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Unraveling the spatio-temporal structure of the atmospheric and oceanic intra-seasonal oscillations during the contrasting monsoon seasons

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ABSTRACT

Using remotely sensed data sets of rainfall and outgoing longwave radiation (OLR) over Indian land and adjacent oceanic regions and sea surface temperature (SST) over adjacent oceanic regions; we examine the major characteristics of the intra-seasonal oscillations of Indian summer monsoon (ISM) during the flood and drought years. Intra-seasonal oscillations of rain, OLR and SST corresponding to 30–60 days transpires to contribute more to the intra-seasonal variability over the Arabian Sea, whereas 10–20 days' mode is found to be more dominating over the Bay of Bengal during the drought years. Therefore, suggesting that both of the Seas surrounding the Indian land region respond in a different way to the below normal rainfall conditions of Indian land region. Another important finding of the present work is that during the drought years, 30–60 days intra-seasonal oscillations of SST over both of the seas follow the intra-seasonal oscillations of rain at 30–60 days' time scale over central India approximately after 26 days. Conversely in the flood years, intra-seasonal oscillations of SST at 30–60 days over the Arabian Sea and Bay of Bengal lead the intra-seasonal oscillations of rain over central India by 6 days. Present analysis also reveals that the intra-seasonal variability of ISM at two different time-scales (10–20 and 30–60 days) possess different spatio-temporal characteristics during the contrasting monsoon conditions over the oceanic regions; therefore it is advisable to study the two modes individually for understanding the underlying physical mechanism. Results presented in this paper may be useful for improved ISM prediction.

1. Introduction

During the South-West monsoon season (i.e. June–July–August–September), the Indian subcontinent receives approximately 80% of its total annual rainfall which essentially controls the agriculture based economy of the country. The food productivity of the country is substantially modulated by the inter-annual variation in the seasonal total rainfall (Krishna Kumar et al., 2004). Inter-annual variability (IAV) of the Indian summer monsoon (ISM) may be divided into two major subdivisions. The first one is the daily variability of rainfall within a season also known as intra-seasonal variability (ISV) which is the part of internal dynamics of monsoon and the second one is the external surface boundary forcing parameters, such as land surface temperature, snow cover, El-Nino-southern oscillation (ENSO) etc., affecting the amount of the rainfall at inter-annual scale. Among these two major contributing factors the first component (ISV) plays the unpredictable and chaotic role in monsoon IAV whereas the second one is potentially more predictable component of IAV (Gsfc, 2000). The percentage of contribution of these two factors overall determines the predictability of ISM rainfall for a particular season (Goswami et al., 1984). Numerous previous studies have established that the spatiotemporal variability of monsoon rainfall shows dominant periodicities at intraseasonal scale. It was established that certain preferred periodicities are primarily observed in the power spectrum of ISV, suggesting that some particular oscillations are predominantly contributing in the generation of ISV (Goswami, 2005). Observational study of Krishnamurti and Bhalme (1976) and other studies (Chen and Chen, 1993; Krishnamurti and Ardanuy, 1980; Singh, 2013; Yasunari, 1979) demonstrated the presence of quasi-biweekly oscillation in most of the elements of monsoon system (e.g., rainfall, cloud cover, and monsoon trough). Dakshinamurthy and Keshavamurthy (1976) observed northward-propagating-30-days periodic oscillations from power spectral and phase analysis of zonal wind data over Indian region. Yasunari, 1979 also had found 30 days and 40 days northward- propagating periodic oscillations respectively in satellite cloudiness data of 1973.

Krishnamurti and Ardanuy (1980) explained that 10–20 days periodicities have generally westward propagation along the latitudinally extended (centered between 20° and 30° N) monsoon trough over central India. In addition to this, the study also revealed that surface pressure between 20° and 30° N during 70% of break spells in the periods of 1933–1972 (40 years) coincided with the arrival of the westward-

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propagating 10–20 days mode ridges. Therefore, it was suggested that the westward-propagating 10–20 days oscillations plays an important role behind the occurrences of active and break spells over central Indian region.

Krishnamurti and Subramanyam (1982) discovered that 30 and 40 days mode of oscillation has global eastward propagation and regional northward propagation over the Indian subcontinent. Later Murakami et al. (1984) and Krishnamurti and Gadgil (1985) mentioned the prominent intraseasonal oscillations (ISOs) in a form of a band of 30–50 days periodicity, instead considering it as a centered periodicity corresponding to 30 days. Using a 70-year (1901–1970) rainfall data over the Indian land region, Hartmann and Michelsen (1989) reported the presence of 40 to 50 days of intra-seasonal periodicity over most of the part of India, South of 23° N. Krishnamurthy and Shukla (2007) also used the same data set and found that there are two dominant ISOs at 20 and 45-day timescales. Several modeling studies also had observed that consideration of air-sea connection in model can simulate ISOs better than considering only atmosphere. The presence of two distinct low frequency ISOs and their propagation behavior have been extensively studied in recent decades based on the satellite data (Hoyos and Webster, 2007; Sengupta and Ravichandran, 2001). By examining the outgoing longwave radiation (OLR), zonal and meridional wind for 20 years (1971–1990) of time period, Goswami (2005) confirmed that the 10–20 days and 30–60 days band of oscillation are the key components of ISOs monsoon. Further to this, it was also mentioned in the aforementioned study that frequency component of 10–20 days oscillation is clearly separated from the more higher frequencies associated with the synoptic activities (1–10 days). The other frequency mode i.e. 30–60 days was also evidently distinguishable from the lower frequencies associated with annual cycles. Initially, the indication of the connection between Northward movements of sub-continental monsoon trough and northward-moving 30–60 days periodic oscillation of monsoon and the possible dual cell structure of 30–60 days ISOs over the Indian longitudes were reported by Sikka and Gadgil (1980). They mentioned that during monsoon season maximum cloud zone (MCZ) or inter-tropical convergence zone (ITCZ) over their two favorable seasonal locations i.e. the sub continental landmasses and equatorial Indian Ocean (EIO) (15°–28° N and 5° N between the longitudes 70°–90° respectively) is generally associated with Northward and Eastward propagation respectively. They found that monsoon trough over Indian land masses had a typical lifespan around 4 weeks (in between, it is either stationary or moving northward) after which it use to disappear and reestablishment of the trough occurs by the northward movement of the other trough over EIO. Similar result also has been reported in later studies carried out by Lawrence and Webster (2002) and Krishnamurthy and Shukla (2007). Recently, Syed et al. (2010) proposed that the active phases over the western part of the summer monsoon domain yield similarity with the large scale monsoon initiation but do not possess any connection with the south Asian intra-seasonal oscillations.

