crucial lead in the intensity and variation of the ISMR. The MLLJ is instigated by differential heating between the latitudes 20N and 20S, which induces pressure gradient forces between the heat low areas over the Indian subcontinent and high pressure zone Mascarene High (Krishnamurti and Bhalme, 1976). Emerging in April above the Somali coast region, the MLLJ turns westerlies in the northern hemisphere, and then drifts over the Indian region during JJAS (Boos and Emanuel, 2009). These MLLJ winds are responsible for transport of moisture from Southern Hemisphere to Northern Hemisphere, nurturing the formation of monsoon inversion layers over the western Arabian Sea and therefore, modulating the amount of rainfall in the Indian sub-continent (Sathiyamoorthy et al., 2013; Dwivedi et al., 2016; Roxy et al. 2017). Joseph and Raman (1966) provided observational evidence for the existence of cross equatorial flow or MLLJ over the peninsular India.

The MLLJ flows eastward over peninsular India at latitude 15°N during active monsoon; whereas it flows southeastward from the central Arabian Sea and moves eastward near to Sri Lanka at latitude between equator and 10°N (Joseph and Sijikumar, 2004). The formation of vertical upward air motion and monsoon depressions over the North Bay of Bengal (BOB) is primarily aided by cyclonic vorticity (rotation of air) north of MLLJ axis over South Asia (Joseph and Simon, 2005). Generally during monsoon season (JJAS), the monsoon depressions originate over the North BOB and moves in northwesterly direction over the Ganges valley up to the central parts of the country before incapacitating. However, the existence of a strong MLLJ over peninsular region of India favors the generation of these monsoon depressions in the North BOB (Sikka, 1978). Halpern and Woiceshyn (1999) observed that the easterly flow of MLLJ strengthens the surface wind convergence and therefore, increases the amount of integrated cloud liquid water along eastern Arabian Sea, which leads to increase the rainfall over the west coast of India.

The diurnal, intra-seasonal and inter-annual variation of MLLJ directly influences the Indian summer monsoon rainfall (Wang et al. 2003; Joseph and Sijikumar 2004; Wilson et al. 2018). Wang et al. 2003 showed that the variations in the intensity of MLLJ will directly affect the amount of water vapor through cross equator flow transported to South Asian and East Asian monsoon regions, which modulates precipitation. This moisture contribution along the MLLJ is mainly due to the northwestwards propagation of the monsoon depressions in JJAS (Sandeep and Ajayamohan, 2015). MLLJ shows distinct diurnal variability with respect to both intensity and height of jet, which is maximum during 0000 UTC and 0600 UTC with maximum wind speed (> 24 m/s) over the western Arabian Sea, vertically ranging from 950 to 850hPa (Nair et al. 2015; Viswanadhapalli et al 2020).

Halpern and Woiceshyn, 2001 found that the intensity of MLLJ influences the magnitude of the rainfall along the Indian west coast on monthly scale. Viswanadhapalli et al. 2020 have studied MLLJ by using WRF model initialized by ERA-Interim data and showed that MLLJ attains its maximum strength and spatial extent in July and August, this might be due to the merging of orographically driven winds from the Red Sea in MLLJ. Joseph and Sijikumar, 2004 found that there is high correlation with a lag of 2–3 days between the strength of the convective heating over the BOB and the strengthening of the MLLJ through peninsular India. On both seasonal and sub-seasonal scales, the variability of the MLLJ is highly correlated with average ISMR (> 95% confidence) except over the regions of extreme north, northeastern India and Tamilnadu (Viswanadhapalli et al 2020).

On inter-annual timescale, it is reported that the MLLJ strength over Indian subcontinents depends on the convective heating of the atmosphere rather than the strength of the south Indian Ocean trade winds

(Wilson et al. 2018). A significant increasing trend (0.08 mm day per decade) in the monsoon rainfall over Northern Hemisphere has been observed as a result of the increased meridional pressure gradients, which leads to increased moisture convergence and enhanced the cross-equatorial flow from Southern to Northern Hemisphere along with intense rainfall over the Asian monsoon regions (Wang et al., 2013). MLLJ seemed to shift pole ward due to the increased land-sea thermal contrast because of global warming which subsequently shift associated rainfall over the Indian region (Sandeep and Ajayamohan, 2015). Krishnamurthy and Ajayamohan (2010) showed that the low-level southwesterly winds and monsoon trough strengthen the moisture transport from Arabian Sea towards the Indian subcontinent, which provides evidence for the intensification of rainfall over central India. Wilson et al. 2018 reported that there is a statistically significant decreasing linear trend in monsoon mean zonal wind through Peninsular India, which is associated with a decrease in the frequency of monsoon depressions and an increase in the number of break monsoon days. Aneesh and Sijikumar (2016), using different reanalysis data sets (ERAI, NCEP2, and MERRA), showed an increasing trend in the MLLJ during July and September. Viswanadhapalli et al. 2020 used WRF model simulations to show that the strength of the MLLJ has a significant decreasing trend in August, which combined with the decrease in the number of depressions in BOB cut off the ISMR during August and this happens as a result of reduced moisture transport from the BOB and Arabian Sea, which further leads to an increase in the number of break conditions over India. A threefold increase in the number of extreme rainfall events over central India has reported, which is significantly associated with the variations in MLLJ over the Arabian Sea (Roxy et al. 2017)

