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Intraseasonal Variability of Rainfall, Wind and Temperature during summer monsoon at an Indian tropical west coast station, Goa– Role of synoptic systems

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ABSTRACT

Rain gauge data of daily rainfall and in-situ high frequency (10 Hz) measurements of turbulent wind and air temperature at Goa (15.5^{0}N, 73.8^{0}E), located on the west coast of India, are subjected to wavelet analysis to understand dominant periods of oscillations during the summer monsoon. Heavy (subdued) rainfall spells over the west coast of India at Goa are associated with intense phase of 3-7 day (10-20 day) mode of Monsoon Rainfall Oscillation (MRO) as revealed by wavelet analysis of daily rainfall. This is unlike that over the monsoon core region where active or weak monsoon is associated with the strong phase of 10-20 day or 30-60 day mode of oscillations, respectively. Intense or weak rainfall spells are found to be coincident with positive or negative wind anomalies at 850 hPa over the Arabian Sea off Goa coast. Maxima or minima in the relative contribution of 3-7 day mode to total variance are mostly coincident with active or feeble/no 'offshore trough' or Somali Jet positive or negative wind anomalies indicating that 'offshore trough' and 'Somali Jet' oscillations could apparently be responsible for dominance of 3-7 day mode over other modes. Oscillations of wind and temperature reveal that 3-7 day and 10-20 day modes are in opposite phase, especially during July and August. When the convection associated with the lows/depressions in the Bay of Bengal extends up to the west coast, the 3-7 day mode of rainfall and wind are 'in phase' and they are in 'opposite phase' when the 'offshore trough' is prominent.

Key words: Monsoon rainfall oscillation, West coast of India, 3-7 day mode, offshore trough.

INTRODUCTION

Intra-seasonal and inter-annual variability in Indian Summer Monsoon Rainfall (ISMR) has been studied by several researchers (Krishnan et al., 2000; De and Mukhopdhyay, 2002; Bhatla et al., 2004; Gadgil and Joseph 2003 and others) and this topic continues to be of interest from the perspective of prediction at various space and time scales. Inter-annual variability depends on intra-seasonal variability (Ferranti et al., 1997; Krishnamurthy and Shukla 2000; Goswami and Mohan, 2001; Lawrence and Webster 2001), which in turn depends on frequency of occurrence of lows, depressions, cyclones and their movement across the Indian landmass as well as the seas on either side of India. The conceptual model of Krishnamurthy and Shukla (2000) suggests that the "active" and "break" phases are fluctuations about seasonally persisting components that vary on inter-annual time scale. If the seasonally persisting components make a relatively large contribution to the seasonal mean rainfall and are related to slowly varying boundary forcing or other low frequency global circulations, the seasonal rainfall anomaly over India may be more predictable.

ISMR exhibits various dominant modes of oscillations or quasi periodicities like 3-7 day, 10-20 day and 30-60 day. While the latter two modes are associated with "active/break" cycle and large-scale circulation features (Kulkarni et al., 2011), the former mode is linked to waves, depressions and storms with a lifetime of 2-7 days that arise from instability induced by horizontal and vertical wind shear and convection (Krishnamurti and Sanjay, 2003). These high-frequency (2 to 7 day) time scales are a major source of energy for the 30-60 day Madden- Julian Oscillation (MJO) (Sheng and Hayashi, 1990 a, b). The above results are the outcome of the analyses of large data of a few decades to 100 years of seasonal rainfall and based mainly on the variability of rainfall over central and north-west India, known as monsoon core region. The west coast of India experiences heavy rainfall (> 10 cm/day) mostly when offshore trough over the Arabian Sea parallel to the peninsular India is prominent and it is usually well-marked during active monsoon conditions. Meso-scale vortices that develop in the offshore trough are responsible for heavy rainfall events over the coast (George, 1956). Field experiments like MONEX-1979 and ARMEX-2002 (Sikka, 2003; Francis and Gadgil, 2006) had been conducted to investigate the organization of strong offshore convection along the west coast of India. Maintenance of offshore convection is attributed to upstream convergence aided by frictional convergence as the monsoon flow approaches the west coast (Grosman and Durran, 1984) and also the dynamics of air-sea fluxes, latent heat release and

