Journal of Marine Research, 58, 721–734, 2000

Detection of Bay of Bengal eddies from TOPEX and *in situ* observations

by A. K. S. Gopalan[1], V. V. Gopala Krishna[2], M. M. Ali[1] and Rashmi Sharma[1]

ABSTRACT

Oceanic eddies have warm or cold temperatures and high or low sea surface height (SSH) at the center depending upon the direction of rotation. However, since the Bay of Bengal waters are highly stratified, sea surface temperature (SST) gradients may not be detectable even though the subsurface temperature sections and the SSH show prominent eddy signatures. In this investigation, SSH observations from TOPEX altimeter data and the expendable bathy thermograph (XBT) temperature sections along the Madras–Andamans track have been analyzed to study the Bay of Bengal eddies. Several cyclonic and anticyclonic eddies are identified from the TOPEX altimeter observations. These eddies located along the ship's tracks have significant variations in amplitudes and show good qualitative agreement with the subsurface isotherm features (troughs and ridges) of the ***in situ*** temperature profiles. However, this agreement does not extend to the surface and hence SST patterns are not good indicators of eddy positions in the Bay of Bengal where the waters are highly stratified. Therefore, a better approach to the study of eddies in regions like the Bay of Bengal is to use SSH observations. Due to the extensive spatial coverage of remote sensing observations, the exact position and shape of the eddies can be characterized from altimeter-derived SSH observations which is not possible using the limited ***in situ*** profiles. Interannual variations in both the positions and intensities of eddies are observed during the study period.

1. Introduction

The Bay of Bengal, influenced by the seasonal reversing monsoon, transient cyclonic storms and freshwater discharges, is unique compared to many other oceanic basins. This region is land locked on three sides undergoing intense air-sea interaction processes. It is also dominated by upwelling-derived plumes, wedges of cold waters, and oceanic eddies. These features are forced by meteorological conditions of winter and summer monsoonal winds and positioned by coastal topography and coastal features. Major manifestations of the oceanic mesoscale features are eddies. Oceanic eddies are circulating water bodies which are either cyclonic (cold water and low sea level at the center) or anticyclonic (warm water and elevated sea level at the center). They are generally formed either by separation of a meander or due to the force exerted by the wind stress curl and maintained by the balance between the pressure gradient, centrifugal and Coriolis forces. In the case of

1. Space Applications Centre, SAC P.O., Ahmedabad 380 053, India ***email: mmali73@hotmail.com***
2. National Institute of Oceanography, Goa, India.

anticyclonic/cyclonic eddies, water converges/diverges at the center of the eddy during the formation process resulting in downward/upward motion of water. Hence vertical thermal sections show trough/ridge in the isothermal patterns.

Information on eddies is required in many oceanic and atmospheric studies like acoustic propagation, optimum ship route planning, fishery, delineating good/bad monsoon years (Dube *et al.,* 1990), heat transport, etc. Eddies can be studied in detail using remote sensors in the microwave region like the radar altimeter, synthetic aperture radar, and those operating in infrared and visible regions. Scatterometer winds also can be used through ocean circulation models. Ali (1990) estimated the movement of the Socotra eddy using INSAT-IB thermal infrared digital data. While infrared and visible sensors have the limitation of the cloud cover, microwave observations like those from altimeter data can be used to detect eddies (Ali and Sharma, 1994) and to study eddy features such as their rotational velocities, dimensions etc. in all weather conditions (Pal and Ali, 1992). Using *in situ* observations, Babu *et al.* (1991) have reported the presence of a subsurface cyclonic eddy in the northern bay, while Sanil Kumar *et al.* (1997) have reported the presence of eddies in association with a poleward-flowing western boundary current. Nevertheless, formation of these eddies in the Bay of Bengal is not supported with any other independent data set. Besides, the rich eddy structure in the Bay of Bengal has not been rigorously examined.

Altimeter-derived SSH seems to hold the promise of studying this phenomenon in detail. Bruce *et al.* (1998) have studied the eddy features in the Arabian Sea using airborne expendable bathythermograph data, TOPEX observations and model results. Under the influence of the freshwater discharge, Bay of Bengal waters are relatively more stratified and the high or low SST at the center is not easily discernible. However, the TOPEX-derived SSH observations clearly show the changes in elevation indicating the presence of eddies. The atlas of the ‘‘North Indian Ocean eddies’’ prepared using the TOPEX altimeter observations shows several eddies in the Bay of Bengal almost throughout the year (Ali *et al.,* 1998). In this article both *in situ* temperature sections and altimeter observations have been used to detect eddies in the Bay of Bengal and also to study their interannual variation.

2. Data

The analysis was carried out with TOPEX altimeter-derived SSH observations during 1993 to 1996 over the Bay of Bengal spanning 5–25N and 75–100E. Geophysical data records of TOPEX altimeter data alone were used to get the SSHs. All the environmental and geophysical corrections were applied to the altimeter observations. The details of the corrections applied and the processing of altimeter data were given by Ali *et al.* (1998). These SSHs were compared with the 10 tide gauge measurements in the Indian Ocean and the root mean square (RMS) deviation between the two observations was found to be 4.7 cm. However, only one tide gauge data of Pulau (6.43N; 99.77E) was available to the authors over the study area. Comparison of this station data with the nearby TOPEX observations (6.0N; 99.0E) gave an RMS error of 4.62 cm with a correlation coefficient of 0.89. The TOPEX observations were found to be more accurate because of the dual frequency altimeter and onboard radiometer for ionospheric and water vapor corrections, respectively. To retain mesoscale variabilities and to remove very low/high spatial frequencies, a band-pass filter with cut-off wave length of less than 1° and greater than 8° was applied. The values were binned into 0.5° × 0.5° latitude × longitude boxes by inverse square interpolation with a search radius of 2 degrees. The processed TOPEX altimeter data have a spatial resolution of 1° along the track and a maximum separation of about 3° across the track at the equator.

