

Chapter 5 – Eddies and mixed layer variability

In the previous chapter the basin-scale variability of the mixed layer and barrier layer were analyzed in the context of large-scale atmospheric forcing and remote forcing. In addition to these large-scale forcing, mixed layer can also be influenced by the meso-scale features such as eddies, both cyclonic (cold-core) and anti-cyclonic (warm-core). To decipher the role of meso-scale eddies in affecting the mixed layer variability, the high resolution *in situ* CTD (Conductivity-Temperature-Depth) data collected during four different seasons, spring intermonsoon, summer monsoon, fall intermonsoon and winter monsoon, along the central Bay (88°E) and western boundary were analyzed and presented in this chapter.

5.1 Spring intermonsoon (12 April to 7 May, 2003)

During the spring intermonsoon MLD along the central Bay was, in general, shallow specially in the south (Fig.5.1.1a). The MLD was about 32 m at 7°N, increased to 42 m at 8°N, and then decreased rapidly to 15 m at 9°N. From 9° to 14°N MLD remained at 15m. North of 14°N MLD showed an increasing trend up to 17°N and again a decrease was seen north of 17°N. The vertical distribution of temperature showed oscillation of isotherms, especially within the thermocline, all along the section. Two regions with large thermocline oscillations were noticed, one between 17° and 18°N and the other centered at 19°N. At 18°N the isotherms showed a large deepening, while that at 19°N showed a steep shoaling. Along the western boundary MLD varied from 35 at 12°N to 45 m at 15°N and north of 15°N it showed a decreasing trend reaching a minimum value of

15 m at 18°N. North of 18°N mixed layer showed a deepening trend (Fig.5.1.1b). The vertical thermal structure along the western boundary also showed thermocline oscillations and the most prominent one was centered between 17° and 18°N.

