Coherent Intraseasonal Oscillations of Ocean and Atmosphere during the Asian Summer Monsoon

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Abstract. The space-time evolution of the ocean and atmosphere associated with 1998-2000 monsoon intraseasonal oscillations (ISO) in the Indian Ocean and west Pacific is studied using validated sea surface temperature (SST) and surface wind speed from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager, and satellite outgoing longwave radiation. Monsoon ISO consist of alternating episodes of active and suppressed atmospheric convection moving northward in the eastern Indian Ocean and the South China Sea. Negative/positive SST anomalies generated by fluctuations of net heat flux at the ocean surface move northward following regions of active/suppressed convection. Such coherent evolution of SST, surface heat flux and convection suggests that air-sea interaction might be important in monsoon ISO.

1. Introduction

The boreal summer tropical intraseasonal oscillations, with period 10-20 and 30-50 days, are active primarily over the Asian monsoon region and are intimately related to the 'active' and 'break' cycles of the Indian monsoon. They show complex space-time evolution [*Kemball-Cook and Wang*, 2001], often moving north from the equatorial region and westward in the south Asian latitudes [*Sikka and Gadgil*, 1990; *Krishnamurti and Ardunay*, 1980]. The first evidence that ISO involve significant modulation of SST and turbulent fluxes at the air-sea interface in the Bay of Bengal and equatorial west Pacific came from the Global Experiment of 1979 [*Krishnamurti et al.*, 1988]. Accurate estimates of surface fluxes were made during the Coupled Ocean Atmosphere Response Experiment (COARE) in the west Pacific in the winter of 1992-93 [*Godfrey et al.*, 1998]. This led to the unambiguous demonstration [*e.g. Anderson et al.*, 1996] that the slow oscillation of SST in the COARE region is a response to intraseasonal fluctuation of surface heat, momentum and buoyancy fluxes associated with the eastward propagating, equatorially confined Madden-Julian oscillations (MJO)[*Madden and Julian*, 1972]. The evolution of atmospheric convection, surface heat fluxes and SST over the Indo-Pacific warm pool associated with MJO have since been studied extensively [*Shinoda et al.*, 1998; *Jones et al.*, 1998; *Woolnough et al.*, 2000]. The results of these studies indicate that at least on intraseasonal time scales, equatorial warm pool SST changes are primarily driven by surface heat flux.

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Relative to MJO, present knowledge of surface fluxes and SST changes associated with monsoon ISO is meagre. A revival of interest in air-sea interaction in the Asian summer monsoon region has led to two major field experiments in the Bay of Bengal during 1998-1999, BOBMEX [*Bhat et al.*, 2001] and JASMINE [*Webster et al.*, 2000], and one in the South China Sea, SCSMEX [*Lau et al.*, 2000]. Recent observations from moored surface buoys in the western Bay of Bengal show coherent 20-40 day SST fluctuations during the summer of 1998 with peak to peak range of upto 2°C, which are not captured by the weekly National Centers for Environmental Prediction (NCEP) SST analysis [*Sengupta and Ravichandran*, 2001](hereafter SR). Large fluctuations in the net surface heat flux $Q_{\rm net}$ are associated with the monsoon ISO. During the active or convective phase of the ISO, the sky is cloudy and surface winds are strong, leading to negative $Q_{\rm net}$ (ocean loses heat) while the calm or quiescent phase is marked by clear skies and light winds, giving large positive $Q_{\rm net}$. SR show that the intraseasonal SST changes can be understood to the first order of approximation as a response to oscillations of $Q_{\rm net}$.

Here we document the coupled evolution and northward propagation of the large scale ocean atmosphere fields associated with the 1998-2000 Asian summer monsoon on intraseasonal time scales, and show that surface heat flux drives intraseasonal SST changes over large parts of the Indian Ocean and west Pacific. The data and methods are described in section 2. Our main results on the structure and propagation of ISO are presented in section 3, followed by a discussion in section 4.

