Life cycle of eddies along the western boundary of the Bay of Bengal and their implications.

M.Nuncio \(^1{}\) \(^2{}\)

*National Institute of Oceanography, Dona Paula, Goa, India-403004*

S. Prasanna Kumar

*National Institute of Oceanography, Dona Paula, Goa, India-403004*

\(^1{}\) Corresponding author

\(^2{}\) Present address and affiliation- National Centre for Antarctic and Ocean Research, Head Land Sada, Vasco Da Gama, Goa, India, 403804

Phone-0091-(0)832-2525528

Fax-0091-(0)832-2520877, email- nuncio@ncaor.org, nuncio.m@gmail.com

**Abstract**

Analysis of vertical thermohaline structure along the western boundary of the Bay of Bengal revealed many undulations during April-May 2003. A prominent feature noticed was a dome in the northwestern boundary of the Bay of Bengal, which was found to be a cyclonic eddy (NCE). This eddy altered the ambient temperature by 6°C and salinity by 0.8 psu. NCE was formed from a meander generated out of an instability due to cross-shore density gradient in the northeastward flowing western boundary current during early February. The cross-shore density gradient was developed under the influence of cyclonic (upwelling) / anticyclonic (downwelling) wind stress curl along the western boundary / open ocean region and the westward propagating Rossby wave. EOFs of SLA showed that annual cycle (EOFs 1 and 2) accounts for 39% of the total variance, while meso-scale eddies contributed up to 25% of the variance. Meso-scale eddies dominate the BOB circulation and are able to enhance the surface chlorophyll whenever the stratification is weak as in the case of intermonsoon 2003.

*Key words: Western boundary currents, Satellite altimetry, Oceanic Eddies, chlorophylls, Indian Ocean, Bay of Bengal*
1. Introduction

Boundaries of the oceans are highly energetic regions due to the interplay of numerous physical processes. Among them the western boundaries are special because they are characterized by intense current systems called western boundary currents (WBC) and are well known for eddy activity, which arises from the instabilities of these currents. The eddy kinetic energy found in these regions is several folds greater than in the rest of the ocean (Wyrtki et al., 1976). The north Indian Ocean (NIO), however, is known more for its response to the seasonal reversal of winds. This seasonal signal can be felt along the western boundaries of the NIO also, as seasonally reversing current systems and upwelling and sinking in accordance with the wind reversals. Nonetheless the presence of eddies is noted in the NIO also. One of the most extensively studied regions in the NIO is the Somali current, which lies along the western margin of the Arabian Sea (AS). Here eddies develop in close association with the development of the boundary current (Robinson, 1983). In a fully developed summer monsoon the Somali current turns off shore near 4°N and recirculates across the equator as the southern gyre, while a second gyre forms in the north known as the “great whirl”. A third gyre is also seen during summer monsoon known as Socotora eddy (Schott et al., 2009). These eddy structures and co-variability of ocean-atmosphere system result in significant modification of net latent heat flux (Vecchi, et al., 2004).

