

## **Bio-physical coupling and ocean dynamics in the central equatorial Indian Ocean during 2006 Indian Ocean Dipole**

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### **Abstract**

The high-frequency times-series data collected during 28<sup>th</sup> October to 21<sup>st</sup> November 2006 onboard R/V Mirai provided the first evidence of short-term bio-physical coupling in the central equatorial Indian Ocean (EIO). The predominant feature of the thermal structure was the down-sloping of 28°C-isotherm and up-sloping of 14°C-isotherm indicating deepening of surface-layer and shoaling of lower-thermocline respectively. Concomitant with the deepening of surface-layer, nitracline and subsurface chlorophyll maximum (SCM) also deepened. From the prominent bi-weekly periodicity in the 14°C-isotherm and the upward phase propagation in the meridional current velocity, we infer that shoaling was the response of mixed Rossby-Gravity (MRG) waves. Based on temperature and currents we propose that deepening of surface-layer was caused by the eastward advection of warmer waters associated with the weakening of Indian Ocean Dipole (IOD). This made the upper ocean more nutrient-depleted and biologically less-productive, an indication that the central EIO is returning to its pre-IOD condition.

## 1. Introduction

The equatorial Indian Ocean (EIO) is unique compared to other equatorial regions of the world ocean because of the semi-annual reversal of surface currents, lack of equatorial upwelling and non-permanent undercurrent all of which arises due to the seasonal reversal of the monsoon winds. Apart from the seasonality, the other strong modes of EIO variability are the Indian Ocean Dipole (IOD) [Saji *et al.*, 1999] on an inter-annual time scale and the Madden Julian Oscillation (MJO) [Madden and Julian, 1972] on an intra-seasonal (30-60 days) time scale. In order to study the detailed features of the onset of MJO convection an observational campaign MISMO (MIRAI Indian Ocean Cruise for the study of the MJO convection Onset) was conducted at equator and 80.5<sup>0</sup>E from Japanese research ship R/V Mirai during late October through November, 2006 when the onset in MJO convection is often observed [Yoneyama *et al.*, 2006]. Unfortunately the MJO onset could not be studied as the strong easterlies evolving in the eastern EIO suppressed eastward propagation of MJO. When the MISMO observations were in progress, the third largest IOD event after 1997 and 1994 was unfolding in the eastern EIO [Vinayachandran *et al.*, 2007; Horii *et al.*, 2008] with a cooling at the southeastern Indian Ocean and the warming at the western EIO, which started in August and terminated in December 2006 [Horii *et al.*, 2008; Masumoto *et al.*, 2008]. However, the high frequency physical and biogeochemical water column data collected during this period provided an unprecedented opportunity to understand the bio-physical coupling over short time scale.

In the EIO collocated physical and biogeochemical data are sporadic and time-series measurements are non-existent. The present study describes the short term bio-physical coupling in the central EIO and explores its relation with internal ocean dynamics.

## 2. Data

The *in-situ* time series data on temperature, salinity, chlorophyll *a*, the nutrients such as nitrate as well as the zonal and meridional current velocities were obtained at the equator and 80.5<sup>0</sup>E (Figure 1) from MR06-05-Leg1 cruise onboard R/V Mirai. The measurements from 28 October to 21 November, 2006 were a part of the MISMO project. The temperature and salinity were measured by a Sea-Bird Electronics CTD (Conductivity-Temperature-Depth) at 3-6 hourly intervals. Nutrient and chlorophyll samples were collected at 6 hourly intervals with the help of 12 liter Niskin samplers attached to the rosette sampler of the CTD. Water samples for nutrient were taken from 10 depths in the upper 150m (5m, 10m, 20m, 40m, 50m, 60m, 80m, 100m, 120m and 150m) and analyzed using auto analyzer