Under the Indian TOGA expendable bathythermograph (XBT) program, upper layer thermal data were collected by the scientific observers using ships of opportunity. XBTs were operated at 50 km spatial intervals close to the Madras coast and at 100 km intervals in the interior at nearly bi-monthly temporal intervals. The distance of about 1300 km (Madras—Andaman Islands) was covered in about two to three days and typically 15–18 XBTs were deployed in each survey. Processed temperature data were used to prepare snap-shot vertical sections. Since most of the XBT surveys were of two to three days duration, the corresponding altimeter data were chosen in such a way that the periods of XBT surveys were centered over ten days (repeat cycle of TOPEX). Although several surveys were conducted along Madras–Andamans during 1993–1996, only August and October data were selected for the present investigation because these two months were covered in all the four years. Further, on two occasions (during October 1993 and October 1995), conductivity temperature and depth (CTD) data were collected along this section.

Because all the sections do not have coincident *in situ* salinity profiles, an analysis was carried out to investigate the impact of salinity effects on the variations of dynamic heights. For this purpose, using the available CTD data dynamic heights w.r.t. 500 db were computed for Oct 1993 and Oct 1995 months (i) by using the measured salinity values and (ii) by keeping a constant salinity of 35.0. Dynamic heights computed are presented in Figure 1a. During 17–21 October 1993 (Fig. 1a), the deviations between the dynamic heights computed with actual and constant salinity values were minimal. However, during 4–8 October 1995 (Fig. 1b) almost a constant bias of about 0.05 dynamic meters was noticed. Thus, the overall patterns of dynamic height remained the same, indicating that salinity does not play a very significant role in studying the spatial variations, at least, in the regions where the *in situ* and satellite observations have been compared. Besides, the vertical distribution of temperature, salinity and density (dynamic height depends upon density) for these two months also indicates that density is mainly controlled by temperature rather than salinity in the central Bay of Bengal. This also confirms that the role played by salinity in the dynamic height (through density) is not very significant, provided the aim of the study is to infer the relative spatial variations.

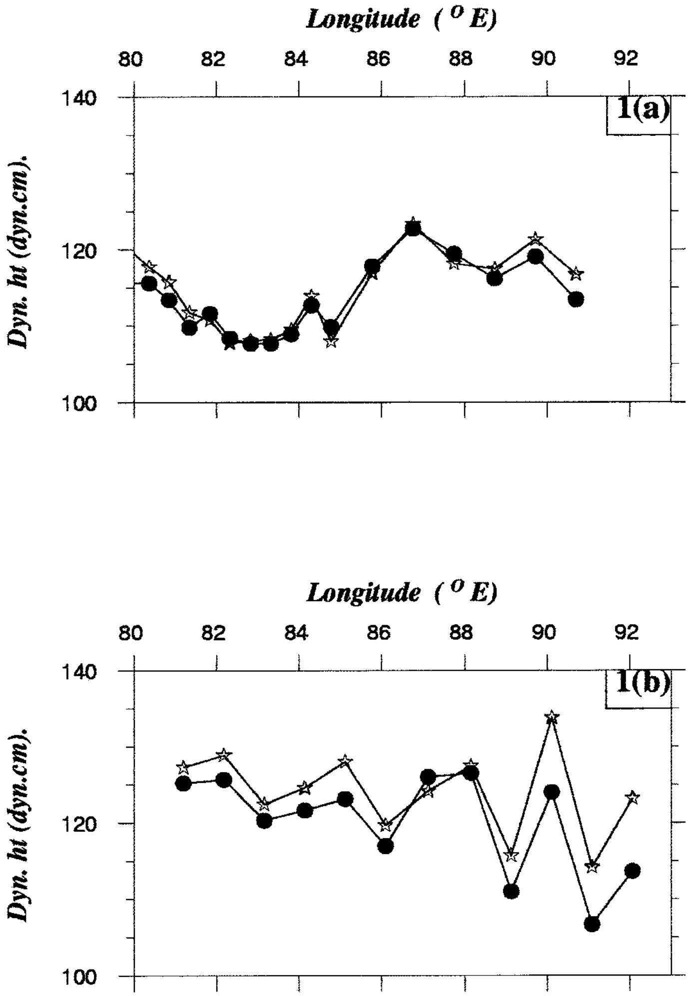

Figure 1. Dynamic height computed using the measured salinity (*) and by using a constant salinity of 35.00, during (a) 19–21 October 1993 and (b) 4–8 October 1995.

3. Results and discussion

a. Detection of eddies

SSH observations derived from TOPEX altimeter observations during August 11–20, 1993, August 5–14, 1994, August 22–31, 1995 and August 14–23, 1996 over the Bay of Bengal are shown in Figure 2. The straight lines in these figures represent the ship's tracks. The corresponding *in situ* temperature sections collected along these tracks during August 14–16, 1993, August 9–11, 1994, August 26–28, 1995 and August 17–19, 1996 are shown in Figure 3. During August 11–20, 1993 a strong anticyclonic eddy with an elevation of 15 cm centered around 14N and 83E is observed. Adjoining this eddy, an elongated

