

Chapter 4 - Eddies in the central Bay of Bengal

4.1. Introduction

Previous chapter dealt with the characteristics, evolution and the generating mechanism of eddies along the western boundary of the BOB. In this chapter, the signature of eddies was explored using hydrographic data collected along the central BOB (88°E) onboard the ship during summer monsoon (10-22 July 2001), fall intermonsoon (17-27 September 2002) and spring intermonsoon (16-25 April 2003). Satellite sea-level anomaly is also used to track the origin and evolution of eddies identified from the hydrography.

4.2 Thermohaline structure

4.2.1 Summer Monsoon 2001

Examination of vertical thermal structure revealed several undulations. Doming of isotherms was noticed centered at 9°N, 16°N and 19°N, where as a depression was noticed at about 18°N. The displacement of isotherms was more prominent in the upper layers in the southern region. For example, 22 and 24°C isotherms underwent a displacement of ~50 m at 9°N (Figure 4.2.1.1a). The upward displacement of isotherms depressed the ambient temperature at 100 m by about 2.5°C, where as in the north the displacement of isotherms was more pronounced in the subsurface layers. At 19°N, 22°C and 24 °C isotherms underwent an upward displacement of ~25 m whereas deeper isotherms 13°C, 14°C, 15°C and 16°C were displaced upwards by about ~ 50 m. This

depressed the ambient temperature by about 2°C. Similarly at 16°N too deeper isotherms underwent maximum upheaval, though the magnitude of displacement was less. In the

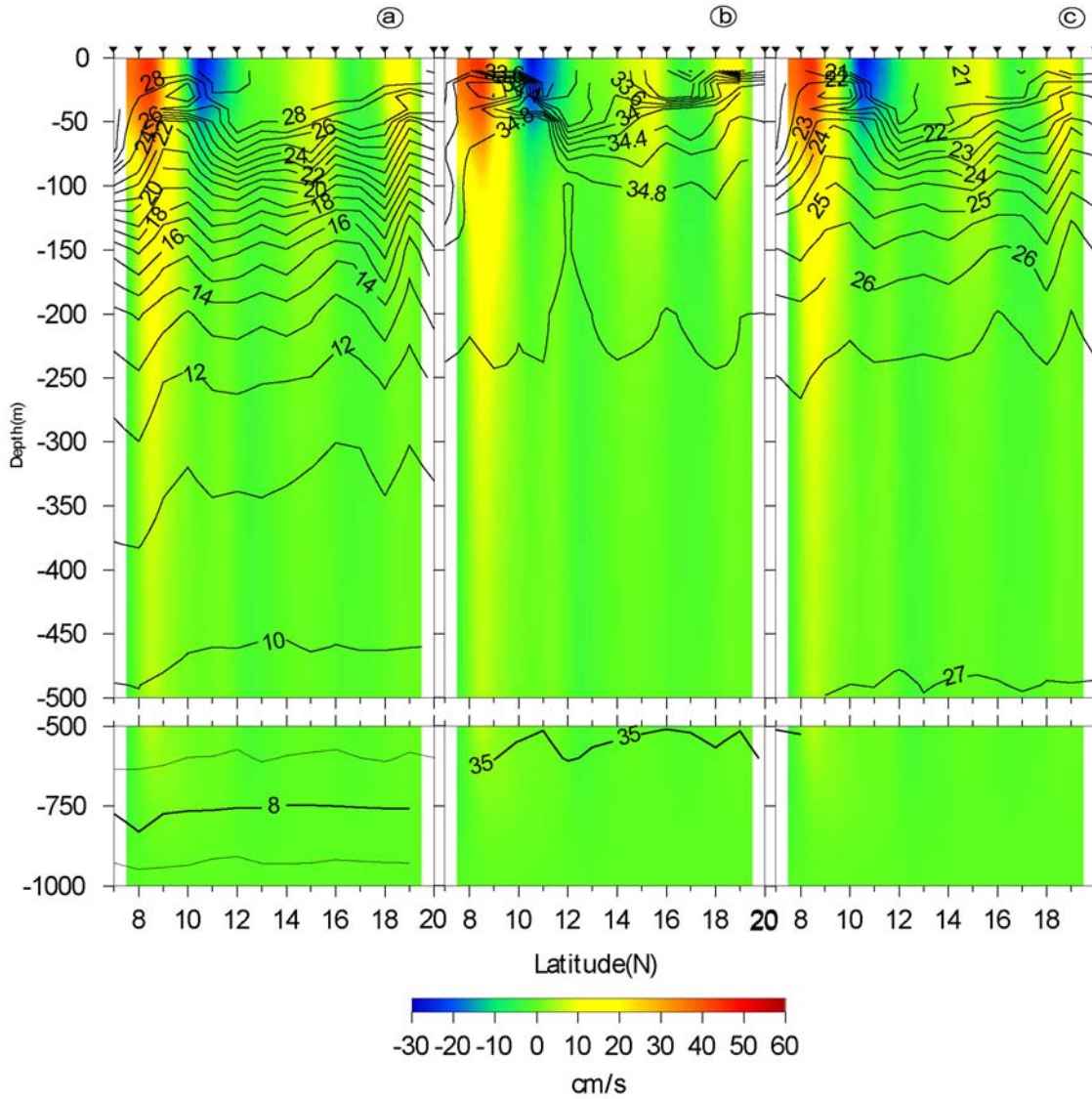


Figure 4.2.1.1 Vertical section of (a) temperature ($^{\circ}\text{C}$), (b) Salinity (psu), and sigma-t (kg/m^3) overlaid on the geostrophic velocity (cm/s) w.r.t 1000 m along the central (88°E) BOB during summer monsoon (10-22 July) 2001. Filled inverted triangles indicate the position of CTD stations.

case of depression centered about 18°N , maximum displacement occurred for isotherms 13°C , 14°C , 15°C and 16°C (~ 30 m), which resulted in an increase of ambient temperature by about 1°C at 150 m depth. However, the 15°C isotherm underwent a

displacement of 40 m. Consistent with the isotherm displacement, the isohalines also showed undulations (Figure 4.2.1.1b). In the south 35 psu isohaline underwent an upward displacement of about 70 m. Though in the north isohalines showed tendencies similar to that of isotherms, the displacement was not prominent. The reason for this is the overwhelming impact of freshwater in the northern Bay, which is evident in the haline structure. The density structure essentially reflected the thermal structure, except in the north, where influence of salinity could be seen in the surface layers. In the south, 24 sigma-t surface displaced upward by about 60 m where as in the north, consistent with the thermal structure, the deeper isopycnals underwent maximum displacement (Figure 4.2.1.1c). For example, the 26 sigma-t isopleth was displaced by ~50 m at 19°N. Relative velocity computed w.r.t 1000 m (Figure 4.2.1.1 shading) showed alternate bands of eastward and westward velocities. In the south an east ward velocity of ~60 cm/s was noticed at 8°N which turned westward at about 11°N. At about 15°N again an eastward flow was noticed which turned to west after 16°N. An eastward flow followed this at 18°N which turned, west once again after 19°N. This turning of the flow coincided with the centers of doming and depression. Thus, centered about 9°, 16° and 19°N signatures of cyclonic flow and centered about 18°N one anticyclonic flow were detected.

4.2.2. Fall intermonsoon 2002

Doming of isotherms was noted at three locations centered about 9°N, 14°N and 18°N (Figure 4.2.2.1a). Apart from these undulations, a depression centered about 12°N along the open ocean transect was also noticed. Similar to the observation during summer monsoon 2001 the isotherms underwent maximum displacement within the first 100 m

for the doming centered at 9°N. For example, the 26°, 27°, 28°C isotherms underwent displacements of about 40-50 m, where as for the depression centered about 12°N the maximum deformation was found to be associated with 16°, 17° and 18°C isotherms.

