Academia Journal of Environmetal Science 6(10): 215-222, October 2018
DOI: 10.15413/ajes.2018.0148
ISSN: ISSN 2315-778X

Research Paper

The influence of near surface atmospheric wind convergence on precipitation over Indian summer monsoon region: A statistical analysis

Accepted 11th October, 2018

ABSTRACT

Converging winds enhance convective activity and increase moisture in the atmosphere through evaporation, which eventually increase regional precipitation. Thus a concurrent relationship exist between atmospheric wind convergence and rainfall. Hence, it becomes important to assess the strength and location of atmospheric wind convergence. Tropical Indian Ocean (TIO) has large-scale convergence zones which plays an important role in regulating moisture and modulating rainfall over Indian land and oceanic regions. In this study, an attempt is made to assess the relationship between precipitation and near-surface divergence/convergence of wind and identify such regions with strong association of these parameters over TIO. The correlation coefficient observed for the month of June, July, August and September are 0.62, 0.63, 0.57 and 0.69, respectively for Equatorial Indian Ocean (EIO) box. Similarly, a correlation coefficient of 0.61, 0.86, 0.46 and 0.68 was observed for the month of June, July, August and September over Arabian sea (AS) region. From this analysis, it can be observed that EIO shows consistent and stable correlation between wind convergence and surface rainfall during the summer monsoon months.

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Key words: Precipitation, wind convergence, tropical Indian ocean, summer monsoon.

INTRODUCTION

Indian Summer Monsoon (ISM) is one of the main components of large-scale Asian Summer Monsoon. Monsoon is mainly controlled by the temperature gradient between land and ocean, large availability of moisture from the Indian Ocean, rotation of Earth, and the solar radiation (Webster et al., 1998; Meehl, 1997). During the summer monsoon season, south westerly winds pick up large amount of moisture from Arabian sea (AS) and Bay of Bengal (BOB) and flow to the Indian sub-continent. These moisture laden winds are responsible for the overall seasonal rainfall over Indian sub-continent and it exhibit converging and diverging patterns over different oceanic regions adjoining Indian landmass. Such regions are referred to as atmospheric convergence/divergence zones (Luis and Pandey, 2004). Converging zones often indicate the location and amount of cloud cover and rainfall in the tropics. The position of these zones have a major influence on rainfall in certain areas and hence, their composite picture reflects the state of the tropical atmosphere (Philander, 1990).

The flow generated by the latent heat release in cumulus clouds is an important component of the low-level convergence below the determinant level of the trade inversion and is largely proportional to the amount of cumulus convection and rainfall (Lindzen and Nigam, 1987). Some numerical simulations (Shukla and Wallace, 1983; Stone and Chervin, 1984) of the atmosphere also revealed that precipitation anomalies are primarily associated with anomalous low-level moisture convergence rather than anomalies in evaporation. The ascending branches of Hadley circulations, associated with the convergence of the north-easterlies from the northern hemisphere and south-easterlies from the southern hemisphere are the best examples of atmospheric convergence and these zones are broadly called "Inter-Tropical Convergence Zone (ITCZ)". Liu and Xie (2002) reported the evidence for the existence of ITCZ on either side of the equator using QuikSCAT derived ocean surface wind. As these zones migrates seasonally, it exhibit inter-annual variations, which has a major effect on local precipitation (Philander, 1990). In particular, the northsouth movement of the ITCZ in the Tropical Indian Ocean (TIO) is vital to the modulation of Indian summer monsoon rainfall, while its eastwest movement affects the local precipitation (Luis and Pandey, 2004). Pisharoty (1965) and Saha (1974) reported that Air-sea interactions over the AS is one of the important factors in explaining fluctuations in the intensity of the monsoon circulations and associated rate of precipitation over India. Since a substantial function of the moisture precipitating as monsoon rainfall comes from the Arabian sea, it is reasonable to expect that the Sea Surface Temperature (SST) and sea surface wind anomalies over the AS have pronounced effects on the monsoon rainfall over India (Shukla and Misra, 1977). Luis and Pandey (2005) showed that ocean surface wind driven Near Surface Atmospheric Wind Convergence (NSAWC) has a noticeable effect on ISMR over AS and BOB. McMurdie et al. (1987) showed that Seasat-A Satellite Scatterometer (SAAS) derived convergence/divergence patterns of wind are consistent with the water vapor and rain rate patterns from the Scanning Multichannel Microwave Radiometer (SMMR) for the mid-latitude cyclones.

