

NOTES AND CORRESPONDENCE

Monsoon Breaks and Subseasonal Sea Surface Temperature Variability in the Bay of Bengal*

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ABSTRACT

The Indian southwest monsoon directly affects the lives of over one billion people, providing almost 90% of the annual precipitation to the Indian subcontinent. An important characteristic of the southwest monsoon is variability on subseasonal timescales, with "active" periods of heavy rain interrupted by drier "break" periods. Both the number of monsoon breaks in a season and the timing of these breaks profoundly impact agricultural output from the Indian subcontinent. Most research on monsoon breaks has emphasized possible atmospheric mechanisms. However, new satellite data reveal large-amplitude basin-scale subseasonal sea surface temperature (SST) variability in the Bay of Bengal (BoB), in which northern BoB cooling precedes monsoon breaks by about 1 week. The relationship is statistically significant at the 95% level over the 3 yr examined, and so offers a potential statistical predictor for short-term monsoon variability. The basinwide averaged amplitude of SST changes is 1°–2°C and local changes can exceed 3°C over 2 weeks; these changes are as large as those seen in the local climatological seasonal cycle. This raises the possibility that air–sea interaction may be a significant factor in monsoon variability; the SST variability is coherent with monsoon variability with a phase relationship consistent with a coupled oscillation. A schematic coupled air–sea oscillator mechanism is offered for further study, in which oceanic changes play a dynamical role in monsoon variability.

1. Introduction

Sea surface temperature (SST) variability occurs on a variety of timescales and space scales. Large spatial-scale SST variability in tropical oceans has been linked to a variety of shifts in weather patterns that affect humanity (e.g., Donguy and Hénin 1980; Rasmusson and Wallace 1983; Nicholls and Kariko 1993; Chandrasekar and Kitoh 1998; Webster et al. 1998). The principal large spatial-scale modes of SST variability that have been explored to date have been on seasonal and longer timescales (e.g., El Niño–Southern Oscillation, Indian Ocean dipole, the seasonal cycle of SST). With the ad-

vent of new satellite-based estimates of SST, the basinwide evolution of tropical SST on weekly and longer timescales can be explored even in the presence of clouds (e.g., Harrison and Vecchi 2001). We here focus on the evolution of SST in the Bay of Bengal (BoB) during the southwest monsoon, and the strong relationship it exhibits with monsoon "breaks."

The Indian southwest monsoon directly affects the lives of over one billion people, providing almost 90% of the annual precipitation to the Indian subcontinent (based on the Xie and Arkin 1996 climatology). An important characteristic of the southwest monsoon is variability on subseasonal timescales, with "active" periods of heavy rain interrupted by dry "break" periods (e.g., Ramamurthy 1969; Krishnamurti and Bhalme 1976; Yasunari 1979; Sikka and Gadgil 1980; Hartmann and Michelsen 1989; Krishnan et al. 2000). Both the number of monsoon breaks in a season and the timing of these breaks profoundly impact agricultural output from the Indian subcontinent (Webster et al. 1998). The mechanisms that control these monsoon breaks are still

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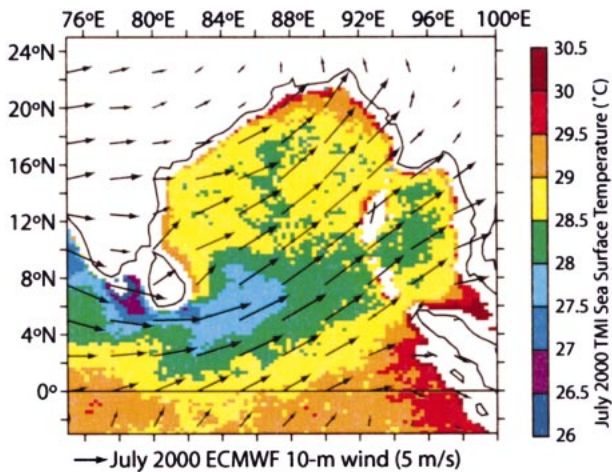


FIG. 1. The background state on which BoB SST variability occurs; Jul 2000 average 10-m winds from ECMWF (scale vector is 5 m s^{-1}), and SST from TMI (color bar indicates values in $^{\circ}\text{C}$).

under investigation (e.g., Krishnamurti et al. 1988; Webster et al. 1998; Maloney and Hartmann 1998; Krishnan et al. 2000). Ocean–atmosphere interactions are thought to be important in the interannual variability of the monsoonal circulation in the Indian Ocean (e.g., Yamazaki 1988; Alapaty et al. 1995; Ju and Slingo 1995; Chandrasekar and Kitoh 1998; Webster et al. 1999; Saji et al. 1999); the extent to which interactions between oceanic changes and the atmospheric variability are important to the evolution of monsoon breaks is also of interest (e.g., Krishnamurti et al. 1988; Webster et al. 1998). We describe a strong relationship between breaks in the southwest monsoon and the subseasonal variations in SST in the Bay of Bengal (BoB).