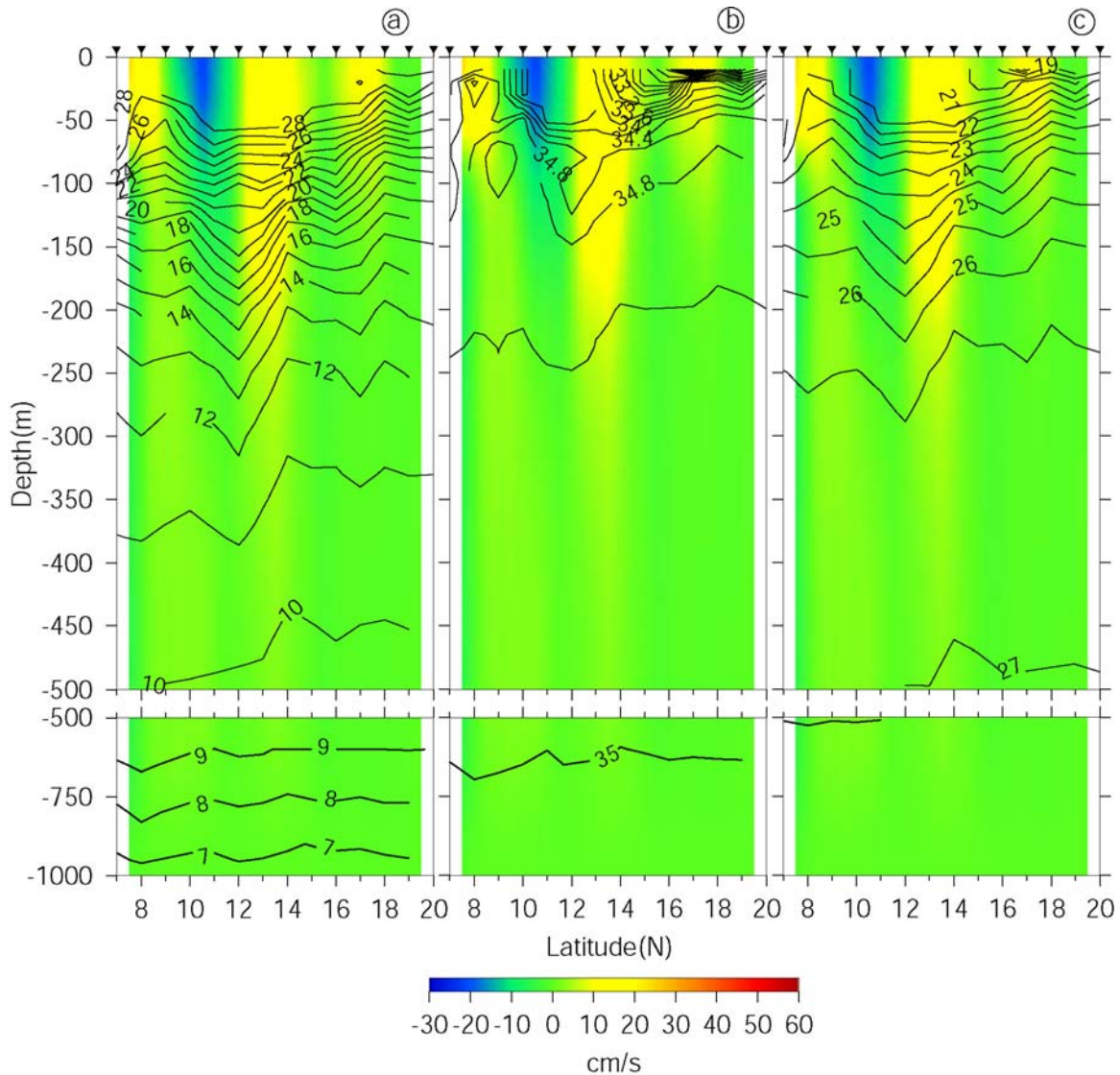


Figure 4.2.2.1 Vertical section of (a) temperature ($^{\circ}\text{C}$), (b) Salinity (psu), and sigma-t (kg/m^3) overlaid on the geostrophic velocity (cm/s) w.r.t 1000 m along the central (88°E) BOB during fall intermonsoon (17-27 September) 2002. Filled inverted triangles indicate the position of CTD stations.

These doming/depressions decreased/increased the ambient temperature by about 2°C .

The doming centered at 18°N was not very conspicuous. The upward and downward

displacements associated with the doming and depression was reflected in the salinity structure also (Figure 4.2.2.1b). The 34.8 psu isohaline displaced upward by about 80 m in the case of doming centered about 9°N and had a downward displacement of about the same amount in the case of depression centered about 12°N. The density structure also showed the salient features of the thermal structure except in the north where overwhelming signals of the fresh water was found. At 9°N the 22.5 sigma-t surface underwent a displacement of approximately 50 m whereas at 12°N the 25 sigma-t surface was depressed by about 40 m (Figure 4.2.2.1c). Consistent with the density structure the relative velocity computed with respect to 1000 m showed alternating bands of eastward and west ward velocities (Figure 4.2.2.1 shading). An eastward velocity of ~25 cm/s was found at 8°N which turned to west at about 10°N. This westward velocity started decreasing and turned east at about 13°N. This was followed by a weak westward flow at 15°N. Velocity was found to be eastward again at 17°N and turned west the north. Thus, consistent with the doming and depression in the temperature/salinity structure the velocities too underwent changes in direction signifying the presence cyclonic eddies centered about 9 , 14°N and 18°N and anticyclonic eddy at 12°N.

4.2.3 Spring intermonsoon 2003

Thermal structure showed many undulations within and beyond the thermocline. Prominent doming was noticed at 11°N, 16°N and 19°N, where as two regions of depression at 13°N and 18°N were also seen (Figure 4.2.3.1a). Maximum displacement of isotherms occurred at three locations, centered at 16°, 18° and 19°N in the upper 500 m of the water column. However, the displacements at 11° and 13°N were confined

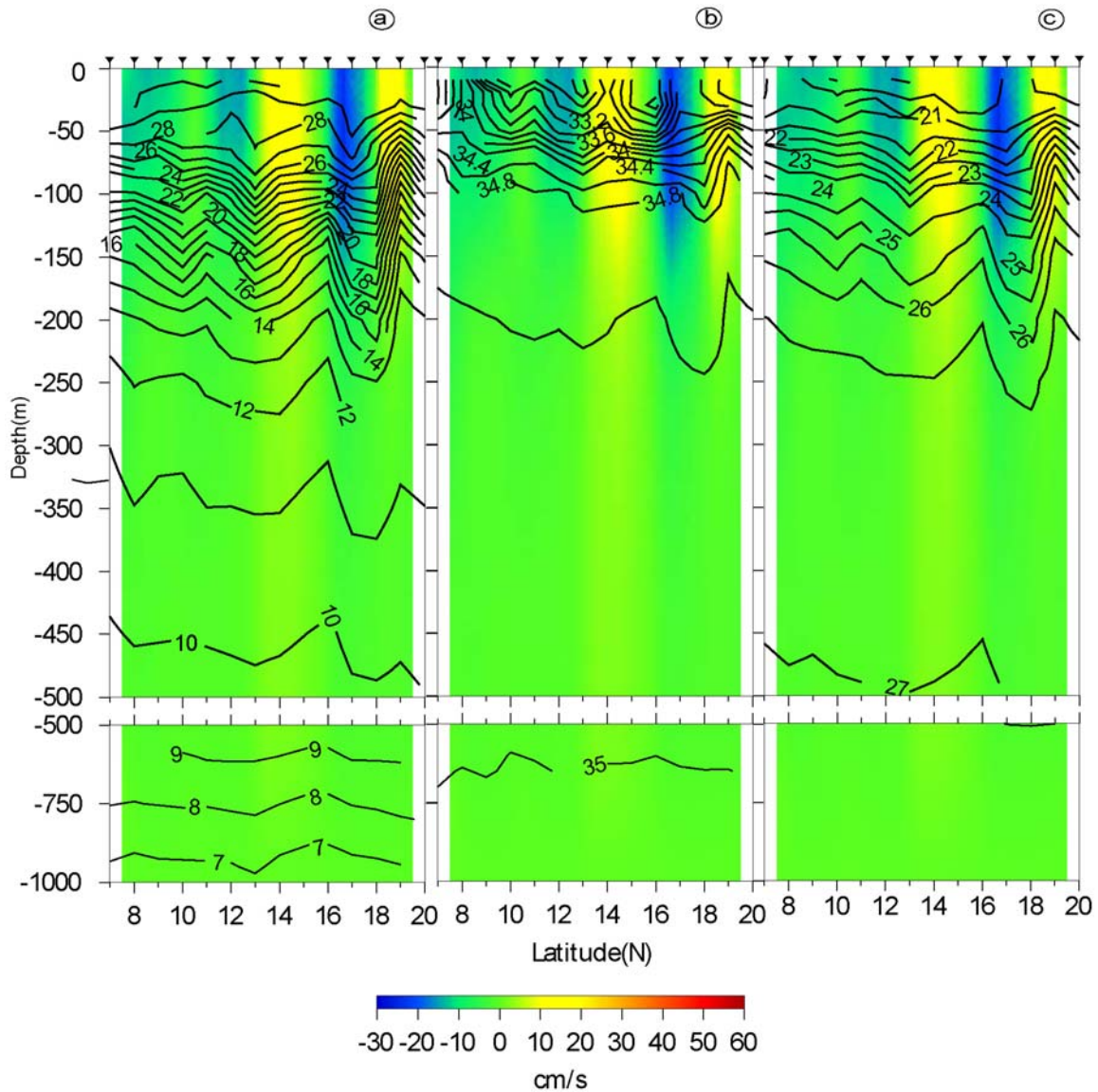


Figure 4.2.3.1 Vertical section of (a) temperature ($^{\circ}\text{C}$), (b) Salinity (psu), and sigma-t (kg/m^3) overlaid on the geostrophic velocity (cm/s) w.r.t 1000 m along the central (88°E) BOB during spring intermonsoon (16-25 April) 2003. Filled inverted triangles indicate the position of CTD stations.

within the thermocline. The 16°C isotherm underwent an upheaval of about 40 m at 16°N while it was depressed by about 60 m at 18°N . Once again the isotherm had undergone an upheaval of about 60 m at 19°N . Salinity structure showed low saline waters even in the southern most part of the transect (Figure 4.2.3.1b). However, it does not exactly mimic the thermal structure except at a few locations. The depression at 13°N and 18°N

and the doming centered about 19°N was conspicuous in the haline structure. However, maximum displacement of isohalines occurred at 18° and 19°N, where 35 psu isohaline was depressed by 60 m at 18 °N and was uplifted by the same distance at 19°N. The density structure essentially reflected the thermal structure with doming at 11°, 16° and 19°N and depressions at 13° and 15°N (Figure 4.2.3.1c).