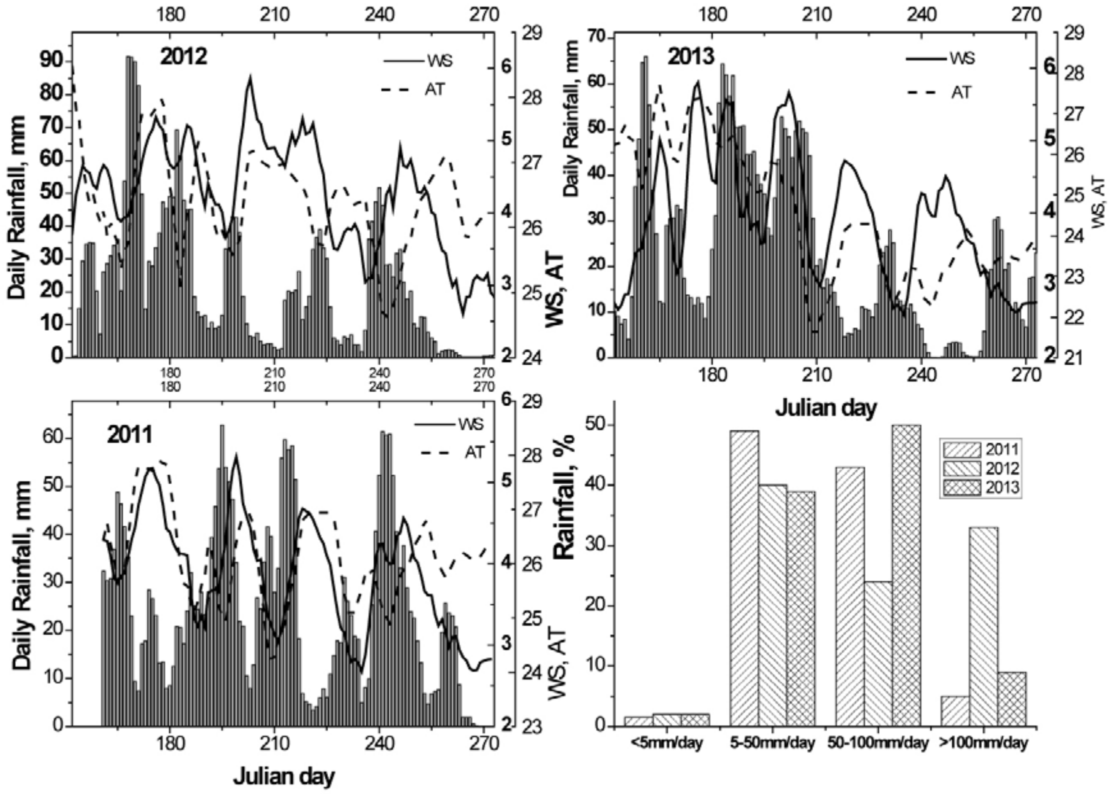

Figure 1. Rainfall (bars), wind speed (solid curve) and air temperature (dashed curve) during monsoon (June to September) (lower left) 2011, (top left) 2012 and (top right) 2013. Wind speed in ms^{-1}, air temperature in deg Celsius. Time series of daily mean are 5-point adjacent averaged to get clarity of oscillations; (lower right) Contribution of rainfall events in three categories (< 5mm; 5-50 mm; 50-100 mm and > 100 mm per day) to seasonal rainfall.

topography of the Western Ghats (Ogura and Yoshizaki, 1988).

Monsoon Rainfall Oscillation (MRO) over the west coast could be different from the central India since it is influenced more by the quasi-stationary mid-tropospheric disturbances and topography-related off-shore vortices while low pressure systems (LPS) over Bay of Bengal contribute little to heavy rainfall (Krishnamurthy and Shukla, 2005). Goa is chosen for the MRO study over the west coast as it is proximate to the Somali Jet and continuous in-situ observations are available. Although satellite and reanalysis estimates of rainfall are available for many years, they suffer from several uncertainties. As reported by Singh and Singh (2013), Quantitative Precipitation Estimates (QPE) derived from Kalpana-1 Satellite and Tropical Rainfall Measuring Mission (TRMM) rainfall did not have good agreement with observed gridded rainfall over six representative regions of India during southwest monsoons 2009 and 2010, though good correlation coefficients existed between the satellite precipitation estimates and actual rainfall. The objective of this study is to understand intraseasonal variability of in-situ observed rainfall, wind and temperature during summer monsoon over the west coast and probable controlling factors.

DATA AND METHODOLOGY

Wind and air temperature were measured at 10 Hz sampling at a height of 25 m using a sonic anemometer (Gill) during the monsoon season (June-September) of 2011, 2012 and 2013 at Saligao, Goa. These data were filtered to remove spikes, if any, and averaged over 30 minutes to prepare half-hourly and then daily time series. Very few missing half-hourly values were filled by linear interpolation. Time series of daily precipitation were obtained from rain gauge measurements. Goa experiences about 3000 mm of rainfall in the season as it is located towards north of the monsoon westerly low level jet core (850 hPa). These daily time series of Rainfall (RF), Wind Speed (WS) and Air Temperature (AT) were subjected to wavelet analysis in order to delineate the dominant modes of oscillations/periodicities and their occurrence as well as duration during the monsoon season. Morlet wavelet and the MATLAB program were used here for computing the power at various time scales and also the global spectrum (time averaged). Details of the technique are available elsewhere (Torrence and Compo, 1998; Foufoula-Georgiou and Kumar, 1995). The relative contribution of various modes of oscillations to the total variance (from all time