Though earlier studies focused on influence of MLLJ variability on ISMR, this study focuses on the relationship of inter-annual and intra-seasonal variability of the MLLJ (Monsoon Low Level Jet) strength and height with ISMR. We examined variation in MLLJ strength and height in the Arabian Sea during monsoon months and studied its impact on monthly monsoon rainfall. The study is structured as follows. Section 2 describes the data used for the study. Section 3 discusses the inter-annual variability of MLLJ and its impact in ISMR with lag0 days, lag 14 days and lag 1 month. Section 4 illustrates the key findings of this study and concludes the remarks.

2. Data And Methodology

This study has used the monthly mean zonal wind profile and daily zonal wind profile over the Indian monsoon region during 40 years (1979–2018), obtained from three reanalysis namely the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis ERA-5 (Hersbach et al., 2020), NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) / Climate Forecast System, version 2(CFSv2) (Saha et al. 2014) and the Modern-Era Retrospective Analysis for Research and Application, version-2 (MERRA-2) (Gelaro et al., 2017). ERA-5 is at 0.25˚×0.25˚ horizontal resolution and 137 vertical pressure levels from surface to 0.01hPa, whereas NCEP-CFSR (1979–2010)/ CFSv2 (2010-present) is at 0.5˚×0.5˚and 40 vertical pressure levels from surface to 1hPa and MERRA-2 data is at 0.5˚×0.625˚ horizontal resolution and 72 vertical pressure levels from surface to 0.01hPa. We used

0.25°×0.25° all India-gridded daily rainfall data for the summer monsoon season (June to September) for the period 1979–2018 from India Meteorology Department (IMD) (www.imdpune.gov.in). This gridded data is generated from the daily rainfall records of 6995 rain gauge stations (Pai et al. 2014).

In this study, portion of the Indian Ocean (0°N- 20°N, 40°E- 80°E) where cross equatorial flow is prominent has been taken as the core domain of MLLJ (Figure-1). The MLLJ strength is calculated by taking an average of zonal wind speed over the domain of MLLJ and then taking the maximum over the vertical pressure levels (700hPa to 1000hPa) for each year. The MLLJ height is considered as the height which the MLLJ speed is maximum over the core domain for each year. In this study, we have analyzed the height in terms of the vertical pressure level. Since the pressure decreases with the increasing height, to avoid the ambiguity, we used MLLJ level while interpreting the results. The monthly rainfall in June, July, August and September over India is calculated by adding the daily rainfall data for respective month. In order to examine the relationship between MLLJ and ISMR we computed the spatial correlation between the anomalies in MLLJ strength/level and monthly rainfall.

3. Results

3.1 The inter-annual variability of MLLJ

The inter-annual and intra-seasonal variability of the MLLJ strength and height has been analyzed for four monsoon months (June, July, August, and September) during the period of 40 years (1979–2018) using ERA-5, NCEP-CFSR and MERRA-2 data sets (Figure-2). It is noted that MLLJ strength attains its maximum (between 8–12 m/s) in the months of July and August (active phase of ISM), and a minimum (between 3–6 m/s) in September. The winds are predominantly westerly at the lower level during June, July and August and then the transition in this lower region from westerly to easterly takes place by end of the September and continue to prevail in winter months (Rachith et al. 2016). This transition might be the reason for the weakening of MLLJ during September. The time series of MLLJ strength during 40 years does not show any significant trend during June in all the three data sets; slight decreasing trend is seen with ERA-5 and CFSR datasets, but slight increasing trend with MERRA-2 (Figure-2). Increasing trends in MLLJ is seen for the months of July and September in all the data sets with most significant trend is seen with MERRA-2 dataset. Trends in MLLJ strength are negative, in general, for the month of August with a significant negative trend observed in CFSR dataset.