2. Datasets and Methods

We use the three-day, 0.25°× 0.25° fields of SST and wind speed measured by the Microwave Imager on-board the TRMM satellite (TMI). TMI SST retrievals are not affected by clouds, aerosols and atmospheric water vapor [*Wentz et al.*, 2000]. Comparison with moored buoy observations in the north Indian Ocean shows that TMI SST and wind speed faithfully captures most of the variability on time scales longer than a few days. The root-mean-square differences between TMI fields and three-day buoy data in this region are about 0.6°C for SST and 1.3 m s^{-1} for wind speed [*Senan et al.*, 2001]. There is somewhat larger day to day variability in the TMI skin SST relative to buoy SST, which are measured at 2.2m depth (Figure 1). Daily interpolated 2.5°× 2.5° NOAA outgoing longwave radiation (OLR), TMI SST and TMI wind speed are used to calculate the net heat flux using algorithms identical to those used in SR, but for two differences. Here we use climatological SST minus air temperature, △T, from the Comprehensive Ocean Atmosphere Data Set (COADS) instead of buoy △T,

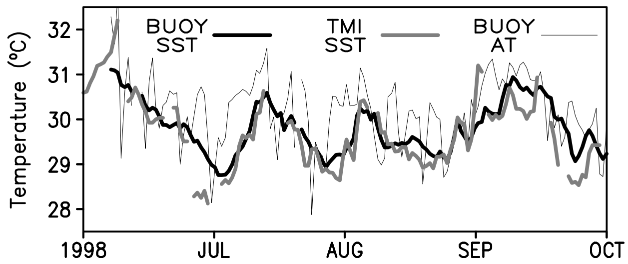

Figure 1. Evolution of daily buoy SST (bold), 3-day TMI SST (grey) and daily buoy air temperature (thin) at 18°N, 88°E in the north Bay of Bengal during summer 1998.

and an estimate of net solar insolation Q_s based on a modification of the formula of *Shinoda et al.* [1998]. We define $Q_s = Q_{\mathrm{ERBE}} + \mathrm{OLR_a} \times (Q_{\mathrm{ERBE}}/\mathrm{OLR_c})$, where Q_{ERBE} is the climatological net insolation from the Earth Radiation Budget Experiment; $\mathrm{OLR_c}$ is the monthly mean OLR climatology based on the same period as ERBE climatology, and $\mathrm{OLR_a}$ is daily OLR minus $\mathrm{OLR_c}$. For the discussion below, anomalies of various fields are computed by removing the seasonal cycle (i.e. the mean and first four harmonics) from the daily fields for each year.

3. The Monsoon Intraseasonal Oscillations

The 10-80 day filtered OLR anomaly averaged over 85-90°E, 15-20°N shows the large variability of convection associated with monsoon ISO over the north Bay of Bengal (BOB; Figure 2a). Sea surface temperature has highest intraseasonal variability in BOB and the northern South China Sea (SCS). Anomaly TMI SST in June-September 1998-2000 averaged over 5°× 5° boxes in these two regions and in the equatorial central Indian Ocean (EQ) is shown in Figure 2b. Peak to peak range of SST ISO can be upto 2°C in BOB (see also Figure 1) and northern SCS, with no invariant phase relation between the two. The SST oscillations in BOB and EQ, on the other hand, tend to be out of phase.

The spatial structure of summer monsoon ISO can be seen in a composite of nine ISO from June-September of 1998-2000 (Figure 3). The reference time series is the BOB OLR anomaly (Figure 2a). All the clear/cloudy composite fields (Figure 3a/3b) except SST are averages over the dates when BOB OLR anomaly is highest/lowest. The SST composites are averages over dates when north Bay is warmest/coolest (Figure 2b) immediately following the highest/lowest OLR anomaly; the time lag between OLR and SST extrema varies from event to event, with a mean of five days.