Recently, Prakash and Gairola (2013) analyzed the relationship between northeast monsoon rainfall and near-surface atmospheric wind convergence over the North Indian Ocean using multi-satellite data. They suggested that near surface atmospheric wind convergence (NSAWC) has great potential in understanding the north eastern monsoon rainfall variability. The horizontal mass convergence is directly proportional to moisture flux convergence and more appropriate diagnostic for convection initiation and can be used for rainfall forecasting at synoptic scale (Banacos and Schultz, 2005).

Luis and Pandey (2004, 2005) first mapped the NSAWC and divergence patterns over the Indian Ocean using scatterometer wind vectors and showed a linear relationship between NSAWC anomalies over the AS and BOB and summer monsoon rainfall over the west coast of India and Gangetic West Bengal, respectively. The relationship between wind driven convergence and rainfall over Tropical Indian Ocean (TIO) is poorly documented.

In this study, an attempt was made to investigate the relationship between convergence/divergence of winds and surface rainfall rate with the help of meteorological satellite data. This study is intended to examine the possibility of quantitatively assessing the relationship between these two variables. This study can also act as a preliminary assessment of using convergence as an indicator for predicting the monsoon rainfall.

MATERIALS AND METHODS

Reanalyzed near surface wind vectors are available in 0.5° × 0.5° latitude/longitude spatial resolution at four synoptic hours namely: 0000, 0600, 1200 and 1800 UTC respectively from era-interim product. The NSAWC over Indian Ocean are computed using the method described by Luis and Pandey (2004, 2005):

$$C = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{1}$$

Where u and v are zonal and meridional wind components in ms^{-1}; positive (negative) values of C indicate divergence (convergence).

To relate with daily and monthly rainfall, NSAWC is temporally averaged to daily and monthly scales. To investigate the relationship between NSAWC and rainfall, linear regression is employed and linear association between them is computed over region of interest. The sub-regions considered here are Equatorial Indian Ocean (EIO) spanning 0° to 10° S and 60° to 100° E, AS spanning 7° N to 20° N and 67° to 76° E and BOB spanning 10° N to 22° N and 82° to 95° E (Figure 1). The pixels corresponding to oceanic coordinates are only considered in each sub-regions for computing linear association. During the South West (SW) monsoon heavy rainfall is expected over much of the northern Indian Ocean including the eastern AS and BOB due to the transport of moisture from south Indian Ocean to the south Asian land mass.

TRMM multi-satellite precipitation analysis (TMPA)-3B42

The Tropical Rainfall Measuring Mission (TRMM) is a joint US-Japan Satellite Mission to monitor tropical and sub-tropical precipitation and allied parameters. It was launched in November, 1997 to a near circular orbit approximately at 350 km altitude (raised to 403 km since 2001) at 350 inclinations from the equatorial plane. After 17 years of productive service in space, the instruments of TRMM was switched off on April 8th, 2015. The TMPA-3B42 version-7 (V7) is a standard and gauge-adjusted rainfall product derived using geostationary infrared data and microwave observations (Huffman et al., 2007) available at 0.25° x 0.25° latitude/longitude spatial resolution and at different temporal resolutions (3-hourly, daily). The data from TRMM satellite are archived and distributed by the National Aeronautics and Space Administration (NASA)

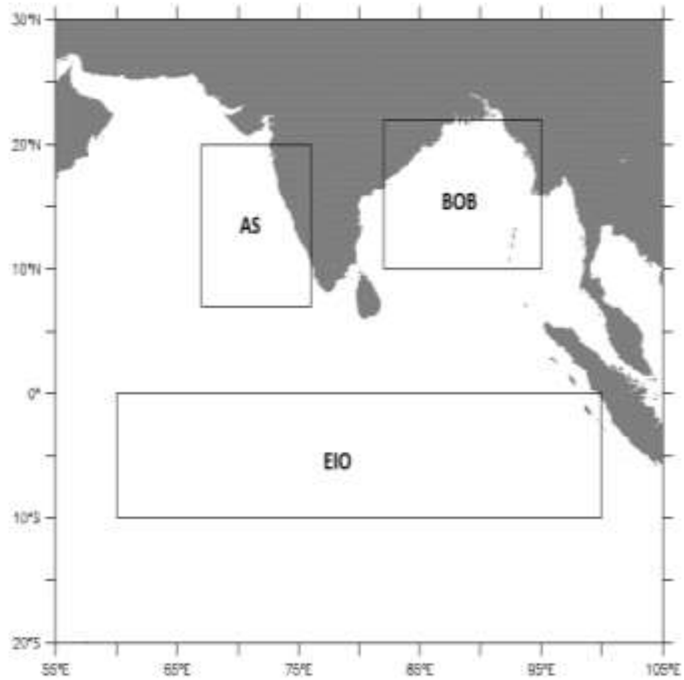

Figure 1: The three boxes representing EIO, AS and BOB sub-regions.