Geostrophic velocities computed w.r.t 1000 m showed alternate bands of positive and negative velocities. The direction was generally westward in the southern part of the transect, however, at about 12°N this westward velocity increased to about 15 cm/s then turned eastward at 14°N. Velocity decreased further north and turned westward again at 17°N with velocity increasing towards north. Once again, the current changed its direction towards east at 19°N and subsequently decreases further north. Thus, from the thermohaline structure and the geostrophic velocity structure the signatures of three cyclonic eddies centered about 11°, 16° and 19°N, and two anticyclonic eddies centered about 14° and 18°N were deciphered during spring intermonsoon 2003.

In summary a total number of 13 cyclonic/ant-cyclonic features were identified from the thermohaline structure along the open ocean transect during the 3 seasons. Of this there were 4 eddies each in summer and fall intermonsoon (3 cyclonic and 1 anticyclonic), and 5 eddies (3 cyclonic and 2 anticyclonic) in spring intermonsoon. To confirm these features and to further understand their evolution, satellite altimeter data were utilized. The Topex/Poseidon, ERS merged sea-level anomalies obtained from AVISO-CNES were analyzed and in the following section.

4.3 Evolution of eddies from T/P ERS merged sea-level anomalies.

From the above analysis it is clear that the doming found at 18°N in the thermohaline structure during summer monsoon was not evident in the SLA snapshots. Again, the doming found at 18°N in the thermohaline structure during fall intermonsoon was found to be a part of the large scale negative sea-level anomaly, and not a mesoscale feature. Similarly, the depression found at 18°N during spring intermonsoon too was a part of the large scale positive sea-level anomaly. Hence no attempt was made to describe these 3 features out of the 13.

4.3.1 Summer monsoon 2001

4.3.1.1 Cyclonic eddy centered at 9°N (CES1)

Important features in the southern BOB during summer monsoon 2001 was the Sri Lankan dome formed by the positive wind-stress curl [Vinayachandran *et al.*, 1998] and the westward propagating anticyclonic vortices [Sengupta *et al.*, 2001]. These anticyclonic vortices are hypothesized to be formed by the interaction of south west Monsoon currents with the west ward propagating Rossby waves [Sengupta *et al.*, 2001]. The cyclonic eddy at 9°N (CES1) was formed during the last week of June 2001 centered about 9°N, 87°E (Figure 3.3.2.5). As the anticyclonic vortex approached closer the SLD, CES1 got intensified and moved northeast following the contours of the anticyclonic vortex during the first week of July and then to southeastward. This cyclonic eddy was sampled in the hydrographic section when it was centered approximately on 10°N, 88°E during the second week of July (Figure 3.3.2.6, top left). The CES1 dissipated by the

first week of August (Figure 3.3.2.6, bottom left). Through out its life time the CES1 was characterized by a sea-level anomaly of -2 to -16 cm and geostrophic velocity anomaly of ~ 10 - 20 cm/s. However, the southern limb of CES1 was characterized by higher velocities (~ 60 cm/s) because the eastward velocity augmented by the eastward velocity component of the anticyclonic vortex.

4.3.1.2 Cyclonic eddy centered at 16°N (CES2)

Signature of a cyclonic circulation was found centered about 15°N 89.5°E during the first week of May 2001 (Figure 3.3.2.3). This was characterized by a negative SLA of 6 cm and geostrophic velocity anomaly of ~ 20 cm/s. However, the western limb of this cyclonic circulation was characterized by higher velocities due to an anticyclonic circulation was found west of it, and the cyclonic circulation intensified in the following weeks. One cyclonic eddy centered about 17°N 88°E , splitted from NCE appeared to have coalesced with this by the third week of May (Figure 3.3.2.4). This forms the CES2 during summer monsoon 2001. Subsequently, CES2 increased in size and displaced northward by 0.5 degrees by last week of June (Figure 3.3.2.5). During this time CES2 was characterized by a SLA of ~ -30 cm and geostrophic velocity anomaly of 40-50 cm/s. Subsequently, it moved northwestward and was found to coalesce with NCE 2001 centered at 16.5°N 84°E . This made it into an elongated structure extending from 15 to 17°N meridionally and 83 to 88°E zonally with two distinct centers (Figure 3.3.2.6). During the time of sampling (Figure 3.3.2.6, last week of July] CES2 was characterized by an SLA of ~ -30 cm and geostrophic velocity anomaly of ~ 40 - 50 cm/s.

4.3.1.3 Cyclonic eddy centered at 19°N (CES3)

A cyclonic circulation was formed centered about 18.6°N 91.5°E during the last week of May 2001 (Figure 3.3.2.4) and was characterized by a sea-level anomaly of -6 cm and geostrophic velocity anomaly of approximately 20-30 cm/s. This cyclonic circulation propagated into the western BOB. During the second week of July this was intensified and characterized by a sea-level anomaly of approximately -12 cm and geostrophic velocity anomaly of ~ 30-40 cm/s (Figure 3.3.2.6) and progressed further westwards to reach 86°E by September 2001. This feature was characterized by a sea-level anomaly of -8 cm and geostrophic velocity anomaly of approximately 20-30 cm/s. In the last week of July when the eddy was sampled it was elongated and extended approximately from 88° to 92°E zonally and 18° to 20°N meridionally (Figure 3.3.2.6, bottom left). By August this feature started diminishing.

4.3.2 Fall intermonsoon 2002

4.3.2.1 Cyclonic eddy centered at 9°N (CEF1)

In the first week of September 2002, a weak cyclonic circulation was observed in the northeast of an anticyclonic vortex centered about 9.5°N 87°E and close to SLD (Figure 3.3.3.1, top left). As the anticyclonic vortex moved further westward by the second week of September, the cyclonic circulation got intensified and moved southeastward. Unlike the CES1, this became a fully developed cyclonic circulation during the second week of September and was characterized by a sea-level anomaly of -14 cm and geostrophic velocity anomalies of approximately 30-40 cm/s (Figure 3.3.3.1, bottom left). This was the closest date matching with the hydrographic sampling from the ship. By 3rd week of

September, another weak anticyclonic circulation was seen approaching the western Bay and with this the cyclonic circulation dissipated.