(Bran+Luebbe Traacs 800 system). The chlorophyll *a* samples were taken from 8 depths in the upper 100m (5m, 10m, 20m, 40m, 50m, 60m, 80m and 100m) and was measured using a Turner Design Fluorometer (10-AU-005). The zonal and meridional current velocities were measured using shipboard acoustic doppler current profiler (ADCP) on five minute interval, which were then averaged to daily. We also have used optimally Interpolated daily sea surface temperature (SST) from Tropical Rainfall Measuring Mission Microwave Imager (TMI) having  $1/4^\circ$  resolution ([http://www.misst.org/data\\_servers/data\\_servers.html](http://www.misst.org/data_servers/data_servers.html)) and surface (15m depth) pentad current data from Ocean Surface Current Analyses - Real time (OSCAR) having  $1^\circ \times 1^\circ$  resolution [Bonjean *et al.*, 2002]. The daily SST anomaly was computed by subtracting the climatological daily mean (for the period 1997 to 2008) from the daily SST. These were subsequently re-gridded to pentad matching with the pentad surface current from OSCAR for the period of *in situ* observation. To verify the robustness of the features inferred from the shipboard measurements of temperature and current, we also used similar data from Research moored array for African-Asian-Australian Monsoon Analysis and prediction (RAMA) [McPhaden *et al.*, 2009] (<http://www.pmel.noaa.gov/tao/disdell/frames/main.html>).

### 3. Results and Discussion

The time evolution of the physical, chemical and biological characteristics of the water column at the central EIO was examined by analyzing the vertical profiles of temperature, salinity, chlorophyll *a* and nitrate (Figure 1). Within a short span of 25 days from 28 October to 21 November, 2006 the study region showed remarkable surface and subsurface variability. The surface layer was warm ( $28^\circ\text{C}$ ), nitrate-depleted and oligotrophic with very low ( $0.1 \text{ mg/m}^3$ ) concentrations of chlorophyll *a*. The predominant features seen in the thermal structure was the deepening of the warm surface layer indicated by the downward sloping of the  $28^\circ\text{C}$  isotherm and shoaling of the lower thermocline indicated by the upward sloping of  $14^\circ\text{C}$  isotherm during the period of study (Figure 1a). A similar feature is also seen in the RAMA mooring [McPhaden *et al.*, 2009] during same time period (Figure S1). Both the above processes led to a progressive decrease in the thickness of the thermocline and increase in its strength (gradient). A warming of the upper 20m layer by  $1^\circ\text{C}$  occurred during the period 8<sup>th</sup> to 17<sup>th</sup> November followed by a mild cooling, which led to the formation of temperature inversion in the upper 50m depth from 17<sup>th</sup> to 21<sup>st</sup> November. In addition, the thermal structure also showed high frequency thermocline oscillations. Consistent with thermal structure, the salinity structure also showed a similar deepening of the upper halocline and shoaling of the lower halocline (Figure 1b). Lowest surface salinity

of 33.9 psu was first seen in 30<sup>th</sup> October, which persisted till 5<sup>th</sup> November. The characteristic of the salinity structure was the presence of high salinity core with a salinity of 35.3 psu, which occurred between the depths of 60m and 125m. The maximum thickness of the core was 65m and occurred in 3<sup>rd</sup> November. The minimum thickness of 20m was in 10<sup>th</sup> November. An examination of density of salinity core (not presented) showed that it is temperature compensated. The vertical structure of the zonal current from the ADCP data at 80.5°E and equator from *Horii et al.* [2011] during MISMO observation period showed a westward flow in the upper 50m and an eastward subsurface flow below it. Thus, the observed large temporal variation in the thickness of the high salinity core appears to be associated with interleaving process under the influence of these opposing flows.

The vertical distribution of chlorophyll *a* was characterized by the presence of subsurface chlorophyll maximum (SCM) and very low concentrations in the upper layer (Figure 1c). The SCM with a concentration of 0.6 mg/m<sup>3</sup> was initially located at 40m, which deepened to 55m during 5<sup>th</sup> to 10<sup>th</sup> November and thereafter to 60m. In addition to the deepening of SCM, the chlorophyll *a* concentration within SCM decreased by a value of 0.15 mg/m<sup>3</sup>. A similar deepening of chlorophyll *a* isopleths was also noticed in the upper layer where the concentration was low (0.2 mg/m<sup>3</sup>). The thickness of the SCM was 20m (30-50m) during 28<sup>th</sup> October to 2<sup>nd</sup> November, which increased to 35m (40-75m) during 3<sup>rd</sup> to 10<sup>th</sup> November and once again decreased to 20m (50-75m) after 10<sup>th</sup> November. Thus, we infer 3 stages of deepening of SCM, while the surface chlorophyll *a* concentration remained low throughout the study period.

