Intra-seasonal oscillations in the central Bay of Bengal during summer monsoon 1999

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Intra-seasonal oscillations were observed in the meteorological and oceanographic fields of Bay of Bengal during the summer monsoon season of 1999. Spectral analysis revealed prominent peaks in the intra-seasonal (10 to 32 days), inertial (2.2 days), diurnal and semi-diurnal bands. Oscillation of intra-seasonal periodicity significantly influences the circulation pattern. The variations in oceanographic fields were dominated by remote forcing compared to local forcing.

ONLY a few studies have been carried out in the Indian Ocean to understand the influence of seasonally reversing monsoon winds on the variability of water characteristics and circulation. A recent study by Yu *et al.*[1] suggested that for a large-scale low frequency forcing associated with monsoon wind, only long Rossby and Kelvin waves are generated. These waves act as a remote forcing, determining the upper layer circulation in the Bay of Bengal. McCreary *et al.*[2] also suggested that the monsoon winds force the ocean locally and excite propagating signals (Kelvin and Rossby waves) that travel a long distance to affect the ocean remotely. Theoretical studies revealed the presence of these waves in the current and temperature fields in the central and western sides of the Bay[3,4]. These studies suggest that the Rossby waves excited by the remotely-forced Kelvin waves play a significant role in the variability of circulation in the Bay of Bengal. This is contrary to some of the earlier studies that stressed the direct influence of meteorological forcing for the observed oceanic oscillation, citing the Madden and Julian[5] discovery of 40 to 50-day oscillation in the wind field of lower tropical troposphere. However, the model of Kindle and Thompson[4] showed that the oscillations are not driven by the atmospheric wind field, but instead are energized by barotropic instability of westerly zonal flow. All these theoretical studies have concluded that these waves contributed significantly to the dynamics of the Bay of Bengal, which needs observational evidence. More recently, Premkumar *et al.*[6] observed intra-seasonal oscillations in sea surface temperature (SST) at different locations in the Bay of Bengal utilizing data from moored buoys. They suggested that the SST variations are determined mainly by variations in cloudiness and wind speed.

Recently a national programme called Bay of Bengal Monsoon Experiment (BOBMEX) was conducted in the Bay of Bengal with an objective to study the air–sea interaction and intra-seasonal oscillations during the summer monsoon season. During this programme, *INS Sagardhwani* occupied a stationary position in the central Bay (13°N, 87°E) (Figure 1) from 17 July to 29 August 1999 in four phases, each extending for a period of five to six days and collected surface marine meteorological information, temperature/salinity (using Mini CTD) and current data (using Acoustic Doppler Current Profiler, ADCP). The currents were measured at three-hourly intervals for 20–30 min duration (at 5 min sampling). The ADCP observations could not be made between 12 and 16 August 1999 due to failure of LAN and GPS. These data sets along with the data (SST, wind speed and direction, current speed and direction for 19–31 August 1999) obtained from the nearby NIOT buoy are also utilized to examine the intra-seasonal oscillation in the central Bay of Bengal. Hereinafter, the station occupied by *INS Sagardhwani* and the NIOT buoy station is referred as SD and DS3, respectively. In general, some departure is noticed between the measurements obtained from SD and DS3, which is mainly due to the difference in measurement of height/depth.

After the onset of monsoon, strong (> 8 m/s with maximum of 12 m/s by 4 August 1999) and consistent south-westerly winds prevailed over the central Bay of Bengal (Figures 2 and 3). However, the south-westerly winds became weak (< 5 m/s) during mid-August 1999, that corresponded to weak monsoon condition as indicated by the India Meteorological Department (IMD) weather summary. This suggested that both active and weak phases of the monsoon were experienced during BOBMEX. One of the notable observations in wind field was the oscillation with different periodicities, which can be clearly seen from the buoy data as well as