4.3.2.2 Anticyclonic eddy centered at 12°N (ACF2)

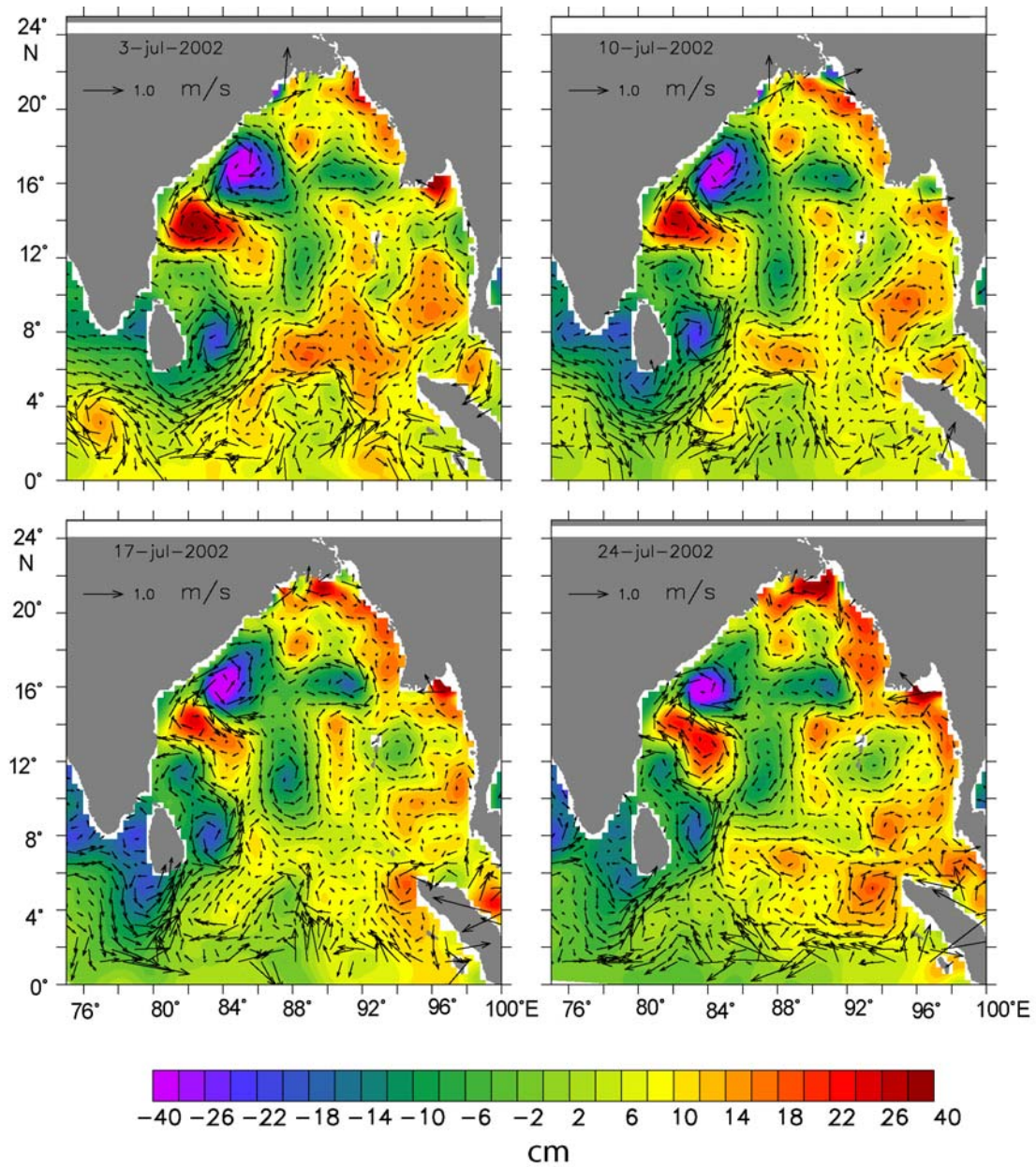


Figure 4.3.2.2.1 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during July 2002.

The depression noted in the thermohaline structure was an anticyclonic eddy pinched-off from a large positive sea-level anomaly formed in the western Andaman region during last week of July 2002 (Figure 4.3.2.2.1) and was characterized by a positive sea-level anomaly of 16 cm and geostrophic velocity anomaly of ~30-40 cm/s. This anticyclonic eddy propagated into the western BOB and was sampled during the third week of September (Figure 3.3.3.1), when it was characterized by a sea-level anomaly of 12 cm and geostrophic velocity anomaly of 20-30 cm/s. By the last week of October the feature started dissipating (Figure 3.3.3.2).

4.3.2.3 Cyclonic centered at 14°N (CEF3)

A cyclonic circulation was developed during the first week of June centered about 17°N and 91°E with a negative SLA of about 8 cm and geostrophic velocity anomaly of about 20 cm/s (Figure 4.3.2.3.1). SLA picture showed that this cyclonic circulation got elongated by last week of June. This elongation appeared to be a result of coalescence of this cyclonic eddy with another one centered at 16°N, 93°E. This forms the CEF3 during fall intermonsoon. Two centers of low SLA could be seen in this elongated CEF3. One centered about 90°E 17°N another one centered about 93°E 16°N. By the first week of July these two centers disappeared and appeared as an elongated cyclonic circulation (Figure 4.3.2.2.1) extending from 89° to 93°E and from 15° to 18°N. The center of CEF3 shifted eastwards to 16°N 91°E by second week of July and was characterized by a SLA of about -30 cm and geostrophic velocity anomaly of ~40 cm/s. By third week of August it intensified and moved westwards (Figure 4.3.2.3.2). Later, by last week of

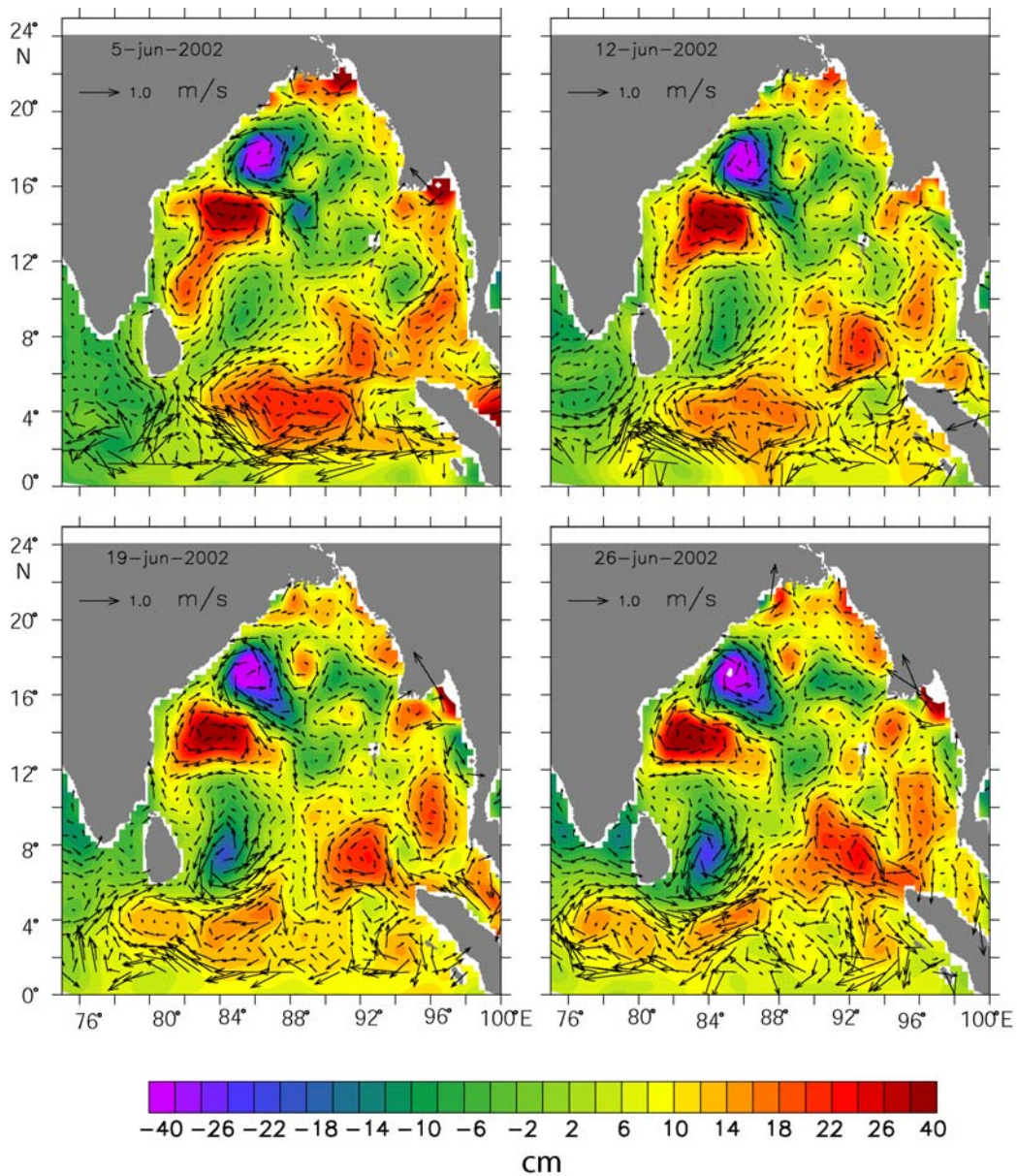


Figure 4.3.2.3.1 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during June 2002.

September CEF3 coalesced with a cyclonic eddy and became a part of large cyclonic circulation that prevailed in the western BOB during fall intermonsoon 2002.