Its eastern counterpart, the Bay of Bengal (BOB), is one of the least studied basins of the world ocean. Though lying in the same latitudinal belts the two seas are markedly different. On an average BOB is warmer and less saline than the AS. This primarily arises from the fact that in the AS evaporation exceeds precipitation, whereas, in the BOB it is the precipitation that exceeds the evaporation (~ 2 m yr⁻¹) (Prasad, 1997). Three major river systems - the Ganges-Bhramaputra, Irrawadi-Salween and the Krishna-Godavari - drain into the BOB. The total runoff from the peninsular rivers, which peaks during summer monsoon, amounts to about 2.95 x 10¹² m³/yr (Sengupta, et al., 2006). This huge quantity of river runoff coupled with the excess precipitation induces large changes in the salinity, which is predominantly felt along its peripheries. However, the temperature shows much less variability except during winter. Low salinity with comparatively weak winds makes the BOB a highly stratified basin. The static stability of the water column in the BOB is 3-4 times greater than that in the AS (Prasanna Kumar et al., 2002) making it increasingly difficult to mix the upper waters of the BOB. Similar to that of the AS, the western boundary of the BOB is also characterized by a strong and seasonal WBC, the northward flowing East India Coastal Current (EICC) (Shetye et al., 1993) which peaks during spring intermonsoon (March-May). Despite low
wind speeds (~4 m/s) EICC attains peak velocity of ~100 cm/s. This is in contrast to the AS where maximum current speeds are obtained when the winds are stronger during summer monsoon. This contrast is explained in terms of the role of remote forcing by the westward propagating Rossby waves and coastally trapped Kelvin waves in the establishment of this current (McCreary et al., 1996; Potemra et al., 1991; Shankar et al., 1996; Shankar et al., 2002; Vinayachandran et al., 1996; Yu et al., 1991). Studies indicate that this current is highly sheared in the vertical (Babu et al., 2003). During fall intermonsoon (October), however, this current is equator ward. Apart from the above features of the BOB, there were reports of occurrence of eddy in the BOB way back in 1957. Ramasastry and Balaramurty (1957) reported the presence of eddy off Vishakhapatnam along the western boundary of the BOB during March-April and October-November. They noticed strong cross-shore temperature gradients during these seasons. Subsequently, Rao and Sastry (1981) reported cyclonic and anti-cyclonic flows and linked the nutrient distribution with these flows. The gyral pattern of circulation in the BOB was also revealed in previous studies (Babu et al, 2003; Varkey, et al 1996). Based on satellite derived sea surface temperature (SST) data using Advanced Very High Resolution Radiometer Legeckis (1987) delineated two warm core eddies in the central and northern Bay during February 1985. Utilizing remote sensing (altimetry) and in situ observations Gopalan et al. (2000) showed strong inter-annual variability in the spatial location and intensity of eddies. Recent studies also indicated presence of eddies near the western boundary of the BOB during March-August (Babu et al., 1991, 2003; Murty et al., 1993; Prasanna Kumar et al., 2004; Sanilkumar et al., 1997; Shetye et al., 1993). The in situ measurements show that these eddies are mostly confine to the upper 500 m of the water column (eg. Babu et al 1991, Prasanna Kumar et al., 2004) and have horizontal dimension of 200 to 300 km. Though the presence of eddies in the BOB is revealed in many studies, very few of them have directly addressed their generation and the thermohaline characteristics (Babu et al., 1991; Prasanna Kumar et al., 1992). Even fewer have studied their significance on biological productivity (Prasanna Kumar et al 2004, 2007). However, the evolution and role of eddies in the BOB has not yet been fully understood. The present article attempts to understand their importance by describing the thermohaline structure from in situ measurements and trace its evolution using the satellite derived sea-level anomalies. This is followed by investigating their role in the hydrography, circulation and surface chlorophyll distribution.
2.0 Data and methods

In order to understand the characteristics of the eddies in the BOB and address their origin and evolution, a suite of data sets, both *in situ* as well as remote sensing, were utilized. *In situ* data used in this study is collected on board Indian research vessel ORV Sagar Kanya (SK) during 2003 along the western boundary of the BOB under a national program Bay of Bengal Process Study (BOBPS).

The temperature and salinity profiles were collected at stations along the western boundary from 11\(^o\)N to 20\(^o\)N during spring intermonsoon (SK191, 16-April-2003 to 6-May-2003) (Figure.1). These profiles were collected from a maximum depth of about 1000 m at one-degree latitude intervals along the western boundary using a Seabird 9/11 plus CTD (Conductivity-Temperature-Depth) system. The station interval along the northwestern part of the track was, however, more than one degree. CTD salinity was calibrated against water samples collected simultaneously by a rosette sampler fitted with 10/30-L Go-Flo bottles and analyzed with a Guildline 8400 Autosal. Using the temperature and salinity profiles, geostrophic currents were computed w.r.t. 1000m using the temperature and salinity data following Helland-Hansen method (Pond and Pickard, 1978). It is important to bear in mind that in the western boundary current regime, though the geostrophic approximation holds for the alongshore currents, the cross-shore currents may not be in geostrophic balance because of nonlinear terms. However, when sufficient along-shore pressure gradient exists the geostrophic approximation may hold good.