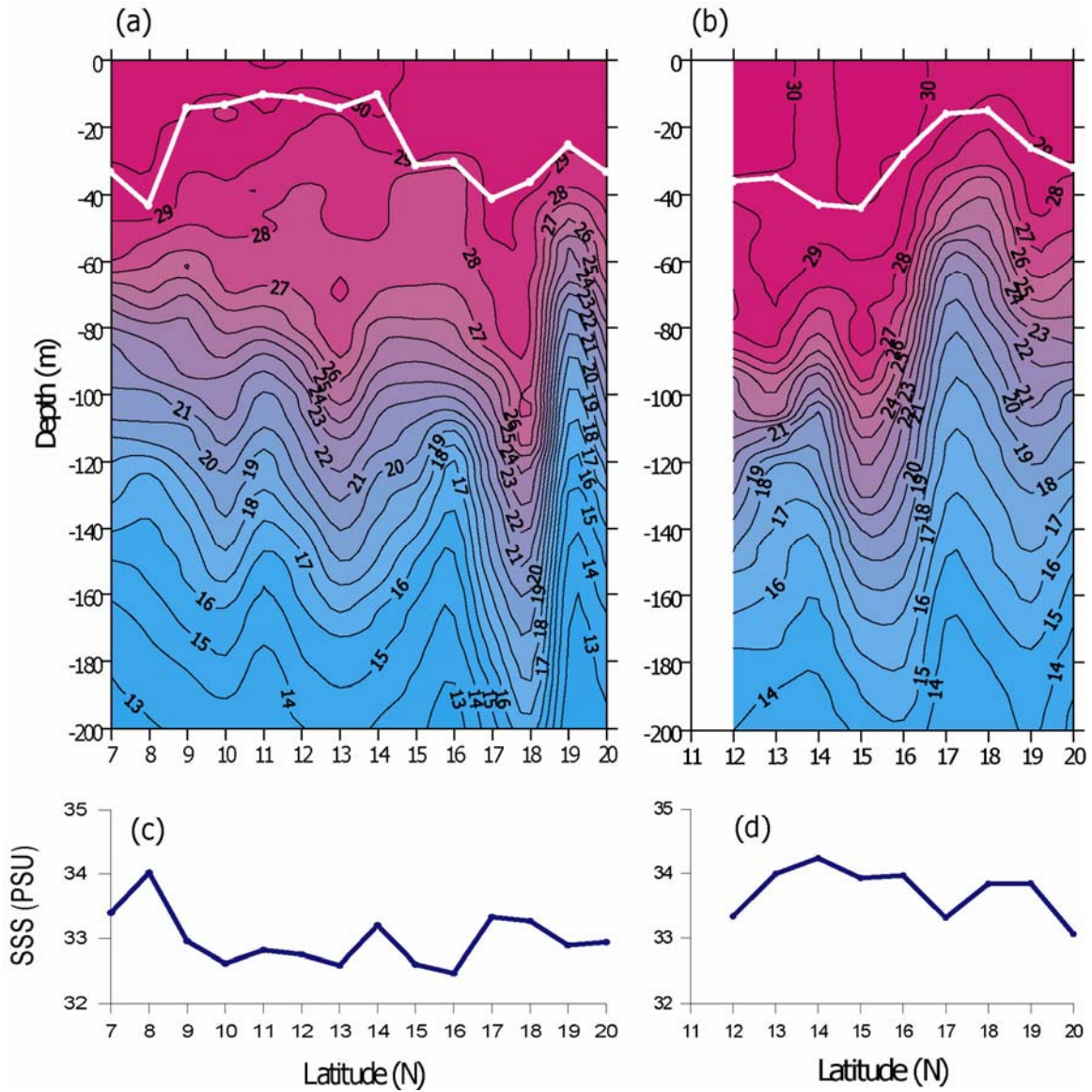


Fig.5.1.1 Vertical distribution of temperature ($^{\circ}\text{C}$) in the upper 200 m along the (a) central Bay of Bengal (88°E) and (b) western boundary during spring intermonsoon (12 April-7 May 2003). The white line indicates the MLD (m). Distribution of surface salinity (psu) along the (c) central Bay and (d) western boundary during the same period.

Along the central Bay, the shallow mixed layer in the south between 9° and 15°N was due to the presence of low salinity water of about 32.5 psu (Fig. 5.1.1c) along with the increased solar radiation in spring intermonsoon which peaked in April as could be seen from Fig.4.1.1d. Accordingly, the net heat gain by the ocean was the highest in April (see Fig.4.2.1d), which was located between 10° and 15°N . Note that the SST in the south (30°C) was about 1°C warmer than that of the north (29°C , Fig.5.1.1a). The low salinity surface waters as well as the peak heating made the water column highly stratified. The weak winds during this period were unable to break the stratification to initiate strong wind-driven mixing and hence the MLD remained shallow. In the north the deep mixed layer at 17°N was driven by the presence of warm core eddy (positive sea-level anomaly) as inferred from the sea-level anomaly (Fig.5.1.2a) as well as depression in the thermal structure between 17° and 18°N (Fig.5.1.1a). The warm core eddy drives an anti-cyclonic circulation and the associated downwelling deepens the MLD. Similarly, the shallow MLD at 19°N was the result of cyclonic eddy (negative sea-level anomaly) inferred from the sea-level anomaly (Fig.5.1.2a) as well as the shoaling in the thermal structure between 18° and 20°N (Fig.5.1.1a). The cold core eddy drives the cyclonic circulation and the associated upwelling shallows the MLD.

Along the western boundary also the SST in the southern part was warmer than the north and surface salinity varied from 33 to 34 psu (Fig.5.1.1d). The warm SST and comparatively low surface salinity should increase the stratification of the upper ocean and this in turn should lead to shallow mixed layer. However, in the southern part of the western boundary the CTD stations at 14° and 15°N were at the periphery of the warm core eddy (positive sea-level anomaly) as inferred from sea-level anomaly (Fig.5.1.2b),

while the stations at 17° and 18°N were within the cold core (negative sea-level anomaly) eddy. Thus, the observed deep and shallow MLD along the western boundary was associated with the prevailing meso-scale eddies.

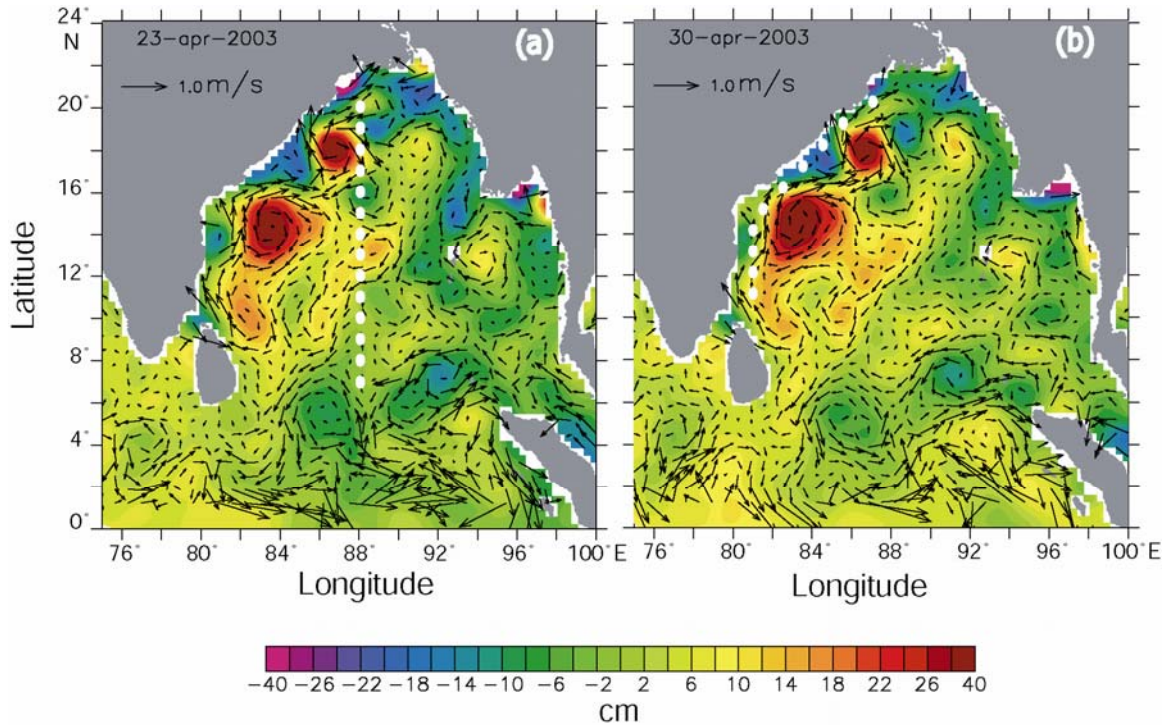


Fig.5.1.2 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during (a) 23-27 April 2003 and (b) 30 April-5 May 2003. The white filled circles denote the location of CTD stations. The CTD stations along the central Bay were occupied during 16-25 April 2003 and that along the western boundary was during 27 April-5 May 2003.

