Antecedents and self-induction of active-break south Asian monsoon unraveled by satellites

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1. Introduction

[2] The Indian summer monsoon exhibits prominent 30–40 day fluctuations with “active” periods of heavy rainfall interrupted by dry “breaks” [Gadgil, 2003; Krishnamurti and Bhalme, 1976]. The circulation anomalies associated with active/break monsoons cover up the entire Indian Ocean and influence remote tropics and North Pacific Ocean [Webster et al., 1998]. A prolonged dry/rainy period will result in severe drought/flooding, which have profound influences on South Asian water cycle, agriculture and societal activity of over one billion people [Gadgil, 2003]. However, the state-of-the-art atmospheric general circulation models have great difficulty in simulating the monsoon cycle [Waliser et al., 2003].

[3] Previous studies have established that the active/break monsoons are triggered by organized northward propagation of heavy precipitating or cloud-free zones from the equatorial region towards the continental land mass [e.g., Yassunari, 1979; Sikka and Gadgil, 1980]. However, a remaining question of some consequence is where and how the convective anomalies that bring about active and break periods of monsoon are generated. There is some support for the idea that the upper-level divergent waves associated with the Madden and Julian [1971] oscillation (MJO) that circumnavigate the globe, could re-initiate convective anomalies over the Indian Ocean [e.g., Lorenz, 1984; Lau and Chan, 1986]. However, Salby and Hendon [1994] show that the decorrelation time of the MJO is less than 1 cycle. Hence, one event tends not to follow another. During boreal summer the equatorial eastward propagating MJO weakens substantially [Hendon and Salby, 1994] and some northward propagating episodes are independent of the MJO [Wang and Rui, 1990]; whether the circumnavigation of these upper tropospheric divergence waves can re-initiate convection over the Indian Ocean remains to be reexamined.

[4] Previous observational data and techniques were unable to detect the genesis process over the ocean, leaving it as a controversial issue in understanding the monsoon weather and climate. Here we take advantage of a suite of unprecedented satellite data to unravel the genesis process and pinpoint the mechanism for maintenance of monsoon cycle. The data we used are a suite of satellite measurements for precipitation rate, surface winds, SST, and cloud liquid water. One distinct advantage of the Tropical Rainfall Measuring Mission (TRMM) is the onboard TRMM Microwave Imager (TMI). TMI can measure a variety of parameters in the presence of cloud [Wenz and Schabel, 2000], providing reliable measurements of SST, precipitation, and cloud liquid water. The surface winds and convergence are derived from QuikSCAT scatterometer [Freilich and Dunbar, 1999]. The outgoing longwave radiation data and the general circulation model reanalysis dataset available from the European Centre for Medium-range Weather Forecast (ECMWF) are used only as a complement reference to satellite data for the study.

[5] Figure 1 shows time series of daily precipitation rate averaged over the eastern EIO (5°S–5°N, 75°–100°E) and the seas adjacent to Indian subcontinent (15°–25°N, 70°–95°E). The 20–50 day oscillations in the eastern EIO rainfall is notably about 180° out of phase with that over the South Asian (SA) region (10°–25°N, 70°–100°E) (figure not shown). Fluctuations with a dominant period of 20–50 days account for majority of the total variance in the time series (The ratio in square root of variance between the 20–50 day filtered and daily time series is 60%, 74%, and 74% for 2000, 2001, and 2003, respectively). From 2000 through 2002, each summer experienced four cycles from mid-May to mid-September. This allows a total of 12 events for the construction of a composite to describe the mean behavior of a monsoon ISO.

[6] Since the periods of individual ISO cycles are irregular, ranging from 25 to 43 days (Figure 1), the method used to construct the composite life cycle was based on eight consecutive phases in each of the 12 cycles shown in Figure 1. Phases 1, 3, 5, and 7 correspond, respectively, to the times when the rainfall anomalies in the eastern EIO are at a minimum, negative-turning-to-positive, a maximum, and...
and positive-turning-to-negative. Because of the out-of-phase relationship between the eastern EIO and India, Phase 1 and 5 are referred to the peak active (wet) and break (drought) phase of the SA monsoon, respectively. The average period of the 12 cycles used in composite is 33 days; thus the mean interval between two adjacent phases is about 4 days. Statistical analysis using the Student-\( t \) test showed that the magnitude of anomalous rainfall rate exceeding 2 mm day\(^{-1}\) and the magnitude of anomalous SST greater than 0.1\( ^\circ \)C in the composite maps shown in Figure 2 are statistically significant at the 90% confidence level.

2. Antecedents and Initiation of the Active/Break Indian Summer Monsoon

Figure 1. Time series of daily rainfall rate derived from TMI data. The black curve represents the three-day running mean daily precipitation rate averaged in the EIO (5\(^\circ\)S–5\(^\circ\)N, 75\(^\circ\)E–100\(^\circ\)E). The red and blue bars denote the 20–50 day anomalous precipitation rates in the EIO and in the Bay of Bengal (15\(^\circ\)N–25\(^\circ\)N, 70\(^\circ\)–95\(^\circ\)E excluding land area), respectively. The circled numbers 1, 3, and 5 mark the timing of Phase 1, 3, and 5 for each oscillation cycle that are selected for the composite analysis.