The spatial structure and the evolution of eddies were examined by analyzing 7-day snap-shots of the merged sea-level anomalies of Topex-Posiedon/ERS 1/2 satellites obtained from AVISO live access server (http://las.aviso.oceanobs.com) having a spatial resolution of 1/3\(^rd\) of a degree during the period October 1992 to January 2004 (Le Traon et al., 1998). This is a proven tool in studying the mesoscale features of the ocean (Le Traon and Dibarboure, 1999). Velocities from the sea-level anomalies were computed assuming the geostrophic relation

\[
2\Omega \sin(\phi) \cdot V = g \tan(i)
\]

where \(\Omega\) is the earth’s angular velocity, \(\phi\) is the latitude, \(V\) is the velocity and \(\tan(i)\) is the slope of the sea surface (Pond and Pickard, 1978). The error associated with the velocity computation amounts to \(\sim 20\%\) of the variance (Le Traon and Dibarboure, 1999), which is small, but not negligible.
In addition, we have analyzed twice daily Quik SCAT wind-stress (Large and Pond algorithm) obtained from PODAAC (JPL Publication, 2003) to compute the curl of the wind-stress which is given by

$$\text{Curl} (\tau) = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}$$

where $\tau_x$ and $\tau_y$ are eastward and northward components of wind-stress. This was used to ascertain the wind conditions during the time of eddy generation since the observation was made ~ 3 months after the eddy generation (see section 4 for more details).

The chlorophyll concentrations for the study period were downloaded from ERDDAP website http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdSHchla8day.html. Here we used 8-day chlorophyll images from Sea-viewing wide field-of-view sensor (SeaWIFS) having a spatial resolution of 9 km x 9 km at the equator.

3.0 Thermohaline structure

Thermal structure showed a warmer and thicker isothermal layer with upper waters in excess of 30°C in the south, south of 16°N (Figure 2a). Towards the north the isothermal layer was shallower and 1°C colder. Important features of the thermal structure were the doming of isotherms centered at 14°N and 18°N respectively and a depression centered at 15.5°N. The doming was more pronounced in the deeper layers (below 250 m) in the former case, while that for the latter was in the upper thermocline (upper 250 m). For example, the 10°C isotherm shoaled by 150 m at 14°N, while it was only about 30 m at 18°N. On the contrary, the 20°C isotherm shoaled maximum, by about 75 m, at 18°N and it was only less than 30 m at 14°N. In the case of the depression 20°C isotherm was deepened by 30 m. The doming centered at 14°N and 18°N depressed the ambient temperature at 100 m by 3°C and 6°C respectively, whereas the depression increased the temperature by 1°C. The salinity distribution also reflected features similar to that of temperature with higher salinity of 34 psu (practical salinity unit), in the south and low salinity (0.5 psu), fresher towards the north (Figure 2b). Consistent with thermal structure, isohalines also showed doming, which was visible only below 50 m centered at 14°N but was evident even at 20 m centered at 18°N. The doming of isohaline at 14°N and 18°N increased the salinity at 50 m by 0.4 psu and 0.8 psu respectively. The 34 psu contour was pushed down to a depth of about 75 m in the center of the depression. The density (sigma-t) distribution (Figure 2c) essentially reflected a structure similar to that of temperature and salinity.
The geostrophic velocities computed w.r.t 1000 m from the hydrographic data revealed an eastward current south of 14°N attaining a maximum velocity of 30 cm/s followed by a weak westward flow with a peak value of 20 cm/s towards the north up to 16°N (Figure 2 shading). Once again eastward and westward velocities were encountered at the southern and northern side of 18°N respectively. The westward currents, however, were much smaller (~10 cm/s) in the latter case. These opposing flows and the doming in the property distribution appear to be a part of the cyclonic circulation feature centered at 14°N and 18°N respectively along the western boundary.