5.2 Summer monsoon (6 July to 2 August, 2001)

The MLD along central Bay during summer showed a large variation with deeper MLD in the south and a progressively shoaling MLD towards the north (Fig.5.2.1a). MLD was as deep as 60 m at 7°N, which showed a sharp decrease to 15 m at 8°N. MLD remained as shallow as 15 m between 8° and 10°N. From 10° to 12°N mixed layer deepened sharply to 50 m and from 12° to 20°N it showed a general shoaling reaching a value as

low as 5 m at 20°N. The vertical thermal structure showed thermocline oscillations, as in the case of spring intermonsoon, with maximum up-down sloping of isotherms between 8°-11°N, and 18°-20°N. Along the western boundary MLD deepened from 25 m at 11°N to 35 m at 15°N (Fig.5.2.1b). North of 15°N MLD showed a general shoaling, decreasing to a minimum value of 5 m at 20°N, as in the case of the central Bay.

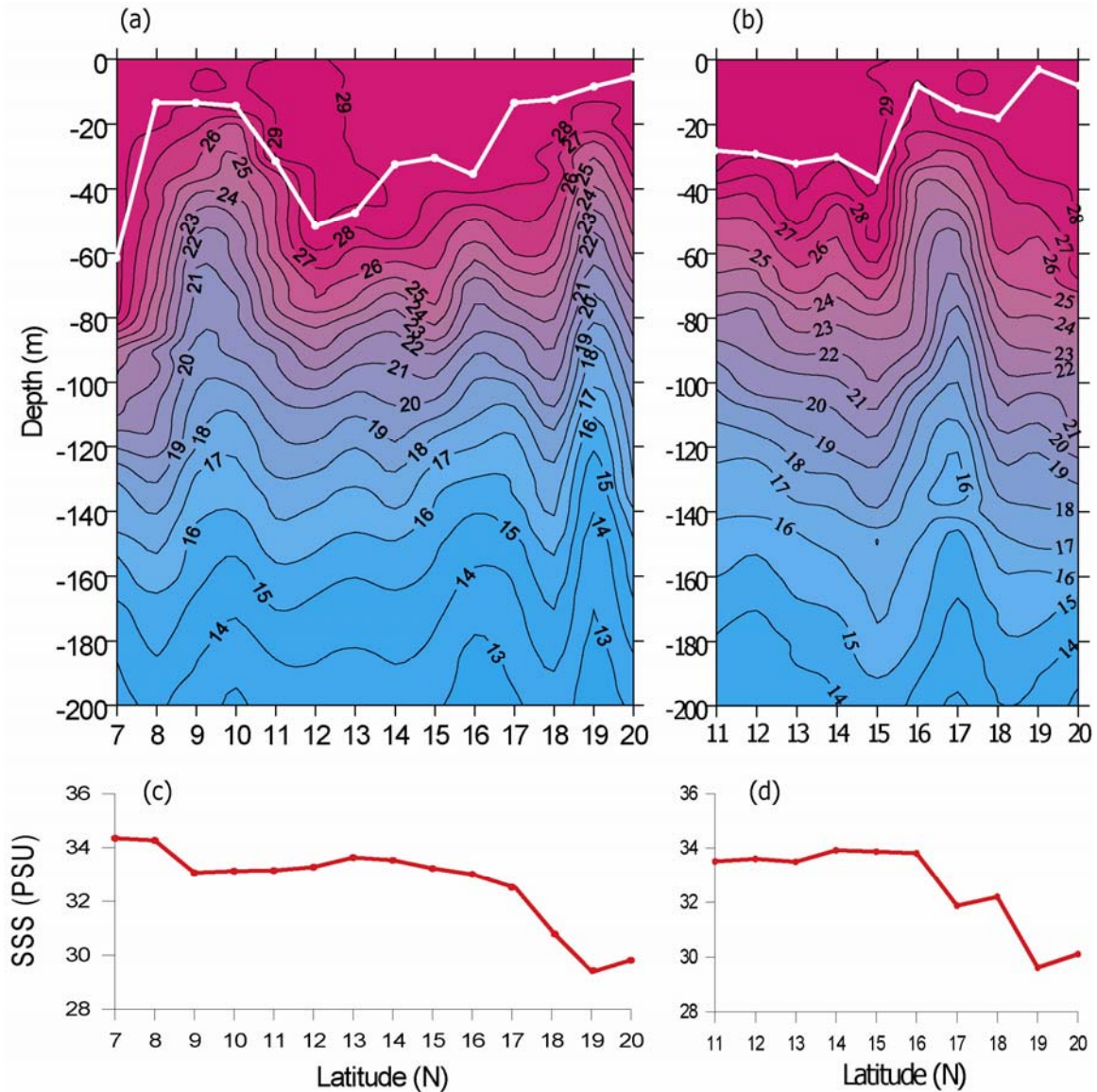


Fig.5.2.1 Vertical distribution of temperature (°C) in the upper 200 m along the (a) central Bay of Bengal (88°E) and (b) western boundary during summer monsoon (6 July to 2 August, 2001). The white line indicates the MLD (m). Distribution of surface salinity (psu) along the (c) central Bay and (d) western boundary during the same period.