Figure 2. Composite life cycle of the SA summer monsoon 20–50 day oscillation. The contours of green (lavender) are positive (negative) precipitation anomalies starting from 2 mm day\(^{-1}\) with a contour interval of 3 mm day\(^{-1}\). The thick green contour outlines the major positive precipitation anomalies. The color shading represents SST anomalies in units of \( ^\circ \)C. The magnitude of anomalous rainfall rate exceeding 2 mm day\(^{-1}\) and anomalous SST greater than 0.1\( ^\circ \)C are statistically significant at the 90% confidence level.
Wang and Xie, 1997; Kemball-Cook and Wang, 2001; Lawrence and Webster, 2001]. Concurrent with this poleward bifurcation of rainband, suppressed convection restarts in the western EIO (60°C176–70°C176E). The life cycle continues with the northward and eastward propagation of the enhanced rain band, causing an active period in the Indian monsoon during Phases 7–8.

To clarify the processes that create the initial convective anomalies, here we focus on the Phase 1–3. During Phase 1 the eastern EIO suppressed convection stimulates westward propagating descending Rossby waves [Gill, 1980], resulting in the twin surface anticyclones and equatorial easterly anomalies in the eastern-central Indian Ocean (Figure 3, Phase 1). The decreasing westward wind speed along the equator favors wind convergence in the western basin. Note that the occurrence of the surface convergence leads local rainfall anomaly by one phase (about four days). Because the heavy rains over India induce large-scale sinking motion (Figure 4, Phase 1) that dominates the EIO, the surface convergence in the western EIO in this phase does not lead to organized convection immediately. However, it permits a moistening of the boundary layer, increasing the convective energy of the source air in the boundary layer and modifying the vertical stratification so that convection can occur again. Therefore, Phase 1 is a 174 period during which the atmosphere is preconditioned for the next cycle. The finding here for the boreal summer ISO differs from the previous hypothesis of convective energy “recharge” process for MJO [Blade and Hartmann, 1993] in that the preconditioning is driven by the surface wind convergence.

During Phase 2, the surface moisture convergence increases rapidly in the western and central EIO due to westward decrease of zonal equatorial wind and the confluence of equatorward winds associated with the southern Indian Ocean anticyclone that had moved westward from Phase 1 to Phase 2 (Figure 3, Phase 2). The organized precipitation anomalies emerge in the western EIO (Figure 2, Phase 2). During Phase 3, the twin anticyclones further extend and move into the Arabian Sea and the southwest Indian Ocean, respectively, due to Rossby wave propagation (Figure 3, Phase 3). The equatorward flows in the eastern part of the twin anticyclones reinforce moisture convergence in the central EIO and the convection. The enhanced convection further draws surface moisture convergence into it. Thus the precipitating clouds grow and expand into organized deep convection as corroborated by significantly more rainfall (Figure 2).

Local atmosphere-ocean interaction may also favor for the genesis process. When the atmosphere over the central EIO is dry (Phase 7–8), the downward solar radiation increases because there are fewer clouds, while
the heat loss resulting from evaporation and entrainment
cooling decreases because the wind speeds decrease. These
arguments are consistent with the previous findings in
analysis of the boreal summer ISO [Kemball-Cook and
Wang, 2001; Vecchi and Harrison, 2002; Webster et al.,
2002; Fu et al., 2003]. These features conspire to produce a
warming of the sea surface about 8 days later in Phase 1–2
(252 Figure 2). On the other hand, the sea surface warming
occurring during the Phase 1–2 may enhance energy flux
into the atmospheric boundary layer, which builds up
collective available potential energy for organized deep
convection. In addition, the surface-warming-induced
sensible heat flux tends to warm the air above, lowering the
surface pressure. The lower surface pressure in turn enhances
the boundary layer moisture convergence and promotes
organized deep convection. Thus, local air-sea interaction
can contribute to initiating of a new rainy phase.

3. Conclusion and Discussion
satellite observations suggest a self-induction mechanism
for the maintenance of the monsoon ISO. Both the surface
wind convergence in the western-central basin and the
ocean surface warming in the central basin, which are
critical for breeding a new convective cycle, are induced by
the anomalous conditions occurring during the peak
phase of the previous cycle. This finding contrasts the
notion that the circumpolar air divergence and upper tropospheric
divergence waves associated with the MJO re-initiates
convective anomalies over the Indian Ocean.

[12] The composite evolution of OLR and 200 hPa
velocity potential anomalies (Figure 4) shows that during
the re-initiation of new convective anomalies, the EIO is
under control of large-scale upper-level convergence and
subsidence. Once deep convection starts in the central EIO,
negative OLR anomaly develops locally; upper-level diver-
gence then occurs later as a result of deep convection rather
than its cause (Figure 4, Phases 3 and 4), confirming that the
initiation of the ISO convection in the western EIO is
primarily a local process within the SA monsoon system.

[13] Satellite measurements pinpoint the origin of the
monsoon ISO and provide a comprehensive, fine-resolution
picture of the ISO’s life cycle. The results here offer some
benchmark features for both the operational models and
seasonal prediction models to validate their performance on
the monsoon ISO. Surface convergence in the western EIO
is noted about one month before heavy monsoon rain
returns over India. This timing offers a focus for the
prediction of the active or break Indian monsoon with
potential predictability about four weeks ahead. To better
understand air-sea interaction processes and their role in
initiating and sustaining the boreal summer ISO, further
collaborated meteorological and oceanographical obser-
vations are needed. In order to test the mechanisms advanced
here, in-situ field observations of the cloud formation and
development are recommended.

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