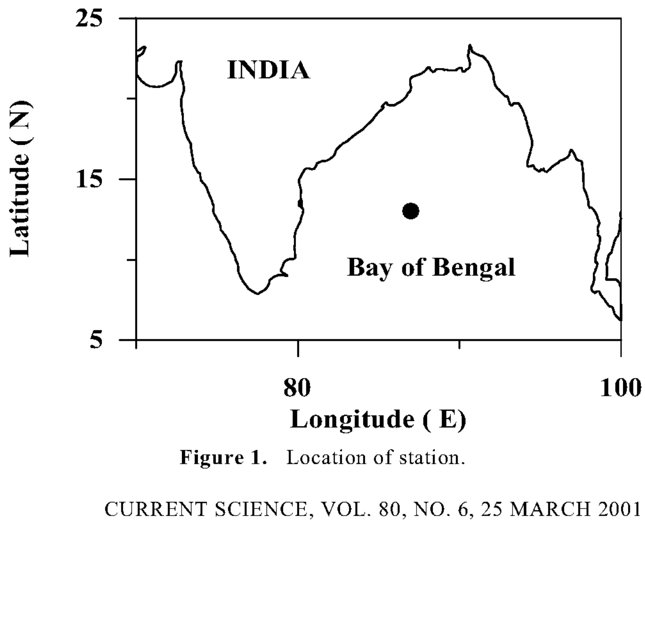

Figure 1. Location of station.

*For correspondence.

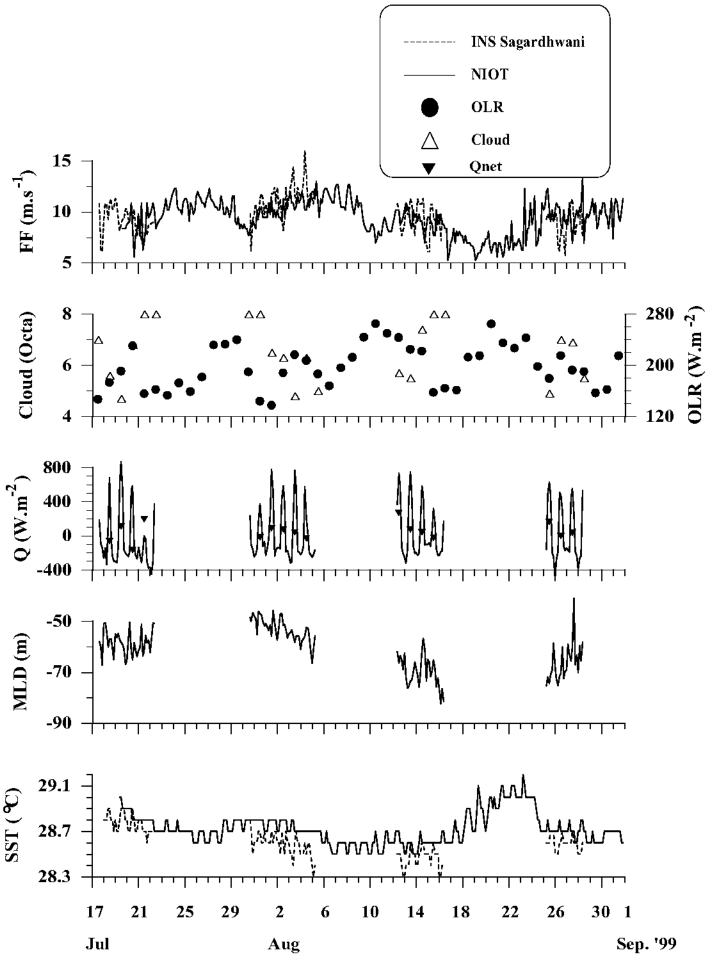

Figure 2. Time series of wind speed (FF), daily averaged cloudiness (cloud), outgoing long wave radiation (OLR), net heat flux (Q), mixed layer depth (MLD; m) and sea surface temperature (SST) at SD and DS3.

