

Author version: *J. Indian Soc. Remote Sens.*, vol.40(1); 2012; 75-83

## **Intra-seasonal oscillations associated with Indian Ocean warm pool and summer monsoon rainfall and their inter-annual variability**

P.M.Muraleedharan, Nisha, P.G., Sathe, P.V., K.U. Sivakumar  
National Institute of Oceanography, Goa 403004, India

Address for correspondence  
Physical Oceanography Division  
National Institute of Oceanography  
Dona Paula,  
Goa 403 004  
India

Key words: Intraseasonal oscillation, IRS-P4, Indian Ocean, rainfall, monsoon, propagation

### **Abstract**

Sea surface temperature (SST) and wind speed (WS) derived from Multichannel Scanning Microwave Radiometer (MSMR), onboard IRS-P4 (Oceansat-1) satellite were used to generate spatially averaged ( $80^{\circ}$  to  $100^{\circ}$  E &  $0^{\circ}$  to  $10^{\circ}$  S) daily data during June to September from 1999 to 2001 along with collocated outgoing long wave radiation (OLR) data from NCEP/NCAR reanalysis product. Daily rainfall data over the peninsular India during the above period was taken from the weekly weather report published by the Indian Meteorological Department. The data were then subjected to power spectral analysis. Dominant 30 to 60 days oscillations were observed over both ocean and land during all the three years investigated. It is quite interesting to note that the intra-seasonal oscillation with 60 days periodicity dominates in both ocean and land during 1999 and then transforms to 30 and 40 days periodicities in 2000 and 2001 respectively with a phase lag of about 25 to 30 days. It was also observed that the time-latitude section of zonally averaged OLR and TMI derived cloud liquid water data clearly depict the propagation of convection and cloud from the equator to the north at the rate of  $0.75^{\circ}$  to  $1^{\circ}$  latitude per day which corroborates well with the rate of propagation derived from the phase lag obtained between the processes occurring at the equatorial Indian Ocean and rainfall recorded at the designated land segments. The results are in good agreement with the observations made by earlier investigators.

## Introduction

The new generation satellite data and model reanalysis products are widely used to study the processes associated with the intra seasonal oscillation (ISO) of the Indian summer monsoon (ISM). Signals of well defined tropical oscillation with a 40-50 day periodicity were detected by Madden and Julian (1971, 1972) (here after MJO) using long term observational records of wind speed from rawinsonde stations. These are the eastward propagating oscillations circum navigating the earth along the equatorial plane. It has been shown beyond ambiguity that the activity of MJO is found to have profound influences on the onset break/active and retreat of the ISM (Sikka and Gadgil, 1980; Krishnamurty, 1985; Hartmann and Michelson, 1989). Extensive modeling work has been conducted in the recent past to examine the oceanic response to the ISO (Shinoda and Hendon, 1998; Han *et al*, 2001, 2004; Sengupta *et al*, 2001, 2007; Schouten *et al*, 2002; Schiller and Godfrey, 2003; Senan *et al*, 2003; Waliser *et al*, 2003, 2004; Han, 2005). Although several intermittent attempts have been made to link the summer monsoon rainfall to the processes occurring all around the tropical Indian Ocean, it is almost certain that the intra-seasonal Madden Julian Oscillation characterized by eastward-propagating disturbances in the atmosphere with deep atmospheric convection primarily evident over the warm pool region of the central Indian Ocean is found to be propagating northward and their link to the Indian summer monsoon rainfall has been well documented (Yasunari, 1979; Krishnamurti and Subramaniam, 1982; Gautier and Di Julio, 1990)

Western equatorial Pacific and eastern equatorial Indian Ocean are considered to be a single warm pool entity where the surface temperature seldom drops below 28 C throughout the year (except during dipole events) with noticeable freshening (0.5 to 1 psu) in the Indian sector (Kumar *et al.*, 2005). Unlike Pacific, Indian Ocean warm pool was not given much attention except few isolated attempts (Vinayachandran and Shetye, 1991; McCreary *et al*, 1993; Schiller *et al*, 1998; Webster *et al*, 1999; Rao and Shivakumar, 2000). It has been shown by Webster *et al*, (1997) that the Indian Ocean warm pool is not only the site of intra-seasonal variability in the monsoon system but also a region where the global climate signals radiate. According to S. Joseph *et al*, (2009), the propensity of eastward propagating intra-seasonal oscillation at the equatorial Indian Ocean during boreal summer is essentially the cause of monsoon draughts over the sub continent.

The meridional movement of convective activity associated with the active-break monsoon cycles had been reported by Yasunary (1979, 1980) using satellite mosaic pictures of cloudiness over South Asia. Krishnamurty and Subramaniam (1982) documented meridional propagation of a train of troughs and ridges from the equator to about 30 N over the Indian summer monsoon region with a phase speed of about 0.75 degree latitude per day. Lau and Chan (1986) found that during eastward propagation of the ISO, there are two branches of the meridional propagation of negative OLR (Out going Long wave Radiation) anomalies: northward toward the Indian subcontinent and northeasward towards the South China Sea. The meridional propagation was also found in the general circulation model experiments (Lau and Lau, 1986; Hayashi and Golder, 1986). The outgoing long wave radiation (infra red radiation) at the top of the atmosphere often associated with clear sky or cloudy atmosphere. Strong convection usually generates clouds that absorb OLR in contrast to high OLR in clear sky situations. Recently Pokhrel et al., (2003) had demonstrated the capability of Multichannel Scanning Microwave Radiometer onboard IRS-P4 satellite to study the intra-seasonal variability of rainfall over the Bay of Bengal and its northward propagation with reasonable accuracy. Webster (1983) proposed that the land surface latent and sensible heat fluxes in the boundary layer, which destabilizes the atmosphere ahead of the ascending zone, were the principal cause of the northward propagation. On the other hand, Lau and Peng (1990) was of the opinion that in the event of an equatorial Kelvin wave crosses the Indian summer monsoon longitude, unstable baroclinic disturbances are generated over India, which causes a rapid northward shift of the rising branch of the local Hadley circulation inducing meridional propagation. According to Li and Wang (1994), the gradient of the antisymmetric component of SST with respect to the equator causes a southward propagation of the tropical intra-seasonal systems towards northern Australia in boreal winter and a northward propagation over the Indian and western Pacific Oceans in boreal summer.