Goddard Space Flight Centre (GSFC). For this study, TMPA-3B42 V7 daily rain estimates available through http://disc2.nascom.nasa.gov/Giovanni/tovas/ is employed.

ECMWF analysis

ERA-Interim is the latest ECMWF (European Center for Medium range Weather Forecast) global atmospheric reanalysis product available from the year 1979 till date and is presented as an improved version of ERA-40 (Dee et al., 2011; Berrisford et al., 2009; Simmons et al., 2006). It generates global model analysis products with a horizontal sampling of 0.75° × 0.75° at four different synoptic hours namely: 0000, 0600, 1200 and 1800 UTC. There are mainly three components of an ECMWF Integrated Forecasting System (IFS) which includes a general circulation model, data assimilation system and an ensemble forecast system. In 1997, this system was upgraded to a four-dimensional variational system (4DVAR). The quality of this product is evaluated (Xie et al., 2006) with observations obtained during the Atmospheric Radiation Measurement (ARM) Mixed-Phase Arctic Cloud Experiment (M-PACE) at its North Slope of Alaska site. Through this experiment, it is found that the ECMWF analysis reasonably represents the dynamic and thermodynamic structures of the large-scale systems. Reanalyzed near surface wind vectors (U10 and V10) from ERA-Interim for summer monsoon (June, July, August and September) 2012 to 2015 is used for this study.

RESULTS AND DISCUSSION

Spatial distribution of monthly averaged NSAWC

Figure 2 shows the monthly mean of NSAWC pattern derived from ECMWF reanalysis data estimated using Equation 1 over Indian Ocean and neighboring land. The variations of monsoonal winds are well exhibited in the map. During the summer monsoon season, due to the annual variation in the incoming solar radiation and the different heat capacity of land and ocean, low-level winds blow from the ocean towards the Indian sub-continent. The low level circulation over Indian Ocean and the Indian sub-continent is dominated by strong cross equatorial flow and southwesterly winds. The magnitude of these winds are maximum during the month of July and August (Figure 2). The monsoonal circulation and moisture is transported from the south Indian Ocean and the AS towards the south Asian land masses and the BOB (Fasullo and Webster, 1999). This enhances the rainfall over Indian sub-continent. During summer monsoon, the convergence is located in AS near 10°S. The eastern part of the AS and the BOB also get strong convergence due to monsoonal winds. At the end of September, the magnitude of convergences decreases and southwesterly wind does same.

Figure 3 represents the mean monthly rainfall over Indian land and oceanic region during summer monsoon estimated from TMPA-3B42 rainfall data. During the summer monsoon, Western Ghats, north east part of India and Arakan Yoma mountain region receives more rainfall than other parts around India (Figure 3). It can be observed from Figures 2 and 3 that regions with a positive convergence pattern exhibits considerable amount of rainfall. It can also be seen that regions near the foothills of Western Ghats and Arakan Yoma (facing the ocean) where strong convergence pattern is observed indicate higher intensity of rainfall. This clearly indicates that NSAWC is one of the main contributing factors for the occurrence of rainfall.

Relationship between NSAWC and rainfall in Indian Ocean

The relationship between NSAWC and rainfall is quantitatively examined at regional scale over Indian Ocean. The scatter plot between mean monthly rainfall and mean monthly NSAWC are generated for the selected boxes for the period of JJAS 2012 to 2015. The correlation coefficient and *p* value is calculated for each box for JJAS and a statistically significant (p value < 0.0001) relationship is observed. Figure 4 shows the scatter plot corresponding to EIO box. The quantitative comparison shows that NSAWC is in good accord with rainfall. Moreover, a direct proportionality between rainfall and NSAWC is observed for EIO box. The higher magnitude of NSAWC leads to more convection which enhances the moisture content in the atmosphere, eventually resulting in heavy rainfall (Luis and Pandey, 2004). The correlation coefficient (CC) observed