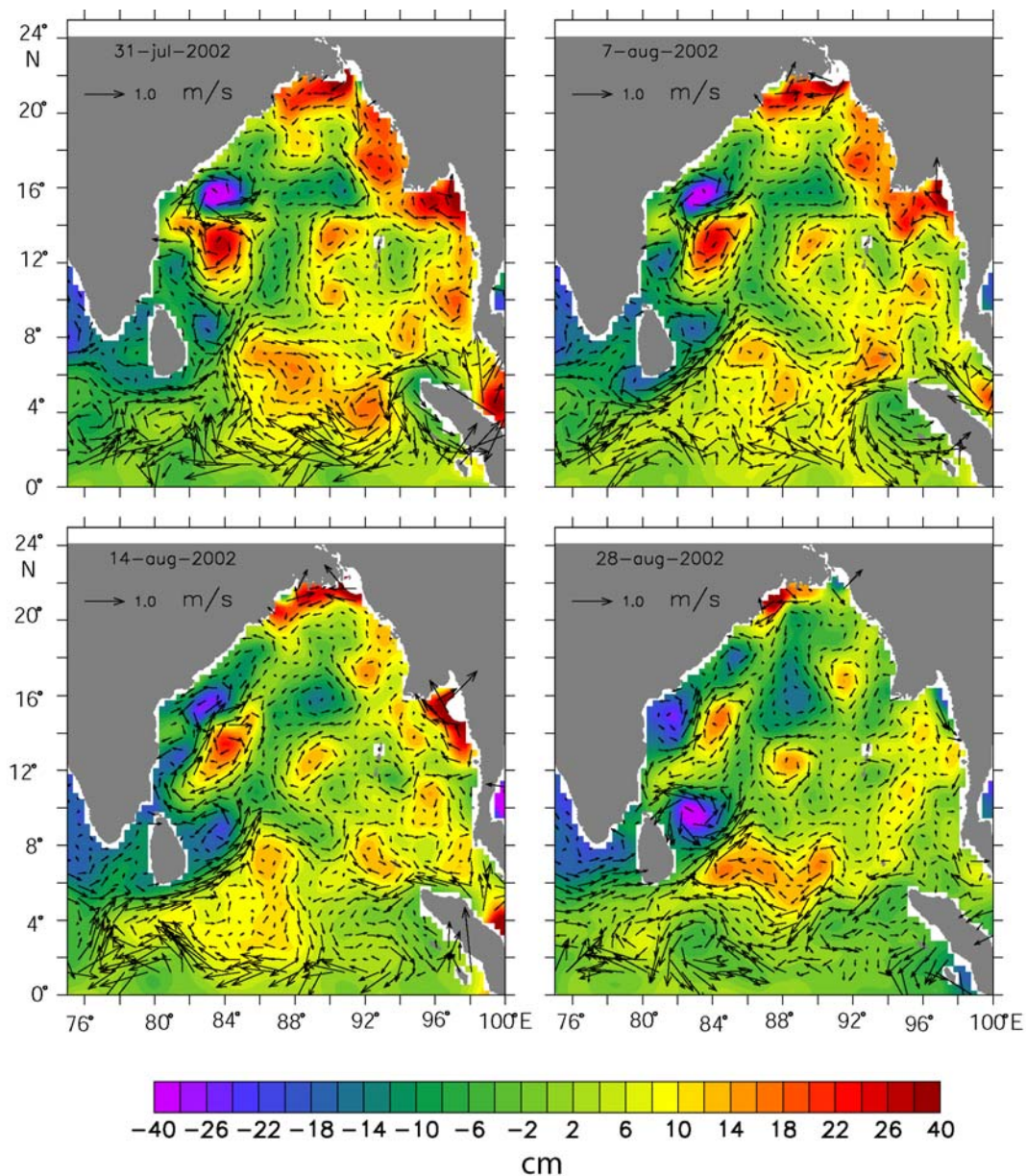


Figure 4.3.2.3.2 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during August 2002.

4.3.3. Spring intermonsoon 2003

4.3.3.1. Cyclonic eddy centered at 11°N (CESP1)

Signatures of a cyclonic circulation could be seen centered about 11°N 90.5°E by first week of April 2003 (CESP1) (Figure 3.3.1.3, top left). During this time CESP1 was

characterized by a SLA of -10 cm and geostrophic velocity anomaly of ~ 25 cm/s. This translated westward and was sampled on 19th April (Figure 3.3.1.3, bottom left). This feature disappeared completely by the end of April 2003 (Figure 3.3.1.4, top left).

4.3.3.2 Anticyclonic eddy centered at 13°N (ACSP2)

An anticyclonic circulation (ACSP2) was developed centered about 15°N and 91.5°E by third week of February 2003 (Figure 3.3.1.1) with a positive SLA of 8 cm and geostrophic velocity anomaly of ~ 25 cm/s. Subsequently it moved southwestward and intensified by early April (Figure 3.3.1.3, top left). During this time it was centered at 14°N and 90°E and characterized by a SLA of 12 cm and geostrophic velocity anomaly of ~ 30 cm/s. By the end of April, ACSP2 moved southwest ward and reached 88°E . During the time of sampling its center was located at 13.5°N and 88.5°E . ACSP2 later merged with the large scale positive sea-level anomaly (figure 3.3.1.4, bottom left).

4.3.3.3 Cyclonic eddy centered at 16°N (CESP3)

A cyclonic circulation was formed with its centre at 17.5°N 93°E during the first week of Jan 2003 (CESP3) (Figure 4.3.3.3.1). This was characterized by a SLA of -16 cm and geostrophic velocity anomalies of about 25 cm/s. West to this negative SLA, prominent anticyclonic circulation was seen. After formation, CESP3 moved westwards and reached 92°E by third week of January 2003. As it continued its westward movement it elongated meridionally during February (Figure 3.3.1.1) and reduced its meridional extent during March (Figure 3.3.1.2). By the end of March CESP3 was located at 17°N 89°E with an SLA of -14 cm and with geostrophic velocity anomaly of about 25 cm/s.

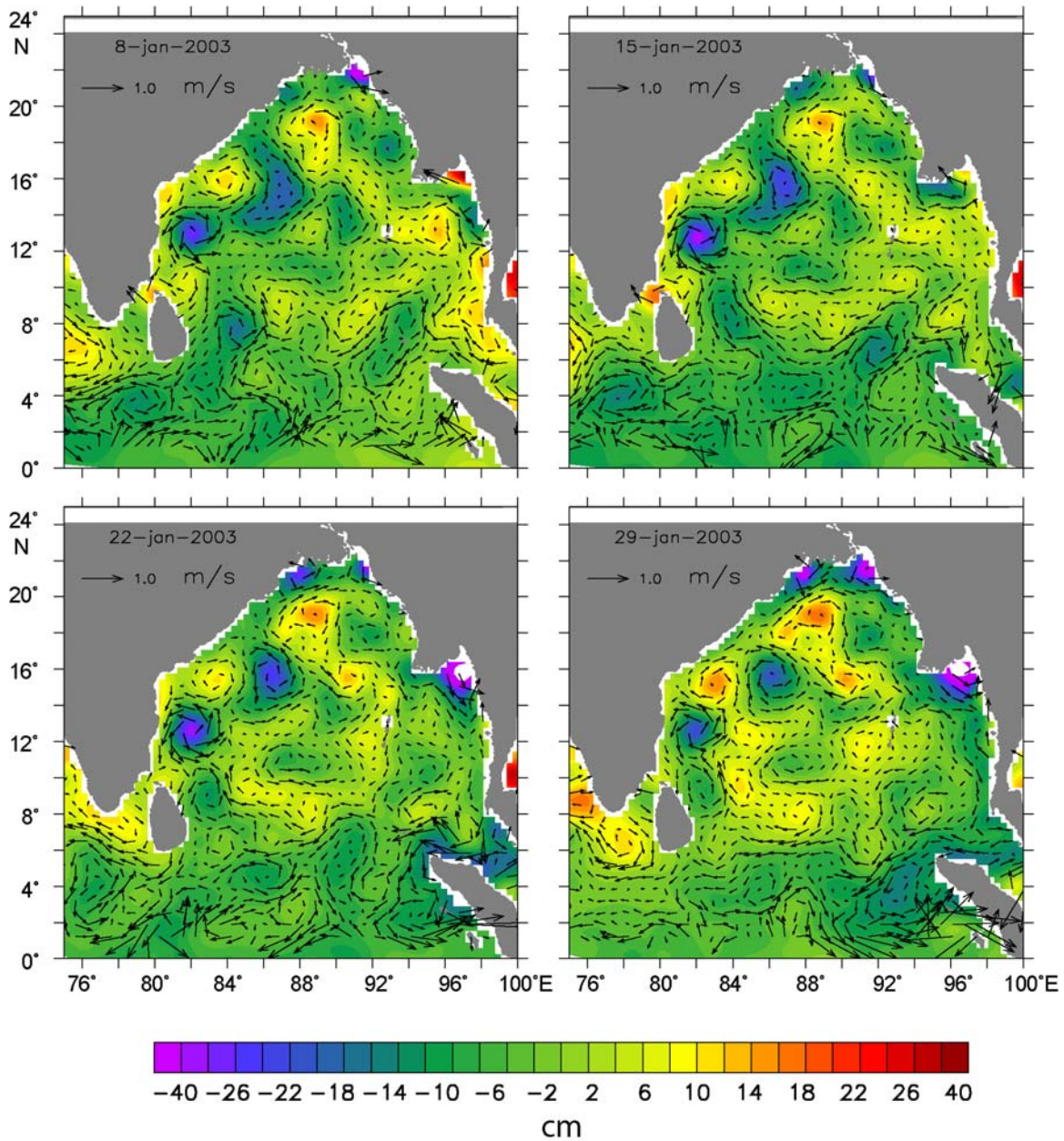


Figure 4.3.3.3.1 7-day snap-shots of Topex/Poseidon ERS1/2 merged sea-level anomalies overlaid with geostrophic velocities during January 2003.