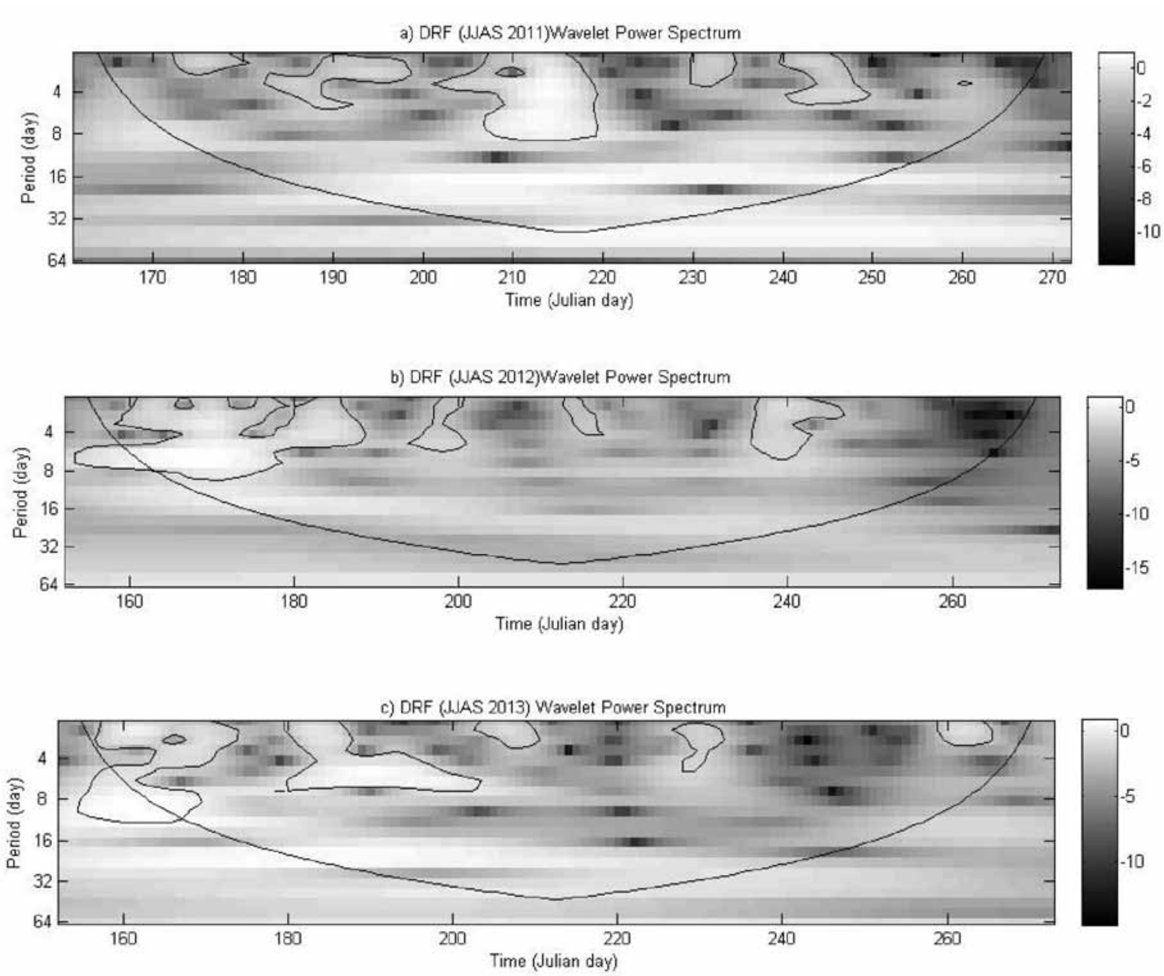

Figure 2. Wavelet power spectra of Daily Rainfall (DRF) for monsoons 2011, 2012 and 2013. Contours indicate power at 95% significance. Thick solid curve indicates 'cone of influence' below which values are dubious. Julian day ranges from 161 to 272 in 2011 (scaling is different) while it is from 152-273 in 2012 and 2013.

scales) was derived by integrating wavelet power (variance) in time scale bands (like 3-7 day; 10-20 day and 30-60 day) and normalizing it with total variance. Thus time series of percentage contributions of various modes to the total variance were compared to know their "active" and "weak" phases during the monsoon season.

Analysis

Time series of daily mean parameters are smoothed by 5 day adjacent averaging to illustrate coherent, "active"/"weak" spells of rainfall during the monsoon season without high frequency fluctuations. Figures 1a-c show time series of RF, WS and AT for 2011, 2012 and 2013. From these figures it can be inferred that there are about 3 to 4 spells of intense rainfall interspersed by approximately 10 or 20 days of subdued or little rainfall. These active phases are uniformly distributed in 2011 whereas they are dominant in June 2012 and in July 2013. Peaks in RF are associated with depressions/minima in WS while AT peaks in between the active spells of RF. ISMR was 102%, 93% and 106% of its Long Period Average (LPA) (www.imd.gov.in IMD monsoon reports) in 2011, 2012 and 2013 respectively and are considered as 'normal' monsoons. Rainfall sorted into 4 categories of < 5 mm/day, 5-50 mm/day, 50-100 m/day and > 100 mm/day indicates that maximum contribution to ISMR is from 5-50 mm/day events in 2011and 2012 while 50-100 mm/day events dominate in 2013 (Figure 1d). Very heavy rainfall (> 100 mm/day) events contributed ~ 32% in 2012, the year that had relatively less seasonal rainfall. Time lags of a few days were observed among RF, WS and AT on some occasions of intense/moderate RF events in all the years. Wind maxima followed intense rainfall events. The AT is expected to rise during the lull period between the heavy rainfall events. This could explain observed time lags among RF, AT and WS.

Wavelet power spectra of the daily RF for 2011, 2012 and 2013 (Figure 2) are depicted as Julian day-wave period

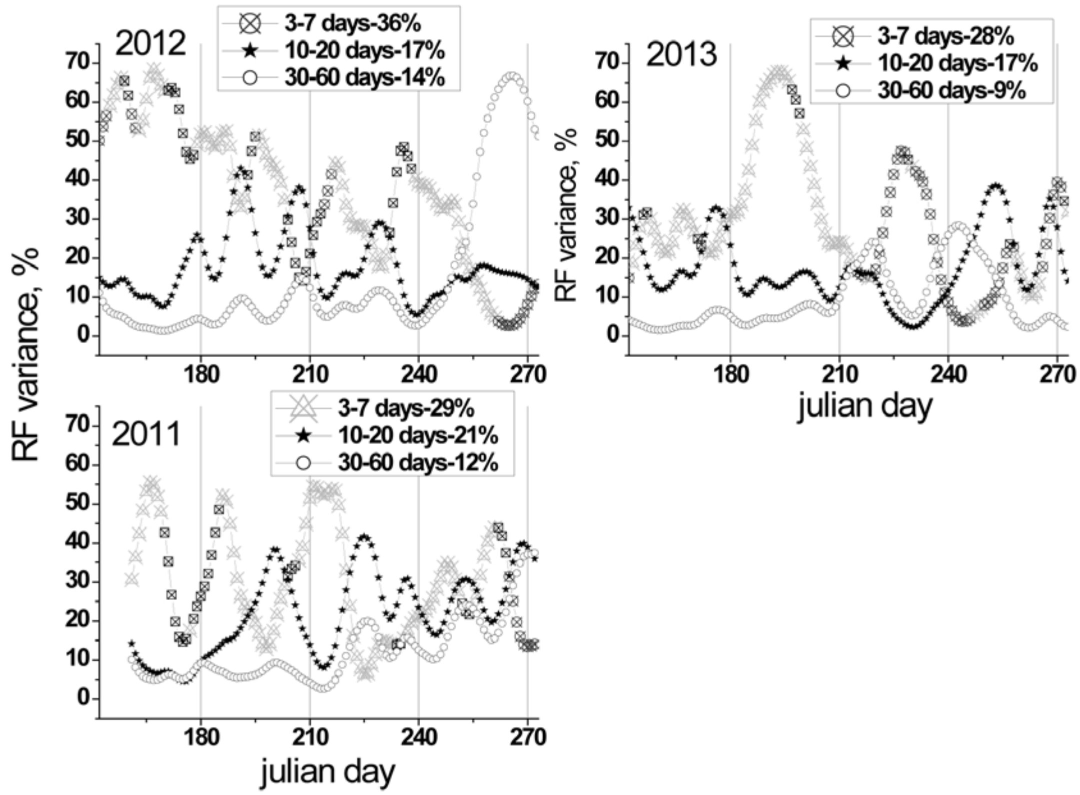

Figure 3. Relative contribution of various modes of Intraseasonal Oscillation (ISO) viz. 3-7 day; 10-20 day and 30-60 day modes, to total variance of rainfall for monsoon (lower left) 2011, (top left) 2012 and (top right) 2013. In the 3-7 day ISO curve, 'Triangle' represents 'active offshore trough'; 'square' and 'circle' indicate 'feeble' and 'No' offshore trough respectively as reported in IMD's annual monsoon reports. It may be noted that maxima in 3-7 day mode curve (active phase of 3-7 day ISO) are in general coincident with 'active' offshore trough while the minima (weak phase of 3-7 day ISO) are associated with 'feeble or 'no' offshore trough.

cross-section of power. It may be noted that less than 8 day periodicities are conspicuous.They occur with a gap of about 20 days in between them and correspond to active spells of RF. In 2011 they are distributed more or less uniformly while in 2012 and 2013 they are prevalent in the first half of the season as compared to the second half.