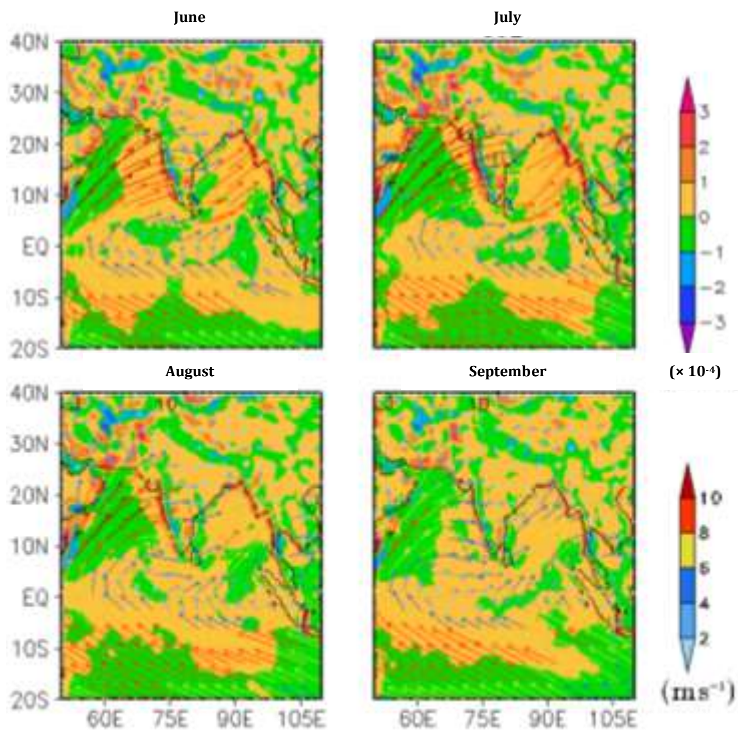

Figure 2: Spatial distributions of mean near surface atmospheric wind convergence (s^{-1}) superimposed with near surface wind vectors over Indian region for JJAS 2012 to 2015.

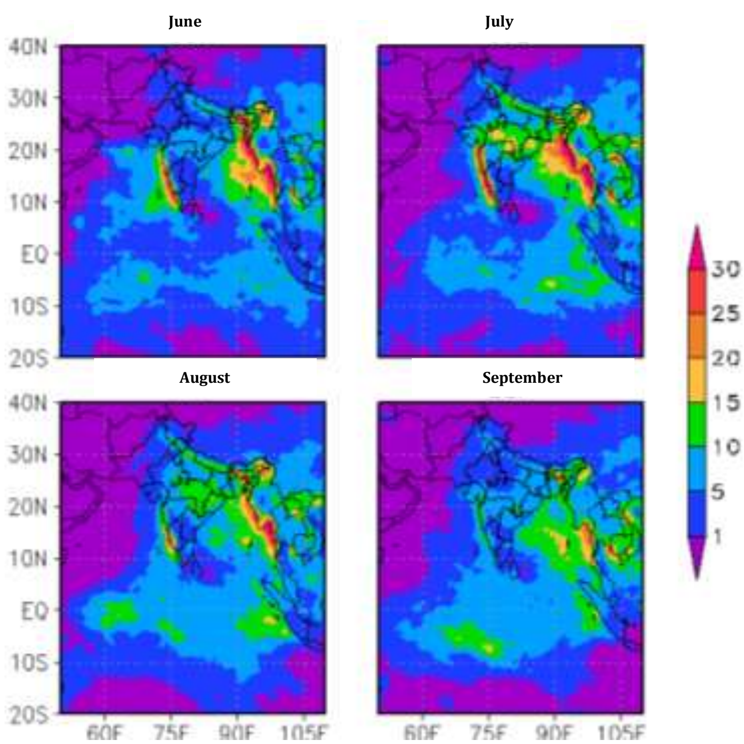

Figure 3: Spatial distributions of mean mean monthly rainfall (mm) over Indian region for JJAS 2012 to 2015.