Aforementioned studies established the fact that the dominant ISV corresponding to 10–20 and 30–60 days of ISM are extremely chaotic in nature, therefore a better understanding of the ISV would be beneficial for the improvement of the ISM predictability. Based on the analysis of 33 years (1965–1997) of low-level wind and 20 years of satellite OLR data from NOAA satellite observatory, Ajaya Mohan and Goswami (2003) concluded that 50% of IAV of ISM is governed by low frequency (LF) ISV. Similar result also has been observed by Joshi et al. (2016). Using satellite data, Hoyos and Webster (2007) also mentioned that IAV of ISM is partially modulated by the cumulative effect of rainfall variability at intra-seasonal time scale (25–80 days).

Several other studies also presented significant connections between oceanic and atmospheric ISOs. Krishnamurti et al. (1988) documented that over BOB and western Pacific, ISOs contribute notable fluctuations on SST and latent heat flux. Sengupta and Ravichandran (2001) also showed large ISOs of SST and heat flux over BOB. Using TMI SST, wind and NOAA OLR data for 1998–2000, Sengupta et al. (2001) reported that 10–90 days SST ISOs has large spatial scale similar to that of the atmospheric ISOs and it has a coherent northward propagation in association with atmospheric ISOs of OLR and wind speed. Further to this, they also mentioned that atmospheric ISOs appear to lead the ISOs of SST by about 7 days. Vecchi and Harrison (2002) later observed that this relationship was useful for prediction of break spells of ISM.

It is imperative to mention here that previous studies established the fact that the ISV (specifically the low frequency oscillations) modulates the ISM variability considerably. Nevertheless, the behavior of ISV in flood and drought years has not attracted as much attention. There are a limited studies on this note for e.g., Vernekar et al. (1993) studied the 30–60 days mode in two contrasting monsoon seasons and found that in a drought year (1987) this mode shows a clear eastward propagation in the equatorial region, whereas there is no propagation in a flood year (1988). Using a 70-year (1901–1970) daily rainfall dataset, Krishnamurthy and Shukla (2007) found that there is no significant difference in the probability distribution of ISV in strong and weak monsoon years. Kripalani et al. (2004) studied the characteristics of ISOs corresponding to 10–20 and 30–60 days during 2002 (drought year) and 2003 (normal monsoon year) by using 31 daily rainfall station data. They found that in 2002 (2003), 30–60 (10 − 20) days mode was the most dominating mode Kulkarni et al., 2009.

One possible reason behind the limited studies on the behavior of the ISOs during the contrasting monsoon conditions could be the lack of continuous daily data availability over a large region (including oceanic regions) for a long time-period (thus reducing the number of extreme condition years). Availability of the satellite data partially improves this problem, and helps address this issue thoroughly. Present study discusses the ISV of different parameters of ISM using satellite data sets so as to bring out detailed characteristics of atmospheric and oceanic ISOs during the contrasting monsoon season of ISM. This study also emphasis on the intersperse of the atmospheric and oceanic ISOs, in addition to this, investigation of the relationship between oceanic ISOs (over BOB and AS) with the rainfall over the Indian land region during contrasting monsoon years has also been carried out. The present study is motivated by several previous studies on ISM intra-seasonal oscillations (for e.g. Goswami, 2005; Kulkarni et al., 2009; Kulkarni et al., 2011; Sengupta et al., 2001; Vecchi and Harrison, 2002; Vernekar et al., 1993) and more importantly Annamalai and Slingo (2001) wherein authors emphasized on the fact that considering the complex nature of the intra-seasonal oscillations of the monsoon, it is worth to study the most of the components of the monsoon system over the monsoon domain so as to bring out a better understanding of sub-seasonal variability of the ISM. Therefore the results on the intra-seasonal variability of rain, OLR and SST over the Indian land and surrounding oceanic regions respectively discussed in the present work may be utilized for the improvement of the prediction skills for ISM rainfall at sub-seasonal scale.

2. Study area and data sets

2.1. Study area

For the purpose to investigate the characteristics of the ISV of ISM, the Indian land region and surrounding oceanic regions viz. Arabian Sea (AS) and Bay of Bengal (BOB) are selected as the region of study. The central Indian (CI) region (16.5 to 26.5° N; 74.5 to 86.5° E) is sufficiently large and considerably homogenous (Goswami et al., 2006), and also represent IAV of ISM in close association with the all India rainfall, therefore CI is selected for the computation of flood/drought years and for the representation of ISOs over the land region. For the purpose to represent the ISOs of SST, rainfall and OLR, the region bounded between 8 to 17° N; 64 to 71° E and the area between 13 to 19° N; 86 to 92° E are selected over AS and BOB respectively.