In order to quantify the relative contribution of various modes of monsoon rainfall oscillations to total variance through the season, percentage variance of 3-7 day, 10-20 day and 30-60 day modes are computed for 2011, 2012 and 2013 and are depicted in Figure 3. The 3 modes contribute 29%, 21% and 12% respectively to total variance indicating the dominance of 3-7 day mode over the other two modes. The peaks in 3-7 day mode roughly correspond to intense spells of RF in time series (Figure 1) indicating that 3-7 days mode are mainly responsible for intense RF spells over the west coast. Time series of 3-7 day mode curve has points of different shapes that represent the status of the 'offshore trough' through the season. 'Triangle' indicates active trough, 'square' corresponds to feeble trough while 'circle' represents 'absence of trough'. Thus the peaks with > 50% contribution are mostly associated with an active offshore trough. The 10-20 day mode is in the opposite phase of 3-7 day mode, especially in July and August; i.e., in general, while the 3-7 day mode is associated with intense rainfall, the 10-20 day mode is related to subdued rainfall. The 30-60 day mode becomes prominent during second half (August and September) and is in phase with the 10-20 day mode. Similar analyses of WS and AT (given in 'supplementary material as SFigure 1, 'SFig' referes to supplementary material) also indicates approximately an opposite phase relationship between 3-7 day and 10-20 day modes for both WS and AT, particularly in July and August. In 2012, the 3-7 day mode contributes on an average 36% to the total variance, which is twice of that by 10-20 day mode (Figure 3). Similar to 2011, generally the peaks in 3-7 day mode are associated with persistence of offshore trough ('Triangle' dots) while the minima are coincident with feeble or absence of offshore trough. The two modes (3-7 day and 10-20 day) are in opposite phase during July and August. The 30-60 day mode is in phase with 10-20 day mode. As shown in SFigure 2, WS and AT depicting

Table 1. Correlations between various modes of RF oscillations and comparison of Goa RF with TRMM rainfall over the west coast and the central India.

Correlation between parameters	Correlation, R		
	2011	2012	2013
Goa RF (Rain gauge) and West coast TRMM RF	0.54	0.21	0.20
Goa TRIMM RF and West coast TRMM RF	0.62	-	-
Goa TRIMM RF and Central India TRMM RF	0.04	-	-
Time series of Goa RF and 3-7 days mode variance of RF	0.31	0.66	0.55
RF modes: 3-7 days & 10-20 days	-0.61	-0.25	-0.38
RF modes: 3-7 days & 30-60 days	-0.46	-0.80	-0.51
RF modes: 10-20 days & 30-60 days	+0.71	-0.01	+0.06
Parameter	Value		
3-7 days mode variance contribution to total variance of RF	29 %	36 %	28 %
RF > 100 mm/day contribution to total RF	5 %	35 %	10 %
5 <RF<100 mm/day contribution to total RF	90 %	65 %	87 %

Note: R-Correlation; RF-Rainfall; TRMM RF (0.25 x 0.25 deg): Goa (lat 15.00, lon 73.25, lat 18.00, lon 74.10); West coast (72.42, 11.09, 75.94, 20.23); Central India (24.00, 78.00, 26.00, 80.00)

the percentage variance contribution through the season for the three modes supports the opposite phase relationship between the 3-7 day and 10-20 day modes in July and August. In 2013, the peaks in 3-7 day mode in June and July are associated with an active offshore trough leading to intense RF spells (Figure 3). In August, RF spell is not associated with an active offshore trough as indicated by absence of trough (Circle dots) suggesting the role of other systems. The 3-7 day and 10-20 day modes are roughly in opposite phase as observed in 2011 and 2012. Time series of variance of WS and AT in 2013 also show that 3-7 day and 10-20 day modes are mostly in opposite phase (SFigure 3).

DISCUSSION

Role of synoptic systems in rainfall variability

Time series of RF, WS and AT reveal that monsoon rain occurs in multiple spells with "active" and "weak/break" periods along with associated wind and temperature variations (Figure 1). An overview of these figures indicates that the peaks in WS follow (lagging) the peaks in RF while AT rises during "weak/break" periods of RF. The west coast of India, in general, is affected by the systems/processes in the Arabian Sea rather than those in the Bay of Bengal due to the presence of the Western Ghats. Since the study location, Goa is situated towards the north of the semi-permanent 'Somali Jet' in the Arabian Sea, it is significantly influenced by shear vorticity of the jet that results in cyclonic circulation and convection leading to intense rainfall. Thus the fluctuations in Somali jet speed and the position of its core with respect to Goa determines the intensity of rainfall as well as wind speed. It appears that intense rainfall occurs (with less wind over Goa) and wind speed increases after the rainfall subsides. Anomalies of wind speed over the Arabian Sea off Goa coast are discussed below. Relatively clear skies and more sensible heat flux causes temperature to rise during the intervening period of active RF spells.