The objective of this investigation is to link the intra-seasonal variability of various oceanic and meteorological parameters at the equatorial Indian Ocean warm pool region with the intra-seasonal variability of summer monsoon rainfall over regions in the subcontinent exhibiting similar hydro-meteorological characteristics and to study its inter-annual variability.

## Materials and Methods

IRS-P4 was the first in the series of operational ocean remote sensing satellite and was launched by PSLV (Polar Satellite Launch Vehicle) on 26th May 1999. It carried an all-weather capable Multi-frequency Scanning Microwave Radiometer (MSMR) payload besides Ocean Colour Monitor (OCM). Channels of MSMR were suitable to retrieve Sea surface temperature (SST), sea surface wind speed (WS), column water vapor and cloud liquid water in a global scale. The MSMR geophysical data product supplied by the National Remote Sensing Agency consists of 24 hr data and has been generated on three different grid sizes viz., 150, 75 & 50 km. Details of payloads and the grids are given in the IRS-P4 Data User's Handbook (IRS-P4 User's Hand book, 1999). The 6.6 GHz channels make the IRS-P4 mission unique when compared with its contemporary satellite missions, enabling it to view the earth round the year to generate SST data, irrespective of adverse weather conditions. Unfortunately the MSMR payload was shutdown due to power problem in November 2001 and hence the data during this three year period was used in the present study.

NOAA interpolated Outgoing Long wave Radiation data (OLR) and daily rainfall estimate (RF) from Indian Daily Weather Report are other data products besides the corrected (Muraleedharan et al, 2004) SST and WS from IRS-P4 payloads analyzed during the monsoon months of 1999 to 2001. Uniform grid size of  $1^{\circ} \times 1^{\circ}$  was chosen so that all data were interpolated to fit in this grid size to minimize the comparison error. The spatially averaged daily data of SST, WS and OLR at the equatorial Indian Ocean ( $0^{\circ}$  to  $10^{\circ}$  S and  $67^{\circ}$  E to  $100^{\circ}$  E) representing the equatorial warm pool during June – September for the years 1999 - 2001 were then subjected to spectral analysis to understand the nature of variability. The study periods witnessed rainfall that was relatively lower than the long period average (LPA) by 4-8 % after a spell of consecutive six normal monsoon years with more than 100% of the LPA (<http://indiabudget.nic.in/es99-2000/chap82.pdf>). However the years 1999 to 2001 remain to be normal monsoon years as long as the all India rainfall index falls between -10 and + 10% of the LPA in accordance with the India Meteorological Department protocol (Meteorological Glossary at [http://www.imd.gov.in/section/nhac/dynamic/Monsoon\\_frame.htm](http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm)). The Indian sub continent is demarcated into four major areas viz; Central Zone (Uttar Pradesh, Bihar, Madhya Pradesh, Jharkhand, Chhattisgarh), West Coast (Gujarat, Maharashtra, Goa, Karnataka, Kerala), East Coast (West Bengal, Orissa, Andhra Pradesh, Tamil Nadu), and North-East Zone (Assam and adjoining areas) as

shown in Fig. 1 based on the similar hydro-meteorological characteristics. Total daily rainfalls averaged over these four areas during the above period were also subjected to the spectral analysis.

The spectral analysis of time series is one of the most commonly used data analysis techniques in the physical sciences. Spectrum analysis is concerned with the exploration of cyclical patterns of data. The spectrum of a time series is the distribution of variance of the series as a function of frequency. The object of spectral analysis is to estimate and study the spectrum. The purpose of the analysis is to decompose a complex time series with cyclical components into a few underlying sinusoidal (sine and cosine) functions of particular wavelengths. Even with today's high-speed computers, it would be very time consuming to analyse even small time series (eg. 8000 obs would result in at least 64 million multiplications). The time requirements changed drastically with the development of the so-called fast Fourier transform algorithm (FFT). Cross spectrum analysis is an extension of single spectrum (Fourier) Analysis to the simultaneous analysis of two series. The purpose of cross-spectrum analysis is to uncover the correlations between two series at different frequencies. The phase shift estimates are measure of the extent to which each frequency component of one series leads the other. However the single spectrum analysis has been adopted in this paper to analyze the time series data of ocean-atmosphere boundary layer parameters and continental rainfall.