Until recently, knowledge of SST in the BoB during the southwest monsoon has been limited: ship and buoy sampling of SST is sparse [e.g., see the Comprehensive Ocean–Atmosphere Data Set (COADS) data distributions; e.g., Harrison and Larkin 1996; Fig. 1], and heavy cloudiness seriously restricts the number of satellite infrared observations. However, since December 1997 the National Aeronautics and Space Administration (NASA) Tropical Rain Measuring Mission (TRMM) Microwave Imager (TMI) has provided an unprecedented view of tropical SST variability, even in the presence of clouds (Wentz 1998; Chelton et al. 2001). Because of its frequent-repeat, non-sun-synchronous orbit, the TMI SST dataset provides an unprecedented look at Indian Ocean basin-scale SST variability under atmospheric convection (e.g., Harrison and Vecchi 2001).

A widely used analysis product for large-scale SST variability on greater-than-weekly timescales is the global National Centers for Environmental Prediction (NCEP) weekly optimally interpolated SST product (Reynolds and Smith 1994). The NCEP SST product has been the main data source for recent analyses of basinwide tropical SST variability on subseasonal time-

scales (e.g., Shinoda et al. 1998; Vecchi and Harrison 2000). However, recent in situ observations of subseasonal SST variability in the Bay of Bengal, have found that the NCEP product greatly underestimates local SST variability on subseasonal timescales (e.g., Premkumar et al. 2000; Sengupta and Ravichandran 2001). The TMI data used here indicate, through spectral analysis of weekly smoothed TMI SST, that there is between two and four times more energy on subseasonal timescales than in the weekly NCEP SST product, over the Indo-Pacific warm pool.

While the TMI data indicate the existence of large subseasonal SST variability in a number of regions in the Indian Ocean, we here focus on that occurring in the BoB during the southwest monsoon. In section 2 we describe the datasets and data processing methods used. In section 3 we explore the structure of subseasonal SST and atmospheric variability in the Bay of Bengal. In section 3a we describe the surface patterns during a representative period and the latitude–time evolution of the basin-averaged SST and outgoing longwave radiation (OLR), and in section 3b we explore the statistical relationships between subseasonal SST variability in the northern Bay of Bengal and monsoon breaks over the Indian subcontinent. Section 4 offers a summary and discussion of the results, and presents some speculative discussion of a possible mechanism linking the observed ocean–atmosphere variability.

2. Data and methods

For this study we use the daily gridded Version 2 TMI SST data (Wentz 2000, available online through Remote Sensing Systems at <http://www.ssmi.com/>). The ascending and descending track data are each linearly interpolated in time and then averaged with each other to produce a filled dataset. The principal features of the SST variability discussed here are evident in the track data itself, and do not result from the filling or averaging technique. The TMI SST data are still being evaluated, but the basin-scale, weekly timescale SST variability described here appears unlikely to be changed qualitatively by algorithm revisions or rainfall screening changes. The accuracy of the TMI SST estimate in rain-free conditions is roughly 0.5°C (Wentz 1998). Recent comparisons of the TMI SST estimates with buoy-measured near-surface ocean temperature has found that, on greater than weekly timescales, TMI SST reproduces the character of the 1-m buoy-observed temperatures in the tropical Pacific (Chelton et al. 2001). A comparison of the TMI SST estimate over the Bay of Bengal with the BoB Monsoon Experiment (BOBMEX) buoy near-surface temperature (at a depth of 2.5 m), finds that although there can be significant instantaneous differences between buoy- and satellite-estimated SST, there is a strong correspondence in the evolution of the two SST estimates on greater-than-weekly timescales (Senan et al. 2001).

Estimates of the 10-m wind fields are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) 12-hourly operational analysis, on a $2.5^\circ \times 2.5^\circ$ grid (ECMWF 1989). As a proxy for atmospheric deep convection we use a global $2.5^\circ \times 2.5^\circ$ daily gridded OLR dataset [provided by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Diagnostics Center, available online at <http://www.cdc.noaa.gov/>]. We use the monthly SST climatology from the 1946–94 COADS dataset (Woodruff et al. 1987), and construct monthly climatologies from the 1979–2000 OLR data and the 1986–2000 ECMWF 10-m wind data. Wind and OLR anomalies are computed relative to these monthly climatologies (by linearly interpolating the monthly climatologies onto the higher time-resolution grids).

