

Chapter 7 – Summary and Conclusions

Eddies in the Bay of Bengal (BOB) have been studied for their thermohaline characteristics, formation and evolution, role in the hydrography, circulation and in the distribution of nutrients and chlorophyll using a suite of data set both *in situ* as well as remote sensing. The *in situ* data includes temperature and salinity profiles measured using CTD at 1-degree from 7°N to 20°N along the central BOB (88°E) transect and from 11°N to 20°N along the western BOB, in the upper 1000 m collected for 3 seasons - summer monsoon (10-July-2001 to 1-August-2001), fall intermonsoon (17-September-2002 to 11-October-2002) and spring intermonsoon (16-April-2003 to 6-May-2003). The nutrient and chlorophyll profiles were obtained from BOBPS CD-ROM (Indian Oceanographic Data Centre product, National Institute of Oceanography, Goa, March 2007). Remote sensing data includes the 7-day snap-shot of merged sea-level anomaly of Topex/Poseidon ERS1/2 satellites at 1/3rd of a degree resolution and twice-daily QuickSCAT wind-stress at 1/4th of a degree resolution, both from 2001 to 2003.

The thermohaline structure along the western boundary was dominated by the signature of eddies manifested by the doming (cyclonic) and depressions (anticyclonic) during all the 3 seasons. Two eddies along the western boundary, namely the northern coastal eddy (NCE) and the southern coastal eddy (SCE), were identified from the thermohaline structure and confirmed using satellite derived sea-level anomaly (SLA) maps. Out of these two, NCE was found in all the 3 seasons and all the 3 years analyzed (2001 to 2003). Hence NCE appeared as a robust feature occurring seasonally every year within

the latitudinal belt $16^{\circ} - 19^{\circ}\text{N}$ and had a span of about 5 months. The NCE cooled the ambient temperature of upper-thermocline, which was maximum during spring intermonsoon by about 6°C and increased the near-surface salinity by 0.8 psu. However, SCE was found only during spring and fall intermonsoons and was located at 14°N and 12°N respectively. The SCE during fall intermonsoon was advected from the Sri Lankan Dome region, while during spring intermonsoon it was formed locally. The SCE cooled the upper thermocline by 3°C and increased the ambient salinity by 0.5 psu. Unlike the NCE, SEC was a transient feature which lasted only for a month. Since NCE was a robust feature which appeared yearly during spring intermonsoon, its evolution and generating mechanism was explored further.

Based on the 7-day SLA maps of 2001 and 2003, it was found that the NCE was formed during the western boundary current (WBC) regime. The WBC starts flowing northward along the western boundary of BOB during the first week of February. A meander centered at 17°N appeared in the WBC during this period and develops into a cyclonic eddy, NCE, in the last week of March. The NCE had a complex life cycle undergoing offshore-onshore movements, southwestward translation, coalescence and splitting before it finally gets dissipated. All of this occurred within a span of approximately 5 months. From the above, it appeared that the trigger for the generation of the cyclonic eddy NCE could be the instability of the WBC. The cross-shore density gradient accompanied by vertical shear in the horizontal velocity field is a necessary condition for baroclinic instability [Pedlosky, 1979]. The possible mechanisms that can lead to this cross-shore density gradient could be (1) topographic changes, (2) wind forcing, and (3) remote

forcing, either individually or in combination. A careful examination of the bathymetry and the location of meander in the WBC rules out the possibility of topographic changes as a trigger for the instability of WBC. Based on the analysis of curl of the wind-stress as well as from the time-longitude plot of zonally de-meanded SLA indicated that both wind forcing as well as remote forcing by Rossby waves plays a key role in generating NCE.

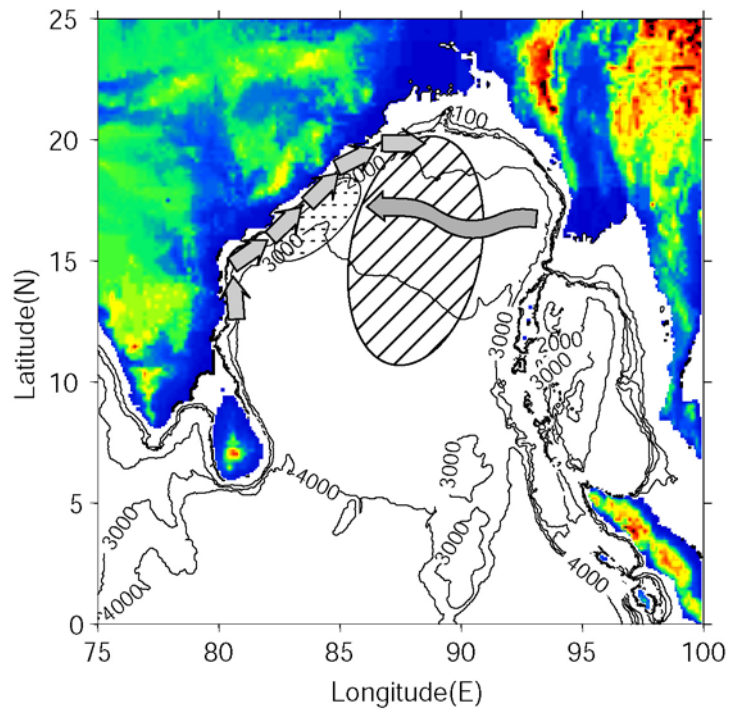


Figure 7.1. Schematic showing the mechanism of generation of northern coastal eddy (NCE) under the influence of wind-stress curl and the Rossby wave. Smaller (bigger) ellipse filled with dots (slanting lines) represents the positive (negative) wind-stress curl. The arrows along the western boundary represents the WBC, while the zonal band with the arrow-head indicates the Rossby wave propagation. Labeled contours indicate bathymetry in meters.