Thus, the most prominent feature of the thermohaline structure was the signature of a cyclonic eddy observed in the northern part of the western Bay of Bengal (16-19°N). This is designated as the northern coastal eddy (NCE). The cyclonic eddy noted at 14°N was designated as the southern coastal eddy (SCE). An examination of the sea-level anomaly showed that the depression noticed was a part of the large anticyclonic circulation. The undulations in the thermohaline structure can be due to internal waves as well. However, we show in the next section, with the help of satellite derived sea-level anomalies, that they are eddies having a life span of a few months.

4.0. Evolution of the northern and southern coastal eddy (NCE, SCE) from sea-level anomaly

Having analyzed the thermohaline structure and identified signatures of eddies from them, it is important to attempt to understand the time evolution of these features in relation to the prevailing circulation. Towards this, seven-day snapshots of the sea-level anomaly maps along with the geostrophic flows computed from them were analyzed. Though the sea-level anomaly maps showed several circulation features, the focus of this study is on the NCE and SCE (see Figure 1 for their location) as these were the most dominant features reflected in the vertical thermohaline structure as well as the geostrophic currents computed from hydrography.

Sea-level anomaly pictures showed a small meander in the northeastward WBC, close to the coast at about 17°N, 84°E during February 2003 (Figure 3a-d), which developed into an elongated cyclonic flow centered at 16°N, 84.5°E by the later fortnight of March (Figure 3g-h.). This cyclonic eddy (NCE) moved onshore, to about 17°N, 84°E by the second fortnight of April (Figure 3k-l) and was sampled from onboard the ship during the last week of April (Figure 3m, see Figure 2 for its thermohaline structure). During this period, the eddy was characterized by a negative sea-level anomaly of about 22 cm and geostrophic velocity of about 30-40 cm/s along its periphery.
Subsequently, as the circulation weakened, the eddy moved offshore and coalesced with another cyclonic eddy by end of May, thereby increasing its strength (Figure 3p).

In the southern part of the western boundary another cyclonic circulation centered at 13.5°N and 81°E was noticed, which formed in the first week of April (Figure 3). After persisting for two weeks, it dissipated by the end of April (Figure 3). It is this cyclonic circulation (SCE) that was captured during the last week of April 2003 in the hydrographic section centered at 14°N along the western boundary.

To assess the relative importance of the mesoscale eddies and its basin-wide characteristics, the SLA data were subjected to an empirical orthogonal function (EOF) analysis (Figure 4). EOF is an efficient method of delineating a spatial and temporal signal from a long time series data over a large spatial domain such as a basin. In the present case the first spatial EOF (EOF-1) of the SLA represents a large-scale circulation pattern with a northward flowing current along the western boundary and southward current away from the boundary (Figure 4a) having an annual periodicity (Figure 4 top left panel). Note the close resemblance of first spatial EOF (EOF-1) with the circulation pattern in early February just before the formation of NCE and also the small meander at about 16°N (see Figure 3b). A similar circulation pattern, which forms a part of the seasonal subtropical gyre, was noticed by earlier authors (Varkey et al., 1996; Shetye et al., 1993). The 2nd spatial EOF (Figure 4b) represents the breakdown of basin scale pattern into smaller gyres having an annual periodicity. Interestingly, the first two EOFs explain only 39% of the variance implying that a significant part of the variability in SLA is contained in the rest of the EOFs. The 3rd to 6th EOFs (Figure 4c-f) account for 25% of the variance and depict the mesoscale characteristics of the western Bay of Bengal having intra-seasonal time scale. These mesoscale features with alternate highs and lows close to the western boundary are a manifestation of cyclonic and anticyclonic eddies in the in situ measurements. The circulation pattern derived from SLA at times resembles higher order EOFs. For example, circulation pattern during 5-March to 26-March with two highs and two lows along the western boundary is best represented by the EOF-4 (Figure 4d). However, this explains only about 6% of the total variance, while the development of the coastal eddy SCE is best represented by EOF-5 (Figure 4e). Though 4th and 5th EOFs explain less variance, their resemblance to spring-time circulation near the western boundary and SCE respectively indicate that these EOFs may be important. The relatively low variance explained by the first two EOFs (39 %), representing the large scale circulation of annual periodicity, implies that the higher EOFs (3rd to 6th) account for a significant amount of variance (25 %). This in turn points to the importance of eddies in the western
Bay of Bengal circulation. Hence we attempt to investigate eddy generation along the western boundary during the late winter-spring intermonsoon. Here we choose NCE as a case study since this was a prominent feature in the thermohaline structure and has a lifespan of a few months.