The MLLJ level (Figure-3) has been observed between 850–900 hPa in ISMR months, but its position is slightly lower (900–950 hPa) during September. It is reported earlier that the MLLJ core heights and maximum wind speeds are positively correlated (Emeis, 2014) means higher position of MLLJ is associated with stronger winds and vice versa. Relatively lower position of MLLJ core during September concurs with lower strength of MLLJ in September as noted above. Significant positive trend (more than 95% confidence) is observed in MLLJ level for all the four ISMR months indicating a relatively higher position of MLLJ and a possible strengthening of prevailing high strength westerly winds in the coming years. Since the MLLJ is strongly influenced by land–sea temperature contrast and the associated surface pressure difference between the high-pressure areas exists over the south Indian Ocean and the low-pressure area exists over the Indian subcontinent, changes in MLLJ may be strongly correlated to the surface temperature and pressure changes over the Indian region. Many studies reported that during ISM months, an increase in land-surface temperature is observed over western India and the Himalayan foothills region during June, over the northern India during July and over the northern and north-western regions during August and September (Prakash and Narouji, 2020;Aneesh and Sijikumar, 2016), while average monthly surface temperature showed significant increasing trends in southern and central India (Chakraborty et al., 2016; Viswanadhapalli et al., 2019). The increase in land-surface temperature can intensify the low-pressure exists over the region, which can lead to the increasing trend in strength and level of MLLJ during the four ISM months. The MLLJ strength has a high and significant linear correlation coefficient with the convective heating of the atmosphere over the BOB (Joseph and Sijikumar, 2004). The significant decreasing trend in the convection over the west coast of peninsular India and the eastern BOB region can be attributed to weakening MLLJ (Aneesh and Sijikumar, 2016).

3.2 Relationship between variability of MLLJ strength and ISMR

The MLLJ plays a crucial role in the moisture transport and associated rainfall in monsoon months over India (Halpern and Woiceshyn, 2001; Izumo et al., 2008). Correlation analysis is carried out between anomalies in MLLJ strength and rainfall during each ISM months for a period of 40 years by comparing winds from ERA-5, NCEP-CFSR and MERRA-2 reanalysis datasets with IMD observed rainfall. Positive correlation between MLLJ strength and all India averaged rainfall is observed during four ISM months (JJAS), significantly (99% confidence)during June, July and September (Table-1). To examine the effect of MLLJ strength on monsoon rainfall over the Indian region, the spatial correlation analysis between the monthly MLLJ strength and the monthly ISMR is carried out (Figure- 4). Strong positive correlation (95% confidence) between MLLJ strength and ISM rainfall is observed in all the three reanalysis datasets except for the month of August. There is a clear and significant positive correlation between MLLJ strength and rainfall during June over the central and eastern part and many pockets of Western Ghats. The MLLJ strength in July showed significant positive correlation with July rainfall over the Western Ghats and central India. The July rainfall in some pockets over the north India also showed positive correlation with MLLJ, whereas many patches of north-eastern India rainfall have negative correlation with MLLJ strength in July. MLLJ strength is positively correlated with rainfall during August over small pockets over the central India while over the north-east India and a small portion of south India, the correlation is negative. Strong positive correlation between MLLJ strength and rainfall in September has been seen in Western Ghats, from western India to eastern India and north India. There is hardly any significant negative correlation between MLLJ strength and rainfall observed in September. In fact, the MLLJ strength had strongest positive correlation relationship with ISM rainfall during the month of September. Correlation between MLLJ strength and rainfall is not much significant over the south east, North West, and north eastern part of India for all the ISM months.

Above results indicate that the variation in MLLJ strength affects rainfall pattern over India on sub-seasonal scale. It clearly leads to an increase in rainfall over the positively correlated regions and a decrease in rainfall over the negatively correlated areas except for the month of August. The trend in MLLJ strength is observed to be significantly increasing in July and September, which points to the possibility of increasing trend in July and September rainfall the central India and western Ghat. The declining trend of MLLJ strength in August has profound influence on the decreasing rainfall over central India in August which is consistent with earlier findings (Viswanadhapalli et al. 2020). It is observed that the MLLJ strength in June and September month showed stronger positive correlation with rainfall (especially central India and eastern India) of these months than the month of July and August. This indicates that MLLJ plays more crucial role to alter the rainfall pattern over the Indian subcontinent during onset and withdrawal months. The rainfall in the Western Ghats regions is observed to have a strong positive correlation with the strength of MLLJ in July and September, which points to the possibility of an increase in rainfall over the Western Ghats in those months. It is noted that the strength of MLLJ is not much correlated to the peninsular India (except the Western Ghats) rainfall, compared to central and north India; the recently reported (Sandeep and Ajayamohan, 2015) northward shift of MLLJ may be the possible reason for this. The rainfall over the northeast India is negatively or weakly correlated with MLLJ strength indicating that monsoon rainfall over this region is relatively less dependent on MLLJ and more likely influenced by BOB branch of monsoon and localized convection. The regions in south India like Tamilnadu, South interior Karnataka, where the North-East monsoon is prominent, showed strong negative correlation in June and August.