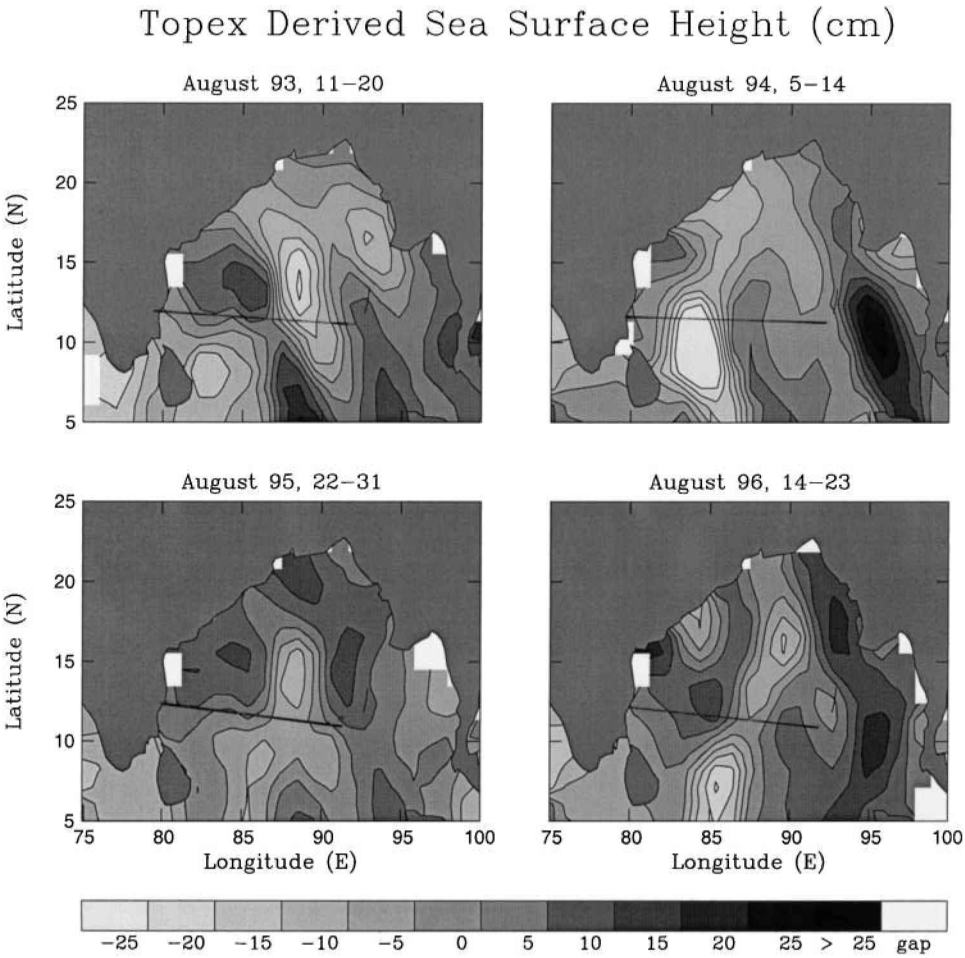

Figure 2. Sea surface height (in cm) derived from TOPEX altimeter observations during 11–20 August 1993, 5–14 August 1994, 22–31 August 1995 and 14–23 August 1996. The straight lines represent the ship's tracks.

cyclonic eddy with a depression of about 25 cm is also present. The *in situ* temperature sections during 14–16 August 1993 along the Madras–Andamans track show two troughs and one ridge (Fig. 3). The first trough observed between 81 to 85E is due to the presence of the anticyclonic eddy while the ridge is due to the cyclonic eddy located from altimeter observations (Fig. 2). The second trough in the thermal sections during August 1993 is due to the elevation observed in the TOPEX observations at the periphery of the elongated anticyclonic eddy.

Eddies identified from the subsurface temperature sections are not discernible in the surface temperatures due to stratification. Other than these eddies identified along the ship's track, two more cyclonic eddies, one in the northeast and other at south of Sri Lanka

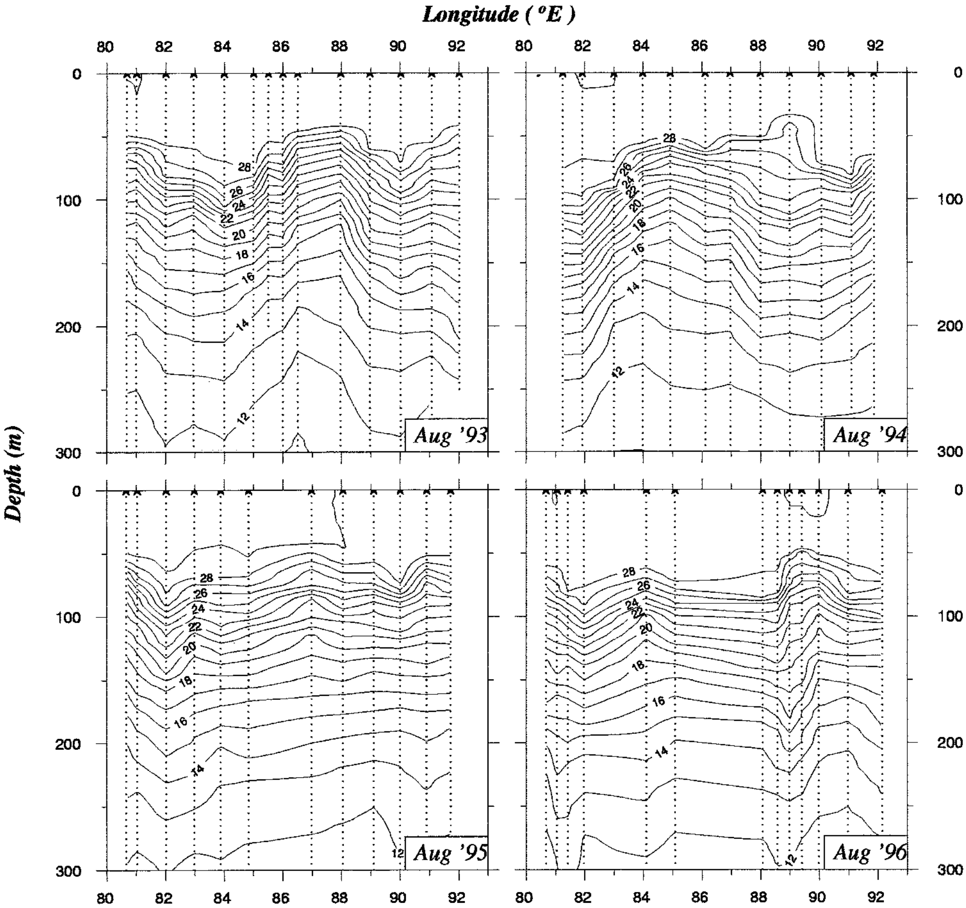

Figure 3. Snapshots of thermal structures (<300 m) along the Madras–Andaman XBT section during 14–16 August 1993, 9–11 August 1994, 26–28 August 1995 and 17–19 August 1996.

coast are clearly noticeable from the TOPEX observations. Thus, due to the extensive coverage, a clear picture of the eddies can be obtained from the altimeter observations whereas temperature sections could capture only troughs and ridges representing a cross-sectional portion of the eddy. Secondly, detection of eddies in the entire basin is also possible from the TOPEX data. The troughs and ridges noticed in the temperature profiles certainly would have been more pronounced if the section had passed through the centers of the eddies.