Large-scale wind-stress curl was negative in the offshore region and showed a positive curl close to the western boundary where the meander in the WBC was noticed. In response to this wind forcing, large-scale convergence and downwelling of warm surface waters will occur under the negative wind-stress curl, while divergence and upwelling of subsurface waters close to the coast under the positive wind-stress curl. In addition, the

westward propagating Rossby wave during this period augments the basin-wide negative wind-stress curl in deepening the pycnocline. Thus, the negative wind-stress curl and Rossby wave act in union to deepen the pycnocline in the offshore region, while the positive wind-stress curl shallows the pycnocline close to the coast. This in turn will generate strong cross-shore density gradient necessary for the baroclinic instability that leads to the generation of NCE. This is schematically represented in Figure 7.1.

The thermohaline structure along the central BOB showed the signature of 10 eddies, both cyclonic as well as anticyclonic, which were confirmed based on the SLA maps. The cyclonic eddies cooled the ambient temperature which ranged from 1 to 3°C, and increased the salinity which ranged from 0.2 to 0.4 psu. The anticyclonic eddies warmed the ambient temperature which ranged from 1 to 2°C, while the decrease in salinity was about 0.2 psu. Unlike their coastal counter part, the eddies seen in the central BOB were not generated out of a process such as meandering of strong current but out of a variety of processes that has strong spatio-temporal dependence. Most of these eddies were formed in the eastern BOB and was advected westward into the central region and beyond (Figure 7.2). Eddies CES1 and CEF1, however, were formed in the western side of the central transect and were moved eastward during summer and fall intermonsoon under the influence of the eastward flowing summer monsoon current.

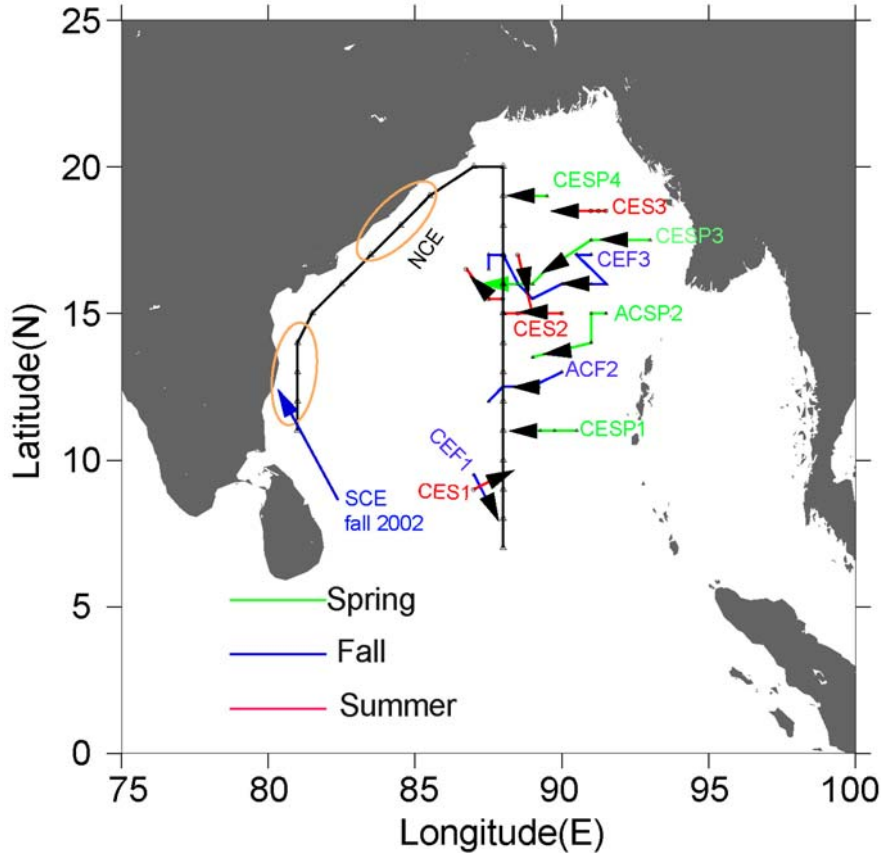


Figure 7.2. Movement of eddies in the Bay of Bengal. All the eddies encountered in the central BOB were formed east of 88°E. Whereas eddies were found to be locally formed along the western boundary, except the SCE found during fall intermonsoon, which was advected from north-east of Sri Lanka. Ellipses along the western boundary represents the region where NCE and SCE were encountered.