## **Results and Discussion**

The power spectral analysis of daily fields of mean OLR over the equatorial Indian Ocean showed a primary spectral peak at a periodicity of 25 days in the year 1999 while a peak of 40 days was seen in 2000 and a combination of 30&40 days periodicity was noticed in 2001 (Fig.2; top row). A secondary peak of 10 to 15 days was also visible during 1999 and 2000 but similar peak was not observed in 2001. Amplitude of the peaks did not indicate any noticeable inter annual variability. Several earlier studies had shown that intra-seasonal 30-60 (10-20) days periodicity is inversely (directly) related to the Indian monsoon strength (Chowdhury et al, 1988; Yasunari, 1980; Vernekar et al, 1993). Spectral analysis of the WS over the equatorial Indian Ocean, however, exhibited primary and secondary peaks in all three years with periodicities ranging from 30 – 60 days and 10 – 15 days respectively (Fig.2; middle row). A dominant primary peak of 60 days periodicity was observed in WS during 1999 followed by 40 days and 30 days peaks with relatively shorter amplitudes in the years 2000 and 2001 respectively. Secondary peaks were also observed in WS during all the three years with amplitudes almost equivalent to 50% of

the respective primary peaks. Spectral signatures of SST during the summer months of 2000 had a solitary peak with 60 days periodicity and such peaks were completely absent during the other two years (Fig. 2; bottom row). However, the 10-15 days mode was more prominent in WS especially during 1999 and 2000 while the OLR during 2000 exhibited similar mode at the equatorial Indian Ocean. In short, the dominant primary peaks noticed from the spectral signatures of OLR, WS and SST at the equatorial Indian Ocean during summer months were 60 days, 40 days and 30 days in the years 1999, 2000 and 2001 respectively.

The accumulated daily rainfall at four designated areas during the summer months of 1999, 2000 and 2001 were also subjected to spectral analysis and the results were displayed in Fig. 3. The scale of the amplitude of the spectrum for West Coast was modified by dividing with 100 to have an appearance at par with other figures. In general the periodicity of the rainfall over the subcontinent closely followed the periodicity of SST, WS and OLR observed at the equatorial region as both witnessed the same 30-60 day oscillation. But it is more informative to look at the year to year comparison of periodicities over ocean and land as the inter-annual variability of such periodicities was quite significant especially over land. In general, West Coast, Central Zone and East Coast depicted very clear signals of 60 day oscillation during the summer months of 1999 (Fig.3; first column) while it switched to an unambiguous 40 day oscillation at all four zones during 2000 (Fig.3; middle column). However, the spectral signatures of rainfall at West Coast and North-East Zone in 2001 showed only marginally dominant 30 day oscillation (Fig.3; last column) except for an unusual 120 days periodicity during 2001. Nevertheless the next dominant mode coincided with the 30 to 60 days periodicity highlighting the significance of a uniform 30 days mode in three out of four regions investigated. Unlike the equatorial ocean, the low frequency 30-60 day oscillations of rainfall over the subcontinent at times coexisted with prominent high frequency secondary modes of 15-20 days periodicity especially at the Western, central and north-eastern part of the subcontinent. East coast, however, did not indicate the influence of any dominant modes or in other words it witnessed the presence of subdued primary and secondary modes.

The 10-20 days and the 30-60 days periodicity had been shown to be associated with the active and break cycles of monsoon rainfall over the Indian region (Krishnamurti and Ardunay, 1980; Sikka and Gadgil, 1980; Kripalani et al, 2004). Analysis of Kripalani et al, (2004) revealed that the faster 10-20 days mode dominated the normal monsoon year of 2003 while the slower 30-60 days mode dominated the draught monsoon year of 2002. Therefore the relatively dominant high frequency mode of 10-20

days during 2000 could be linked with the observation of more number of subdivisions with excess rainfall (5 sub-divisions) ([indiabudget.nic.in/es2001-02/chapt2002/chap82.pdf](http://indiabudget.nic.in/es2001-02/chapt2002/chap82.pdf)). Less dominant high frequency mode observed in 1999 was linked to 3 sub-divisions with excess rainfall while the absence of such high frequency mode in 2001 might have caused the solitary subdivision with excess rainfall. However, the percent of long period average (LPA) rainfall for the country as a whole were 96, 92 and 92 during 1999, 2000 and 2001 respectively demarcating all these years as normal monsoon years. The results indicated that the dominant high frequency mode of 10-20 days periodicity could transform the monsoon from normal to excess rainfall year with LPA crosses the 100 mark as mentioned by Kripalani et al, (2004). Therefore it was anticipated that the dominant low frequency mode of 30-60 days periodicity could result in the transformation from normal to deficit rainfall year with LPA falling below the 100% mark. But this was not observed during 1999-2001 periods. The apparently dominant high frequency mode of 10-20 days periodicity in 2000 did not make much difference with the year 2001 (that depicted a vague 30-40 day mode) in terms of rainfall. Both years were recorded as normal monsoon years with 92 % of long period average rainfall for the country as a whole. In both years the rainfall activity was subdued for 61 days and 92 days respectively (Mausam, 2001 & 2002). In contrast to the observation of Kripalani et al, (2004), the low frequency dominant (60 days periodicity) year of 1999 exhibited a better estimate of 96 % of LPA rainfall with only 38 days of subdued rainfall activity over the subcontinent (Mausam, 2000).