The eddy showed a prominent southwestward translation during March possibly because of the southward flow associated with the anticyclonic circulation to its west. It was centered at 16°N 89°E during 23 April 2003, when eddy was sampled from the ship (Figure 3.3.1.3). It moved southwestward and coalesced with the northern coastal eddy (NCE) by the third week of May.

4.3.3.4. Cyclonic eddy centered at 19°N (CESP4)

The observed cyclonic circulation (CESP4) in the temperature/salinity field centered at 19°N was found to be formed during second week of April 2003 (Figure 3.3.1.3). This was centered at 19.75°N and 89.5°E and was characterized by SLA of -16 cm and geostrophic velocity anomaly of 25cm/s. This moved westwards and was centered at 19°N 88°E by third week of April. By first week of May this was intensified and was found to have a SLA of -40 cm and geostrophic velocity anomaly of 40-50 cm/s Figure 3.3.1.4). CESP3 further moved westward and reached the east coast by second week of July.

4.4. Mechanisms of generation

In the previous sections 10 eddies have been delineated and their evolution described based on the thermohaline structure as well as sea-level anomaly maps. From the analysis of hydrographic data during summer, fall intermonsoon and spring intermonsoon as well as the sea-level anomaly maps during 2001 to 2003 it has been found that eddies are ubiquitous in the BOB. A synopsis of the ten eddies studied in the previous sections of this chapter is given in the following Table.4.4.1. In chapter 3 (section 3.4) generating mechanism of eddies from the western boundary current has been examined. In the open BOB no such strong current exists any time of the year, except in the south during summer monsoon. In summer the southwest monsoon current enters the southern BOB via south of Sri Lanka as a strong and narrow jet (Figure 1.2.5). However, unlike the generation of NCE from the WBC, the formation

Table.4.4.1 Synopsis of the eddies encountered along central (88°E) BOB track during 2001 July to 2003 April obtained from the thermohaline structure and confirmed by satellite derived sea-level anomaly data .

Name of eddy	Time and year of formation	Location of formation	Type of eddy	Lifespan (months)
CESP3	January 2003	17.5°N, 93°E	Cyclonic	5
ACPS2	February 2003	15°N, 91.5°E	Anticyclonic	2
CESP1	April 2003	11°N, 91°E	Cyclonic	1
CESP4	April 2003	19.75°N, 89.5°E	Cyclonic	4
CES2	May 2001	15°N, 89.5°E	Cyclonic	3
CES3	May 2001	18.5°N, 91.5°E	Cyclonic	3
CES1	June 2001	9°, 87°E	Cyclonic	1
CEF3	June 2002	17°N, 91°E	Cyclonic	2
ACF2	August 2002	Western Andaman Sea	Anticyclonic	3
CEF1	September 2002	9.5°N, 87°E	Cyclonic	1

of CES1 and CEF1 was not associated with any meander in this jet (Figure 3.3.2.5 & Figure 3.3.3.1, and also see Figure 4.3.2.3.2). The factors responsible for the generation of eddy in the open BOB could be (1) direct atmospheric forcing, (2) topographic effect, and (3) breaking of Rossby waves [La Casce and Pedlosky, 2004; Chelton *et al.*, 2007]. Since all the eddies discussed above were found to occur in the upper 500 m of the water column, well away from the influence of the bottom topography, the possibility of topographic effect in generating these eddies may be discounted. In order to examine the role of direct wind forcing in the generation of eddies, the curl of the wind-stress was examined. In summer monsoon the curl of the wind-stress during June is positive (Figure 4.4.1). This large-scale cyclonic wind-stress curl drives the formation of SLD [Vinayachandran *et al.*, 1998]. During the same period, the downwelling Rossby wave propagates from eastern BOB towards west [Sengupta *et al.*, 2001] and could be located at ~ 90°E in the sea-level anomaly map as a high (Figure 3.3.2.5). Thus, the juxtaposition

of the cyclonic wind-stress curl driving the colder water towards the surface and the anticyclonic circulation

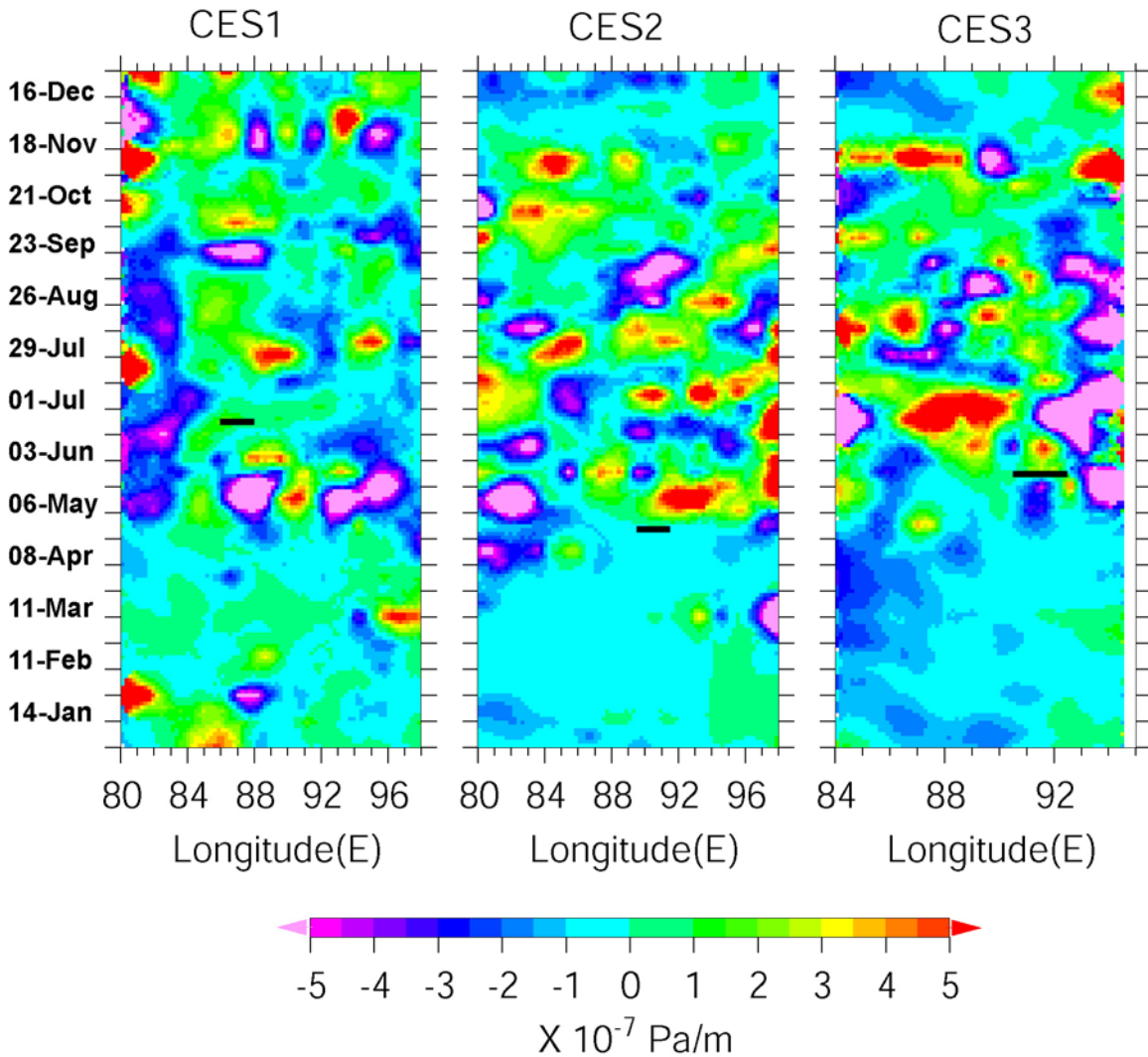


Figure 4.4.1 Curl of wind-stress obtained from QuickSCAT wind-stress (see chapter 2 for details) at the latitude of formation of eddies CES1(9°N), CES2 (15°N), and CES3 (18.5°N) for 2001. Thick horizontal line indicates the location and approximate zonal dimension of eddy.

associated with the Rossby waves driving the warm surface waters towards deeper levels, creates a strong horizontal density gradient leading to vertical shear, a necessary condition for the generation of baroclinic instability. Hence, it would seem that the formation of CES1 in June 2001, as inferred from the time evolution of sea-level

anomaly maps and the wind-stress curl, was linked to this process. The plausible mechanism of generation of CES2 and CES3 in the north ($\sim 15^{\circ}\text{N}$ & 18.5°N) during May 2001 is the following. At both these locations a strong positive sea-level anomaly adjacent to a weak negative sea-level anomaly was noticed (Figure 3.3.2.4). The wind-stress curl changed from negative to positive at the locations of CES2 and CES3 at the first and last week of May 2001 respectively (Figure 4.4.1). This cyclonic wind-stress curl augments the negative sea-level anomaly which in turn can intensify the horizontal density gradient and can lead to vertical shear leading to baroclinic instability, and generates the cyclonic eddy.