3.3 Relationship between variability of MLLJ level and ISMR

The above discussion showed that MLLJ strength is found to have positive link with ISMR. However, there are hardly studies which discussed the impact of the variation in MLLJ height on the ISMR. Our analysis showed that a significant negative correlation exists between MLLJ level and all India average rainfall for all the four ISM months (Table-2), indicating that an uptrend in MLLJ level coincides with increase in ISMR. As discussed earlier (Emeis, 2014), an uptrend in MLLJ level indicates increasing trend in MLLJ strength and vice versa. Hence, the increasing trend observed in MLLJ strength in the previous section can be attributed to the uptrend in MLLJ level. An uptrend in MLLJ level associated with stronger winds indicates the possibility of increase in the ISMR during these months. The spatial distribution of anomaly correlation between June MLLJ level from different reanalysis and June rainfall over India indicated negative correlation in Western Ghats and north India irrespective of data sets (Figure-5); implies that June rainfall was lower over these regions during the years when MLLJ position was lower compared to its mean position and vice versa. In July, there is significant negative correlation in Western Ghats and central India (more prominent in ERA-5 data) while positive correlation observed in north eastern region (more prominent in MERRA-2). There is no significant correlation during August, except the negative correlation over the west coast and Western Ghats. In September, a strong negative correlation extends from western India to eastern India, including the Western Ghats is observed with all data sets. It is noted that MLLJ level has significant negative correlation with the rainfall over the Western Ghats in all the four ISM months. It is found that MLLJ strength as well as height is not much correlated with rainfall over the south India except Western Ghats.

3.4 Lag correlations between MLLJ and ISMR

To see the influence of pre-monsoon MLLJ strength and height on monsoon rainfall, we examined one month lag anomaly correlation between MLLJ and monthly rainfall. The spatial lag-1 month anomaly correlation analysis of MLLJ strength (May, June, July and August) and monthly rainfall (June, July, August and September) is carried out. The time series of MLLJ strength for May showed that there is an increasing trend in its strength during May (though a significant trend is seen only in MERRA data) and as expected, the strength of MLLJ is weak as the monsoon cross equatorial flow is more prominent only in the second half of May (Figure- 6). It is noted that there is significant upward trend (strongest in MERRA data) in MLLJ level during the month of May in all the three reanalysis data.

The lag – 1 month correlation between MLLJ strength and all India average rainfall for each JJAS month (Table-3) showed that there is positive correlation in June and negative correlation in other three months for all reanalysis data sets. From the spatial correlation plot (Figure-7), it is clear that there is significant positive correlation in central India and negative correlation in some pockets of south India and northern India during June. However, there is significant negative correlation over Western Ghats and south west India region and positive correlation over some pockets of north India in September. There is no significant one-month lag correlation between MLLJ strength and rainfall during July and August (not shown). These results show that the lag-1 month MLLJ strength mostly affects the rainfall during the onset and withdrawal phases of monsoon. The lag-1 month correlation of MLLJ level and monthly rainfall is mostly negative (Table-4). The spatial plot of lag – 1 month correlation of MLLJ level and JJAS months showed that significant correlation exists only in the month of June over the central India (Fig. 8) and there is hardly any significant correlation for rest of the months (not shown). From lag-1 month analysis, we have found that the lag – 1 month MLLJ strength and level has lesser influence on the pattern of rainfall over Indian region in ISMR months.

We also analyzed the influence of lag – 14 days MLLJ strength and level on monthly ISM rainfall by computing the lag – 14 days anomaly correlation of MLLJ strength (and level) with the monthly rainfall. The lag – 14 days correlation between MLLJ strength and all India average rainfall is positive in June and August, whereas it is negative in July and September (Table 5). The spatial correlation plot for lag – 14 days showed that the strength of MLLJ has significant positive correlation with the June rainfall over central India, but has significant negative correlation over some pockets in south India and upper north part of India (Fig. 9). In July, negative correlation is found over the Western Ghats and south east India while positive correlation is observed upper side of east India. However, in August, the areas having significant correlation is relatively less except some region in north India. In September, there is significant positive correlation observed in east and north-east India, while a large area in west and south-west India showed a strong negative correlation.

There is a negative correlation between lag – 14 days MLLJ level and all India average rainfall for each month (significant in June and August) in all three reanalysis datasets (Table 6). The spatial anomaly correlation plot of monthly rainfall and lag – 14 days MLLJ level for ISM months (Figure-10) showed a negative correlation in central India and some region of north India, however positive correlation over upper region of north India in June (nor clear in CFSR data). Correlation is much weaker during July and there are no consistent significant correlation patterns among the three reanalysis datasets. In August, there is strong negative correlation over north–western region of India (more prominent in ERA-5 data). The September rainfall is positively correlated with lag – 14 days MLLJ level over south west India. The correlation is positive over the northern most part and eastern part; however, the correlation patterns are not strictly consistent among the three reanalysis datasets. These results indicate that the variability of MLLJ strength and level 14 days prior to respective monsoon months has influence on ISMR distribution.