This general decrease of MLD towards north could be explained in the context of salinity distribution. The surface salinity along both the central Bay (Fig.5.2.1c) as well as the western boundary (Fig.5.2.1d) showed a sharp decrease towards the north from 33 psu at 16°N to 29 psu at 20°N. Though the wind speed during summer was high (~8-9.5 m/s, Fig.4.3.2) in the northern Bay of Bengal, the increased stratification due to the presence of low salinity waters curtailed the strong wind-driven mixing leading to shallow mixed layer. But the deep MLD at 7°N (Fig 5.2.1a) was driven by the presence of warm core eddy as could be seen from the sea-level anomaly, which was positive (Fig.5.2.2a). As the 7°N station was located within the warm core eddy, the anti-cyclonic circulation and the associated downwelling deepened the mixed layer. The shallow MLD from 8 to 10°N

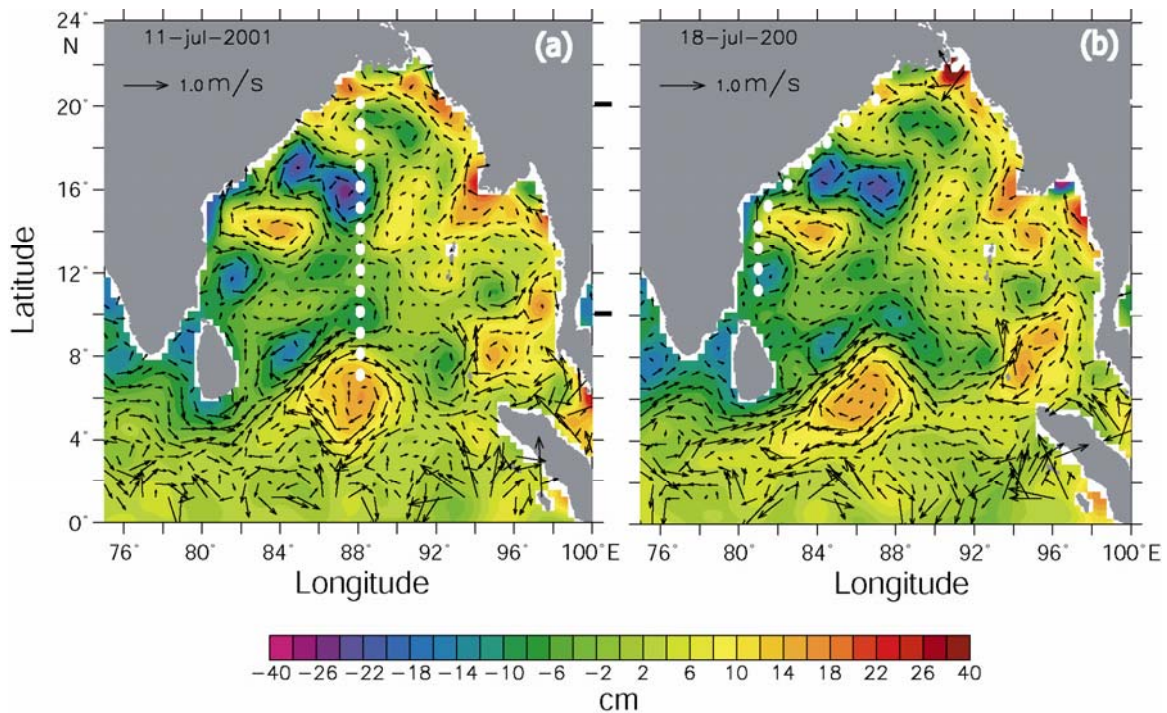


Fig.5.2.2 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during (a) 11-17 July 2001 and (b) 18-24 July 2001. The white filled circles denote the location of CTD stations. The CTD stations along the central Bay were occupied during 10-21 July 2001 and that along the western boundary was during 23 July-1 August 2001.

was due to the presence of cold core eddy (negative sea-level anomaly). The cyclonic circulation associated with the cold core eddy drives the upwelling and the upheaval of isotherms between 8° and 10°N (Fig.5.2.1a) was the manifestation of this. Thus, the existence of warm core eddy adjacent to the cold core eddy leads to the sharp shoaling of MLD from 7° to 10°N . Again, the shallow MLD from 14° to 16°N was a result of cold core eddy located at this location as inferred from the sea-level anomaly map.