the ship observations, details of which are discussed later. The daily average values of total cloudiness measured on-board *INS Sagardhwani* showed overcast conditions during July 1999 and partially clear conditions during the first half of August 1999. Moreover, during the observational period, the clear sky condition was extremely sparse. When the sky was overcast (8 octa), the outgoing long wave radiation (OLR) was low (< 140 W m^{-2}) and when the sky was partially clear (< 5 octa), OLR was comparatively higher (> 200 W m^{-2}). The low values of OLR were also associated with stronger winds. Even though the average OLR was around 200 W m^{-2}, it also exhibited oscillations with periodicity around 4 days. To delineate the role of air–sea exchange processes on the thermal structure, the net heat flux (Q) was computed from the three-hourly marine meteorological parameters. As direct solar radiation measurements were not available, it was estimated following Lumb[7], while the effective back-radiation was estimated following Budyko[8] and latent and sensible heat fluxes following the bulk aerodynamic formulae. Intense air–sea exchange in the near surface boundary layer was quite evident from the repeated cycles of ocean heat loss/heat gain (Q). In general, the ocean gained heat during the day and lost heat during the night. Variations of Q were related to cloud cover, wind speed and air–sea temperature difference. As a result, both OLR and the daily averaged Q showed similar pattern of variation.

The mixed layer depth (MLD) is defined as the depth at which a drop of 0.2°C from SST has occurred. In general, the relationship between MLD and atmospheric forcing was very weak, as indicated by the weak correlation coefficient between MLD and local wind speed/net air–sea heat flux (< 0.2). The shoaling of MLD during 17–22 July 1999 and deepening during 30 July to 5 August 1999 was associated with decrease and increase in wind speed, respectively. However, corresponding to the decrease/increase in wind speed during 12–16 August 1999/25–28 August 1999, the mixed layer deepened/shoaled, respectively, suggesting a weak relationship. On closer examination it can be seen that the

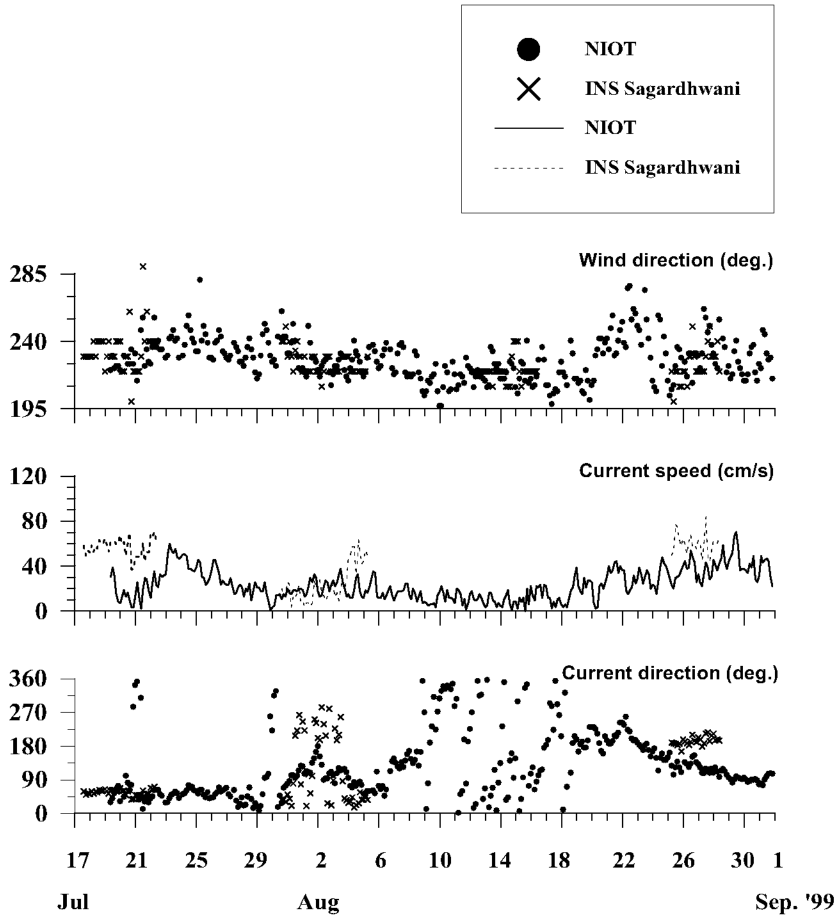

Figure 3. Time series of wind direction, current speed and direction at SD and DS3.