5.0 Generation of NCE

Studies on the generation of eddies along the western boundary of the Bay of Bengal are rare. Here we examine various observational evidences that can cause a meander and eddy along the western boundary of the Bay of Bengal.

The possible mechanisms that can lead to the meandering of WBC could be the instability induced by (1) topographic changes, (2) wind forcing, and (3) remote forcing, either individually or in combination.

An examination of the topography along the western boundary of the BOB from 15° to 20°N, obtained from ETOPO data having five-minute resolution, showed that the orientation of the coast turns eastward at about 16°N. Though this could induce instability, in the present case, the meander of WBC as inferred from the sea-level maps was centered at 17°N in February.

To explore the role of wind forcing, we analyzed the wind stress curl computed from QuikSCAT, which showed a region of positive curl close to the coast during early February (Figure 5a). This positive curl was most intense during the first week of February \(5 \times 10^{-7} \text{ Pa/m}\) and dissipated by the second week. Recall that it is during this period that we noticed a meander in the WBC. We also noticed a Rossby wave reaching the western boundary almost at the same time (Figure 5b). Based on this, we suggest the following mechanism, which would lead to baroclinic instability, causing a meander and generation of NCE. Earlier Prasanna Kumar et al. (1992) speculated the baroclinic instability arising from two opposing currents along the western boundary as a mechanism of eddy generation.

In the present case, the cyclonic wind stress curl near the western boundary during February induces up-ward Ekman-pumping bringing the subsurface cold waters to the surface. In the offshore region, the anticyclonic curl induces a downwelling of warm surface waters. The Rossby wave which arrives at this time augments the wind curl-induced downwelling. Thus, the upwelling near the western boundary and downwelling offshore will create a cross-shore density gradient, which is evident in the sea-level anomaly during February (Figure 5b). This cross-shore density gradient triggers
6.0 Implications of eddies along the western boundary

Examination of the thermohaline structure and the satellite sea-level anomaly in the previous sections showed that eddies are ubiquitous in the western boundary of the BOB. Thermohaline structure showed that the isopycnals can be displaced significantly within the eddy. This results in increase/decrease of temperature (in case of NCE 2003 this was 6°C) and salinity (~0.3 to 1 psu) at the locations of eddies. Evolution of these features, studied using satellite sea-level anomalies, showed that they can have a life span of 1-5 months or more. Impact of these features in the biological productivity of the BOB is examined by analyzing the satellite derived chlorophyll pigment concentrations in the following section.