4. Conclusion

The pressure gradient force between the low pressure zone over the Indian subcontinent and the Mascarene high pressure zone develops and maintains the monsoon low-level jet (MLLJ) during Indian Summer Monsoon (ISM). It plays an integral role in bringing moisture towards the Indian subcontinent during ISM (June-September). Understanding the characteristics and variability of this monsoon circulation provides an important lead to understand the variations in ISMR over the different regions of Indian subcontinent. This study analyses the variability of MLLJ strength and height and its impact on ISM (June-September) rainfall during 40 years (1979–2018) using ERA-5, NCEP-CFSR, and MERRA-2 data sets. In general, our analyses showed that the MLLJ strength is positively linked with ISMR, whereas the MLLJ level is negatively linked with ISMR. This implies that monsoon rainfall increases with increase in MLLJ strength and vice versa. Similarly, an uptrend in MLLJ level (relatively higher position from surface) leads to increase in ISMR and vice versa. MLLJ plays more crucial role to alter the rainfall pattern over the Indian subcontinent during the onset and withdrawal phases.

An upward trend in MLLJ level during ISMR indicates strengthening of prevailing westerly winds during monsoon. Strong positive correlation (95% confidence) between MLLJ strength and rainfall is observed during ISM months except during August. A clear and significant positive correlation is observed between MLLJ strength and rainfall over the central-eastern part of India and many pockets of Western Ghats except during August. However, the correlation is not significant over the south east, north-west, and north eastern part of India. The MLLJ strength shows hardly any correlation with rainfall over South India except Western Ghats. The increasing trend in MLLJ height indicated the possibility of increase in rainfall over many regions in India especially Western Ghat and Central India. The MLLJ has relatively more profound influence rainfall pattern over the Indian subcontinent during the onset and withdrawal phases of monsoon. It is noted that MLLJ level has significant negative correlation with the rainfall over the Western Ghats in all the four ISM months. The relationship between MLLJ strength and level with ISMR is strongest during the month of September. Our analysis showed that lag anomaly correlation between MLLJ and ISMR is relatively weaker when compared to zero lag correlations. The lag – 14 days MLLJ strength showed strong positive correlation with the June rainfall over central India while lag – 14 days

MLLJ level is negatively correlated with all India average rainfall for different ISM months. This study is indicating MLLJ strength as well as level influences the ISMR intensity and distribution over the Indian subcontinent. This shows that the variability of MLLJ strength and level can be an important precursor for predicting ISMR distribution and it has huge implications in while predicting monsoon rainfall using numerical and statistical models.

Declarations

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Figures

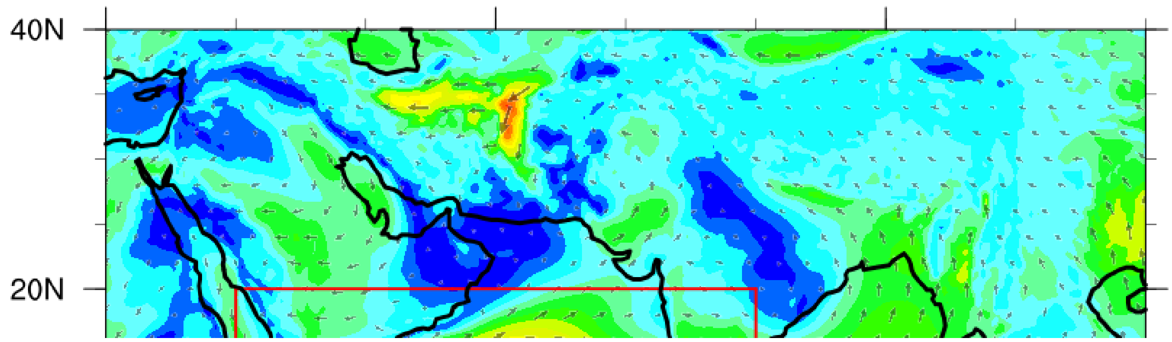

Figure 1

The mean winds for the month of Juneover the studyarea. The region considered for computing the variability in MLLJ strength/level is marked as red box.

Figure 2

Long term trend in MLLJ strength from ERA-5, NCEP-CFSR and MERRA-2 reanalysis datasets(* showing 90% significance, ** showing 95% significance and ***showing 99% significance)