We make use of a “monsoon break index” based on the composite monsoon break structure of OLR, which shows a dipole between the Indian subcontinent and the southeast Indian Ocean (see Krishnan et al. 2000; Fig. 2a). We define as our monsoon break index the difference between normalized 7-day boxcar-smoothed OLR anomalies averaged (10° – 30° N, 65° – 85° E) and (10° S– 5° N, 75° – 95° E), minus its 50-day centered mean (to focus on subseasonal variability). The index is positive (negative) for monsoon breaks (active periods), and is consistent with pentad precipitation anomalies in the Indian subcontinent from the NOAA Merged Analysis of Precipitation (Xie and Arkin 1996; provided by the NOAA–CIRES Climate Diagnostics Center, available online at <http://www.cdc.noaa.gov/>).

3. Results

a. Basin-scale subseasonal ocean–atmosphere variability in the Bay of Bengal

The structure and evolution of the TMI-observed SST changes in the Bay of Bengal during the summer monsoon are described in this section. We first show a time sequence of BoB SST and 10-m wind maps from a representative period of SST change (22 June–3 August 2000). We then use the latitude–time evolution of the basin-averaged SST and OLR in the summer of 2000 to illustrate the relationships seen between those two quantities in each of the summers 1998–2000.

The background state on which the SST and 10-m wind variations occur is important; to set the stage for our discussion of the subseasonal variability, Fig. 1 shows the July 2000 average TMI SST and the ECMWF 10-m winds. Notice the southwesterly winds across the BoB, while the winds south of India and Sri Lanka are westerly. SST is warmer than 28° C over the central and northern BoB, while there is a tongue of cooler water ($<28^\circ$ C) extending east from Sri Lanka across the southern BoB. These features are part of the climatological seasonal cycle. Every summer the south and southeast

Asia region is strongly heated, leading to low atmospheric pressure over the continent. The pressure difference from land to sea produces westerly winds to the south of India and Sri Lanka and southwesterlies in the BoB. The westerlies drive the cooler SST tongue extending across the southern BoB.

Figure 2 presents snapshots every 6 days of the 7-day smoothed TMI SST and ECMWF 10-m wind anomaly in the northeast Indian Ocean from late June to early August 2000. On 22 June, SST in the BoB is generally greater than 28.5° C and the surface wind anomalies are weak. Between the end of June and 4 July, the westerlies south of Sri Lanka strengthen and a tongue of cooler (27° – 28° C) water forms and extends eastward across the southern BoB. Meanwhile, the wind anomalies in the northern BoB become easterly, there is reduced convection in the northern BoB (see Fig. 3), and the SST warms to 29.5° – 30.5° C. This period corresponds to a transition from break to active monsoon (see Fig. 4). Over these 12 days SST averaged over the northern (southern) BoB has warmed (cooled) by $\sim 1.5^\circ$ C ($\sim 1^\circ$ C), and a meridional temperature gradient of $\sim 2.5^\circ$ C per 15° latitude has developed.

Between 4 and 16 July the westerly anomalies in the BoB increase (and total wind speed increases to 8 – 10 m s^{-1}), beginning in the center of the BoB and propagating northward. Under these propagating strong westerly anomalies BoB SST north of 15° N quickly drops below 28° C. By 16 July the strong positive meridional SST gradient (evident in 4 July) has disappeared. This period corresponds to a transition from strong to reduced BoB convection (see Fig. 3).

Between 16 and 28 July, the wind anomalies across the BoB weaken, and the SST begins to warm. This period is the beginning of a break in the monsoon (see Fig. 4). The SST warming continues through 3 August, by which time the northern BoB SST has returned to over 29° C. During this period northern and central BoB wind anomalies become easterly (and total wind speed weakens), and a strong meridional SST gradient is reestablished across the BoB. Over the period 16 July–3 August, the SST averaged over the northern BoB warmed by over 1° C. By early August, atmospheric convection was reestablished in the BoB (see Fig. 3). This pattern of evolution of winds, OLR, and SST during late June–early August 2000 is roughly repeated over the next 45 days, and similar cycles are clear in the southwest monsoons of 1998 and 1999.