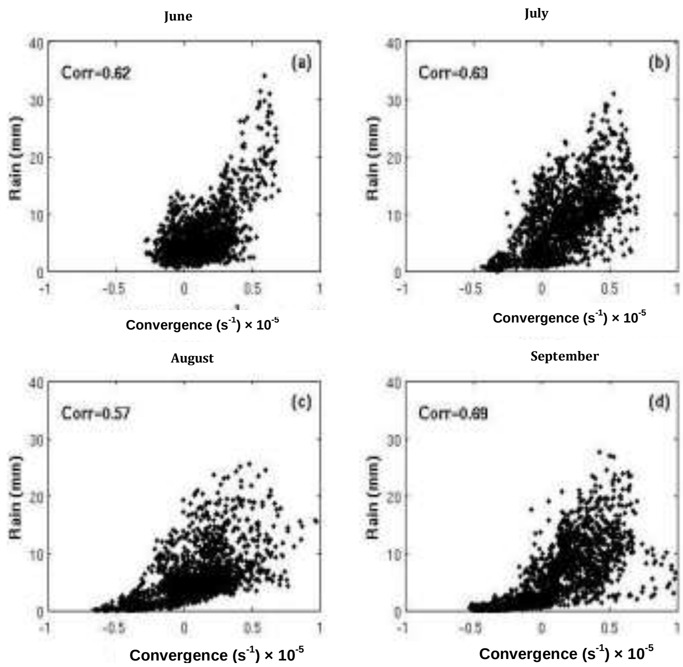

Figure 4: Scatter plot between mean monthly rainfall and mean monthly near surface atmospheric wind convergence over the EIO (10°S to 0°N and 60°E to 110°E) box during the summer monsoon season for the period of 2012 to 2015.

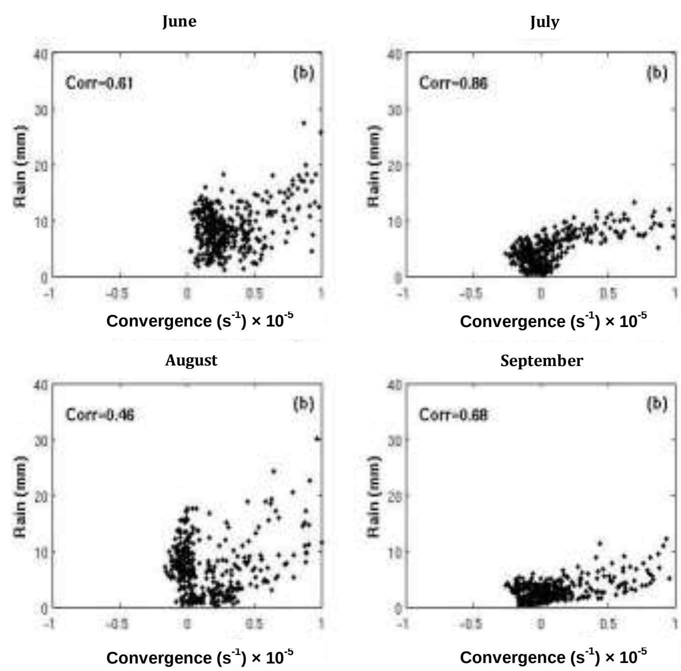

Figure 5: Scatter plot between mean monthly rainfall and mean monthly near surface atmospheric wind convergence over the AS (7°N to 20°N and 67°E to 76°E) box during the summer monsoon season for the period of 2012 to 2015.

for the month of June, July, August and September are 0.62, 0.63, 0.57 and 0.69, respectively for EIO box.

Figure 5 shows the scatter plot between mean monthly rainfall and mean monthly NSAWC for AS box generated.