During the formation of CEF1 in September 2002, though the wind-stress curl was anticyclonic (Figure 4.4.2), the negative sea-level anomaly associated with SLD was most intense (-40 cm). Adjacent to SLD, a strong positive sea-level anomaly (25 cm) associated with the Rossby wave propagation was also seen (Figure 3.3.3.1). Thus, it appeared that the strong horizontal density gradient necessary for the formation of cyclonic eddy in September 2002 arises due to the strong upward pumping of colder waters by the SLD and downwelling of warmer surface waters under the influence of anticyclonic circulation associated with Rossby waves. This condition was similar to that of the formation of CES1, except that the wind-stress curl in the latter case was cyclonic and strength of SLD was much weaker.

The formation of ACF2 in July 2002 can be explained in the context of curl of the wind-stress and sea-level anomaly. During the formation of the anticyclonic eddy (ACF2) in the mid of July, curl of the wind-stress was negative (Figure 4.4.2) and the sea-level

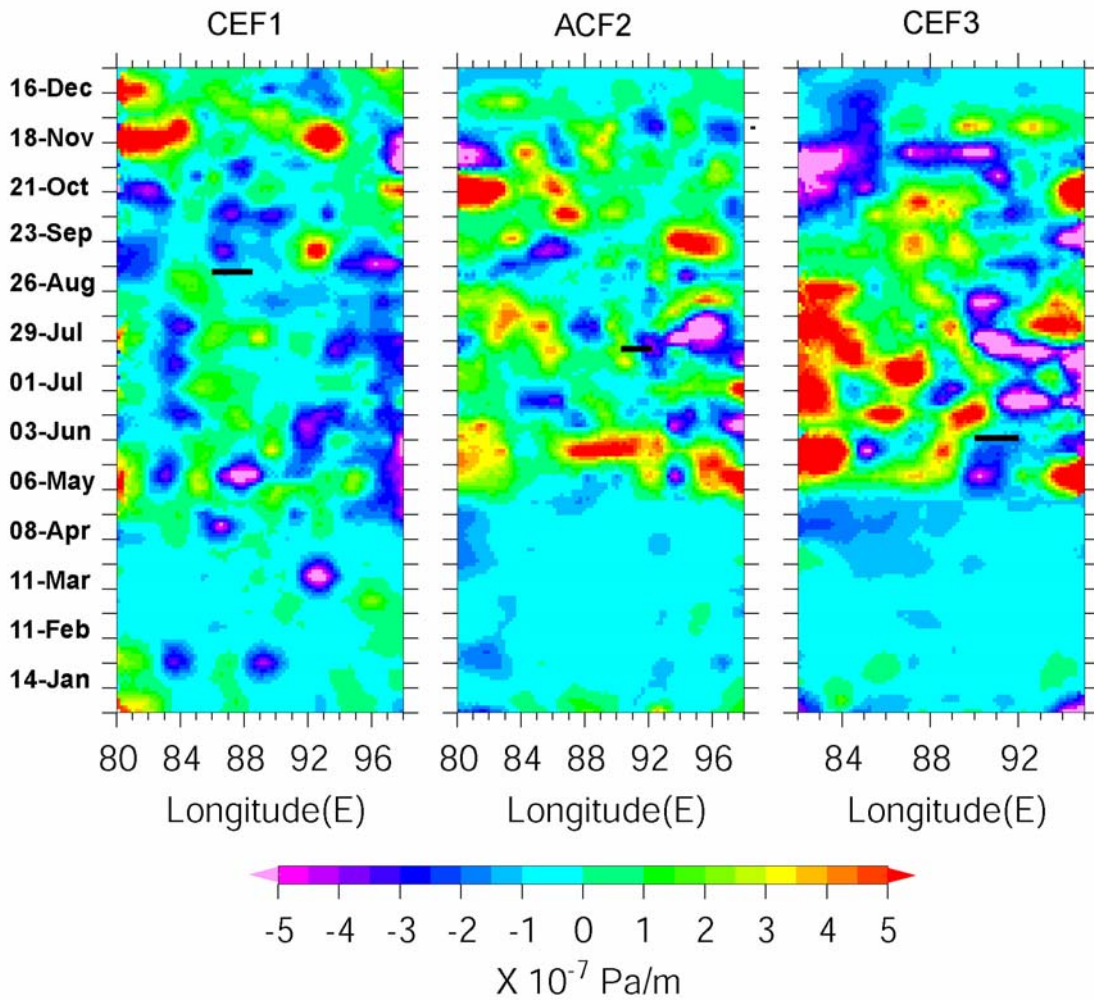


Figure 4.4.2 Curl of wind-stress obtained from QuickSCAT wind-stress (see chapter 2 for details) at the latitude of formation of eddies CEF1(9.5°N), ACF2 (13.5°N), and CEF3 (17°N) for 2002. Thick horizontal line indicates the location and approximate zonal dimension of eddy.

anomaly was positive (Figure 4.3.2.3.2). However, towards the west of the positive sea-level anomaly a negative sea-level anomaly was noticed. Thus, the zonally organized positive and negative sea-level anomaly drives a horizontal gradient in density field and the anticyclonic wind-stress curl further augments the positive sea-level anomaly, thereby creating the necessary instability for the generation of the ACF2.

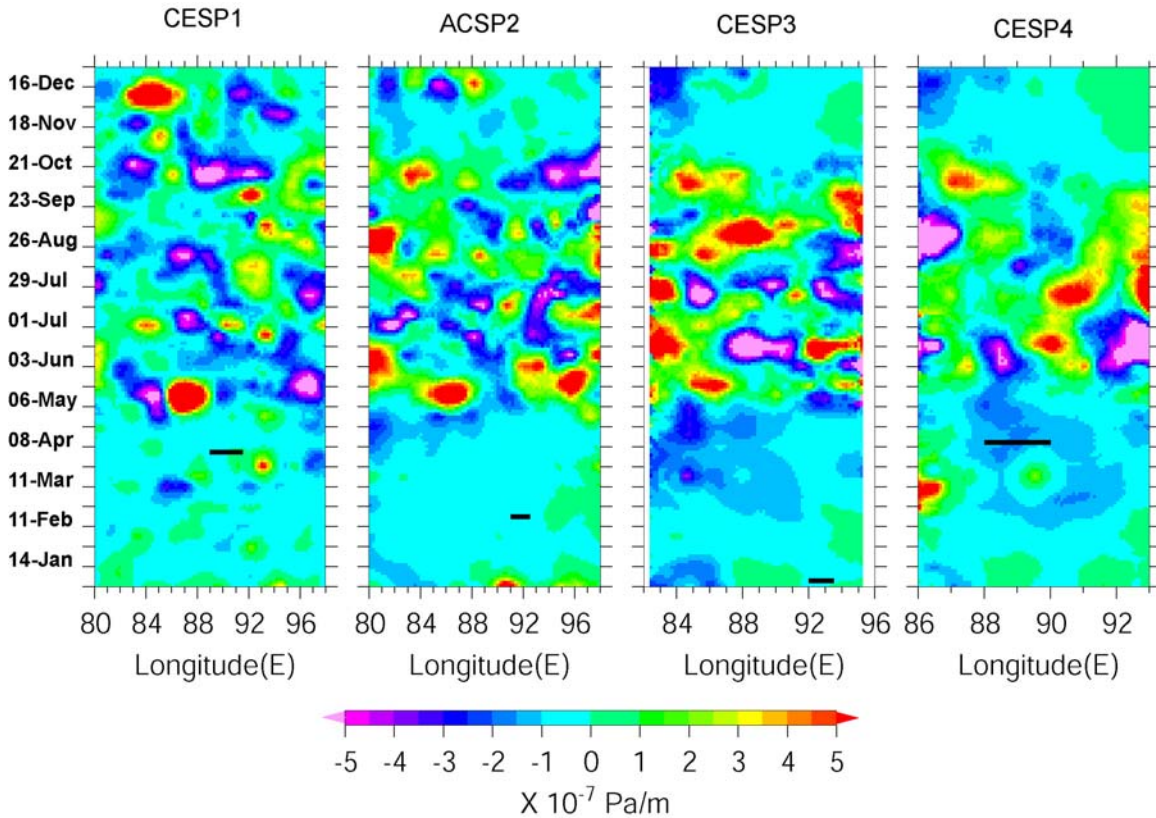


Figure 4.4.3 Curl of wind-stress obtained from QuickSCAT wind-stress (see chapter 2 for details) at the latitude of formation of eddies CESP1 (11°N), ACSP2 (15°N), CESP3 (17.5°N), and CESP4 (19.75°N) for 2003. Thick horizontal line indicates the location and approximate zonal dimension of eddy.