6.2. Surface chlorophyll distribution.

The BOB, in general, away from the coastal boundary, was found to be a region of low chlorophyll biomass and primary production. This low productivity can be ascribed to various factors, including heavy sediment load (~1.382 x 10^9 ton yr⁻¹, Subramanian et al., 1993), lack of an intense upwelling region and reduced wind mixing owing to high stratification and low winds (Prasanna Kumar et al., 2002 & 2010). It is in this context that mesoscale eddies like the NCE can play an important role not only by initiating high production rates but also by sustaining it for prolonged periods corresponding to its lifespan (~4 months in this case). Spot measurements showed that NCE during spring sustains a high level of chlorophyll (0.6 mg m⁻³) at the subsurface level (Prasanna Kumar, et al., 2007). However, the magnitude of enhancement related to NCE and associated spatial and temporal scales are not known. The SeaWIFS data set coinciding with the time of development of NCE is presented for the year 2003 (Figure 6). Surface chlorophyll levels were found to be 0.3 mg m⁻³ along the western boundary during early February (Figure 6a), except very close to the coast, where concentrations of up to 5 mg m⁻³ can be found. The NCE was formed from a meander in the northeast-ward flowing WBC, which developed into a cyclonic eddy during the second fortnight of March (Fig.6c). Also a filament of relatively high chlorophyll concentration was found to extend

instability in the WBC as a meander and leads to the formation of NCE. When compared with the topographic effect we suggest this as a more probable mechanism as the meander was formed at 17°N and the topographic feature was at 16°N. However, this is a very qualitative approach and requires numerical experiments using models, which is beyond the scope of the present study.
from the western boundary to about 85°E, which became more distinguishable during March (Figure 6c-d). A thick patch of chlorophyll of 0.3 mg m$^{-3}$ could be seen centered about 16°N 84°E (Figure 6d-e). This indicates the offshore advection of chlorophyll from coast to open ocean. Thus, the formation of eddy from the northwest-ward flowing WBC not only enhanced the chlorophyll levels in an oligotrophic system but helped transport of chlorophyll from the western boundary to the open ocean. The chlorophyll patch closely followed the eddy and was found close to the coast during the last week of April (Figure 6e) when the ship-board observation was made. Enhanced chlorophyll values were also found near 14°N close to the location of SCE as well. This shows some resemblance of the surface chlorophyll fields to the SLA. However, it may be noted that the surface enhancement of the chlorophyll from the satellite data is very much weaker compared to the subsurface enhancement by eddies reported by Prasanna Kumar et al. (2007). To understand the basin-wide structure and variability of the remotely sensed chlorophyll we conducted an EOF analysis of surface chlorophyll anomalies.

The first spatial EOF (46% of variance) of chlorophyll (Figure 7a) showed negative values along the western boundary, the magnitude of which decreased towards the open ocean region. This represents the onshore-offshore reversal in chlorophyll concentration (Figure 7b), with maximum values along the coast (open ocean) during fall intermonsoon (winter monsoon). The second spatial EOF, which showed a dipole pattern along the western boundary with positive values in the north and negative values in the south (Figure 7b), explained 14% of the total variance. The temporal function showed peak values for this mode during summer and winter. The 2$^{nd}$ spatial EOF of chlorophyll showed some correspondence with that of SLA. For example, the high SLA in the southwestern BOB correlates well with the negative chlorophyll anomalies at this location. The 3$^{rd}$ and especially the 4$^{th}$ spatial EOFs (Figure 7c-d) of chlorophyll, which together accounts for 8% of the total variance, also showed some correspondence with that of SLA in the southwestern BOB. Their temporal functions showed intra-seasonal time scales. Subsequent EOFs of chlorophyll, however, did not show any similarities with that of SLA. From the above discussion it follows that spatial dependence of surface chlorophyll and SLA are prominent only in the southwestern BOB during winter and during spring intermonsoon. However, no such clear correspondence between chlorophyll concentration and SLA was found in the northwestern BOB. We examine the reasons for it.