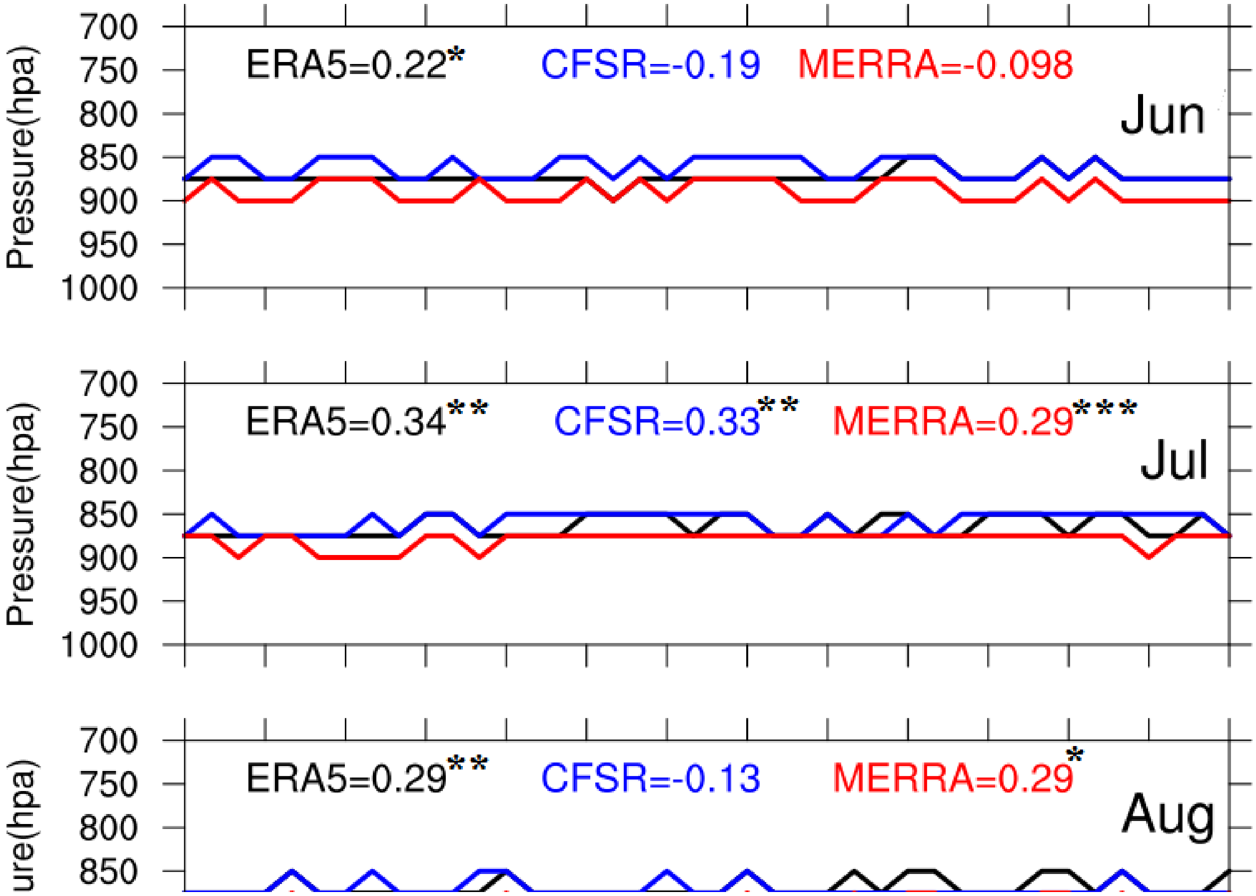

Figure 3

Long term trend in MLLJ position from ERA-5, NCEP-CFSR and MERRA-2 reanalysis datasets (* showing 90% significance, ** showing 95% significance and ***showing 99% significance)

Figure 4

The spatial correlation between the anomalies in MLLJ strength and Rainfall for June (upper panel), July (2^{nd} panel), August (3^{rd} panel) and September (lower panel). Correlation above 95% significant level is only shown.

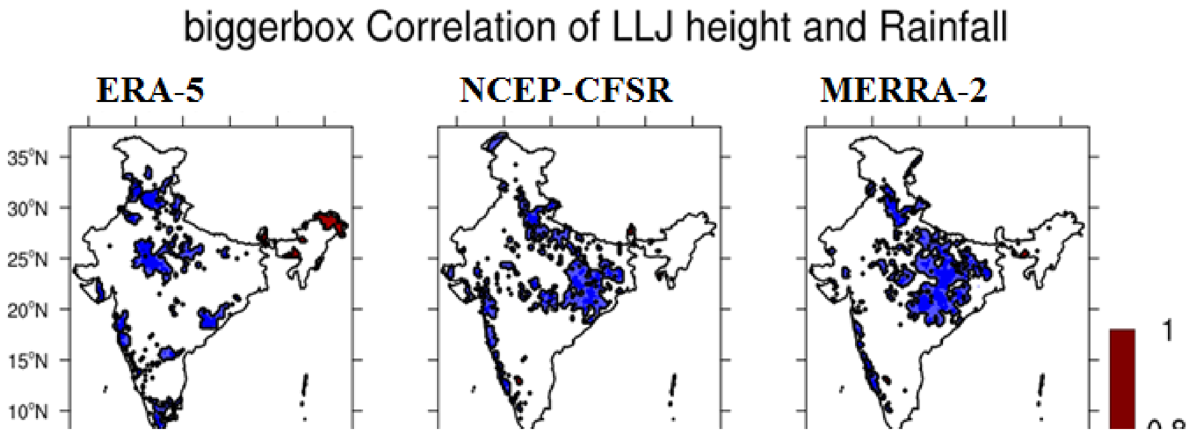

Figure 5

The spatial correlation between the anomalies in MLLJ level and Rainfall for June (upper panel), July (2nd panel), August (3rd panel) and September (lower panel).Correlation above 95% significant level is only shown.