During August 5–14, 1994, a strong elongated cyclonic eddy with a depression of 25 cm is noticed northeast of Sri Lanka. The ship's track passed over the northern periphery of this eddy and the broad ridge noticed from 84–86E in the corresponding thermal section is due to this eddy. A thermal section centered around 89E depicts complicated patterns. Although this section exhibits deep rooted trough structure between 87 and 92E in the subsurface, a small ridge is present in the upper thermocline (0–75 m). Earlier, Gopala Krishna *et al.* (1996) reported such a stretching of isothermal pattern (thermocline spreading) in the same longitudinal belt with CTD data during previous southwest monsoon season (July 1993 and August 1991). They identified the presence of a strong northward flowing Indian monsoon current advecting high salinity waters of Arabian Sea origin in to the bay. They further noticed that sea surface dynamic height (w.r.t. 1000 db) is also high at the region of thermocline spreading indicating the dominant influence of the depressed thermocline below 75 m on the computed sea surface dynamic height. TOPEX SSH (+ve values) around 88–89E during 5–14 August 1994 (Fig. 2) reflect the dominance of subsurface thermal structure over the surface layers. Another strong anticyclonic eddy is noticed east of 93E in the SSH observations where XBT observations are not available.

No prominent eddies were present during August 1995 unlike the other years. The well-defined trough at 82E and the weak ridge centered at 87E in the thermal sections are well reflected in the TOPEX observations as elevation (10 cm) and depression (5 cm), respectively. Such small scale features in the thermal section are well reflected in the TOPEX derived SSH. During August 1996, isothermal patterns, in general, show two troughs at 84E and 89E and two ridges at 87E and 90E. The ship's track passed through the northern periphery of the elongated cyclonic eddy with a depression of about 25 cm located east of Sri Lanka. The ridge at 87E observed in the temperature section is due to this eddy. The other troughs and ridge in the temperature sections are reflected as the rise and fall of SSH noticed in Figure 2.

The number of eddies in October (Fig. 4) is relatively less compared to August. Three prominent cyclonic eddies, one in 1994 and two in 1996, are observed in agreement with the *in situ* temperature profiles (Fig. 5). The SSH changes from −10 cm to 10 cm which is clearly reflected in the thermal section with a ridge at 82E followed by a broad trough. Thermal sections of October 1995 also exhibit the possible presence of an undercurrent at 87E as observed in August 1994. The positive SSH noticed at this location confirms the dominance of subsurface thermal features over surface structure.

In the present study, *in situ* observations are for two to three days whereas the satellite observations are for over 10 days, the repeat cycle of the TOPEX. Although *in situ* observations are centered around the satellite 10-day repeat period, a maximum time difference of 6 days could be present between the actual *in situ* measurement and the satellite observation. For example, during August 1994, the *in situ* observations are from the 14th to 16th, while the TOPEX observations are from the 11th to 20th. For the 14th of August 1994 *in situ* observation, the corresponding altimeter pass could be on the 20th, which results in a maximum time lag of 6 days. The locational inaccuracy of the oceanographic features arising out of the difference in periods of *in situ* and TOPEX observations is examined for both months for all the years of the study period. However, the features during August 1994 alone are shown in Figure 6 for four 10-day periods (1–10, 4–13, 7–16 and 9–18). The cyclonic eddy east of Sri Lanka observed during the 1st–10th is slightly weakened by that observed during the 9th–18th, while the anticyclonic eddy east of