maximum MLD (> 80 m) coincided with the trough and the minimum (< 50 m) with the crest of an oscillation of around 20 to 30-day periodicity. Recently, Premkumar *et al.*[6] reported intra-seasonal oscillation in SST field at various locations in the Bay of Bengal, which is consistent with this study. Moreover, the present study shows intra-seasonal oscillation of MLD, which was quite different from the oscillation in SST. This study suggested that the MLD variability in the Bay of Bengal during the monsoon period was rather complex and both remote as well as local forcing influence its variability. It is also possible that influence of local atmospheric forcing on the MLD field might have been overshadowed by the oscillations of intra-seasonal periodicity.

The surface circulation in the north Indian Ocean during the summer monsoon season is characterized by counter-rotating eddies in the Bay of Bengal, an eastward flowing Indian Monsoon Current and a westward flowing South Equatorial Current[9]. However, on a finer scale, oscillations of several periodicities embedded on the general circulation pattern. To have an idea of the prevailing flow pattern, the surface currents obtained from the ADCP on-board *INS Sagardhwani* and the nearby buoy are presented (Figure 3). As the time series station was located close to the centre of the gyre, drastic variations are observed both in the current speed and direction. The surface currents were strong (> 45 cm/s) and north-easterly (45°) till 29 July 1999. During this period, very good agreement was noticed in the current direction obtained from both platforms. The speed reduced considerably after 29 July 1999 and was associated with a change in direction to south-eastward and later to south-westward. During mid-August, i.e. between 10 and 18 August 1999, the flow fluctuated between north-westerly and north-easterly. But the speed showed a steady decrease. Thereafter, the flow again changed to south-westerly and to south-easterly with an increase in their speed. However, such variations are not evident in the wind field. On closer examination it can be seen that the current speed and direction also exhibited oscillations with different periodicities. An important point here is that the current direction was not consistent with the local south-westerly winds. The spectral analysis of currents in the Bay of Bengal by Potemra *et al.*[3] also suggested the presence of oscillations of 20 to 30-day periodicity and attributed to long-period Rossby waves excited by remotely-forced Kelvin waves.

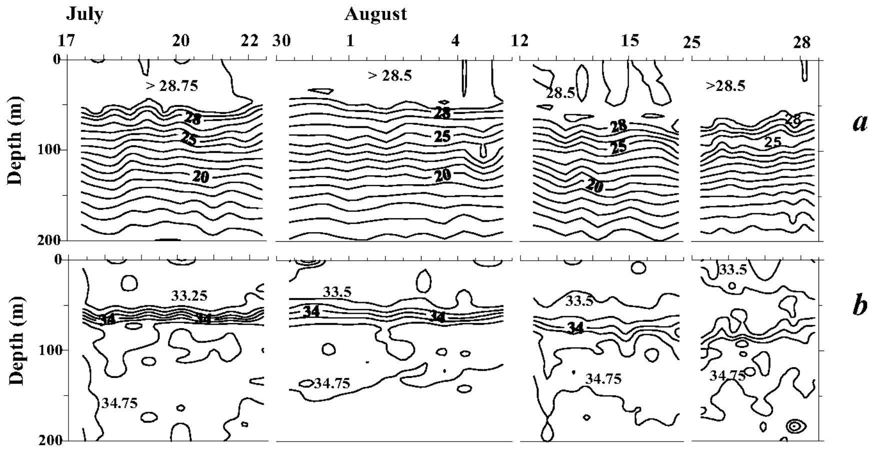

Figure 4. Evolution of ***a***, temperature; and ***b***, salinity at SD.