Figure 6

Long term trend in MLLJ strength (upper panel) and position (lower panel) for May from ERA-5, NCEP-CFSR and MERRA-2 reanalysis datasets (* showing 90% significance, ** showing 95% significance and ***showing 99% significance)

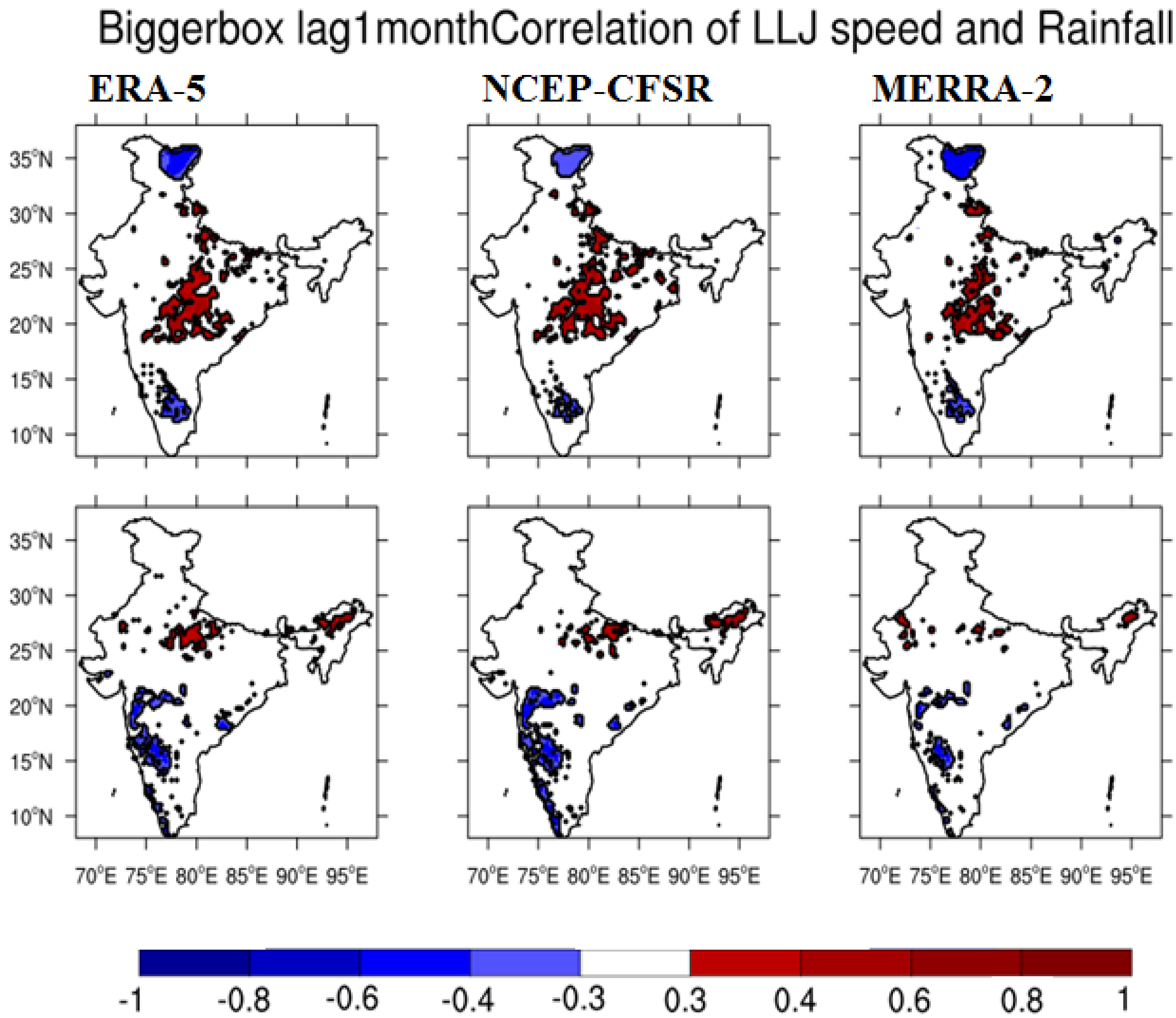

Figure 7

The lag -1 month spatial correlation between the anomalies in MLLJ strength and rainfall for June (upper panel) and September (lower panel). Correlation above 95% significant level is only shown.