The nitrate distribution showed that at the beginning of the time series the upper 20m of the water column was devoid of nitrate (Figure 1d). From 1<sup>st</sup> November this layer showed a gradual deepening until 5<sup>th</sup> followed by a rapid deepening until 11<sup>th</sup> November. At this time the upper 75m was devoid of nitrate and subsequently the depth of this layer showed nominal variation. Another important feature was the presence of oscillation within the nitracline, similar to that seen in the thermocline. It appears that the deepening of the SCM and its strengthening followed by its weakening towards the end is linked to the deepening of warm oligotrophic surface layer and shoaling of cold nutrient rich deeper layer. This in turn seems to be coupled to the equatorial dynamics on the intra-seasonal time scale, but not associated with MJO.

An examination of the Chi-squared distribution [*Emery and Thompson, 1997*] of the depth of 14°C isotherm showed a prominent peak at 11-day (Figure 2a) indicating a biweekly variability in the lower

thermocline. A similar biweekly variability with 11-day peak was also observed in the depth of chlorophyll maximum (Figure 2b). In order to understand this further, we examined the meridional current velocity obtained from the shipboard ADCP onboard R/V Mirai, which showed a prominent peak at 9-day (Figure 2c) and the signature of upward phase propagation (Figure 2d). From the prominent biweekly periodicity and the upward phase propagation in the meridional current velocity we infer that these are the signature of the mixed Rossby-gravity (MRG) wave [McPhaden, 1982]. A similar conclusion was arrived at by *Horii et al.* [2011] who obtained a quasi-biweekly period of 11-16 days in the vertical velocity in the central EIO from the moored subsurface ADCPs deployed during the MISMO measurement period. Biweekly variability of the meridional current in the EIO was reported earlier by *Sengupta et al.* [2004]. More recently *David et al.* [2011] using a long time-series data, during 2003 to 2007 from an equatorial mooring at 77°E, identified the occurrence of both higher (7-23 days) and lower (24-40 days) frequency MRG waves in the upper water column during positive IOD years including 2006.

From the above discussion we conclude that the observed variability in the lower thermocline is the response of the MRG waves. However, to understand the deepening of the upper thermocline/nitracline and the depth of the chlorophyll maximum we examined the prevailing ocean dynamics. Prior to the MISMO observation period eastward flowing southwest monsoon current (SMC) prevails in the central EIO (80.5°E and equator) as could be seen from the time evolution of the zonal current obtained from RAMA mooring at 10m and 40m during September 2006 (Figure S2a). During the period of MISMO observation, when the eastern Indian Ocean was experiencing the IOD event with strong easterly winds [*Horii et al., 2008; Masumato et al., 2008*], the currents at the central EIO was westward in the upper 10m, which strengthened with time attaining the maximum value of 105cm/s. At 40m, however, the currents were weaker (30cm/s) compared to 10m and the direction switched between eastward and westward. After mid-October the westward current at 10m weakened with time. From end of November the zonal currents at 10m and 40m showed an eastward flow, which strengthened with time (95cm/s).

A similar feature could be inferred from the time evolution of the vertical structure of the zonal current obtained from the shipboard ADCP (Figure S2b), though the data in the upper 30m was not available. Thus, at MISMO time-series location (central EIO) we notice a weakening of eastward SMC in September followed by a strengthening of westward current in October. We infer this as the influence of IOD. Generally, the westward flowing south equatorial current (SEC) in the Indian Ocean is located between 10°S and 20°S. Under the influence of the strong easterly winds during IOD, the westward

flowing south equatorial current (SEC) shifts northward towards the equator [David *et al.*, 2011] carrying along with it the cold upwelled waters. Horii *et al.* [2011] showed that the westward zonal current associated with the evolution of IOD peaked in October and started weakening in November. Based on remotely sensed sea surface height data Palastanga *et al.* [2006] showed that during positive IOD the subtropical gyre of which the SEC is a part shifted northward. With the weakening of IOD in the eastern EIO, the eastward current prevails once again by the end of November as could be seen from RAMA mooring data (Figure S2a).