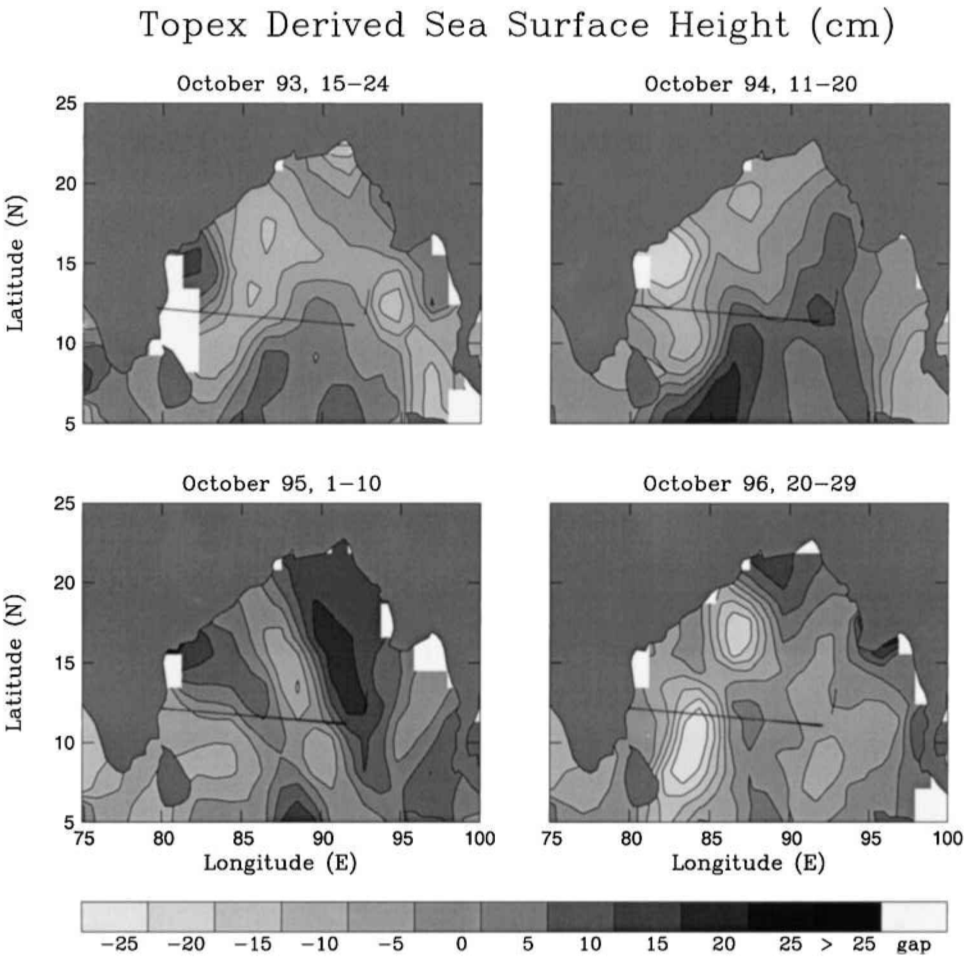

Figure 4. Sea surface height (in cm) derived from TOPEX altimeter observations during 15–24 October 1993, 11–20 October 1994, 1–10 October 1995 and 20–19 October 1996. The straight lines represent the ship's tracks.

Andaman Islands has intensified. However, the positions of these eddies have not changed significantly. Even though slight variations in the oceanographic features are evident, overall patterns remain unchanged. Similar results are obtained for other periods/years implying that the 10-day average SSH observations and two to three day *in situ* temperature profiles represent the same oceanographic features within the range of the movement of the eddies in the study region.

To study the propagation of these eddies, *x-t* plots were generated at each latitudes starting from 0 to 16N. Below 6N the positive and negative bands of SSH are not well separated due to the interference of eastward-propagating Kelvin waves. From north of 6N

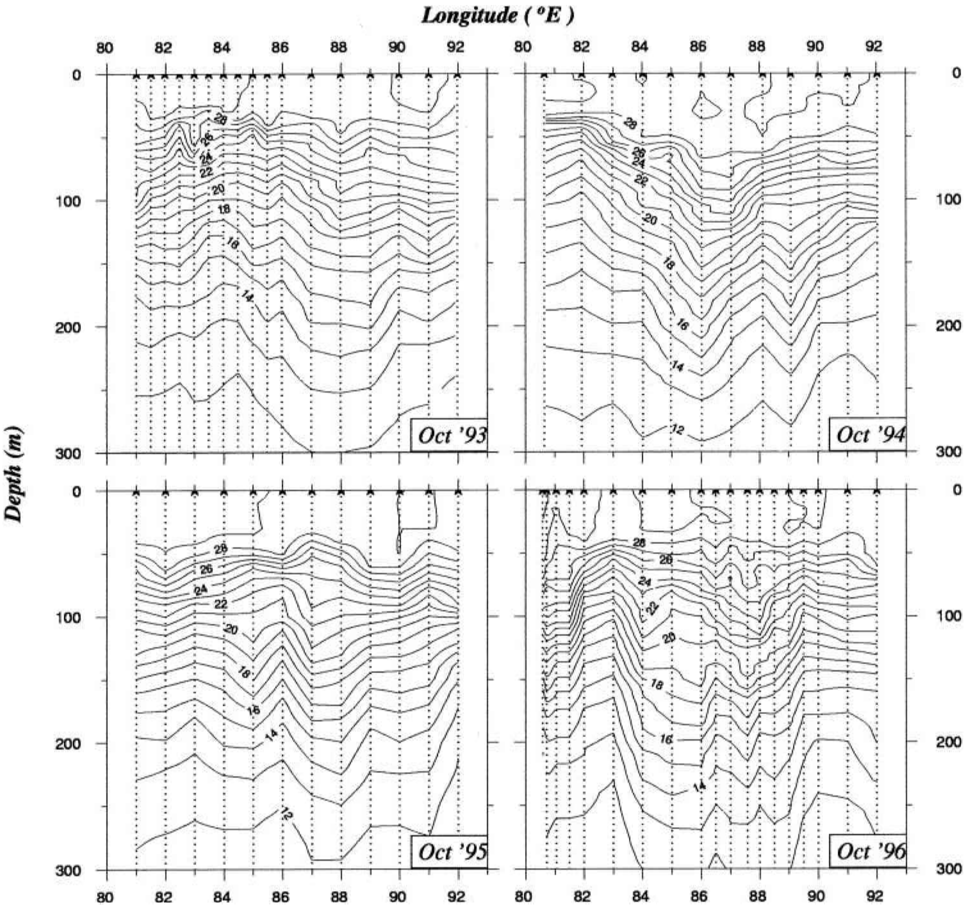

Figure 5. Snapshots of thermal structures (<300 m) along the Madras–Andaman XBT section during 17–21 October 1993, 15–16 October 1994, 4–8 October 1995 and 23–25 October 1996.

onward, the westward propagation of eddies becomes more prominent. However, only one Hovmoller diagram, from January 1993 to December 1994, is shown (Fig. 7) at 12N (the average latitude of the ship's track) between 85E and 95E longitudes. Propagation speed of these waves is estimated to be about 6.4 cm/sec, corresponding to 0.5° in 10 days. This is a very small speed to be detected in the 10-day snapshots presented in Figure 6. Perhaps this slow motion of eddies is typical of the Bay of Bengal region. Kumar and Unnikrishnan (1995) analyzed the Levitus (1982) temperature data to study the Rossby wave signatures over the Bay of Bengal. The propagation speeds of 8 cm/sec and 4.7 cm/sec have been estimated along 12.5N (between 80 and 95E longitudes) and along 17.5N (between 83E and 92E longitudes), respectively. From the speed of even 8 cm/sec, the movement comes to about 0.62° in 10 days.