#### *Lead-lag correlation*

The mean daily OLR, WS and SST at the equatorial Indian Ocean were correlated with the mean daily rainfall over the four designated areas and over the entire peninsular India from 1999 to 2001 and the correlation coefficient was determined when rainfall leading the above parameters from 0 to 30 days (Table.1). Except for very few occasions, the correlation between the processes occurring at the equatorial Indian Ocean and the rainfall at the designated land segments was significant ( $r$  varies from 0.18 (significant at 10% level) to 0.36 (significant at 0.1% level). However, the correlation was relatively weaker at the East coast. In general rainfall was leading WS and SST by about 30 days at the central zone where OLR was lagging rainfall by 9 to 20 days during the period of investigation. Both WS and SST consistently lagged rainfall over the West Coast by about 25 to 30 days. Similar consistency was not seen in the case of OLR at the West Coast especially during 2000 and 2001. Although the rainfall leads WS and SST at the East Coast by 20 to 30 days, the coefficient of correlation

did not support a strong relationship. The OLR, again failed to support the 20 to 30 days lead showed by SST and WS. Strong and significant relationships between rainfall and the three boundary layer parameters were observed in the North-East Zone during all the three years investigated. So it was quite natural that the OLR did not consistently follow the phase lag exhibited by both WS and SST as high OLR is analogous to weak convection. High correlation of WS and SST with rainfall with a phase lag of 20 to 30 days would mean high convection at the equator 20 to 30 days prior to high rainfall observed over the four land segments. High convection not necessarily supports high OLR with the same phase lag. Therefore the difference in phase lag between OLR and rainfall is anticipated and is in line with the argument that a reversal of relationship is expected with the same 20 to 30 days phase lag to support the convection arise from the enhanced WS and SST. The total rainfall over the peninsular India is compared with the oceanic parameters and the results are in general resembles the relationship obtained for the selected regions over the subcontinent (Table 1). However, the relationship tend to get reversed especially during 1999 (for all parameters) and in 2001 (for WS) although the phase difference remained to be the same. The discrepancy may be attributed to the irregular rain pattern influenced by local factors observed over the terrain other than the selected zones.

#### *Northward propagation of the MJO mode*

The Madden-Julian Oscillation (Madden and Julian, 1971) is a tropically centred low frequency, eastward moving wave. MJO has a northward component during summer over the north Indian Ocean (Waliser, 2006) that is responsible for the Intra-seasonal Oscillation (ISO) of Indian summer monsoon. The 30-60 days oscillations are characterized by northward movement of weather anomalies including rainfall and outgoing long-wave radiation (Yasunari, 1979; Gadgil, 1990; Singh and Kripalani, 1986; Kripalani et al, 1991). The daily OLR data averaged over the longitude (50 to 100° E) were plotted as contours with time (June to September) in the X-axis and latitude in the Y-axis for the years 1999 to 2001 in Fig. 4 (left panel). Bands of low OLR values (analogous to convection) were appear to be propagating from about 10° S to 25° N during 2000 and the propagation was less prominent in other two years. The TMI derived cloud liquid water content averaged over the longitude (80° to 100° E) also exhibited similar northward propagation from 10° S to 25° N during 1999-2001 establishing the propagation of convection in the form of clouds (Fig. 4: right panel). A rough visual estimate of time of propagation of OLR and clouds made from the time-latitude plots during 2000 was about 15 to 20 days to cover a distance of 15° latitude which would roughly amounts to the rate of propagation of about 0.75



to 1° latitude per day. This was about 4-5 kms per hour. The 20-30 days phase lag obtained from the lead-lag correlation between rainfall over the land segments and the air-sea interaction processes occurring at the equator that gave rise to a propagation rate of 0.5 to 1° latitude per day which corroborates well with the visual estimation. Sikka and Gadgil (1980) were of the opinion that equatorial cloud bands moves towards the monsoon trough at the rate of around 1° latitude per day. This was comparable with the estimate of 0.75 degree per day reported by Krishnamurty and Subramaniam (1982).

### **Summary**

Spatially averaged daily fields of Sea surface temperature, wind speed and out going long wave radiation representing the monsoon months of three consecutive years from 1999 over the eastern equatorial Indian Ocean along with spatially averaged daily rainfall estimate over the four designated land segments (West, East, Central and North-East) over the peninsular India were subjected to power spectral analysis. Although the overall pattern during this three year period resembles the MJO (30 to 60 days oscillation), the dominant modes of 60, 40 and 30 days were noticed from the three parameters to represent the years 1999, 2000 and 2001 respectively. Interestingly these periodicities were reproduced by the rainfall at various zones over the peninsular India during the above three years with a definite phase difference. The phase difference was determined by studying the lead-lag correlations between the parameters at the equator and the rainfall estimate over the land segments. A phase lag of 25 to 30 days was found out between the processes occurring at the equator and over the peninsular India which pointed out to the fact that the processes occurring at the equatorial Indian Ocean would have propagated northward to affect the rainfall over the land segments. Signatures of propagation were detected in the OLR and cloud liquid water data where a propagation rate of 0.75 to 1° latitude per day was noticed and the results were in good agreement with the estimation derived from the lead-lag correlation experiment and the results documented elsewhere (Sikka and Gadgil, 1980; Krishnamurty and Subramaniam, 1982).

**Acknowledgements:** Authors are thankful to the Director, National Institute of Oceanography for facilities provided. We acknowledge the funding support provided by the Space Application Center, Ahmedabad for IRS-P4 validation program. We thank A.A. Fernandes, Scientist at NIO for soft ware support. We are also thankful to the staffs of Marine Instrumentation and Computer Division of NIO for their constructive participation in the IRS-P4 validation exercise. This is NIO contribution number \*\*\*\*.