An interesting relationship between the periods of large-amplitude subseasonal SST variability and atmospheric convection is illustrated in Fig. 3, which shows a time–latitude contour plot of atmospheric convection (as inferred from OLR) and SST averaged over the BoB in the summer of 2000. We note that the evolution in the other summers (1998, 1999) is similar. Under active atmospheric convection SST cools over the Bay of Bengal (north of 4° N). After zonally averaged SST has cooled by around 1° C or so, convection is

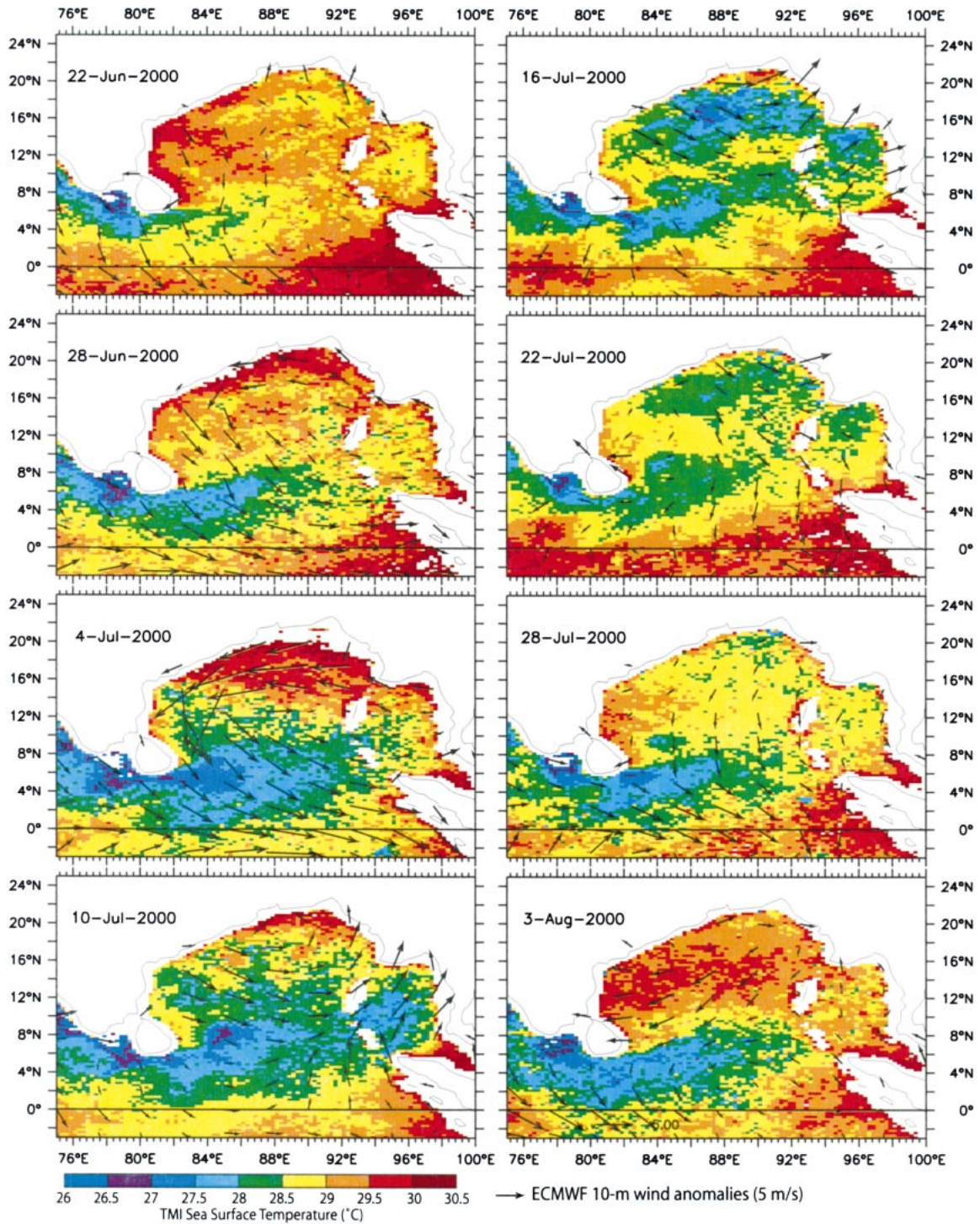


FIG. 2. One subseasonal SST event (Jun–Aug 2000); snapshots of the 7-day smoothed TMI SST (shaded) and ECMWF 10-m wind anomalies (vectors). The color bar indicates values of SST (in $^{\circ}\text{C}$), and the scale vector is 5 m s^{-1} .

reduced. An SST warming period follows, and then convection returns. In each of the three convective events shown here, there is a distinctive propagation of the SST cooling and the cessation of convection over the BoB.

b. Northern Bay of Bengal SST and monsoon breaks

All of the southwest monsoons for which there is TMI data exhibit similar relationships between subseasonal SST variability and breaks in the monsoon. To illustrate