In the Bay of Bengal, presence of intra-seasonal oscillation was not well established due to paucity of long time-series measurements. Some studies indicated the presence of this type of oscillation in SST obtained from mooring in the Bay of Bengal. However, at subsurface levels, this oscillation still remains unexplored. In order to have an idea about this oscillation, the temporal evolution of temperature and salinity for the upper 200 m is shown in Figure 4. The depth–time sections of temperature clearly revealed the progressive cooling of the whole mixed layer (> 28.8° to < 28.5°C) till 16 August 1999 and warming afterwards. The appearance of the 28.5°C isotherms during 12–16 August 1999 was mainly due to daytime heating (Figure 2). Utilizing the NIOT buoy data collected during 1998, Premkumar *et al.*[6] concluded that the SST variations are determined by variations in cloudiness and wind speed. The increase in SST during 17–20 July 1999 and 18–24 August 1999 was associated with weak winds and increasing OLR (Figure 2). The SST dropped after 24 August 1999, when the wind speed increased (> 8 m/s) and OLR reduced (< 200 W m^{-2}). However, during the periods 25–29 July 1999 and 8–11 August 1999, even though the OLR was high the SST remained steady or slightly dropped. These periods are characterized by strong winds (> 7 m/s). This suggests that SST depends more on wind variation than OLR during this period. However, it is interesting to note that the period of cooling was mostly associated with the northerly currents, while surface temperature slightly increased when the flow became southerly/south-westerly. This suggests that the prevailing circulation, which was remotely forced, also contributed significantly to the SST variability.

In the Bay of Bengal salinity variations are quite conspicuous, especially in the upper layers, mainly due to massive freshwater discharges. Even though the time series station was located in the central Bay, the influence of this low-salinity water was clearly evident. In the surface layer, salinity continuously increased from 33.25 PSU on 17 July 1999 to values over 33.5 PSU towards the end (Figure 4). The increase in salinity and cooling in the mixed layer suggests that the prevailing northerly flow was carrying water from south. Low salinities (< 33 PSU) observed during 18 and 19 July 1999 were due to heavy rain on these days. A notable feature on the salinity structure is the diffusion of the strong halocline (just below the mixed layer) with progress of time.

The temperature field at various depth levels (0, 70, 80, 90 and 100 m) clearly indicated the presence of a long-period wave with crest during the initial (around 19 July 1999) and third (14 August 1999) phases and trough during end July/early August 1999 (Figure 5). This suggests the approximate period of this wave, i.e. between 20 and 30 days. Moreover, influence of this wave became more prominent below 70 m, i.e. below the mixed layer, as evident from the well-developed trough and crest. However, the amplitude of this wave reduced with depth, i.e. > 3°C at 70 m to < 2°C at 100 m.

The time-varying signals in the atmosphere and ocean can be explored by various techniques. To have a detailed understanding of the prevailing oscillations, U- and V-components of winds and currents, air temperature and SST collected from the moored buoy (19 July to 23 September 1999, i.e. for approximately 66 days) were subjected to spectral analysis using Fast Fourier Transformation (FFT) technique (Figure 6). The analysis revealed prominent peaks in the intra-seasonal (10 to 32 days), inertial (2.2 days), diurnal and semi-diurnal bands. Out of these, maximum spectral energy was noticed in the intra-seasonal band. Prominent peaks noticed around 24 h and 12 h suggested the diurnal and semi-diurnal scale variability in this region. The peak noticed around 2.2 days corresponds to the local inertial period (12 h/sin(ϕ), where ϕ is the latitude) and was evident in all the fields. A prominent peak was noticed around 10.6 days in the north-south component (i.e. V-component) of wind field (Figure 2). Moreover, the two peaks corresponding to 22 days in the U-component

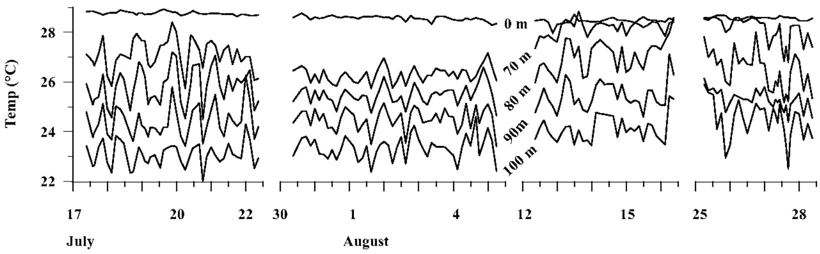

Figure 5. Distribution of temperature at the surface, 70, 80, 90 and 100 m at SD.