Our analyses find that 3-7 day mode of oscillation in RF dominates over the other two modes during active rainfall spells over the west coast, which is different from that over the monsoon core region or central India where the intense phases of 10-20 day mode and 30-60 day modes are related to "active/break" cycles respectively of monsoon (Kulkarni et al., 2011). Another contrasting feature is that 10-20 day and 30-60 day are in opposite phase over central India (Kulkarini et al., 2011) while the 3-7 day and 10-20 day are in opposite phase over the west coast. This implies that the intense phase of 10-20 day mode is related to subdued rainfall over the west coast while the same is related to active/intense rainfall over central/rest of India. According to Kulkarni et al., (2011) the intense phase is associated with anti-cyclonic circulation over the Indian Ocean, easterly flow over the equatorial Pacific Ocean resembling the normal or cold phase (La Nina) of El Nino Southern Oscillation (ENSO) phenomenon, and weakening of the north Pacific Sub-tropical High. It may be noted that in their paper Figure 1 indicates negative anomalies of rainfall over the west coast for strong phases of both 10-20 day and 30-60 day modes suggesting that the physical mechanism influencing the west coast could be different from that of central India. Our analysis of rainfall during the monsoons of 2011, 2012 and 2013, brings out the fact that good rainfall spells over Goa, representative of the west coast are associated with intense phase of 3-7 day mode, not the 10-20 day mode as over the rest of India.

Rainfall over Goa is compared to that over the west coast as well as the central India, obtained from Tropical Rainfall Measuring Mission, TRMM (Geovanni). Correlations between various modes of oscillations and rainfall are provided in Table 1. For 2011, TRMM rainfall (0.25 x 0.25 deg) over the west coast of India and Goa rainfall (Rain gauge) has a correlation (R) of 0.54 while it has R = 0.62 with Goa TRMM rainfall. For 2012 and 2013, the correlation between Goa RF and West coast TRMM RF is 0.21 and 0.20, respectively. In 2011 rainfall over Goa is uniformly distributed through the monsoon season with heavy rain events (> 100 mm/day) contributing ~ 5% to seasonal RF. In 2012 and 2013, heavy rain events contributed ~ 35% and 10%, respectively. It appears that when RF is moderate (RF between 5 and 100 mm/day contributes ~ 90%) and intense RF events are meager, TRMM RF over the west coast and Goa RF match reasonably well (in 2011) but they mismatch if intense rain events are significant (with 35% and 10% contribution to total RF) as in 2012 and 2013. No correlation is observed between the west coast and the central India RF as obtained from TRMM. Time series of Goa RF and 3-7 day mode variance of RF have R=0.31, 0.66, 0.55 in 2011, 2012 and 2013, respectively suggesting that if there are significant intense rainfall events then active RF spells are relatively better associated with 3-7 day mode of oscillation. Correlations among 3-7 day, 10-20 day and 30-60 day modes of RF oscillations indicate that reasonably better relationship is observed in 2011 (with a few heavy RF events) as compared to 2012 and 2013 (Table 1). Comparison of TRMM and Goa RF, thus indicates that Goa represents the west coast in RF variability reasonably well in 2011 but not so in 2012 and 2013. No relationship is observed between the west coast RF and the Central India RF, which may be indicating that different physical mechanism or same mechanism with different degrees of influence are in operation at these two locations. Central India (Monsoon core region) is prone to monsoon trough oscillations, "active/break" cycles, LPS in Bay of Bengal (BOB), Somali jet, etc. while the west coast is very much influenced by offshore trough, Somali jet, the Western Ghats and to some extent by LPS in Bay of Bengal (BOB) and the Arabian Sea. In addition to these synoptic scale systems that transport moisture leading to moisture convergence over land, inland terrestrial ecosystems pump in much moisture into the atmosphere through evapo-transpiration. Thus, it is quite difficult to explain from observations alone, which process dominates at what time to induce precipitation.

In addition to 'Somali jet' and 'offshore trough' over the Arabian Sea, there are several other synoptic systems (like low pressure systems and depressions and cyclonic circulations) that may also contribute partially to rainfall over the west coast in spite of the presence of the Western Ghats. There are 10 LPSs in 2011 out of which 5 formed over land, 4 over the BOB and 1 over the Arabian Sea. Depression over BOB during June 16-23 and the same over land during July 22-23 are coincident with strong and moderate phases of 3-7 day mode of RF. The one during September 22-24 also coincides with intense phase. In 2012 there are 10 LPS (2 in July; 5 in August; 3 in September) and no depressions. The monsoon trough was in its normal position during July 20 – August 16 giving wide spread rainfall. During the same period the 3-7 days mode shows weak and intense phases consecutively. There are no LPS in June but in the 3rd week intense rainfall of 90 mm/day occured over the west coast, which is related to positive wind anomalies of 'Somali jet'.

As shown in Figure 3, majority of the peaks in 3-7 day mode variance through the season are associated with active 'offshore trough'. But there are some exceptions like that in August 2013 (Figure 3c) that show 'absence of offshore trough' (Circle dots) but 3-7 day mode is in intense phase as well as rainfall (Figure 1c). IMD's monsoon report for 2013 mentioned that there were one depression over land and 5 low pressure systems of short duration in BOB in August. In July there are 3 LPSs and 1 depression in BOB and one LPS over land and intense and continuous rainfall is noticed in July 2013. From the perspective of the influence of lows and depressions and monsoon trough position on rainfall, it may be inferred that although the rainfall over the west coast shows dominance of 3-7 day mode, its intense phase (coincident with intense rainfall spell) cannot be attributed to a single one system like 'offshore trough' or 'low/depression' or 'monsoon trough oscillation'. At times there may be contributions from other systems like a sub-tropical westerly jet, Mascarene High, etc. However, most of the intense spells of rainfall (associated with peaks in 3-7 day mode variance) are found to be associated with an active 'offshore trough' as evident from Figure 3.

OLR from NOAA/ESRL weekly averaged plots (not shown here) indicate propagation/spread of convective cores over BOB to the peninsular India and the west coast in July and August 2013. There are 4 and 3 LPS in June and September, respectively in 2013. Thus the synoptic systems in BOB also influence the rainfall over the west coast to some extent since low OLR values indicate thick clouds that may or may not confirm precipitation always.