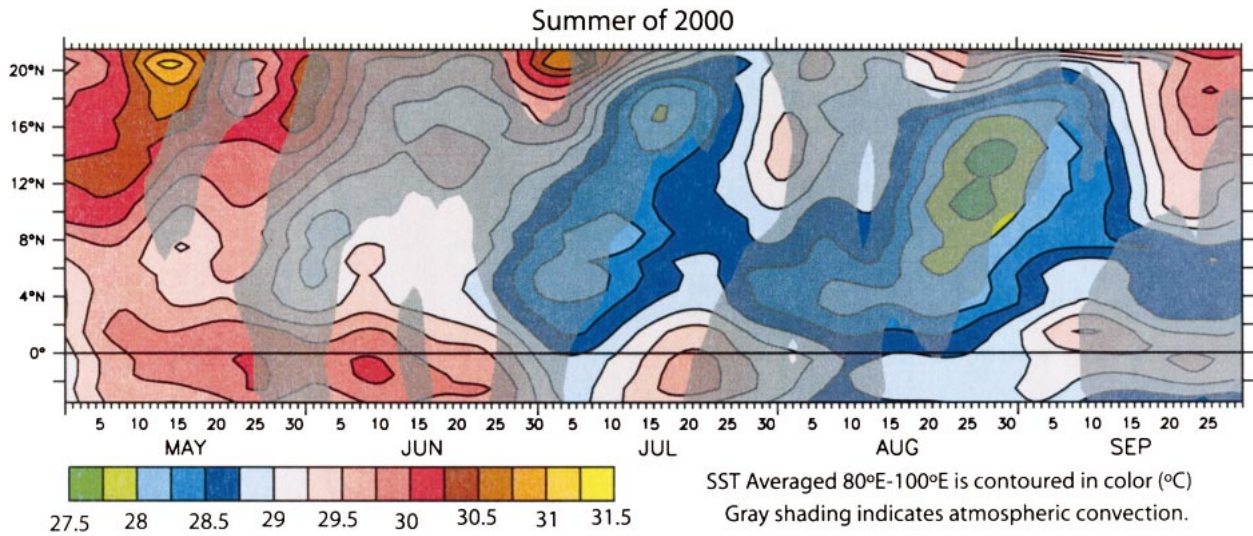


FIG. 3. Time-latitude plots of SST and “atmospheric convection” averaged 80°–100°E, over the summer of 2000. Color shading and contours indicates zonally averaged, 7-day boxcar-smoothed TMI SST. Gray overshading indicated areas where zonally averaged 7-day boxcar-smoothed OLR is less than 210 W m⁻². Contour interval for SST is 0.25°C.

the relationship between northern BoB SST and monsoon breaks, Fig. 4 shows time series of the OLR-based monsoon break index (see section 2), of weekly smoothed northern BoB TMI SST minus its 50-day centered mean for each of the 1998–2000 southwest monsoons. Figure 4 also includes time series of the actual weekly smoothed northern BoB SST from TMI (the seasonal climatology of SST from COADS is included for reference). Notice that on subseasonal timescales the two time series appear coherent at ~90° phase; this phase relationship is consistent both with the SST being

driven by independent variability in the atmosphere and with the SST–atmospheric changes resulting from a coupled oscillation. The strongest relationships that appear to exist are that each large-positive peak in the monsoon break index is preceded by a minimum in SST, and every minimum in SST precedes a maximum in monsoon break index.

We computed correlation coefficients for the two time series over the summers of 1998–2000 (defining the summer as the period from 15 May to 15 October of each year; the solutions are not sensitive to reasonable