## References

- Chowdhury A, Sinha Ray KC and Mukhopadhyay RK (1988) Intra-seasonal cloud variations over India during summer monsoon. *Mausam* 39: 359-366
- Gadgil S (1990) Poleward propagation of the ITCZ: Observations and theory. *Mausam* 41: 285-290
- Gautier C and DiJulio B (1990) Cloud effects on air-se interactions during the 1979 Indian summer monsoon as studies from satellite observation. *Meteor. Atmos. Phys.* 44, 251-263
- Han W, Lawrence DM and Webster PJ (2001) Dynamical response of equatorial Indian Ocean to intra-seasonal winds: Zonal flow. *Geophys Res Lett* 28(22): 4215 - 4218
- Han W, Webster PJ, Lukas R, Hacker P and Hu A (2004) Impact of atmospheric intra-seasonal variability in the Indian Ocean: Low-frequency rectification in equatorial surface current and transport. *J Phys Oceanogr* 34(6): 1350-1372
- Han W (2005) Origins and dynamics of the 90-day and 30–60-day variations in the equatorial Indian Ocean. *J Phys Oceanogr* 35(5): 708-728
- Hartmann DL and Michelson ML (1989) Intra seasonal periodicities in Indian rainfall. *J Atmos Sci* 46(18): 2838 - 2862
- Hayashi Y and Golder DG (1986) Tropical intra seasonal oscillations appearing in a GFDL general circulation model and FGGE data. Part 1: Phase propagation. *J Atmos Sci* 43(24): 3058 - 3067
- IRS-P4 Data User's Handbook (1999) Indian Remote Sensing Satellite –P4 (OCEANSAT-1), National Remote Sensing Agency, Department of Space, Govt. of India, Hyderabad, pp 74
- Joseph, S, Sahai, A.K., Goswami, B.N (2009) Eastward propagating MJO during boreal summer and Indian monsoon draughts. *Clim. Dyn.* 32, 1139-1153. DOI 10.1007/s00382-008-0412-8.
- Kripalani RH, Ashwini Kulkarni, Sabade SS, Revadekar JV, Patwardhan, SK and Kulkarni JR (2004) Intra-seasonal oscillations during monsoon 2002 and 2003. *Current Science* 87 (3): 325-331
- Kripalani RH, Singh SV and Arkin PA (1991) Large scale features of rainfall and out going long-wave radiation over Indian and adjoining regions. *Contrib Atmos Phys* 64: 159-168
- Kripalani RH, Ashwini Kulkarni, Sabade SS, Revadekar JV, Patwardhan SK and Kulkarni JR (2004) Intra-seasonal oscillations during monsoon 2002 and 2003. *Current Science* 87 (3): 325 - 331
- Krishnamurti TN and Ardunay P (1980) The 10-20 day westward propagating mode and breaks in the monsoon. *Tellus* 32(1): 15-26
- Krishnamurti TN and Subramanyam D (1982) The 30–50 day mode at 850 mb during MONEX. *J Atmos Sci* 39(9): 2088-2095

- Krishnmurti TN (1985) Summer Monsoon Experiment: A Review. *Mon Wea Rev* 113(9): 1590 - 1626
- Kumar, S.P., Akio Ishida, Yoneyama, K., Ramesh Kumar, M.R., Yuji Kashino, Humio Mitsudera (2005) Dynamics and thermodynamics of the Indian Ocean warm pool in a high resolution global general circulation model. *Deep Sea Res., II*, 52, 2031-2047.
- Lau N-C and K-M Lau (1986) The structure and propagation of intra-seasonal oscillations appearing in a GFDL General Circulation Model. *J Atmos Sci* 43(19): 2023-2047
- Lau K-M and Chan PH (1988) Intra-seasonal and inter-annual variations of tropical convection: A possible link between the 40–50 day oscillation and ENSO? *J Atmos Sci* 45(3): 506-521
- Lau K-M and Peng L (1990) Origin of low frequency (intra seasonal) oscillations in the tropical atmosphere. Part III: Monsoon dynamics. *J Atmos Sci* 47(12): 1443 - 1462
- Li T and Wang B (1994) The influence of Sea Surface Temperature on the Tropical Intra-seasonal Oscillation: A Numerical Study. *Mon Wea Rev* 122(10): 2349 – 2362
- Madden RA and Julian PR (1971) Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *J Atmos Sci* 28(5): 702-708
- Madden RA and Julian PR (1972) Description of global-scale circulation cells in the Tropics with a 40–50 day period. *J Atmos Sci* 29(6): 1109-1123
- McCreary, J.P., Kundu, P.K., Molinari R.L. (1993) A numerical investigation of dynamics, thermodynamics and mixed-layer processes in the Indian Ocean. *Progress in Oceanography*, 31, 181-244.
- Rao, R.R., Shivakumar, R. (2000) Seasonal variability of near-surface thermal structure and heat budget of the mixed layer of the tropical Indian Ocean from a new global ocean temperature climatology. *J. Geophys. Res.*, 105, 985-1015.
- Samir Pokhrel, A.K. Varma, R.M.Gairola, and Vijay K. Agarwal (2003) Distribution and intraseasonal variability of rain over Indian Oceanic region from Indian Remote Sensing Satellite IRS-P4 Multifrequency Scanning Microwave Radiometer. *J. Geophys. Res.*, 108 (C10), doi:10.1029/2003JC001886
- Schiller A and Godfrey J.S (2003) Indian Ocean intra-seasonal variability in an Ocean General Circulation Model. *Journal of Climate* 16(1): 21-39
- Schiller, A., Godfrey, J.S., McIntosh, P.C., Mayers, G., Wijffels, S.E. (1998) Seasonal near-surface dynamics and thermodynamics of the Indian Ocean and Indonesian throughflow in a global ocean general circulation model. *J. Physical Ocean.*, 28, 2288-2312
- Schouten MW, de Ruijter WPM, van Leeuwen PJ and Dijkstra HA (2002) An oceanic teleconnection between the equatorial and southern Indian Ocean. *Geophys Res Lett* 29(16): 1812, doi:10.1029/2001GL014542