Oscillations in wind and temperature along with rainfall in terms of percentage variance in 3-7 day mode is depicted in SFigure 4 to understand the similarities in their modes of oscillations through the season. In 2011 there is one active RF spell in June, July and August and 2 spells in September as indicated by peaks in 3-7 day mode. In July and August the intense phase in RF is coincident with the weak phase of WS and vice versa while they are in same phase in June. In September some lag is observed between RF and WS phases. In 2012 also RF and WS are mostly

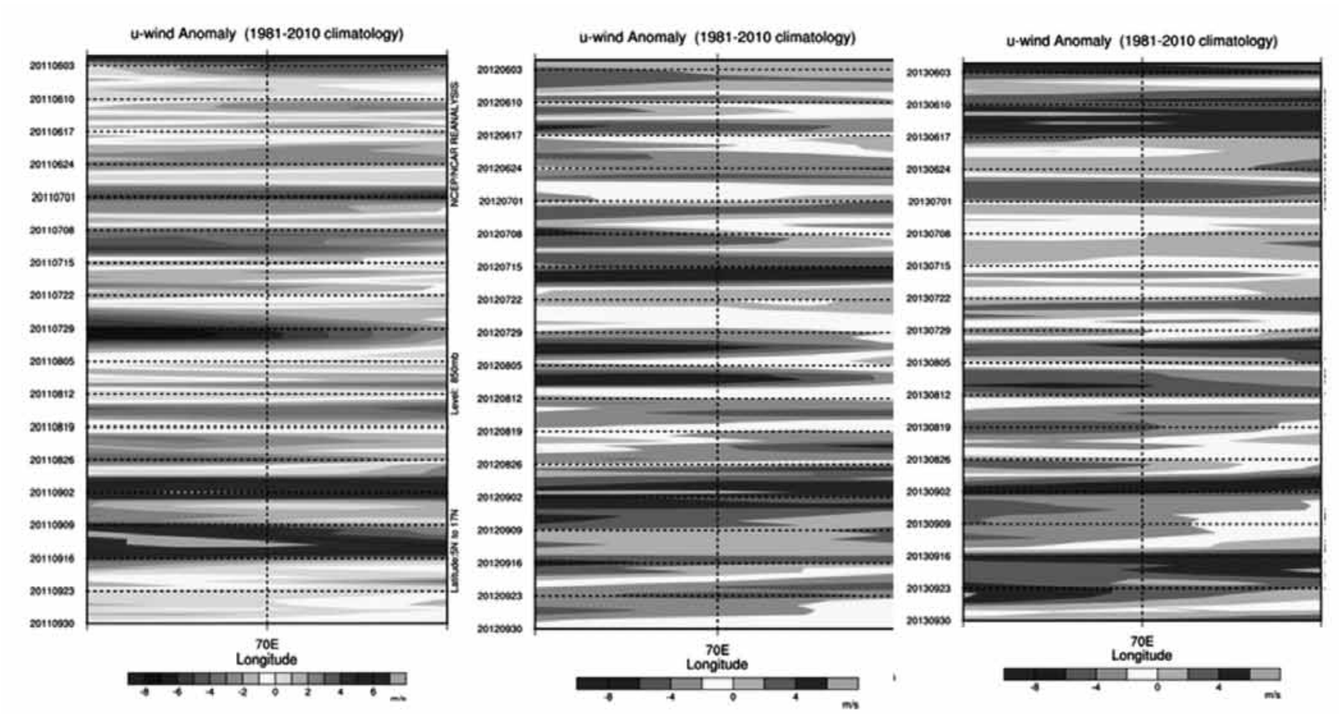

Figure 4. Time-longitude (65⁰E to 75⁰E) section of U-wind anomaly averaged between 5⁰N to 17⁰N to illustrate variability of 'Somali jet' strength during the summer monsoon a) 2011, b) 2012 and c) 2013 (left to right) respectively. Time axis starts from top to bottom (i.e. from June to September). Images have been obtained from NCEP/NCAR Reanalysis visualization website.

in opposite phase except during the last week of August. In 2013 during July (influenced by synoptic systems) RF, WS and AT are in phase while during August (with LPS of short duration) RF and WS are in opposite phase. No specific phase relationship is discernable between RF and AT for the 3-7 day mode of oscillation.

Objective analysis of synoptic systems and rainfall

Oscillations of monsoon rainfall are quite complex with interactions of various waves of different periodicities like the 3-7 day, 10-20 day and 30-60 day modes. The 10-20 day and 30-60 day modes are, in general, associated with "active/break" cycles of monsoon and MJO, respectively (Madden and Julian, 1972; Kulkarni et al., 2011 and several references therein), The 3-7 day mode is related to monsoon trough oscillations (Tyagi et al., 2012). Surface fluxes of momentum and moisture (thus wind and convection/rainfall) are observed to be amplified as the waves in MJO time scales interact with synoptic scales of 2-7 days (Krishnamurti et al., 2003). RF, WS and AT are in phase (SFigure 4) during the active spell of rain throughout July 2013 when synoptic activity is very strong (3 LPS in BOB; one over land) while RF and WS are roughly in opposite phase in August 2013 when synoptic systems are relatively weak with LPS of short duration. It appears that RF and WS are in opposite phase when offshore trough is prominent and in phase when lows/depressions are dominant in BOB with convective clouds extending up to the west coast (as inferred from OLR plots). 'Somali jet' being one of the major characteristic features of the summer monsoon influencing moisture transport over the Indian land mass (Joseph and Sijikumar, 2004), its effect on the west coast (especially over Goa as it crosses the coast at Goa latitude) is expected to be much more. Time-longitude cross-section of wind anomalies at 850 hPa (averaged between latitudes 5⁰ N and 17⁰ N) over the Arabian Sea off Goa coast (65⁰E to 75⁰E) is illustrated in Figure 4 for 2011, 2012 and 2013, respectively (Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.esrl.noaa.gov/psd/). It may be noted that in general positive (negative) anomalies of U-wind are associated with intense (weak) rainfall spells (Figure 4a and Figure 1a). Similar feature (correspondence between wind anomalies and rainfall spells) is exhibited during the 2012 (Figure 4b and Figure 1b) as well as in 2013 (Figure 4c and Figure 1c). Intense rainfall during August 29 – September 15 in 2011 (Figure 1a) is associated with positive wind anomalies (Figure 4a) while the weak rainfall spell during July 25 – August 3 relates to negative wind anomalies. Similarly, heavy or subdued rainfall (Figure 1b) during August 26 – September 15 in 2012 (August 1 – 19) corresponds to positive or negative wind anomalies (Figure 4b). However, intense spell during June 15-22 (Figure 1b)