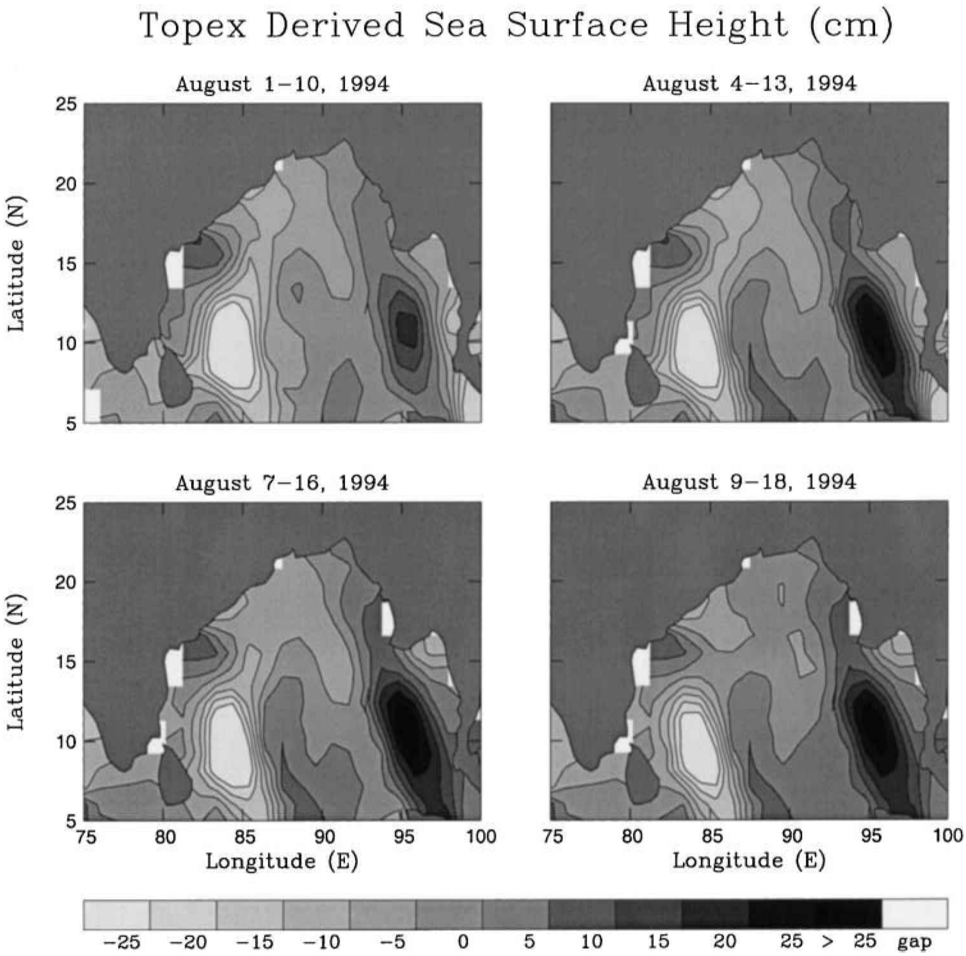

Figure 6. Sea surface height (in cm) derived from TOPEX altimeter observations during 1–10, 4–13, 7–16 and 9–18 August 1994.

b. Interannual variability

To study the interannual variation of the eddies, snapshots of the TOPEX SSH observations from the 1st to 10th of August and October have been presented (Figs. 8 and 9, respectively) for the four years. Interannual variability is evident in August and October. For example, an anticyclonic eddy present in the central Bay of Bengal during 1993 is noticed with weak signatures and with a shift in its position in the other years. Similarly, the sizes, locations and intensities have changed from year to year during the study period. Thus a strong interannual variation, both in the position and intensity of eddies, is evident indicating the need for time to time monitoring of the eddies.