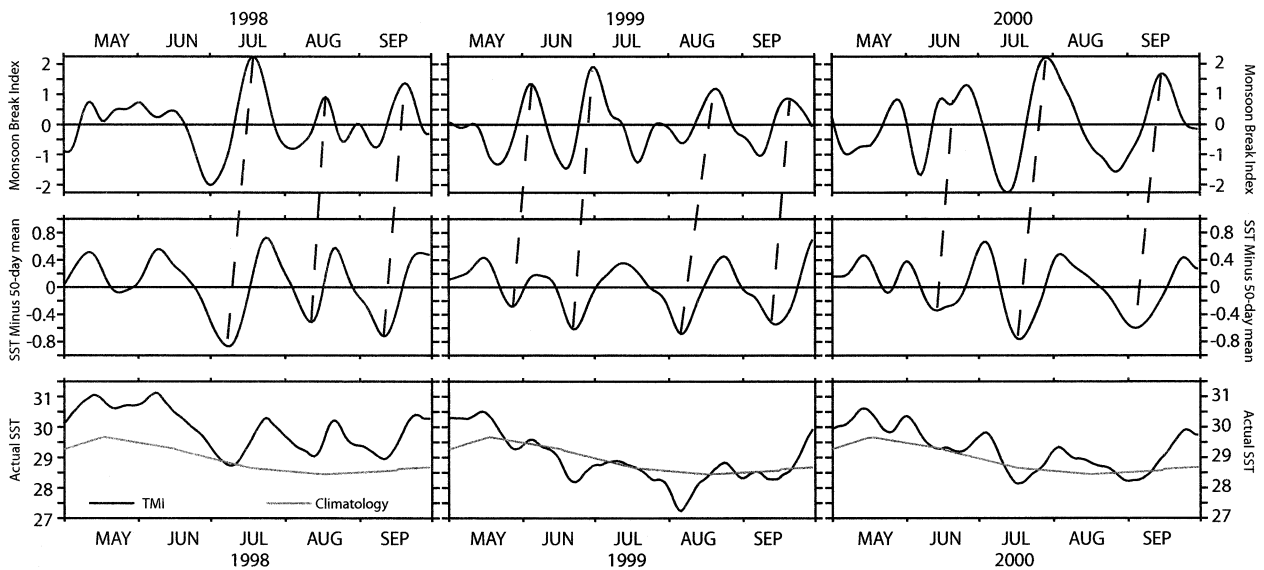


FIG. 4. The subseasonal SST events correlate strongly with monsoon variability; plots of weekly smoothed: (a)–(c) OLR-based monsoon break index (positive values indicate a monsoon break), (d)–(f) TMI SST averaged 15°–22°N in the BoB minus its 50-day centered mean, and (g)–(i) TMI SST (black line) and COADS climatological SST (red line) averaged 15°–22°N in the BoB, for each of the southwest monsoons 1998–2000.

changes in the definition of “summer”). We find that the maximum positive lagged correlation is ~ 0.7 at 7 days with positive monsoon break index leading positive SST, and the largest negative lagged correlation is ~ 0.67 at 10 days with negative SST leading positive monsoon break index. Both these correlation coefficient estimates are significantly different from zero at a 95% level (if normal statistics are assumed and the number of degrees of freedom is taken to be the number of large-positive monsoon breaks—10). The relationship apparent in the time series is reproduced in the statistical analysis, with a $\sim 90^\circ$ phase relationship between the two time series and a period of ~ 40 days. This statistical relationship may be of value for short-term monsoon break forecasts.

Notice also that the subseasonal pulses in SST are of the same amplitude as the seasonal cycle of SST in the northern BoB; these are major regional SST events. Also of interest is that the cooling during May–July in climatology occurs in each of the years as a sequence of subseasonal cooling events. Evidently, these subseasonal events are how the northern BoB moves through this part of its climatological seasonal cycle.

4. Summary and discussion

In the previous sections we described the structure of a distinctive type of basinwide subseasonal SST variability in the Bay of Bengal (BoB) during the southwest summer monsoon, which consists of a large-amplitude (1° – 2°C) basin scale that is associated with large-scale changes in surface winds and atmospheric convection. The periods of cooling happen under increased wind speed and cloudiness, and the periods of warming happening during decreased wind speed and cloudiness. Northern BoB SST changes exhibit a strong statistical connection with “breaks” in the Indian monsoon; cooling (warming) occurs during active (break) periods in the monsoon, and northern BoB SST minima lead breaks in the monsoon by ~ 10 days.

The amplitude and time evolution of the satellite-based basinwide SST changes described here are consistent with point observations during the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) (Krishnamurti et al. 1988), and from 1998 buoy data in the central BoB (see Sengupta and Ravichandran 2001; Premkumar et al. 2000; Senan et al. 2001). The point observations found local subseasonal fluctuations in SST of 1° – 3°C , associated with changes in surface wind, atmospheric convection, surface heat flux, and oceanic mixed layer depth. Recent observations of the upper-ocean structure during the BOBMEX and JASMINE field experiments (see JASMINE 2000; Hareesh Kumar et al. 2001; Bhat et al. 2001) also have found large-amplitude changes in the structure of upper-ocean temperature, salinity, and currents during the southwest monsoon in the BoB.