In order to understand the spatial extend of the eastward and westward currents obtained from the RAMA mooring as well as the shipboard ADCP data, we have further examined the daily SST anomaly from TMI and the pentad surface currents from OSCAR (Figure 3). We noticed the presence of colder waters with strong westward current at the time-series location (blue box in Figure 3) during 28<sup>th</sup> October to 1<sup>st</sup> November 2006, while the region of warm waters with an eastward flow was located away from it (Figure 3a,b). This westward flowing cold water and the eastward flowing warm water generate a thermal front. Notice the thick black line in figure 3, which separates the warmer waters from colder waters. With the weakening of IOD the westward zonal current and associated advection of cold water weakens. This moved the thermal front eastward during the period between 6<sup>th</sup> and 11<sup>th</sup> November 2006 advecting the warm waters to the time-series location (Figure 3c,d). These warm waters persisted until the end of the time series (Figure 3e,f). The advection of warm waters led to the deepening of the surface layer. Notice the deepening of the 28°C isotherm from 30m to 80m as captured in the observation (Figure 1a). Since the nutrients reside below the mixed layer and close to the upper thermocline, this deepening of the upper layer lead to a vertical extension of the oligotrophic waters there by hampering the phytoplankton growth. Hence, we propose that the deepening of the upper layer was associated with the eastward advection of thermal front due to the weakening of the IOD conditions.

Thus, the observed deepening of the upper thermocline/nitracline and the depth of the chlorophyll maximum during 1<sup>st</sup> to 21<sup>st</sup> November 2006 was the manifestation of the processes associated with weakening IOD, while the shoaling of the lower-thermocline was associated with the propagation of high frequency Yanai wave. It is reasonable to believe that when the IOD is active the shoaling of the lower thermocline/nitracline, due to the upward phase propagation of Yanai wave, could continue unhindered close to surface there by supporting an elevated chlorophyll biomass. We did not capture this in our observation as our sampling period was temporally different. Neither the satellite derived chlorophyll pigment concentration reveal this feature (figure not presented), which we presume was due

to the process being confined to the sub-surface layer. A similar situation was encountered by *Wiggert et al.* [2009] in the southern tropical Indian Ocean where the anomalous sub-surface biochemical distribution revealed by the *in situ* measurement was not captured in the SeaWiFs data. However, what we could capture is the return of the central EIO to its usual oligotrophic and biologically less productive condition. We need more high-frequency and longer time-series data sets to assess our hypothesis and to understand the importance of short-term phytoplankton variation in the overall biological productivity in the EIO.

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## Figure Captions

**Figure 1.** The vertical distribution of (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity (psu), (c) chlorophyll *a* ( $\text{mg}/\text{m}^3$ ) and (d) nitrate ( $\mu\text{M}$ ) at  $80.5^{\circ}\text{E}$  and equator during 28 October to 21 November, 2006. The white dashed line in (a) and (b) in the near surface and subsurface represents the deepening and shoaling feature in the water column. Note the change in the contour interval of the dashed lines in (d).

**Figure 2.** The chi-squared distribution (tukeywin filter of window length equal to the sample size and a ratio of cosine-tapered section length to the entire window length of 0.5 is used) of (a) the three hourly depth of  $14^{\circ}\text{C}$  isotherm, (b) the daily depth of chlorophyll maximum, and (c) the hourly meridional current velocity ( $\text{m}/\text{s}$ ) at 200m depth and (d) the time evolution of the vertical structure of the hourly meridional current velocity ( $\text{m}/\text{s}$ ). The current velocity is obtained from ADCP onboard R/V Mirai during 28 October to 21 November, 2006 at  $80.5^{\circ}\text{E}$  and equator. The dashed curve in (a), (b) and (c) represents 95% CL, the dashed contour in (d) represents the zero current velocity and the thick dashed line shows the upward phase propagation in the meridional current velocity.