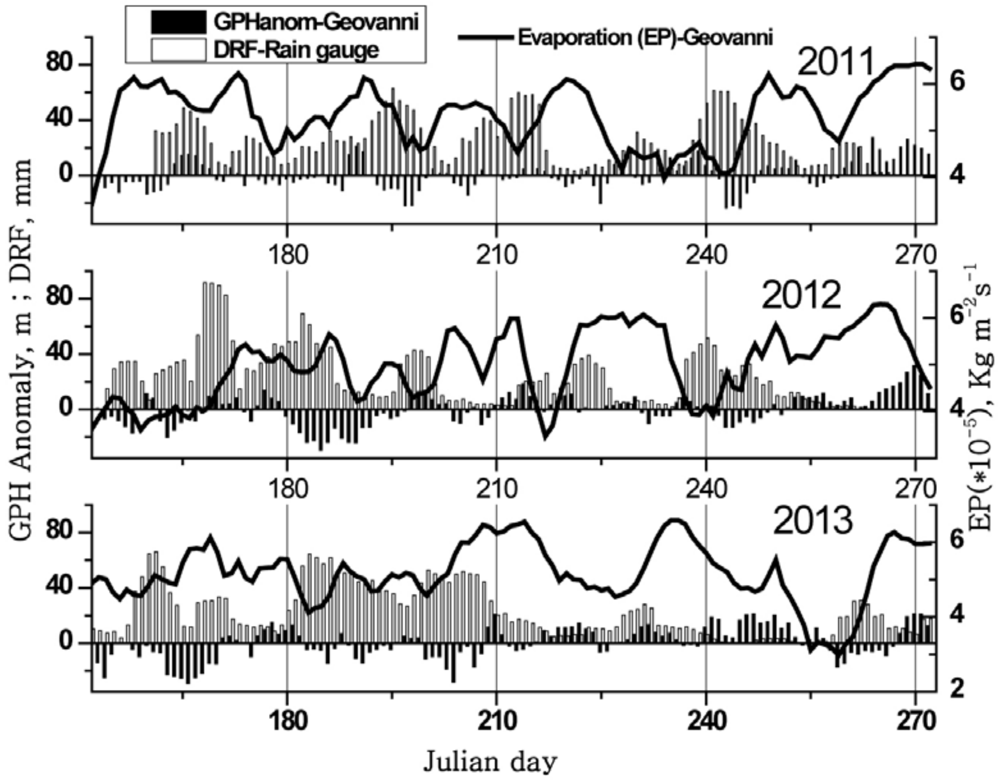

Figure 5. Time series of Daily rainfall (DRF), Geopotential height anomaly (GPH anom) and Evaporation rate (EP).

is not associated with positive wind anomalies, but near to 75^{0}E there are positive wind anomalies. In 2013 no rainfall is observed during September 1-15 (Figure 1c) and it coincides with strong negative wind anomalies (Figure 4c). It appears that in general positive wind anomalies over the Arabian Sea tend to produce intense rainfall over the coast.

In order to understand the role of LPS or depressions, Somali jet wind anomalies and offshore trough in causing intense rain spells, we have tabulated the presence of these systems during each one of the rain spells in 2011, 2012 and 2013 (Table 2). There are 4 active rain spells in 2011, 5 spells each in 2012 and 2013. To be more precise about the offshore trough, we have obtained geopotential height at 850 hPa from Geovanni – Atmospheric InfraRed Sounder (AIRX3STD_006_GPHeight_A/D, 1.0 x 1.0 deg) over the west coast (area-averaged over Lon 65-75; Lat 5-17deg). As shown in Figure 5, there are inconsistencies between rain spells, offshore trough, Offshore Trough (OST) (negative geopotential height) and wind anomalies and they are provided in Table 2 along with LPS/depressions. It may be noted that different systems prevailed during different spells. Though there are several LPS in BoB in 2011, 2012 and 2013, most of them are not coincident with active rain spells over Goa. Only 2 LPS/depressions formed over land are coincident with intense rainfall over Goa (i.e., Aug 12-14, 2012 and Aug 20-22, 2013) when offshore trough is absent as well as –ve wind anomalies are present. On two occasions (Aug 1-7, 2011 and June 15-22, 2012) no system/favorable condition prevailed, but intense rainfall occurred ,which could be due to local convection due to increase in evaporation.

Surface Evaporation (EP) (from Geovanni-Merra, 0.5 x 0.667 deg) at Goa (Lat 15.4-16.3, Lon 73.8-74.5 deg) indicates enhanced evaporation in between the intense rain spells (Figure 5) on most of the times. Although negative wind anomalies reduce moisture transport, terrestrial evapo-transpiration over the coast might be playing a role in increasing moisture and convection resulting in intense rainfall. As shown in SFigure 5, time series of area averaged total column water vapor (precipitable water) in 2011 over Goa (Lon 73.25-74.1; Lat 15-18 deg) during June-Sep remains mostly constant 50±2 kg m^{-2} as obtained from Geovanni Atmospheric InfraRed Sounder (AIRS AIRX3STD v006). It has little correlation with rainfall variability. The correlation between in-situ rainfall (at Goa) and OLR as well as geopotential height anomalies (area-averaged as above from Geovanni AIRS) is -0.3. As shown in SFigure 5 most of the rain spells are found to be associated with OLR (over Goa box as above) equal to or less than 200 Wm^{-2} (a value normally used to indicate deep convection by IMD). In July 2013, there were 4 LPS and 1 Depression that clearly indicated the spread of convection from BOB

Table 2. Distribution of Active rain spells over Goa, Offshore trough and Somali jet (wind anomaly) during the summer monsoons of 2011, 2012 and 2013.