Along the western boundary the deep MLD in the south between 11° and 15°N was driven by the strong winds which are able to initiate deeper wind-driven mixing as the upper ocean was less stratified due to the presence of comparatively high surface salinity (~ 33.5 psu, Fig.5.2.1d) The shallow MLD at 16°N was driven by the presence of cold core eddy as could be inferred from the vertical thermal structure which shows the upheaval of isotherms at 16°N (Fig.5.2.1b) as well as from the sea-level anomaly map which was negative (Fig.5.2.2b).

5.3 Fall intermonsoon (14 September to 12 October, 2002)

In the central Bay of Bengal MLD showed a deepening from 25 m at 7°N to 65 m at 11°N during fall intermonsoon (Fig.5.3.1a). From 11°N onwards MLD showed a gradual decrease towards north with the lowest value of 5 m at 20°N . The vertical thermal structure showed thermocline oscillations the prominent ones were centered between 7° and 9°N , and between 17° and 19°N within which the isotherms showed large up-down sloping. The largest isotherm depression was noticed between 11° and 13°N . Along the western margin also the MLD showed a shoaling trend (Fig.5.3.1b). The MLD was 20 m at 11°N , which shoaled to 5 m at 18° as well as 20°N . Thermal structure showed

prominent thermocline oscillation located at two regions, one between 11° and 13°N and the other between 17° and 19°N.

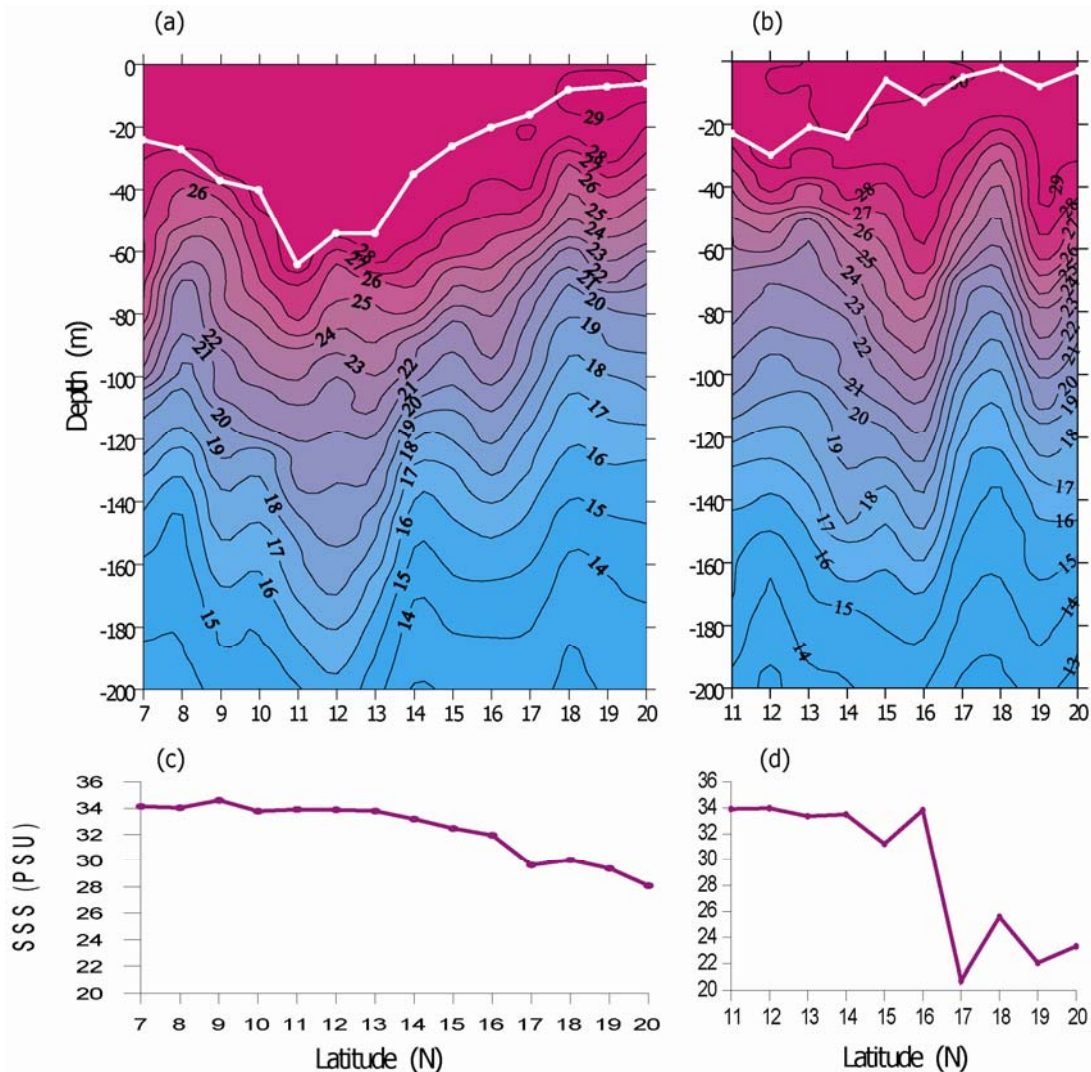


Fig.5.3.1 Vertical distribution of temperature (°C) in the upper 200 m along the (a) central Bay of Bengal (88°E) and (b) western boundary during fall intermonsoon (14 September to 12 October, 2002). The white line indicates the MLD (m). Distribution of surface salinity (psu) along the (c) central Bay and (d) western boundary during the same period.