Observational studies have indicated eddy induced chlorophyll enhancement at the subsurface levels in the BOB, while no such clear-cut enhancement was discernible at the surface chlorophyll
concentrations (Prasanna Kumar, et al., 2004, 2007, 2010). The reason for this has been attributed to the stability of the water column which restricts the upwelling associated with these eddies to the subsurface levels. However, when the stratification is weak these mesoscale eddies are capable of upwelling the nutrients to the upper ocean and fertilizing the surface layers also. The observed weak enhancement of the surface chlorophyll from SeaWiFS (Figure .6) is the response of NCE, which was captured in the in situ measurements by Prasanna Kumar et al. (2007, 2010) as a strong subsurface enhancement of nitrate as well as chlorophyll during spring intermonsoon. Thus, the evolution of surface chlorophyll seen in the SeaWiFS data during spring intermonsoon 2003 is a consequence of NCE.

7.0 Summary and conclusions

The study brings out some interesting physical and biological features of meso-scale eddy in the BOB using both in situ measurements as well as satellite derived remote sensing data. EOF analysis of SLA reveal that the seasonal circulation (1st and 2nd EOFs) accounted for 39% of the total variance while the meso-scale eddies contributed to 25% of the variance (3rd to 6th EOF). In contrast, spatial EOFs of chlorophyll did not show dominance of meso-scale variability. The discord between the spatial EOF of SLA and surface chlorophyll points to an important aspect of the BOB. Though meso-scale eddies dominate the BOB circulation and enhance the subsurface chlorophyll, they are unable to influence the surface chlorophyll. This is because of the presence of strong stratification that inhibits the upwelling of subsurface nutrients, thereby preventing surface chlorophyll enhancement. This stratification exists especially in the northern BOB for a major part of the year. However, when the stratification is weak as in the case of spring intermonsoon 2003, the eddy is capable of enhancing the surface chlorophyll. The study documents the origin of eddies along the western boundary during spring intermonsoon 2003. The generating mechanism of eddy is the cross-shore density gradient under the influence of cyclonic (anti-cyclonic) wind stress curl and upwelling (down welling) near (away from) the western boundary. The down welling away from the western boundary is augmented by the Rossby wave, which arrives at this time from the eastern BoB. This cross-shore density gradient triggers instability in the WBC as a meander and leads to the formation of NCE.

As a concluding remark we would like to state that since the BOB circulation is dominated by mesoscale eddies, higher EOFs, though they account for less than 10% of the variance, may be important in understanding and prediction of BOB circulation. More in situ measurement as well as
numerical modeling studies are needed to quantitatively determine the generation mechanisms of mesoscale eddies and its influence on basin-wide enhancement of chlorophyll.

Acknowledgements: Authors are thankful to P.M.Muraleedharan, Late G.Nampoothiri and Jayu Narvekar for helping data collection. This work was supported by Ministry of earth sciences (MoES), New Delhi under the programme Bay of Bengal Process studies (BOBPS). We acknowledge Director, NIO, Goa and Council of Scientific and Industrial Research (CSIR), New Delhi for all the support and encouragement. M. Nuncio acknowledges Director NCAOR for his keen interest and support. The chlorophyll images and data used in this study were acquired from NOAA’s ERDDAp web site http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdSHchla8day.html. Sea level anomalies were downloaded from AVISO live access server (http://las.aviso.oceanobs.com). Nuncio. M was supported by the Senior Research Fellowship of the CSIR, India when the work was carried out. This is NIO contribution number xxxxx.

References


Bruce, J.G.,1979. Eddies off the Somali Coast during the southwest monsoon, J. Geophys. Res. 84C, 7742-7748.


Schott, F., 1983. Monsoon response of the Somali Current and associated upwelling, Prog. Oceanogr. 12, 357-381.


Figure captions

**Figure 1.** Map showing the monthly mean climatology (October 1992 to January 2004) of geostrophic currents in the Bay of Bengal during April. Shaded is the scalar velocity derived from merged anomalies of sea-level from Topex/Poseidon ERS1/2 satellites overlaid with vectors. The yellow and red band close to the western boundary indicates the northward flowing WBC during spring intermonsoon. Filled circle within the hollow circle along the western boundary indicates the location of CTD stations occupied under Bay of Bengal Process Studies (BOBPS) programme (see text for details). Ellipses with dash-line is the region of NCE (northern coastal eddy) and SCE (southern coastal eddy) as seen from the in situ data.