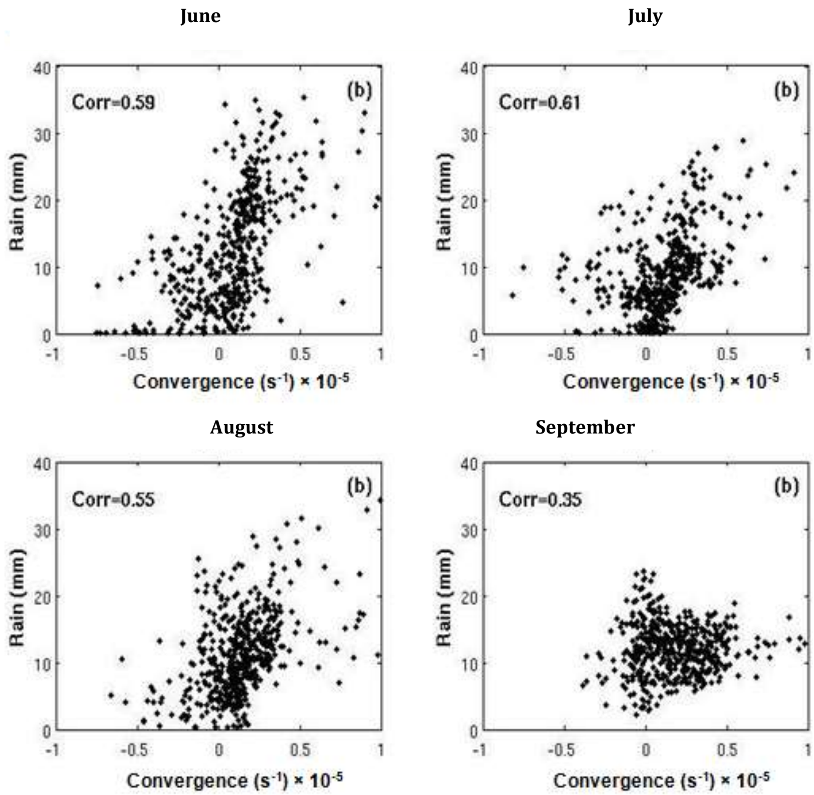

Figure 6: Scatter plot between mean monthly rainfall and mean monthly near surface atmospheric wind convergence over the BOB (10°N to 22°N and 82°E to 95°E) box during the summer monsoon season for the period of 2012 to 2015.

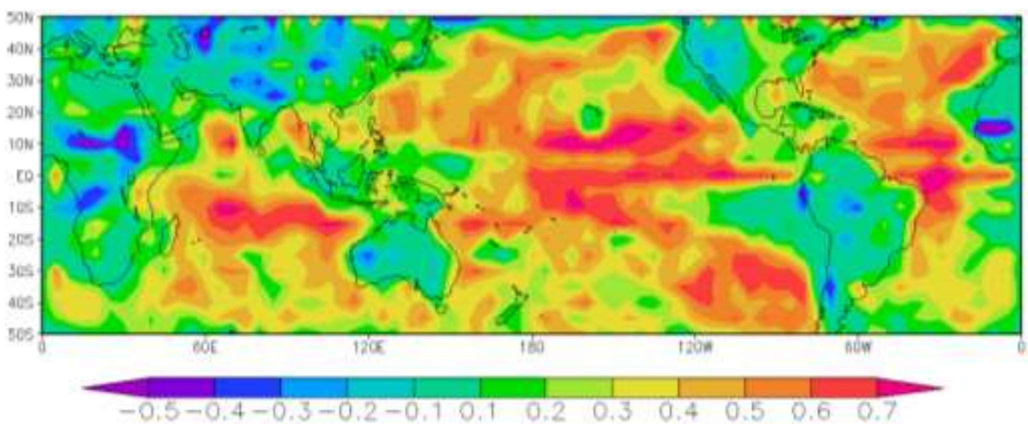

Figure 7: Spatial distribution of correlation coefficient between daily rainall and daily NSAWC for the period of JJAS 2012 to 2015.

Over these sub-regions, the CC observed for the month of June, July, August and September are 0.61, 0.86, 0.46 and 0.68, respectively. A similar kind of trend is observed for AS box as in EIO box.

Similarly, the scatter plot corresponds to BOB box as shown in Figure 6. The CC observed for BOB box for the month of June, July, August and September are 0.59, 0.61, 0.55 and 0.35, respectively. Furthermore, the scatter shows a spread indicating comparitively weaker relationship between mean monthly rainfall and mean monthly NSAWC over BOB sub-region as compared to EIO and AS sub-regions.

Additionally, the spatial distribution of correlation between NSAWC and rainfall for the period of JJAS 2012 to 2015 is represented in Figure 7. This correlation has been computed for all the points within each 5° × 5° latitude/