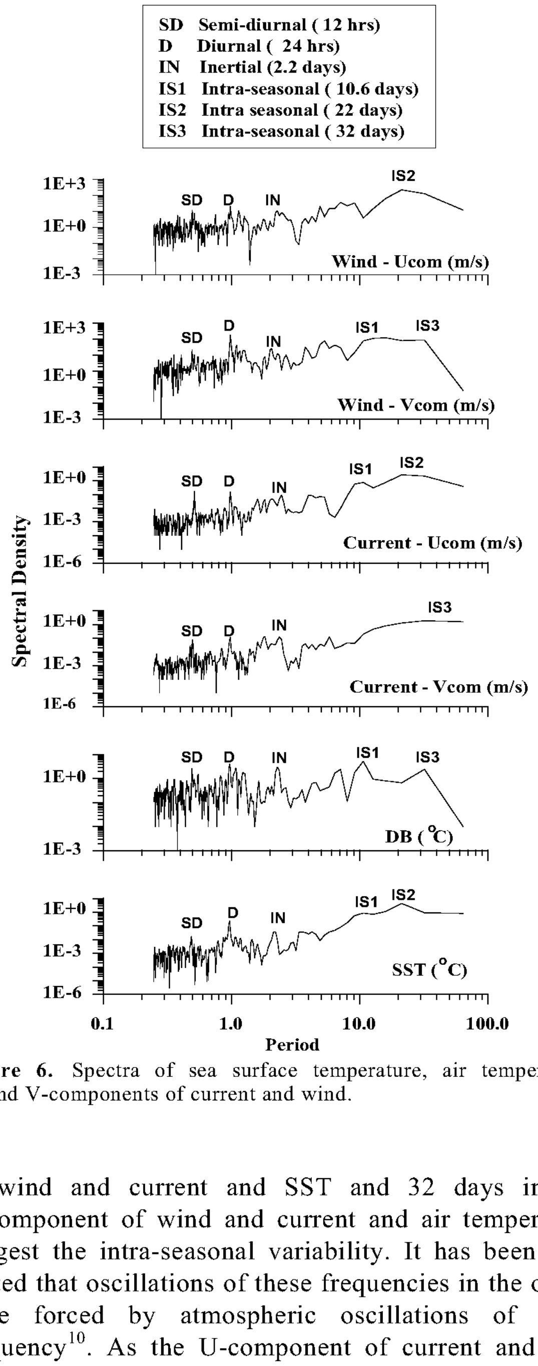

Figure 6. Spectra of sea surface temperature, air temperature, U- and V-components of current and wind.

of wind and current and SST and 32 days in the V-component of wind and current and air temperature suggest the intra-seasonal variability. It has been suggested that oscillations of these frequencies in the ocean were forced by atmospheric oscillations of same frequency[10]. As the U-component of current and SST revealed a prominent peak around 22 days, the intra-seasonal variability in SST might have been caused by the variability of east-westerly currents also, apart from the local forcing. The spectral peaks noticed in current and SST are well within the periodicity of a remotely-forced long-period Rossby wave[1,3], which is consistent with the findings of Potemra *et al.*[3] and Yu *et al.*[1]. Even though the present data sets are not sufficient to resolve all the features of intra-seasonal oscillation during the monsoon, both the FFT analysis and actual observations showed its occurrence in atmosphere and ocean. Hence, a detailed analysis with a long-time series data has to be carried out to understand more about intra-seasonal oscillation in the Bay of Bengal.

The study highlighted the presence of intra-seasonal oscillation, both in the meteorological and oceanographic fields. Spectral analysis revealed prominent peaks in the intra-seasonal (10 to 32 days), inertial (2.2 days), diurnal and semi-diurnal bands. The waves of intra-seasonal periodicity significantly influence the circulation pattern. The variations in oceanographic field are mostly dominated by remote forcing, compared to local forcing.

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