Based on data from three buoys in the BoB during the summer monsoon of 1998 Sengupta and Ravichan-

dran (2001) found that a large part of the subseasonal SST changes could be explained by variations in the net surface heat fluxes at each buoy. Though they also found that at times the heat balance was more subtle, with an apparent influence of near-surface freshwater stratification. We are unable to perform a basinwide examination of the vertical structure of the oceanic temperature and current changes with the datasets currently available to us, thus we cannot explore the coupled air-sea dynamics that led to the observed SST changes. Even our ability to estimate the air-sea heat fluxes is limited by the fact that the NCEP–National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996) and ECMWF (ECMWF 1989) global atmospheric analyses use the NCEP SST product as a boundary condition, and this SST product has been found to greatly underestimate BoB SST variability on subseasonal timescales (see Sengupta and Ravichandran 2001; Premkumar et al. 2000; the present paper). Depending on the depth over which the temperature changes occurred, the observed variability in surface heat flux could be sufficient to explain the oceanic thermal variability. The uncertainties in the amplitude of the surface heat fluxes in the operational products in this region are large enough that we do not attempt to quantify the role of heat flux in the SST changes. As more results based on the observations in the JASMINE and BOBMEX field programs become available and as regional ocean circulation models improve, dynamical interpretation of the observed basin-scale SST changes will become possible.

It is possible that the observed SST changes were important in the evolution of the regional atmospheric circulation in the BoB. The structure of SST has been suggested as important in the evolution of atmospheric variability on a variety of timescales and space scales: the large-scale structure of the near-equatorial trade winds in the eastern Pacific Ocean (Wallace et al. 1989), the local structure of wind stress divergence and curl over tropical instability waves in the near-equatorial Pacific (Chelton et al. 2001), the Madden–Julian oscillation (Wang and Xie 1998; Harrison and Vecchi 2001), the variability of monsoonal circulation (Krishnamurti et al. 1988; Alapathy et al. 1995; Chandrasekar and Kitoh 1998; Webster et al. 1999; Saji et al. 1999), and El Niño (e.g., Bjerknes 1969; Battisti and Hirst 1989; Schopf and Suarez 1989).

Ju and Slingo (1995) and Chandrasekar and Kitoh (1998) use a series of atmospheric model experiments to examine the effect of Indian Ocean SST on monsoon circulation on interannual timescales. Their work suggests that relatively moderate changes in SST (relative to the changes described here and in Harrison and Vecchi 2001) can have large impacts on atmospheric circulation in the Indian Ocean on interannual timescales. Alapathy et al. (1995) explore the effect of using analyzed basinwide daily SSTs on the evolution of a regional atmospheric model of the Indian monsoon region. Even

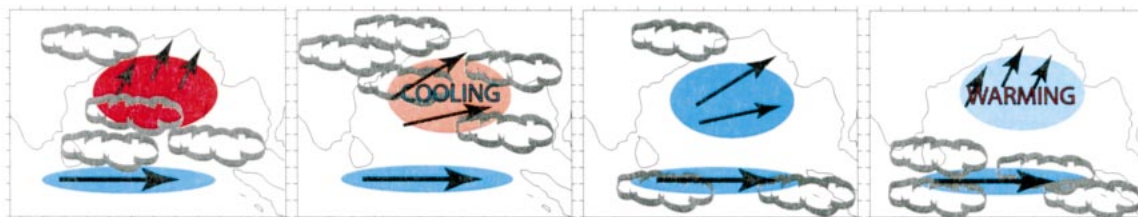


FIG. 5. Schematic evolution of the subseasonal SST events. SST is shaded with warm (cool) colors if warm (cool) compared with the background state; “COOLING” and “WARMING” indicate the time rate of change of SST. Cloud shapes indicate atmospheric convection, and arrows indicate surface winds.

though the SSTs used in their experiment do not include the full effect of the large-amplitude SST signals described here, Alapaty et al. (1995) find changes of 20% in evaporation and 10% in precipitation, when compared with a run forced with climatological SST. Thus, it appears that it is plausible that large-amplitude changes in SST—such as those described here—can play a significant role in the evolution of the atmosphere in the Indian monsoon region.

The subseasonal SST changes are associated with changes in the surface winds and atmospheric convection over the BoB that are consistent with the atmospheric changes driving the observed SST variability. Sengupta and Ravichandran (2001) discuss observations of the mechanisms for this forward atmosphere to ocean connection. Their recent examination of buoy- and ship-based data in the BoB found that subseasonal SST oscillations during the monsoon are mainly driven by surface heat flux changes associated with variations in wind speed and atmospheric convection. This “forced ocean” view is consistent with the observed $\sim 90^\circ$ phase relationship between subseasonal atmospheric and SST variability.

However, the possibility that the observed ocean–atmosphere variability is a coupled phenomenon merits examination. The large amplitude and spatial coherence of the SST changes, and the temporal and spatial relationship of the observed wind and convection changes to the SST structures, is suggestive that the SST changes may play an important role in the evolution of the atmospheric boundary layer during monsoon breaks. Thus, we here offer a schematic coupled ocean–atmosphere oscillation—based on the observed SST–wind–convection relationships—to serve as a hypothesis for a dynamical connection between monsoon breaks and subseasonal SST variability in the BoB.