**Figure 3.** Pentad SST anomaly (shading) from TMI overlaid with the pentad surface current data from OSCAR (vectors) for the period (a) 27-31 October (b) 1-5 November, (c) 6-10 November, (d) 11-15 November, (e) 16-20 November and (f) 21-25 November 2006. The black line is the zero SST anomaly contour, while the dark blue box is the location of the time-series observation.

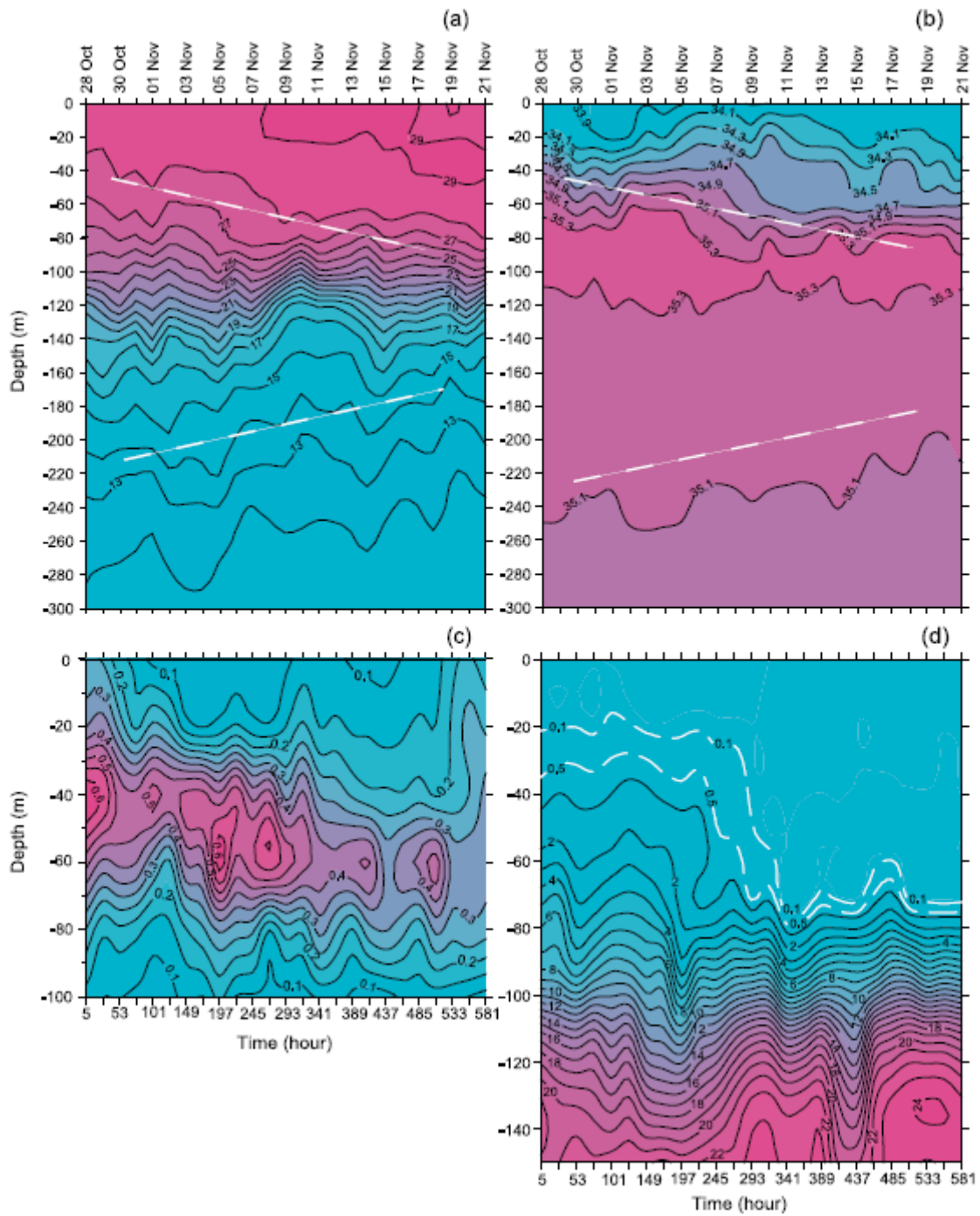


Figure 1

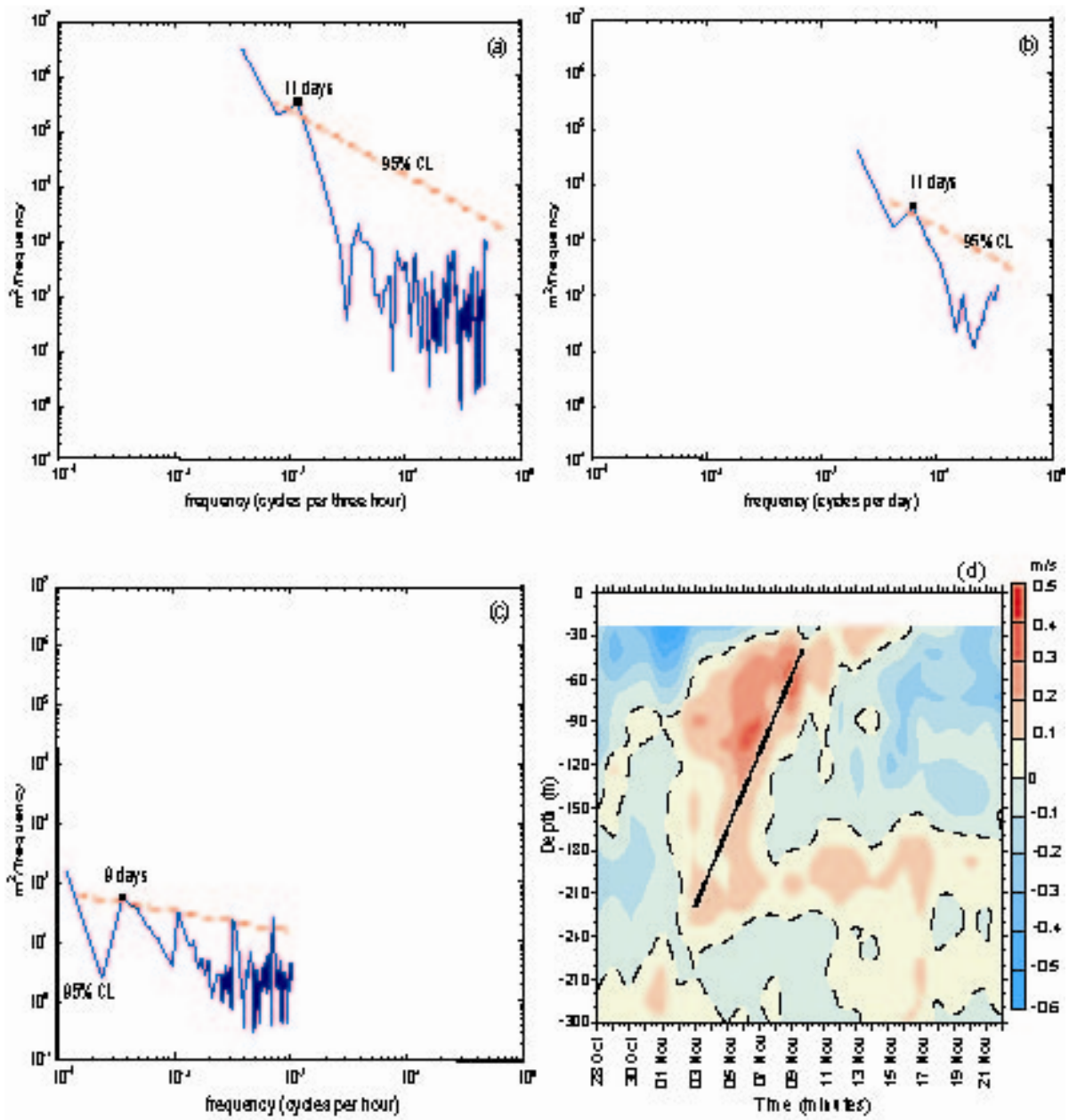


Figure 2

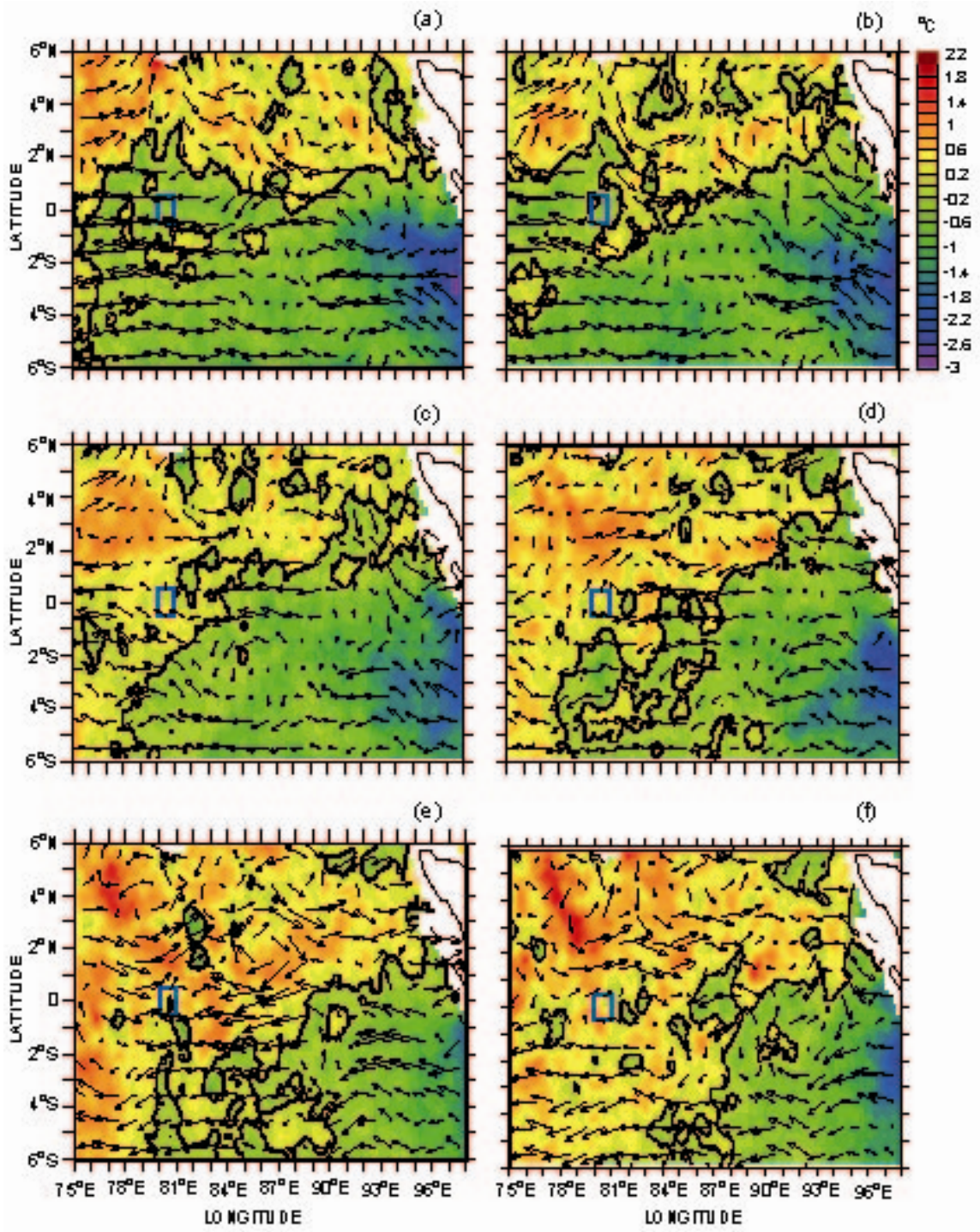


Figure 3