- Senan R, Sengupta D and Goswami BN (2003) Intra-seasonal “monsoon jets” in the equatorial Indian Ocean. *Geophys Res Lett* 30(14): 1750, doi:10.1029/2003GL017583
- Sengupta D, Senan R and Goswami BN (2001) Origin of intra-seasonal variability of circulation in the tropical central Indian Ocean. *Geophys Res Lett* 28(7): 1267-1270
- Senugupta D, Senan R, Goswami, BN and Vialard J (2007) Intra-seasonal Variability of Equatorial Indian Ocean Zonal Currents. *Journal of Climate* 20 (13): 3036-3055
- Shinoda T, and Hendon HH (1998) Mixed layer modelling of intra-seasonal variability in the tropical western Pacific and Indian Oceans. *Journal of Climate* 11(10), 2668-2685
- Sikka DR and Gadgil S (1980) On the maximum cloud zone and the ITCZ over Indian longitudes during southwest monsoon. *Mon Wea Rev* 108(11): 1840-1853
- Singh SV and Kripalani RH (1986) Application of EEOF analysis to interrelationships and sequential evolutions of monsoon fields. *Mon Wea Rev* 114(8): 1603-1610
- Vernekar AD, Thapliyal V, Kripalani RH, Singh SV and Kirtman B (1993) Global structure of the Madden-Julian oscillations during two contrasting summer monsoon seasons over India. *Meteorol Atmos Phys* 52: 37-47
- Vinayachandran, P.N., Shetye, S.R. (1991). The warm pool in the Indian Ocean. Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences) 100, 165-175.
- Waliser DE, Murtugudde R and Lucas LE (2003) Indo-Pacific Ocean response to atmospheric intra-seasonal variability. Part I: Austral summer and the Madden–Julian oscillation. *J Geophys Res* 108(C5): 3160, doi:10.1029/2002JC001620
- Waliser DE, Murtugudde R and Lucas LE (2004) Indo-Pacific ocean response to atmospheric intra-seasonal variability: 2. Boreal summer and the intra-seasonal oscillation. *J Geophys Res* 109(C0): 3030, doi:10.1029/2003JC002002
- Waliser DE (2006) Intra-seasonal variability. In: *The Asian Monsoon* (Ed: B. Wang). Springer-Verlag 203–257
- Webster PJ (1983) Mechanisms of monsoon low-frequency variability: Surface hydrological effects. *J Atmos Sci* 40(9): 2110-2124
- Webster, P.J., Moore, A.M., Loschnigg, J.P., Leben, R.R. (1999) Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. *Nature*, 401, 356-359.
- Yasunari T (1979) Cloudiness fluctuation associated with the Northern Hemisphere summer monsoon. *J Meteor Soc Japan* 57(3): 227-242
- Yasunari T (1979) Cloudiness fluctuations associated with Northern Hemisphere summer monsoon. *J Meteor. Soc. Japan*, 57, 227-242.
- Yasunari T (1980) A quasi-stationary appearance of 30–40 day period in the cloudiness fluctuations during the summer monsoon over India. *J Meteor Soc Japan* 58(3): 225-229

**Figure Captions:**

- Figure 1. Area of study. The equatorial warm pool area is shaded. Four land segments (colored) chosen based on the similar hydro-meteorological characteristics.
- Figure 2. Spectral analysis of OLR (top panel), WS (middle panel), SST (bottom panel) at the equatorial warm pool during the years 1999 (left panel), 2000 (middle panel), and 2001 (right panel).
- Figure 3. Spectral analysis of daily rainfall (June-Sept.) over Central Zone (top panel), North-East Zone (second from top panel), West Coast (third from top panel), And Ease Coast (bottom panel) during 1999 (left panel), 2000 (middle panel) and 2001 (right panel). The scale of the amplitude of West Coast is multiplied by 100.
- Figure 4. Time latitude section of OLR (tope panel) and Cloud Liquid Water (bottom panel) during 1999 (left panel), 2000 (middle panel) and 2001 (right panel)

Land Segments	SST			WS			OLR		
	1999	2000	2001	1999	2000	2001	1999	2000	2001
Central	30(0.42)	30(0.42)	22(0.26)	30(0.28)	28(0.22)	28(0.36)	16(0.28)	20(0.29)	9(0.31)
West	29(0.18)	25(0.53)	22(0.20)	29(0.60)	28(0.22)	26(0.22)	30(0.42)	7(0.45)	11(0.28)
East	26(0.21)	24(0.12)	25(0.17)	19(0.24)	28(0.13)	25(0.28)	15(0.15)	4(0.26)	26(0.20)
NE	26(0.30)	17(0.26)	27(0.24)	20(0.24)	26(0.35)	24(0.46)	22(0.29)	26(0.18)	27(0.27)
All India	30(-0.35)	28(0.59)	22(0.32)	29(-0.59)	20(0.36)	29(-0.40)	12(-0.40)	0(0.38)	0(0.30)

Table 1. Rainfall leading various parameters from 0 to 30 days over selected land segments. Coefficient of correlation is given in brackets. The relationship is significant at 10, 5, 2,1 and 0.1 percent level for coefficient of correlations 0.18, 0.22, 0.26, 0.28 and 0.36 respectively when number of observations exceeds 80.