The principal features of these SST events are idealized in Fig. 5. To understand the evolution of the coupled system it is necessary to examine the total wind, as processes that control the time rate of change of SST depend on the full wind speed. The arrows in Fig. 5 result from adding a background wind field like that in Fig. 1 to the wind anomalies shown in Fig. 2.

If we assume that a decrease (increase) in SST produces an increase (decrease) in SLP (e.g., Lindzen and Nigam 1987), and that the wind changes resulting from

surface pressure changes are roughly geostrophic, then a simple coupled oscillation in SST and surface winds can exist that is consistent in structure with Figs. 2, 3, and 5. The cool tongue south of the BoB results in a meridional pressure gradient, with high pressure to the south, which enhances the southern BoB westerly wind component. Meanwhile, the warm SSTs in the north of the basin would tend to reduce the land–sea pressure difference, weakening the BoB southwesterlies. These enhanced (reduced) winds would tend to cool (warm) the SST in the southern (northern) BoB through a variety of processes. Westerlies would enhance wind speed that increases latent and sensible heat fluxes across the air–sea interface, and vertical mixing in the ocean, all generally resulting in reduced SST. Wind stress curl is also increased during the westerly acceleration, which would lead to enhanced Ekman suction through divergence at the ocean’s surface. Additionally, the enhanced evaporation associated with increased wind speed would tend to increase atmospheric convection and cloudiness and reduce incoming solar radiation.

As the southern BoB cools, a pressure gradient is established across the central BoB, increasing the winds in the central BoB. Once again, an increase in wind speed results in SST cooling, and moves the area of SST/SLP gradient northward. Eventually the reduced land–sea pressure difference in the northern BoB is balanced by the enhanced north–south pressure difference. Northern BoB winds return to normal cooling the northern BoB, and enhancing land–sea pressure difference. This in turn further enhances the winds, reducing the north–south SST gradient.

As the SST gradients across the BoB disappear, the surface winds weaken. These cool SST/weak wind conditions are associated with reduced atmospheric convection and cloudiness. Under the lower wind speed and less cloudy conditions, BoB SST warms. This warming reestablishes the meridional SST (and SLP) gradient across the southern BoB. When the SLP gradient returns, southern BoB winds are increased and the cycle can repeat. Thus an oscillation of SST, SLP, and surface winds can result from the meridional SST gradient developed by the large-scale monsoonal land–sea pressure difference and by the land configuration in the Indian subcontinent/BoB.

However, it is important to note that a boundary layer

model (e.g., Lindzen and Nigam 1987) run with the observed SST changes does not reproduce the observed wind velocity changes. Much of the observed wind variability is driven by changes in atmospheric heating due to changes in convection. We see that atmospheric convection tends to decrease over cooler SSTs in the BoB (see Fig. 4), yet mechanisms connecting the SST changes to changes in atmospheric convection remain to be elucidated. In every cooling event during 1998–2000, SST cooling in the BoB was followed by a reduction in atmospheric convection and cloudiness. We note that the strongest atmospheric convection over the BoB tends to overlie areas of largest wind speed and SST. The observed SST–atmospheric convection relationship in the BoB may result from a reduction of evaporation under reduced wind speed and SST conditions. However, the detailed relationships between convective, SST, and wind changes are beyond the scope of this simple schematic model, which is intended only to illustrate the possibility of a coupled oscillation in SST/winds and convection.

This simple coupled oscillator mechanism needs to be evaluated with observational and model studies to examine the extent to which the oceanic changes are dynamically essential to the evolution of this process. The results from the recent Joint Air–Sea Monsoon Interaction Experiment (JASMINE) and Bay of Bengal Monsoon Experiment (BOBMEX) field programs may assist in exploring this potentially coupled oscillation. A better understanding of the coupled processes leading to the observed changes will allow for more realistic models.

Even were there no dynamical air–sea coupling at work, the strong statistical connection between subseasonal SST changes and monsoon variability described here is clear, and may enhance short-term predictions of Indian subcontinent precipitation. If oceanic variability is fundamental to the evolution of Indian monsoon breaks through the above (or other) processes, improved understanding and monitoring of oceanic variability in the BoB may result in improved predictability of variations in the monsoon. Should coupled processes be fundamental, interannual changes in ocean state could lead to changes in monsoon variability, by coupling to atmospheric variability through changes in the controls to SST change (such as mixed layer depth, vertical temperature gradients). The roles of subseasonal SST variability in the subseasonal, seasonal, and interannual evolution of the coupled Indian subcontinent/Bay of Bengal ocean–atmosphere–land system, and on Indian monsoon breaks in particular, deserve further examination.

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