An examination of the sea-level anomaly map showed the presence of a weak cold core eddy (negative sea-level anomaly) between 7° and 9°N (Fig.5.3.2a) within which shallow MLD was noticed and the thermal structure also showed a large up-sloping of isotherms

(Fig.5.3.2a). Thus, the shallow MLD could be explained in terms of this negative sea-level anomaly, which drives the cyclonic circulation and upwelling leading to shallow mixed layer. The deep MLD between 11°N to 13°N was due to the effect of warm core eddy as seen from the positive sea-level anomaly (Fig.5.3.2a) that drives the downwelling and results in deep mixed layer. The shoaling of mixed layer from 14° to 20°N was the result of decrease in salinity from 33 psu at 14°N to 28 psu at 20°N (Fig.5.3.1c). The presence of cold core eddy in the region of 16-18°N, though helped in decreasing the MLD, the rapid decrease of salinity towards the north made the upper layers highly stratified. The comparatively weaker winds (~5-6 m/s) during fall intermonsoon (Fig.4.3.3a&b) inhibited wind-driven mixing and there by making the mixed layer shallow.

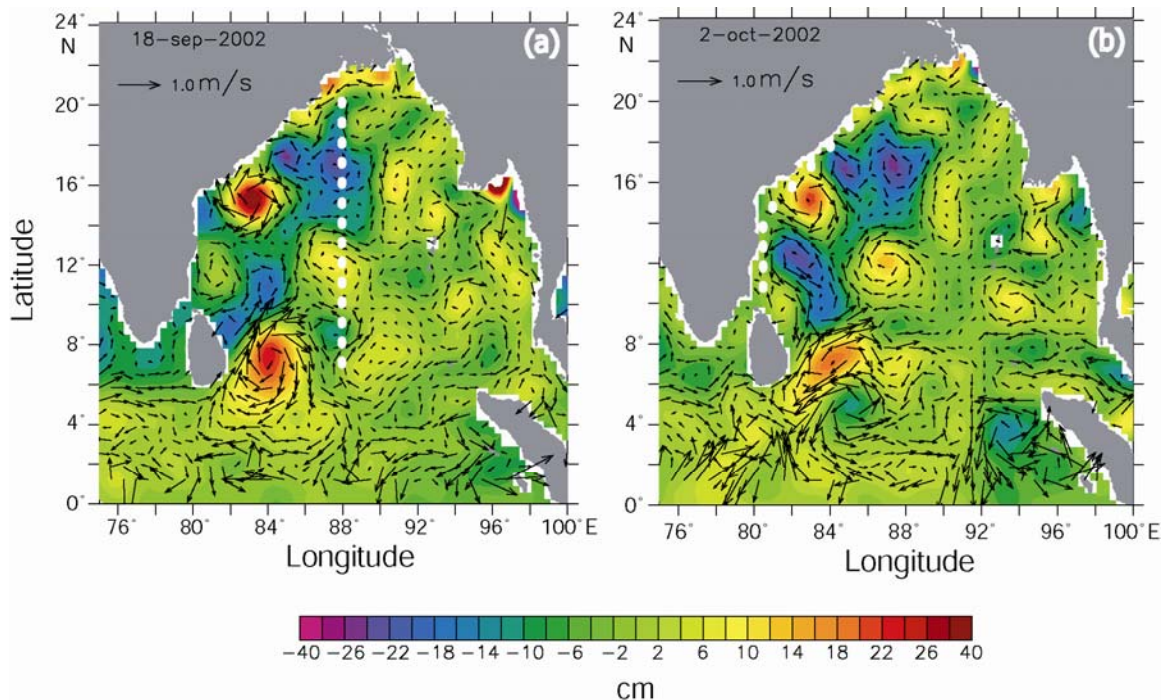


Fig.5.3.2 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during (a) 18-24 September 2002 and (b) 2-8 October 2002. The white filled circles denote the location of CTD stations. The CTD stations along the central Bay were occupied during 15-27 September 2002 and that along the western boundary was during 30 September-11 October 2002.

Along the western boundary the stations at 11°N and 18°N were in the vicinity of cold core eddies (negative sea-level anomaly), while 16°N was in the vicinity of a warm core (positive sea-level anomaly) eddy (Fig.5.3.2b). As a result, the thermal structure showed shoaling at 11°N and 18°N, while a deepening at 16°N (Fig.5.3.1b). Thus, the deepening and shoaling of MLD at these locations were driven by the eddy-induced downwelling and upwelling. However, in the north, the rapid decrease of salinity from about 33 psu at 16°N to about 22 psu at 20°N had much greater influence on MLD. The strong stratification associated with the low salinity waters in the north lead to the shallow MLD.