When the north Bay is clear (Figure 3a), there is enhanced convection in the equatorial central and east Indian Ocean. Surface wind speed anomalies are negative in BOB and SCS, and positive in the equatorial central and east Indian Ocean. Peak convection over the north Bay of Bengal is accompanied by convection over a wide region from the southeastern Arabian Sea (70°E) to the tropical northwest Pacific (140°E), and diminished convection over the equatorial eastern Indian Ocean (Figure 3b). Wind speed anomaly in BOB is highest somewhat to the south of the lowest OLR anomaly. The wind speed anomalies in the Arabian Sea appear to be strongly correlated with episodes of enhanced convective heating of the atmosphere to the east. The pattern of net heat flux is consistent with the OLR and wind speed distribution. As in SR, large latent heat loss and low insolation make Q_{net} negative during the active phase of the ISO (cloudy BOB); Q_{net} is positive in the quiescent phase (clear BOB) due to low latent heat loss and high insolation. We wish to point out that the full Q_{net}, not just anomaly Q_{net}, alternates between negative and positive values (not shown). Three to five days after the magnitude of the BOB Q_{net} anomaly reaches its peak value (50 W m^{-2}), the size of the BOB SST anomaly touches 0.6°C. The lag between Q_{net} and SST is discussed further in the next section. High SST variability off Arabia and the Horn of Africa is not due to changes in Q_{net}, but appears to be mainly due to changes in upwelling. Composite fields centered in the northern SCS show amplitudes comparable to the BOB composites, but the ISO have much smaller zonal extent both to the east and west (not shown).

Coherent northward propagation of atmosphere-ocean fields associated with monsoon ISO is seen in all years. We choose the period May to September 1998 to illustrate this in the longitudes of the western BOB. 10-80 day filtered anomalies of OLR, wind speed and Q_{net} all show clear propagation of ISO from 5°S to the northern boundary of the Bay (Figure 4). SST anomalies propagate northward in response to northward moving, alternating positive and negative anomalies of Q_{net}. Since the period of the oscillations is about a month in 1998 and 2000 and the northward speed is about 1.4°day^{-1} (1.8 m s^{-1}), the phase of the ISO at the equator is opposite to that in the north Bay (Figure 3). We note that this anti-correlation is not clear in 1999 because the 10-20 day monsoon ISO is energetic. In the South China Sea, a few episodes of northward propagation of convection and Q_{net} anomalies are clear to the north of 5°N, followed by strong northward moving SST anomalies (not shown), as in the Bay.

4. Discussion and Conclusions

Comparison between buoy observations, NCEP weekly SST and TMI SST in the Bay of Bengal shows that the TMI

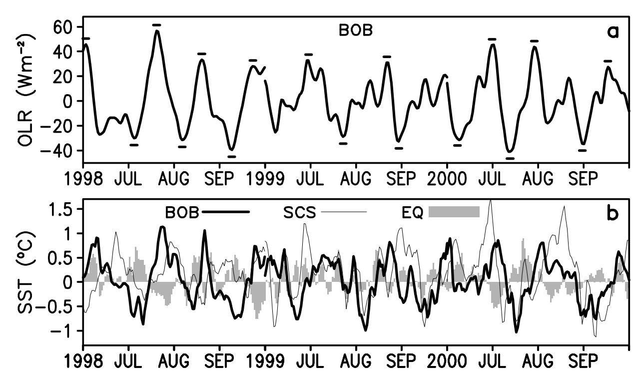

Figure 2. June-September 1998-2000 evolution of (a) 10-80 day filtered BOB OLR anomaly, with small bars (each of length 3 days) indicating dates used in the composites shown in Figure 3, and (b) SST anomaly averaged over BOB (bold), 15-20°N, 115-120°E (SCS, thin) and 2.5°S-2.5°N, 85-90°E (EQ, shaded).