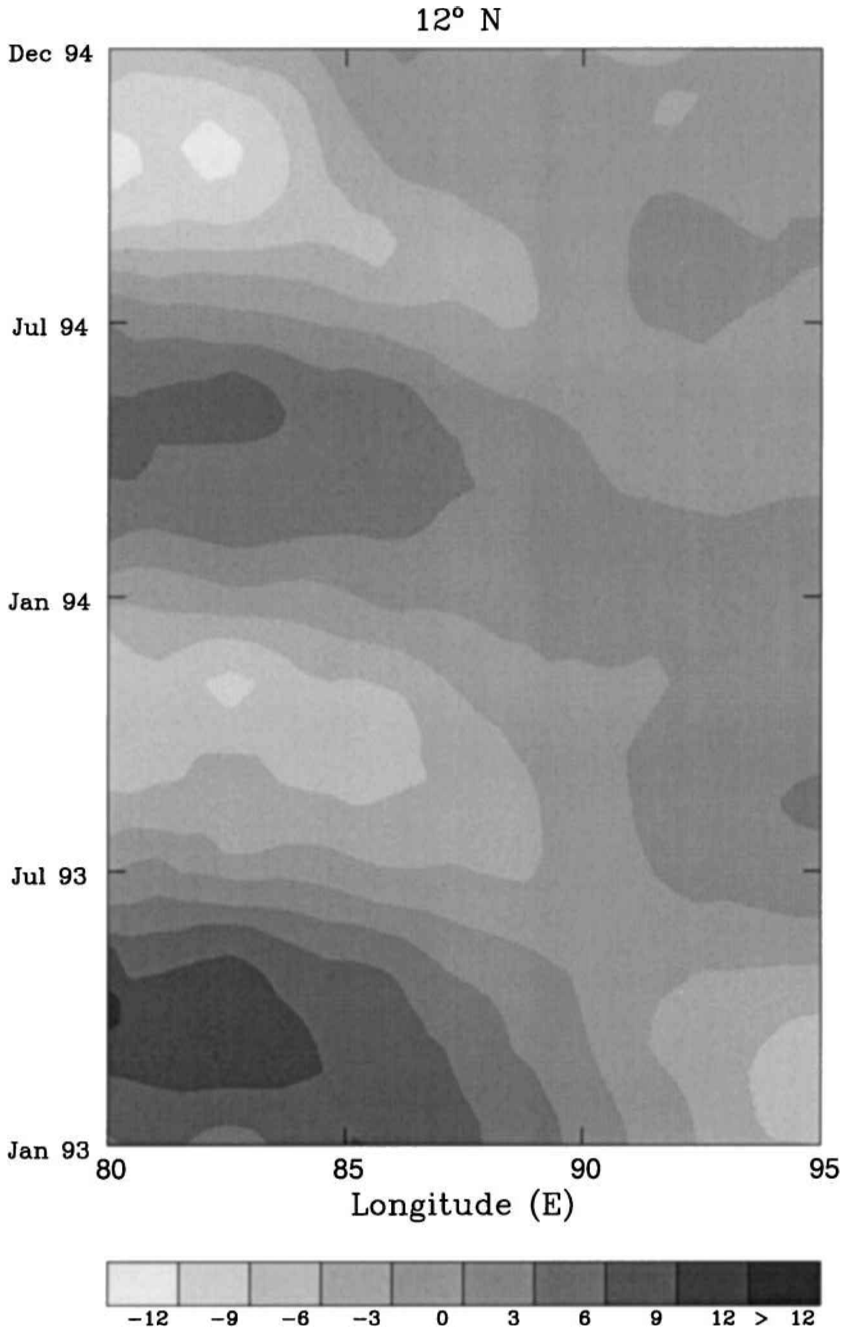

Figure 7. Zonal propagation of eddies from January 1993 to December 1994 at 12N.

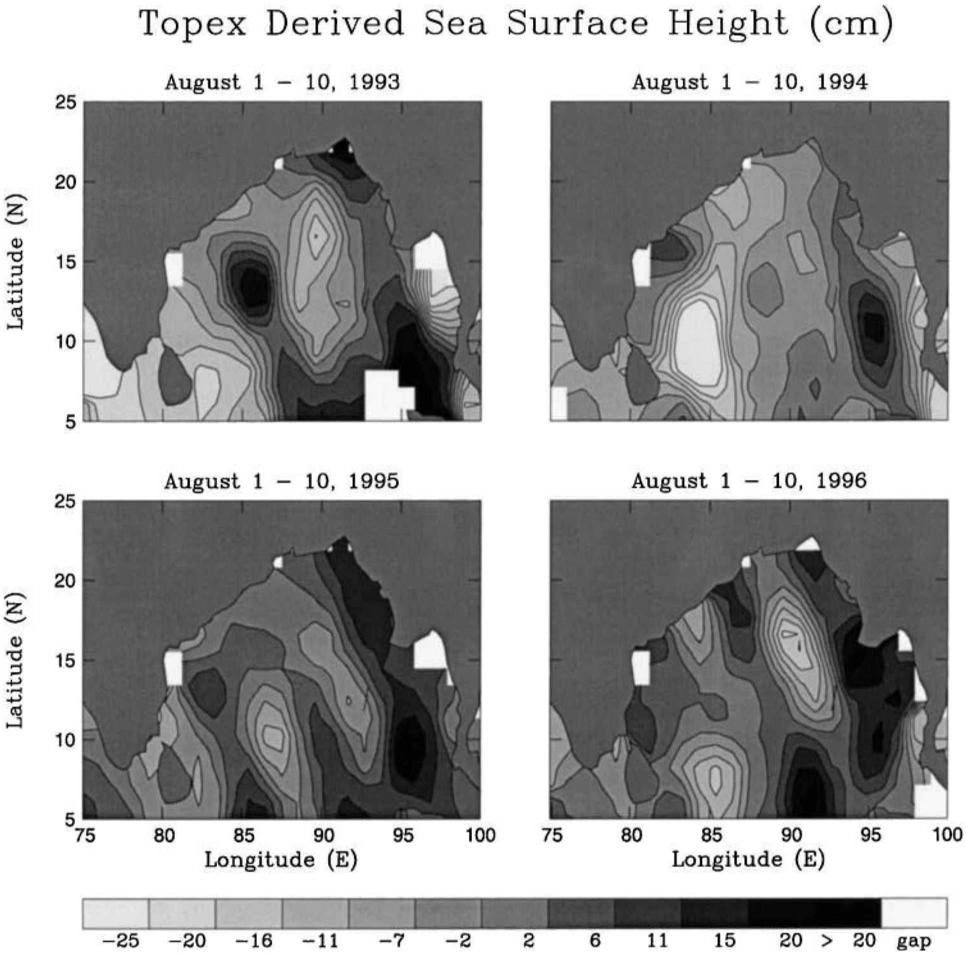

Figure 8. Sea surface height (in cm) derived from TOPEX altimeter observations during 1–10 August of 1993, 1994, 1995 and 1996.

4. Conclusion

The cyclonic and anticyclonic eddies identified in the Bay of Bengal from the TOPEX altimeter observations are confirmed by the independent *in situ* temperature sections. Since these waters are highly stratified, the subsurface thermal signals of eddies are not reflected in the surface temperatures whereas the SSH signatures are well captured. Thus, altimeter data are very useful in detecting oceanic eddies. Due to the extensive spatial coverage of remote sensing observations, the exact position and shape of the eddies can be characterized from altimeter-derived SSH observations which is not possible using the limited *in situ* profiles. Inter-annual variations in both position and intensity of eddies are observed during the study period suggesting a need for time to time monitoring of the eddies from remote sensing platforms.