5.4 Winter monsoon (25 November 2005 to 4 January 2006)

During winter season MLD along the open ocean transect showed shoaling and deepening consistent with the isotherm oscillations (Fig.5.4.1a). The MLD was about 30 m at 7°N, which deepened to 45 m at 8°N. From 8° to 13°N, MLD was about 40 m. A steep decrease in MLD was noticed from 14° to 15°N where MLD decreased to 30 m. Once again MLD showed a sharp deepening north of 16°N, with maximum value of 75 m at 19°N. Along the western boundary MLD was 50 m at 11°N, which showed a decreasing trend from 11° to 13°N reaching a value of 30 m (Fig.5.4.1b). From 13° to 15°N MLD varied between 30 to 40 m and from 15° to 17°N MLD showed a sharp increase of about 30 m. Again from 17° to 18°N MLD showed a drastic decrease of 40 m and then on remained shallow north of 18°N with a value of ~20 m.

An examination of sea-level anomaly map showed a number of cyclonic and anti-cyclonic circulation features during winter near the central Bay of Bengal as well as along the western boundary (Fig.5.4.2 a&b). The deep MLD observed between 8° and

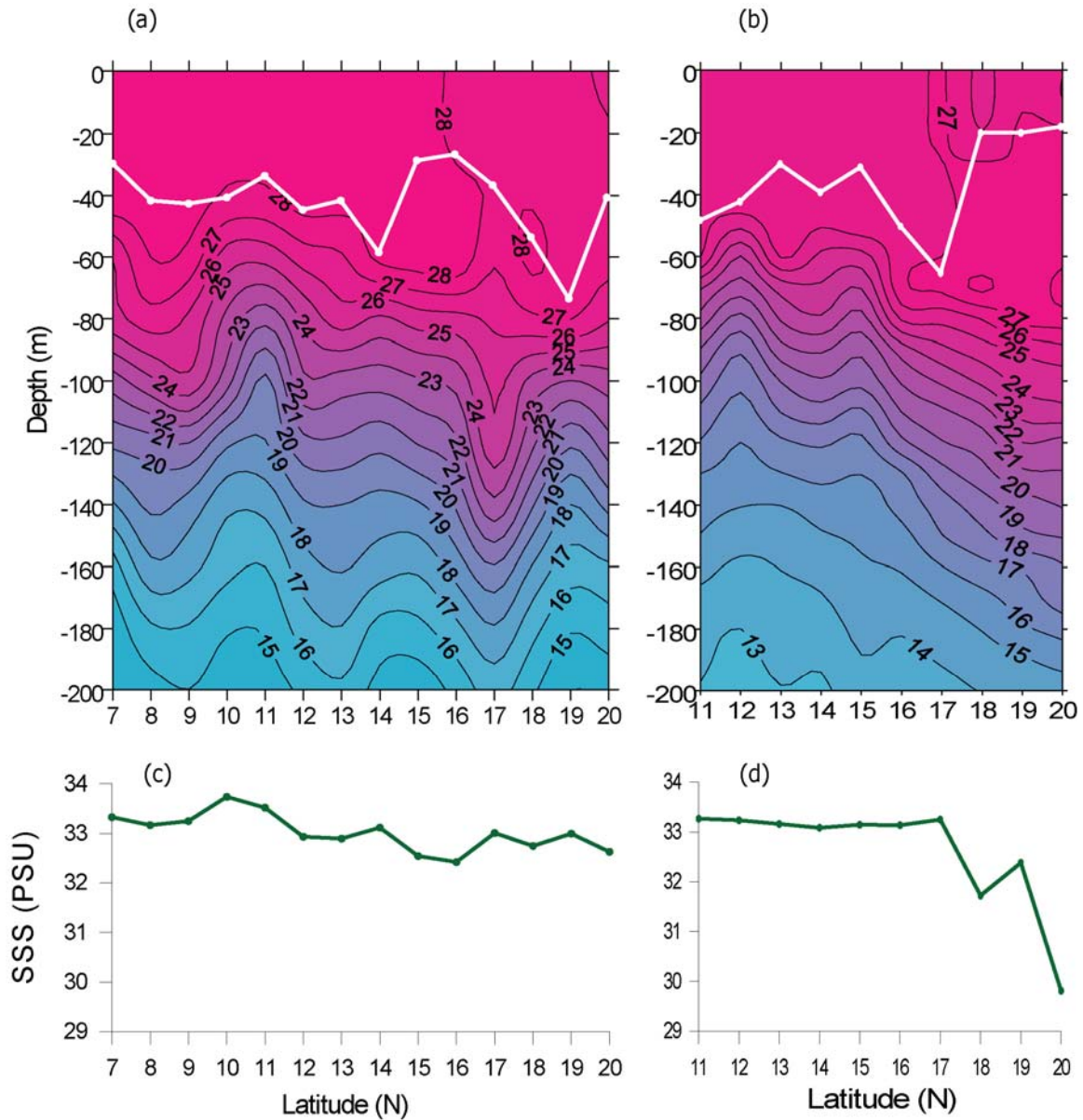


Fig.5.4.1 Vertical distribution of temperature ($^{\circ}\text{C}$) in the upper 200 m along the (a) central Bay of Bengal (88°E) and (b) western boundary during winter monsoon (25 November 2005 to 4 January 2006). The white line indicates the MLD (m). Distribution of surface salinity (psu) along the (c) central Bay and (d) western boundary during the same period.