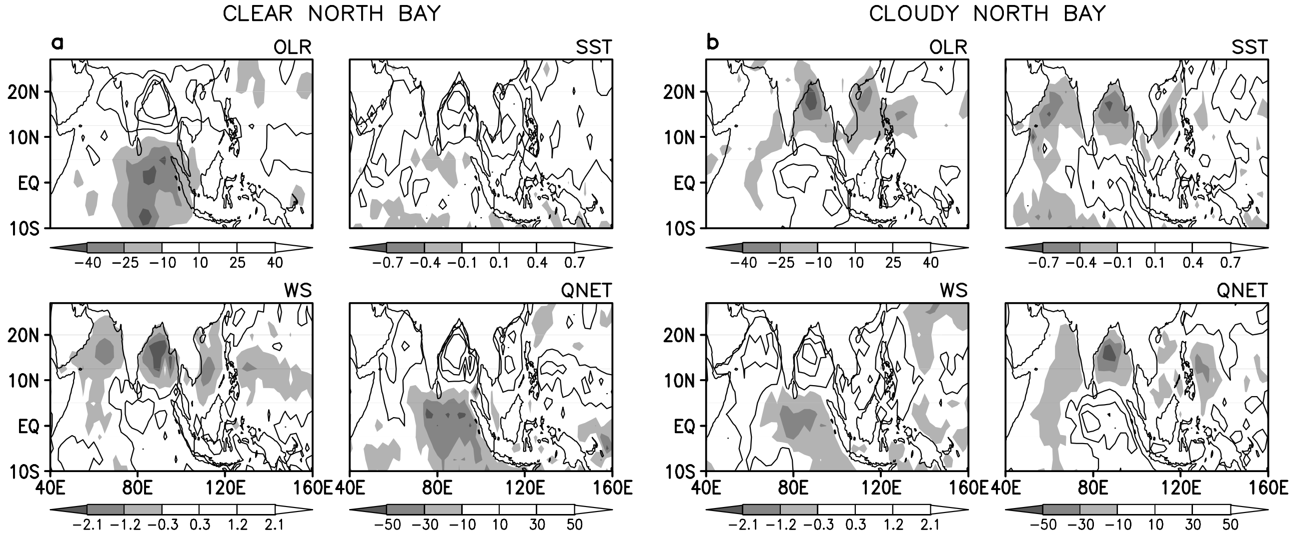

Figure 3. Composite structure of monsoon ISO in the (a) clear and (b) cloudy BOB phases. Anomalies of OLR (W m^{-2}), wind speed (WS; m s^{-1}), $Q_{\rm net}$ (W m^{-2}) and SST (°C) are shown.

product used in this study is possibly the first reliable SST dataset for the study of intraseasonal space-time variability in the cloudy, humid conditions of the summer monsoon [SR, *Senan et al.*, 2001]. The recent work of *Kemball-Cook and Wang* [2001] on the trajectories of the typical May-June and August-October ISO is similar in spirit to the present study. It documents in detail the movement of summertime convection in the Indian and west Pacific Ocean using several ocean and atmosphere fields. It differs significantly from our work because it uses skin temperature and surface heat fluxes from NCEP reanalysis, and does not discuss the origin of SST variability in any detail.

The large scale spatial structure and northward propagation of convection and low level wind fields associated with monsoon ISO are consistent with earlier studies [*Webster et al.*, 1998; *Goswami et al.*, 1998; *Goswami and Ajaya Mohan*, 2001]. Broadly speaking, the large scale monsoon winds are strengthened/weakened when the north BOB convection is active/quiescent. The anomaly wind fields during active and quiescent phases of the monsoon are not mirror images of each other (Figure 3), consistent with differences in the spatial pattern of convective heating of the atmosphere. We find that wind speed is highest directly beneath and somewhat to the south of the lowest OLR region when convection peaks in the northern BOB or SCS (see *Zhang and McPhaden* [2000] for the spatial structure of MJO in the west Pacific), suggesting that the large scale mean wind field and convective momentum transport have a role to play in the response of wind to convective heating.

The $Q_{\rm net}$ and SST anomaly fields have large zonal extent, from the Arabian Sea to the South China Sea and beyond, during the active and quiescent phases of the monsoon (Figure 3, see also *Webster et al.* [1998]). Although our estimate of $Q_{\rm net}$ is based on a number of approximations, its variability is in reasonable agreement with that obtained by SR based on BOB buoy data but for one important difference. Buoy data from the northwestern BOB shows that air temperature in the summer monsoon can be higher than SST, particularly in periods when the sky is clear and SST is