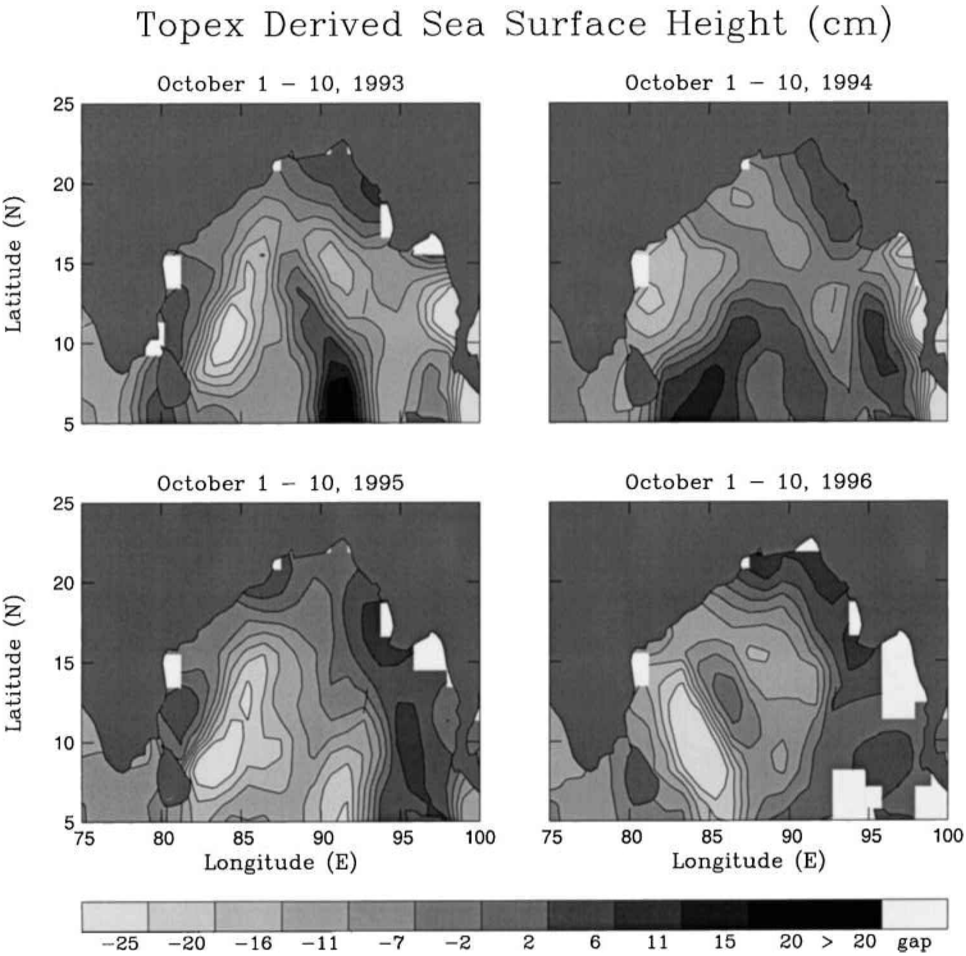

Figure 9. Sea surface height (in cm) derived from TOPEX altimeter observations during 1–10 October of 1993, 1994, 1995 and 1996.

Acknowledgments. XBT data collection program along Madras–Andamans route is supported by the Department of Science & Technology, New Delhi. TOPEX SSH observations were provided by Bob Cheney of NOAA. The authors thank the two anonymous referees for their constructive suggestions.

REFERENCES

Ali, M. M. 1990. Estimation of the horizontal velocity of the Socotra eddy and some observations of sea surface thermal features using INSAT-1B. Int. J. Rem. Sens., *11,* 41–47.

Ali, M. M. and R. Sharma. 1994. Detection of Arabian Sea eddy using ERS-1 altimeter data, Proceedings Second ERS-1 symposium—space at the service of our environment, Hamburg, Germany, ESA SP-361, 557–563 pp.

Ali, M. M., R. Sharma and R. Cheney. 1998. An atlas of the North Indian Ocean eddies from TOPEX altimeter derived sea surface heights. Indian Space Research Organization, Special Report.

Babu, M. T., S. Prasanna Kumar and D. P. Rao. 1991. A subsurface cyclonic eddy in the Bay of Bengal. J. Mar. Res., *49,* 404–410.

Bruce, J. G., J. C. Kindle, L. H. Kantha, J. L. Kerling and J. F. Baily. 1998. Recent observations and modeling in the Arabian Sea Laccadive High region. J. Geophy. Res., *103,* 7598–7600.

Dube, S. K., M. E. Luther and J. J. O'Brien. 1990. Relationships between the inter-annual variability of ocean fields and the wind stress curl over the central Arabian Sea and the Indian summer monsoon rainfall. Meteor. Atmosph. Phy., *4,* 153–165.

Gopala Krishna, V. V., S. M. Pednekar and V. S. N. Murty. 1996. T-S variability and volume transport in the central Bay of Bengal during south west monsoon. Ind. J. Mar. Sci., *25,* 50–55.

Kumar, P. S. and A. S. Unnikrishnan. 1995. Seasonal cycle of temperature and associated wave phenomena in the upper layers of Bay of Bengal. J. Geophys. Res., *100,* 13585–13593.

Levitus, S. 1982. Climatological atlas of the world ocean. NOAA professional paper 13, US Government Printing Office, Washington DC, 173 pp.

Pal, P. K. and M. M. Ali. 1992. Estimation of the azimuthal velocity and the elevation of an eddy from simulated altimeter data. Int. J. Rem. Sens., *13,* 2215–2222.

Sanilkumar, K. V., T. V. Kuruvilla, D. Jogendranath and R. R. Rao. 1997. Observations of the western boundary current of the Bay of Bengal from a hydrographic survey during March 1993. Deep-Sea Res., *44,* 135–145.

Received: *10 June, 1999;* revised: *23 May, 2000.*