A common feature that was observed during the formation of eddies described above was the horizontal SLA gradient which generates the vertical shear, a necessary condition for the baroclinic instability. The horizontal SLA gradient was generated by a combination of processes. In the case of CES1 and CEF1 which forms in the vicinity of Sri Lankan dome during summer and fall intermonsoon respectively, the horizontal gradient was generated by the Sri Lankan dome (negative SLA) and the westward propagating anticyclonic vortices (positive SLA). The formation of cyclonic eddy CES2 in the early summer was due to the SLA gradient generated by a negative SLA adjacent to positive SLA driven by a large-scale anticyclonic circulation. The eddy was found to intensify

when the curl of the wind-stress changed from negative to positive in the month of May. A similar situation was observed during the generation of CES3, the only exception was the positive SLA towards east which was the manifestation of coastally trapped Kelvin wave. The anticyclonic eddy ACF2 formed during summer (July) when there was a negative wind-stress curl overlying a positive SLA. Towards the west of this, there was a positive SLA and this created the horizontal density gradient necessary for the generation of ACF2. The condition during the formation of cyclonic eddy CEF3 during fall intermonsoon was similar to that of cyclonic eddy CES3 during summer (Figure 7.2), except that the wind-stress curl was negative at the location of CEF3.

The condition that existed during the generation spring time eddies CESP1, ACSP2, CESP3 and CESP4 was the following. The large-scale wind-stress over BOB was uniform and negative during April and underlying the wind field was the westward propagating upwelling Rossby wave manifested by the low SLA. The upwelling Rossby wave imparts a cyclonic motion to the water column whereas the negative wind-stress curl imparts an anticyclonic motion, and hence opposing each other. In such situation it is difficult to explain the development of horizontal gradient in SLA.

Thus, the formation of eddies observed in the central BOB takes place due to a combination of variety of processes that were specific to the space and season, all of which lead to the generation of horizontal gradient in the SLA. This has been represented schematically in Figure 7.3.



From the above discussion it is clear that eddies are ubiquitous in the BOB and present during all the seasons studied. Since eddies are ubiquitous, it natural to expect that these features would influence the hydrography and circulation of BOB. The estimation of heat and salt content in the upper 150 m of the water column showed the dominant effect of eddies over the seasonal variability, which amounted to $200-300 \times 10^{12}$ J/m and 5×10^6 Kg/m of heat and salt content respectively. These eddy-induced changes were more pronounced in the heat content rather than salt content. The reason for this lies in the

characteristics of the BOB which has a very strong halocline in a very thin upper layer. The cyclonic eddies are unable to break the strong stratification associated with this halocline. Hence, eddy-pumping cannot alter the salinity structure as dramatically as that of temperature. The volume transport computation showed that the contribution from wind-driven Ekman transport was far too small compared to geostrophic transport. The geostrophic volume transport in the top 150 m was dominated by eddies, which varied from 2 to 8 Sv. The heat and salt transport also showed maximum variability in the region of eddies. The eddy-induced heat transport varied from 100 to 650×10^{12} J/m/day, while the salt transport varied from 20 to 200×10^6 Kg/m/day. Thus, in the BOB eddies play an important role in the transport and exchange of heat and salt.

Eddies not only influenced the thermohaline characteristics of the BOB but also showed its role in altering the water column nutrient as well as chlorophyll pigment concentrations. Eddy-pumping of nutrient was instrumental in enhancing the chlorophyll concentrations by 2 to 6 times the ambient values in the BOB. Thus, eddies plays a vital role in enhancing the biological productivity of BOB which was traditionally known for its low biological productivity. This may in part resolve the paradox of comparable rates of annual organic carbon flux to the deeper waters in the high productive Arabian Sea and low productive BOB.

Epilogue

The attempt in this thesis was to study the characteristics and role of eddies in the Bay of Bengal. A suite of data sets has been used to accomplish this objective. To this end the evolution and the generating mechanisms were studied first followed by their role in the hydrography, circulation and in the distribution of nutrients and chlorophyll. The study brings out the role eddy in mediating physical, chemical and biological changes. However some questions remain. The study has not been able to answer all the possible mechanisms of generation of eddy in the Bay of Bengal. The process of instabilities has to be tackled in a more quantitative fashion. A first step towards that will be eddy-specific observations to understand the processes involved so that it could be modelled. The next step will be the use of eddy resolving ocean circulation models coupled with good ecosystem dynamics. There is enough scope to explore the mechanisms of geophysical turbulence and associated energy cascade. Recent studies show that this is true even for baroclinic oceans. But the bottle neck is the length at which this cascade is arrested. For barotropic ocean this happens at the Rhines length. However there is no perfect analogy of this for a baroclinic ocean.

It is satisfying that the thesis has found answers to some of the questions posed but at the same time opens door to new avenues. Attempting such questions would add to the understanding of the underlying dynamics of the Bay of Bengal and kindle further excitement.

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