**Figure 2** Vertical sections of (a) temperature (°C), (b) salinity (psu), and (c) sigma-t (kg/m3) overlaid on the geostrophic velocity (cm/s) w.r.t 1000 m along the western boundary in the BOB during spring intermonsoon (April-May)2003. Filled inverted triangles indicate the position of CTD stations.

**Figure 3** 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during February-May 2003. The white encircled region shows NCE (thick line) and SCE (broken) as they evolve during spring intermonsoon 2003. The closest date of SLA matching with the hydrographic observation is 30-April-2003 for NCE and 7-May 2003 for SCE.

**Figure 4.** EOs of the SLA. Line graph in the right most panel indicates the temporal function. Black/Red lines are the temporal function for the left/middle panels in each row.

**Figure 5** (a) Curl of wind stress (x 10⁻⁷ Pa/m) derived from QuikSCAT during 1-14 February 2003 and (b) zonally de-meaned merged SLA of Topex/Poseidon-ERS 1/2 series of satellites along 17°N (positive values are contoured) during June 2002 to June 2003. Bold slanting line indicates the Rossby wave propagation during respective years. Broken line shows the cross-shore SLA gradient which is a result of upwelling along the western boundary and downwelling offshore.

**Figure 6.** Evolution of satellite derived surface chlorophyll during Feb-April 2003 in the western Bay of Bengal. The ovals indicate approximate positions of the NCE. Plotted values are averaged over 1/3 of a degree in space and 16 days in time.

**Figure 7.** Same as that of Figure 4 but for chlorophyll concentrations.
Fig. 1. Map showing the monthly mean climatology (October 1992 to January 2004) of geostrophic currents in the Bay of Bengal during April. Shaded is the scalar velocity derived from merged anomalies of sea-level from Topex/Poseidon ERS1/2 satellites overlaid with vectors. The yellow and red band close to the western boundary indicates the northward flowing WBC during spring intermonsoon. Filled circle within the hollow circle along the western boundary indicates the location of CTD stations occupied under Bay of Bengal Process Studies (BOBPS) programme (see text for details). Ellipses with dash-line is the region of NCE (northern coastal eddy) and SCE (southern coastal eddy) as seen from the in situ data.
Figure 2. Vertical sections of (a) temperature (°C), (b) salinity (psu), and (c) sigma-t (kg/m³) overlayed on the geostrophic velocity (cm/s) w.r.t 1000 m along the western boundary in the BOB during spring intermonsoon (April-May) 2003. Filled inverted triangles indicate the position of CTD stations.
Figure 3 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during February-May 2003. The white encircled region shows NCE (thick line) and SCE (broken) as they evolve during spring intermonsoons 2003. The closest date of SLA matching with the hydrographic observation is 30-April-2003 for NCE and 7-May 2003 for SCE.
Correct "righ" to "right"
Figure 5 (a) Curl of wind stress (x $10^{-7}$ Pa/m) derived from QuikSCAT during 1-14 February 2003 and (b) zonally de-meaned merged SLA of Topex/Poseidon-ERS 1/2 series of satellites along 17°N (positive values are contoured) during June 2002 to June 2003. Bold slanting line indicates the Rossby wave propagation during respective years. Broken line shows the cross-shore SLA gradient which is a result of upwelling along the western boundary and downwelling offshore.
Correct “averegad” to “averaged”

Figure 6. Evolution of satellite derived surface chlorophyll during Feb-April 2003 in the western Bay of Bengal. The ovals indicate approximate positions of the NCE. Plotted values are averaged over 1/3 of a degree in space and 16 days in time.
Figure 7. EOFs of surface chlorophyll concentrations and their temporal functions. Black lines represent the temporal function for the left most EOF in each row.