Monsoon 2011					
Active rainfall spell	Around June 15, 2011	Around July 15, 2011	**Aug 1-7, 2011**	Sep 1-15, 2011	
OST(-ve GPH anomaly)	NO	YES	NO	YES	
Wind anomaly	+VE	-VE	-VE	+VE	
Monsoon 2012					
Active rainfall spell	**June 15-22, 2012**	July 1-7, 2012	July 15-22, 2012	**Aug 7-15, 2012**	Around Sep 1, 2012
OST(-ve GPH anomaly)	NO	YES	NO	NO	YES
Wind anomaly	-VE	+VE	-VE -Jul 15-18 +VE -Jul 19-22	-VE	+VE

Note: GPH – Geopotential Height at 850 hPa. In 2011 there were no LPS or Depression coincident with the active rain spells at Goa. The four active spells marked BOLD are the ones during which both 'Offshore Trough (OST)' and 'Positive Wind anomalies' were absent. However, the events during Aug 12-14, 2012 and Aug 20-22, 2013 were coincident with LPS and Depression respectively over land. Other active spells were coincident with either OST or Positive Wind anomaly of Somali Jet or both. Thus active rain spells over Goa seem to be mainly influenced by OST and Somali Jet.

to the west coast as seen in OLR anomalies (NOAA/ESRL visualization-- not shown here). Since offshore trough and positive wind anomalies (Figure 5) are also present, it is hardly possible to single out one system as the cause of intense rain spells in July 2013. Although active rain spells are correlated with Offshore trough intensity ($R = -0.3$), wind anomalies are not consistent with some rainfall spells (June and July) indicating that moisture transport from the Arabian Sea may not be as important as expected. Since the total water vapor is not varying much, the expected decrease in moisture transport (by negative wind anomalies) appears to be compensated by local evapo-transpiration. As shown in Figure 1, wind and air temperature peaks in between intense rainfall events suggests that high temperature and wind result in more evaporation from the land surface leading to intense rainfall after a few days (Figure 5). At smaller spatial scales, local factors (such as air temperature) influence intense rainfall spells more than the large scale factors (Mondal and Mujumdar, 2015). Our results corroborate this fact that local processes also at times contribute much to building up of moisture leading to active rain spells when the synoptic scale environment is unfavorable.

Thus the rainfall over the west coast seems to be mainly affected by Somali jet anomalies and offshore trough intensity and its variability exhibits relatively dominant mode of 3-7 day of monsoon oscillation during intense RF period. Recent study by Karmakar et al., (2015) inferring that the relative strength of Low Frequency Oscillation (LFO) (20–60 day) modes have a significant decreasing trend during the past six decades and this reduction being compensated by a gain in synoptic-scale (3–9 day) variability, corroborates our results. Predictability of seasonal monsoon rainfall increases if the LFO contribution (seasonally persisting component) is significant as it depends on slowly varying boundary conditions and large scale circulations (Krishnamurthy and Shukla, 2000). At smaller spatial scales, local factors (such as air temperature) influence intense rainfall spells more than the large scale factors (Mondal and Mujumdar, 2015). Our study confirms that high frequency mode (3-7 day) associated with semi-permanent systems over the Arabian Sea plays a significant role in rainfall variability over the west coast.

CONCLUSION

Variability of the summer monsoon rainfall over the west coast is dominated by 3-7 day mode as compared to 10-20 day and 30-60 day modes. Unlike the monsoon rainfall over core region, which is dominated by strong 10-20 day mode during the active monsoon period, the rainfall over west coast of India is dominated by an intense phase of 3-7 day mode during active spells of rainfall. Similarly, the 3-7 day and 10-20 day modes are in opposite phase over the west coast, especially during July and August while the 10-20 day and 30-60 day modes are in opposite phase over the monsoon core region. Intense phase of the 3-7 day mode over the west coast is observed to be mostly governed by active 'offshore trough', Somali jet positive wind anomalies and local surface evaporation while some low pressure systes/depressions in Bay of Bengal also contribute to the convection over the west coast. Rainfall and wind are in opposite phase in terms of relative contribution of 3-7 day mode of oscillation to total variance when the 'offshore trough' is active while they are in phase when the influence of lows/depressions in Bay of Bengal is relatively dominant over the west coast. Thus monsoon rainfall oscillatory modes associated with active rainfall spells over the west coast are unique and different to that observed over monsoon core region. This is mainly due to different degrees of influence by synoptic and semi-permanent systems.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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Mysterious Intraseasonal Oscillations in Monsoons

India's summer monsoon is a major event, single-handedly supplying water for agriculture across all of southern Asia. Because of its widespread effect on the region's environmental and socioeconomic health, the monsoon has long been studied by meteorologists, climatologists, and oceanographers hoping to understand and forecast its behaviour. One phenomenon in particular, the monsoon intraseasonal oscillations (MISOs), has captured scientists' interest. MISOs are alternating periods of heavy and minimal rainfall, each lasting for about a month or so and tending to follow a cyclical, northward shifting pattern from the equator to southern Asia. Although they were once believed to be a function of the tropical atmosphere, more recent studies have suggested that MISOs come from some kind of powerful atmosphere-ocean interaction.

For one such study, researchers examined the pathways of MISOs traveling across the Bay of Bengal, a region where the monsoon undergoes changes in intensity and frequency.

The same team has previously examined the role of ocean salinity stratification (layering of seawater with different salt contents) in variations in sea surface temperature and the atmospheric processes that produce rainfall. Here, however, they addressed the contribution from two other variables: the depth of the mixed layer, which lies just below the sea surface, and the thickness of the barrier layer, which forms the bottom of the mixed layer.Using an ocean model with data from 2000 to 2014, the researchers investigated how these upper ocean processes affect sea surface temperature (and how variations in sea surface temperature, in turn, affect rain formation in the MISOs). An influx of freshwater from the monsoon, the researchers found, creates a shallow mixed layer and a thick barrier layer, causing dramatic fluctuations in sea surface temperature over the course of the season. What's more, these air-sea interactions lead to the highly irregular rainfall patterns seen as the MISOs reach Asia.

Using advanced models and checking them against satellite data allowed the researchers to pinpoint these driving forces behind MISOs with more precision than in previous studies. Their efforts promise to improve the accuracy of future simulations and forecasts of the MISOs that occur during India's summer monsoon. (**Source**: Li et al, 2017,*Jou of Geophy Res: Oceans*, https://doi.org/10.1002/2017JC012692, 2017)