In the case of CEF3, the condition that existed during the formative period is the following. At the latitude where CEF3 was developed, a negative sea-level anomaly co-existed with positive sea-level anomaly to its east. Note that the magnitude of the negative sea-level anomaly is small (Figure 4.3.2.3.1). This condition could give rise to a horizontal density gradient in the zonal direction. However, the anticyclonic wind-stress

curl at this time near the generating region of CEF3 (Figure 4.4.2) would decrease the gradient by weakening the negative sea-level anomaly. Hence, it is not clear what would have caused the generation of CEF3. The condition is similar to that existed during the formation of CES3, except that the wind-stress curl was augmenting the negative sea-level anomaly.

The wind-stress curl in the region of formation of CESP1, ACSP2, CESP3 and CESP4 was weakly negative (0 to -1×10^{-7} Pa/m) during January to April (Figure 4.4.3). During this period propagation of an upwelling Rossby wave was discernible in the form of low sea-level anomaly (Figure 4.4.4). This would induce a cyclonic vorticity into the water column which is acted upon by a weak anticyclonic wind-stress curl. Thus it is not possible to attribute an instability mechanism based on the action of wind-stress curl and propagating Rossby wave during January till April 2003. This warrants other mechanisms such as breaking of Rossby waves [La Casce, 2004, Isachsen et al., 2006] to explain the eddy formation in the open waters of the BOB. An examination of the time-latitude plot of the sea-level anomaly, where the CESP3 and CESP1 were generated, showed that the Rossby wave propagation is not continuous (Figure 4.4.4), which could be an indication of this.

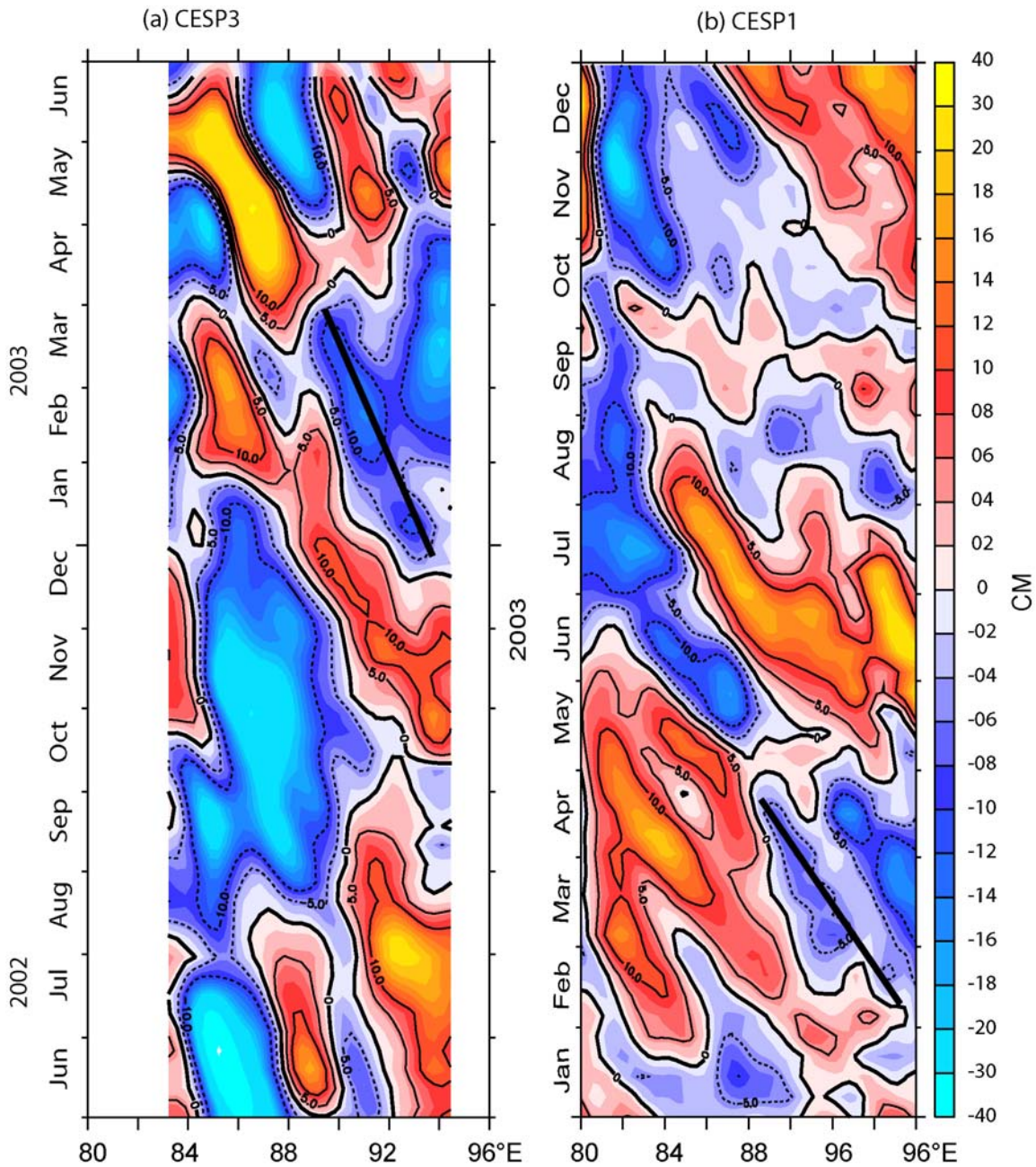


Figure. 4.4 4. Rossby wave propagation at the location of formation of (a) CESP3 (17.5°N) and (b) CESP1 (11°N).

4.5 Summary

Based on the thermohaline structure along the central BOB 10 mesoscale features (both cyclonic and anticyclonic eddies) were identified and confirmed with the satellite derived sea-level anomaly maps. These eddies changed the ambient temperature by about 2°C.

However, the changes in the salinity field due to these eddies were much smaller, < 1 psu. In the north, where the influence of river discharge dominates, the eddy was confined below the strongly stratified upper layer. The life span of eddies varied from a month as in the case of southern eddies to about 4-5 months as in the case of cyclonic eddy during spring intermonsoon in the north (CESP3).

The time evolution of these eddies based on sea-level anomaly maps showed that, in general, they originated east of the central BOB transect and moved in a westward direction. However, the eddy encountered in the SLD region, was found to be generated locally. Unlike their coastal counterparts, eddies encountered in the open waters of the BOB were not formed from any meander of current. It has been found that direct wind forcing alone cannot explain the formation of all eddies. The generation of eddy in most of the observed 10 cases could be explained in the context of the interaction between the wind-stress curl and propagating Rossby wave. In the southern BOB, during summer and fall intermonsoon the upward pumping of cold and high salinity waters within the Sri Lanka dome (SLD) under the influence of cyclonic wind-stress curl and the sinking of warm and low salinity waters under the influence of high sea-level anomaly (Rossby wave) creates the necessary horizontal density gradient to cause baroclinic instability and generate cyclonic eddy. In the northern BOB, during summer monsoon, CES2 and CES3 was generated under the presence of cyclonic wind-stress curl acting upon the existing large-scale positive and negative sea-level anomaly. The large scale positive and negative sea-level anomaly preconditions and creates initial zonal gradient in density and the action of cyclonic wind-stress curl provides the necessary trigger for the instability

and generation of eddy. This large scale positive and negative sea-level anomaly may arise due to several reasons. In the case of CES2 it was the propagating upwelling Rossby wave and the anticyclonic circulation to its west, while in the case of CES3 it was the coastally trapped Kelvin wave in the eastern region and the relatively weak negative sea-level anomaly to the west. During fall intermonsoon the generation ACF2 is similar to that of CES2 with the difference that a positive sea-level anomaly (downwelling Rossby wave) towards the east and negative sea-level anomaly towards the west. The wind-stress curl at the location of eddy changes to anticyclonic. In the spring intermonsoon, the wind-stress curl and the sea-level anomaly created by the propagating Rossby wave cannot explain the generation of observed eddies.