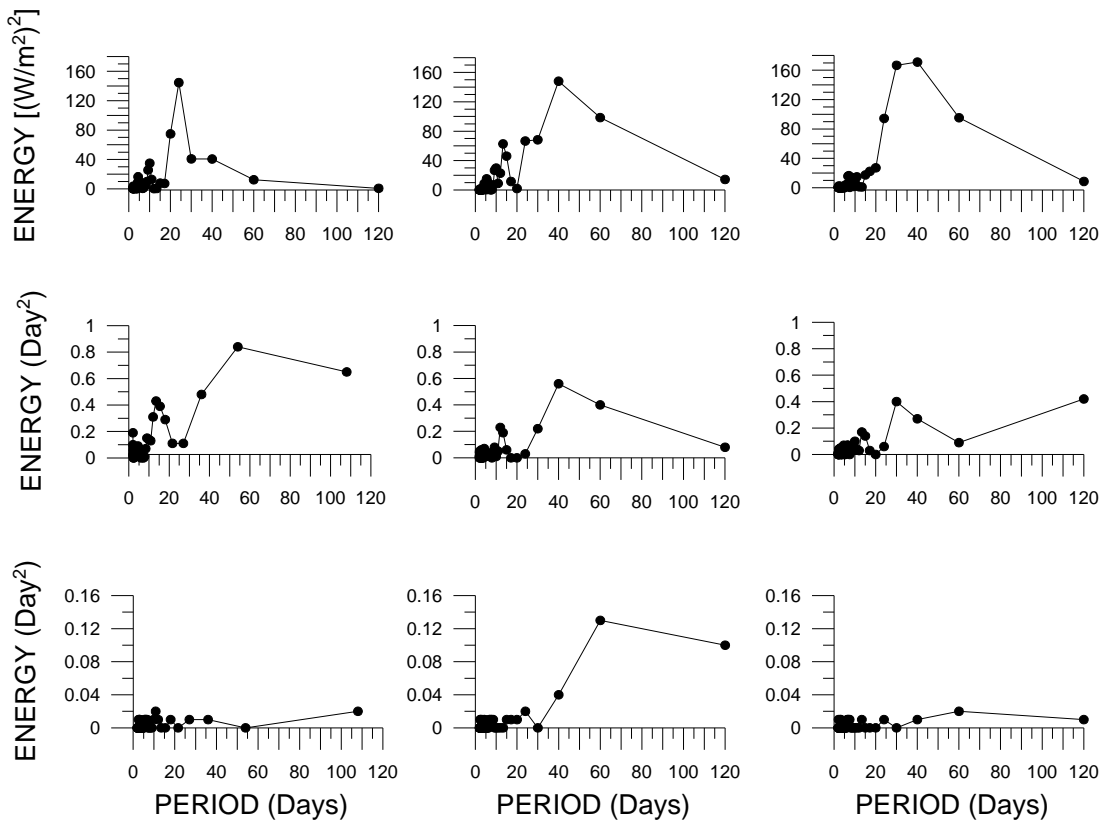
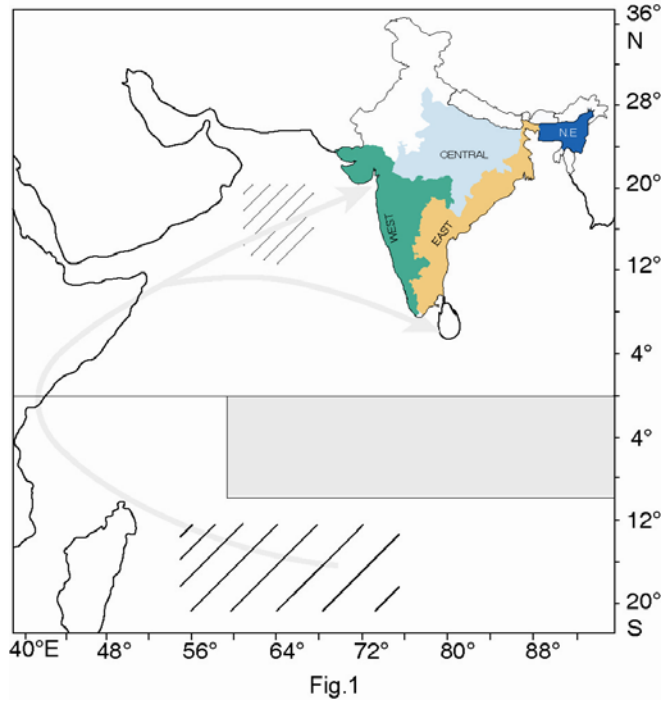