10°N and between 13° and 14°N was driven by the warm core eddy (positive sea-level anomaly) located in this region. The anti-cyclonic circulation associated with the warm core eddy and the downwelling led to the deepening of mixed layer. In the north, the surface salinity was about 33 psu (Fig.5.4.1c), which would lead to strong stratification and prevent any deepening of MLD. On the contrary a deepening of mixed layer between 16° and 19°N was noticed. This could be explained with the help of sea-level anomaly. The sea-level anomaly map showed the CTD sampling stations from 16° to 20°N was very close to the positive sea-level anomaly and the associated anti-cyclonic circulation. In fact CTD station at 19°N was much closer to the warm core eddy than the rest of the station and hence showed the highest deepening of MLD.

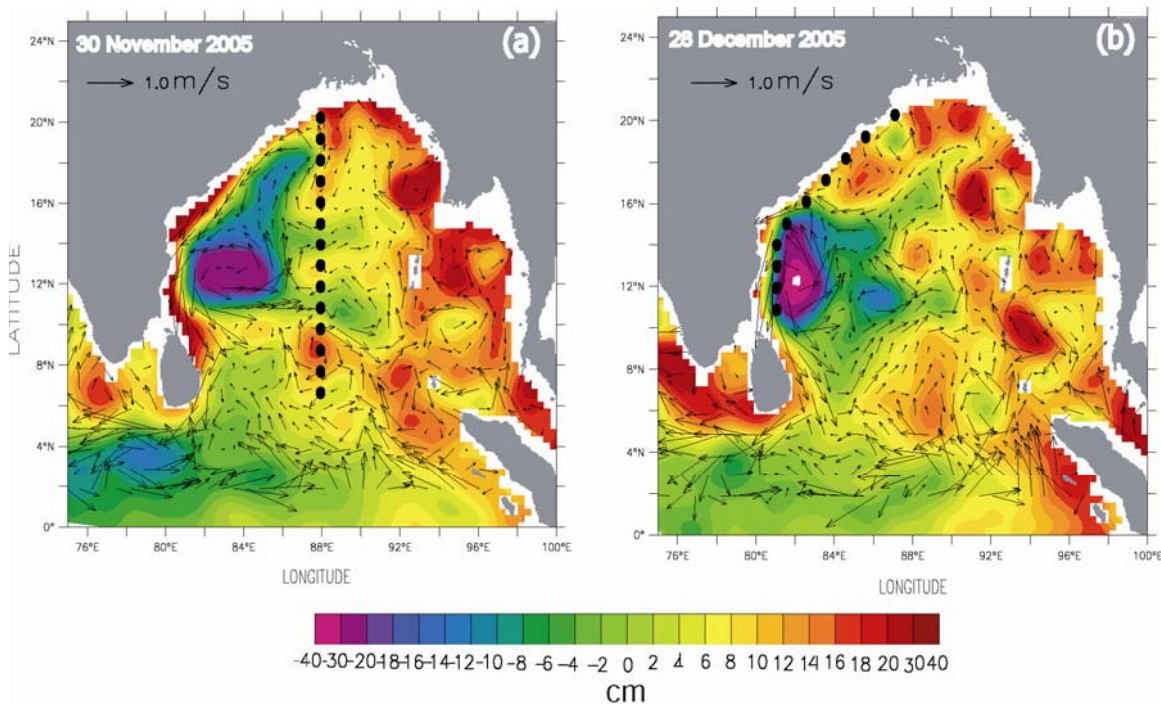


Fig.5.4.2 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during (a) 30 November -6 December 2005 and (b) 28 December 2005 -3 January 2006. The black filled circles denote the location of CTD stations. The CTD stations along the central Bay were occupied during 29 November-10 December 2005 and that along the western boundary was during 11 December 2005-1 January 2006.

Along the western boundary, the shallow MLD from 13° to 15°N was due to the proximity of the station close to an elongated cold core eddy (negative sea-level anomaly) which drove upwelling associated with cyclonic circulation (Fig.5.4.2b) as well as the vertical thermal structure (Fig.5.4.1b). Similarly, the deep MLD of more than 60 m at 17°N was due to the presence of warm core eddy (positive sea-level anomaly) and the associated downwelling due to the anti-cyclonic circulation. North of 17°N, the shallow MLD was due to the rapid decrease of salinity from 33 to 29.8 psu (Fig.5.4.1d). This very low salinity led to strong stratification and the moderate winds (4-5 m/s, Fig.4.3.1) were unable to break this stratification to deepen the mixed layer by wind-driven mixing.

In summary, meso-scale eddies were seen as an integral part of the Bay of Bengal as they occurred in all over the basin in all the 4 seasons during which the Bay of Bengal was sampled along the central and the western boundary. The cyclonic circulation associated with the cold core eddies drive the upwelling which reduced the depth of the mixed layer. The anti-cyclonic circulation associated with the warm core eddy drive downwelling and resulted in the deepening of the mixed layer. However, in summer and fall intermonsoon the low salinity water in the north had more influence on mixed layer depth as they increased the upper ocean stratification, which the prevailing winds were unable to break and initiate strong wind-driven mixing.