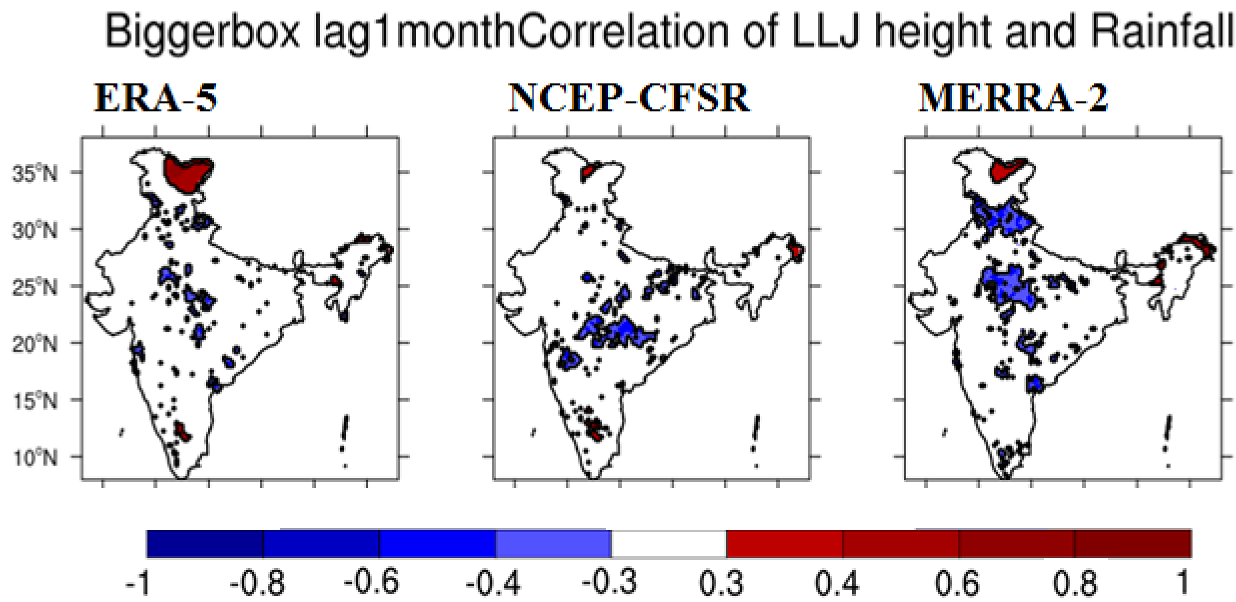

Figure 8

The lag -1 month spatial correlation between anomalies of MLLJ level and rainfall for June. Correlation above 95% significant level is only shown.

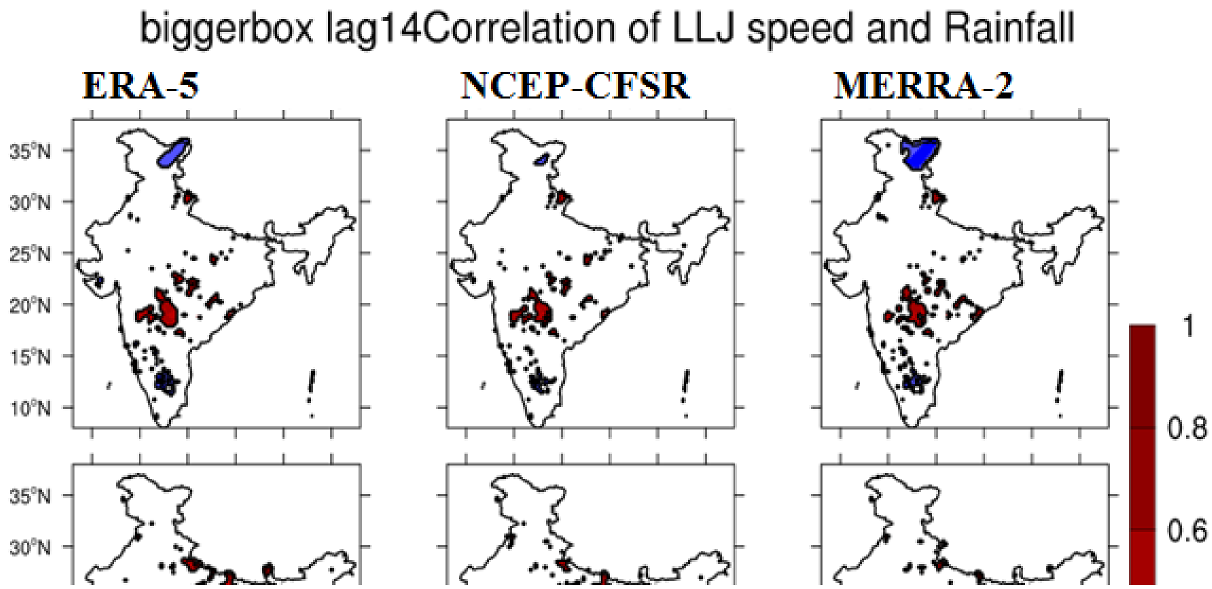

Figure 9

The spatial lag -14 days correlation between anomalies of MLLJ strength and rainfall for June (upper panel), July (2nd panel), August (3rd panel) and September (lower panel). Correlation above 95% significant level is only shown.

Figure 10

The lag -14 days spatial correlation between the anomalies in MLLJ level and rainfall for June (upper panel), July (2nd panel), August (3rd panel) and September (lower panel). Correlation above 95% significant level is only shown.