FIG 2

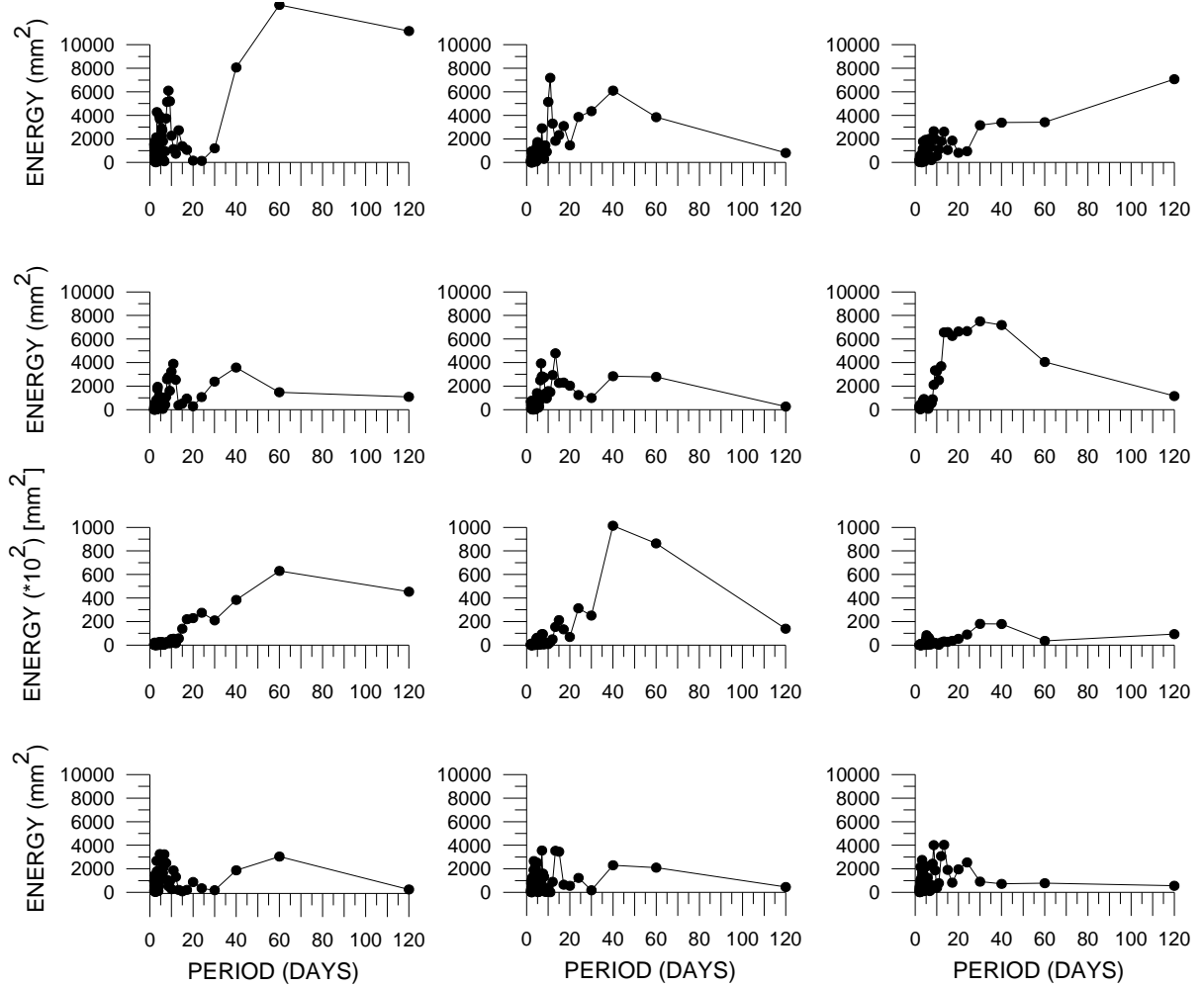


FIG 3



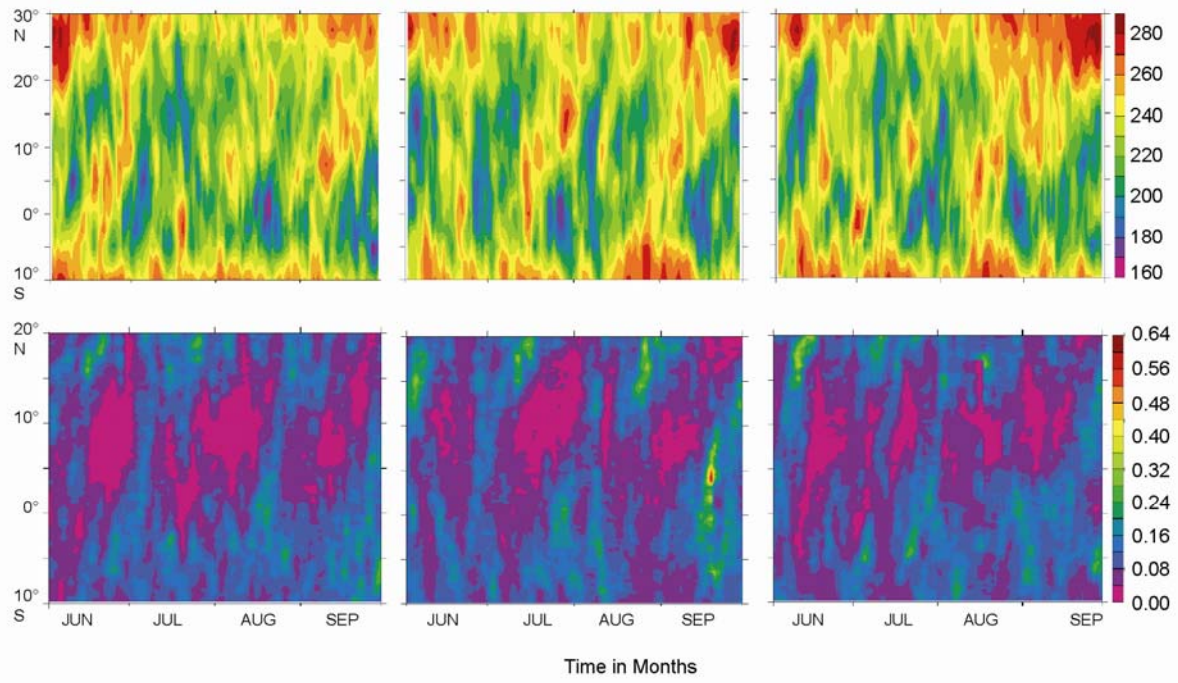


Fig.4