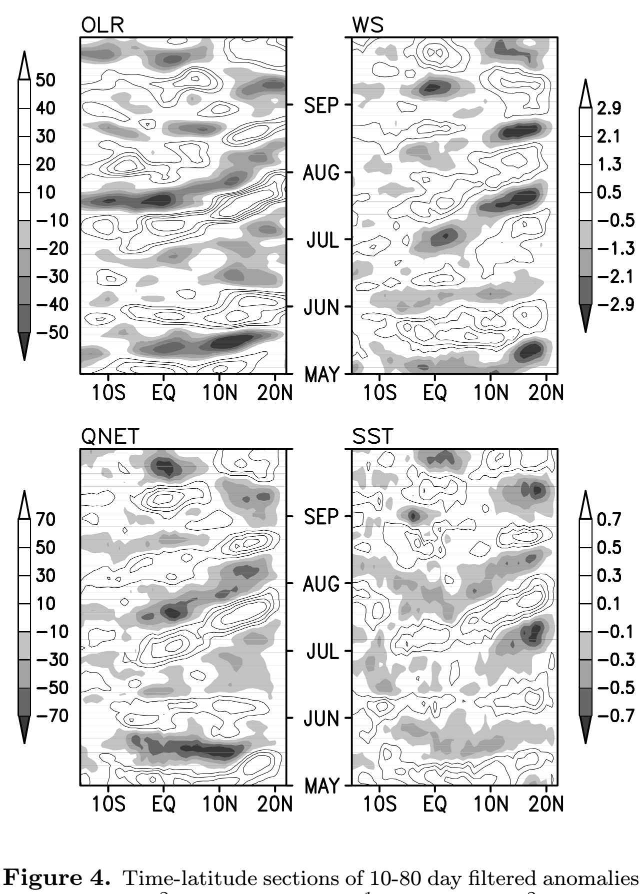

Figure 4. Time-latitude sections of 10-80 day filtered anomalies of OLR (W m^{-2}), windspeed (m s^{-1}), $Q_{\rm net}$ (W m^{-2}) and SST (°C) averaged over 85-90°E in the summer of 1998.

rising (Figure 1). This is not inconsistent with COADS climatological SST minus air temperature, which is negative in the western Bay from April to September. However, the magnitude of COADS △T used in our calculation of $Q_{\rm net}$ is small compared to the (negative) buoy △T in intraseasonal episodes of warming SST. As a result, our calculations overestimate latent heat loss by upto a few tens of W m^{-2}, and therefore underestimate the lag between $Q_{\rm net}$ and SST in the warming phase over northern BOB (section 3). Test calculations of $Q_{\rm net}$ using buoy air temperature show that SST lags $Q_{\rm net}$ by a quarter cycle (as in SR), clear indication that SST warming is due to surface heat flux. Entrainment of subsurface water into the mixed layer might be important during episodes of cooling SST [*Zhang and McPhaden*, 2000]. Further, TMI SST sometimes shows short-lived episodes of large cooling and warming rates in small pockets in the neighbourhood of missing data [*Senan et al.*, 2001]; it is possible that these "spikes" are artefacts of the retrieval algorithm (Frank Wentz, personal communication). With the above caveats, the agreement between time series of $Q_{\rm net}$ and rate of change of SST (not shown) suggests that intraseasonal SST anomalies are mainly forced by $Q_{\rm net}$ fluctuations in the central and eastern tropical Indian Ocean and in SCS away from the coast. Other physical processes such as upwelling or advection are implicated in the western Indian Ocean, near coastlines and occasionally in the equatorial Indian Ocean. The amplitude of SST ISO in EQ is about half that in BOB (Figure 2), mainly because of shallower mixed layers in the latter region due to freshwater flux from rivers and rain (SR). The opposite signs of SST anomaly in BOB and EQ (Figures 2 and 3) is related to the known see-saw in convection over these two regions [*Webster et al.*, 1998; *Goswami and Ajaya Mohan*, 2001].

Theoretical studies (see *Zhang and McPhaden* [2000]) and experiments with models show that inclusion of feedback from the ocean can influence the phase propagation of MJO and render the large scale convection more coherent, bringing the model MJO closer to observations [*Flatau et al.*, 1997; *Waliser et al.*, 1999]. The coherent space-time evolution of atmospheric convection and SST associated with monsoon ISO is suggestive of air-sea interaction. How variations of SST and surface turbulent heat fluxes feedback to monsoon convection and winds is a question that requires further work.

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