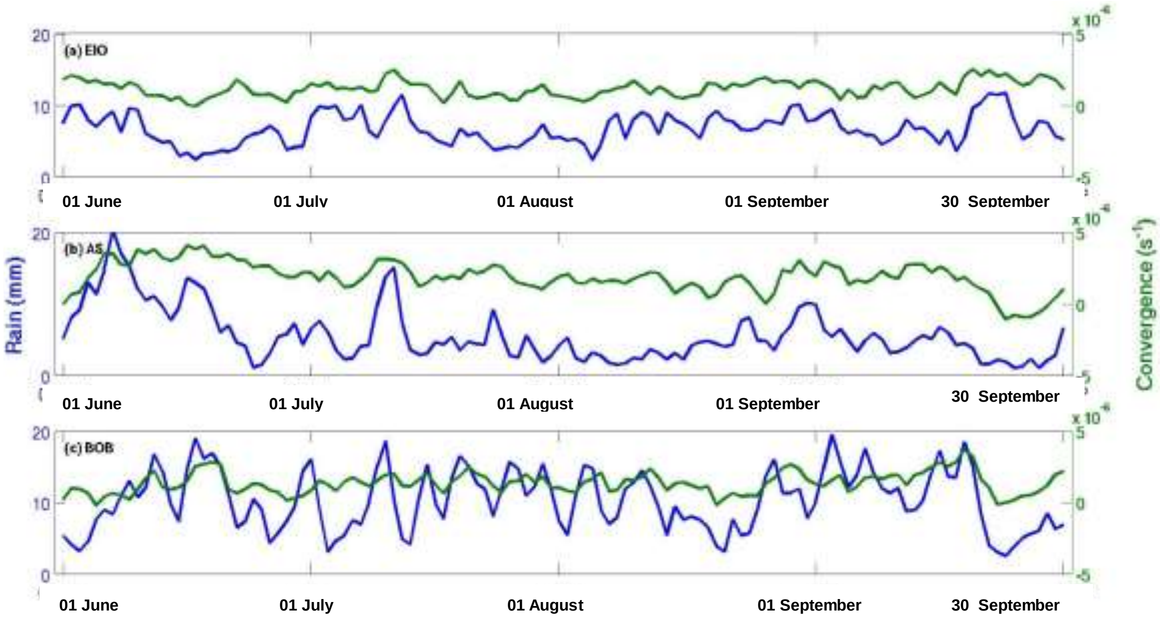

Figure 8: Temporal variations of average daily rainfall and average daily near surface atmospheric wind convergence over (a) EIO box (b) AS box and (c) BOB box during the summer monsoon season for the period of 2012 to 2015.

longitude spatial resolution grid globally. It can be observed from Figure 7 that the correlation between the daily rainall and daily NSAWC is higher over tropical ocean which is due to the presence of rainfall associated with strong convergence zone (ITCZ) over the tropics during summer monsoon season. It is also observed that the correlation is higher over oceanic regions as compared to the land regions.

Temporal variability of NSAWC and rainfall

This study was also carried out to analyze the seasonal variability of NSAWC and rainfall as well as, the relationship between them for each geographical box. Figure 8 shows the average daily rainfall and average NSAWC averaged over the EIO box, AS box and BOB box for JJAS 2012 to 2015. It is observed that the intensity of average daily rainfall is high during the days which show a peak in NSAWC pattern. In addition, the variability in rainfall can be seen in accordance with the variability in NSAWC. Also, the rainfall intensity shows a higher value during the days of increase in the NSAWC followed by a dip.

Conclusions

An attempt was made to investigate the quantitative relationship between convergence/divergence of winds and surface rainfall rate during the period of 2012 to 2015 over BOB, AS and EIO sub-regions. The scatter plots and the analysis of corresponding correlation between the two variables over the study regions during JJAS months suggest that the convergence show strong and stable correlation with surface rainfall over EIO with an average cross correlation value of ~0.65. Arabian Sea shows strong correlation during the month of July (~0.86), whereas comparatively weak correlation is shown in August (0.46). BOB sub-region also showed stable correlation with an average correlation of ~0.52, but the scatter plot shows a spread indicating a weaker correlation compared to other two sub-regions. From this analysis, it can be observed that EIO shows strong and stable correlation between convergence and surface rainfall during the summer monsoon months (JJAS), and convergence over this region may be a stable indicator of the total surface rainfall occurring during the monsoon period. Further, a global map of correlation coefficient between NSAWC and rainfall was generated for SW monsoon months of 2012 to 2015.

ACKNOWLEDGEMENTS

The authors would like to appreciate the effort of the Director of the Space Applications Centre, the Deputy Director, EPSA, and the Group Director, AOSG in the course of this research. The TMPA-3B42 rainfall data from TRMM Online Visualization and Archive System (TOVAS), and the ECMWF data is also acknowledged.

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Cite this article as:

Bushair MT, Sathiyamoorthy V, Mahesh C, Gairola RM (2018). The influence of near surface atmospheric wind convergence on precipitation over Indian summer monsoon region: A statistical analysis. Acad. J. Environ. Sci. 6(10): 215-222.

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