

## Chapter 5 - Role of eddies in hydrography and circulation

### 5.1. Introduction

Examination of thermohaline structure and the satellite sea-level anomaly in the previous chapters showed that eddies are ubiquitous in the BOB. Thermohaline structure showed that the isopycnals can be displaced significantly within the eddy. This results in increase/decrease of temperature (average of 2°C, in case of NCE 2003 this was 6°C) and salinity (~0.3 to 1 psu) at the locations of anticyclonic and cyclonic eddies. Evolution of these features studied using satellite sea-level anomalies showed that they have a life span of 1-5 months. In all ten such eddies in the open ocean, three during summer monsoon- CES1(9°N), CES2 (16°N), CES3(19°N), three during fall intermonsoon- CEF1(10°N), ACF2 (12°N), CEF3(14°N) and four during spring intermonsoon- CESP1 (11°N), ACSP2(13°N), CESP3 (16°N) and CESP4 (19°N), have been studied. In addition 5 cyclonic eddies were identified along the western boundary, 2 (NCE & SCE) each during spring and fall intermonsoons and one in summer (NCE). The aim of this chapter is to examine the impact of eddy-induced changes in heat and salt content and transport. Heat and salt content were calculated as  $\iint \rho C_p T \, dz \, dy$  and  $\iint \rho S \, dz \, dy$  respectively, where  $\rho=1023 \text{ kg/m}^3$ ,  $C_p = 4187 \text{ J/Kg/C}$ ,  $T$  is the temperature and  $S$  salinity. In addition to this heat and salt content anomaly also was calculated using  $\iint \rho C_p (T - T_r) \, dz \, dy$  and  $\iint \rho (S - S_r) \, dz \, dy$ , where  $T_r$  and  $S_r$  are climatological monthly mean corresponding to the time period of observation obtained from WOA01 climatology [Conkright et al., 2002]. The volume transport was estimated as  $\iint v \, dz \, dy$ , while the heat and salt transport by  $\iint v \rho C_p T \, dz \, dy$  and  $\iint v \rho S \, dz \, dy$  respectively, where  $v$  is the cross track velocity,  $dz$  and  $dy$  are the depth interval and along-track station spacing.

The uncertainty associated with the temperature and conductivity measurements are 0.001°C and 0.0003 S/m respectively. This would translate into an error of 0.003 psu in salinity measurements and would result in an error of approximately 1.7 cm/s in velocity in the south and about 1 cm/s in the north. When integrated over the top 150 m, this would result in an error of  $\sim 0.2$  Sv ( $Sv=10^6$  m<sup>3</sup>/s) in volume computations. The errors in the temperature and salinity would result in an error of  $\sim 7 \times 10^{10}$  J/m and  $5 \times 10^4$  Kg/m in the heat and salt content respectively, which are  $\sim 4$ -5 orders of magnitude less than the variability.

The Ekman transport along the transects was also computed to examine the wind-driven part of the volume transport. The wind for this purpose was taken from the surface meteorological data collected onboard at stations. The methodology of Ekman transport computation is described in chapter 2. As the geostrophic volume transport yields only the cross-track component, in the case of the Ekman volume transport also only across-track component is presented. Along the central BOB track this is  $\int(\tau_y/\rho f)dy$  where  $\tau_y$  is the meridional component of the wind stress  $dy$  the distance between the stations  $\rho$ , and  $f$  mean sea water density for upper 150 m of water column and the coriolis parameter respectively. However, along the western boundary between 19°N and 15°N  $\tau_y$  is rotated to about 45 degrees anticlockwise since the cruise track is roughly oriented in a northeast-southwest direction in this region. The results obtained are summarized in the following section.

## 5.2. Results

Heat content along the central BOB and western boundary are presented in Figure 5.2.1. and Figure 5.2.2. In general, the heat content integrated over 150 meters in the central

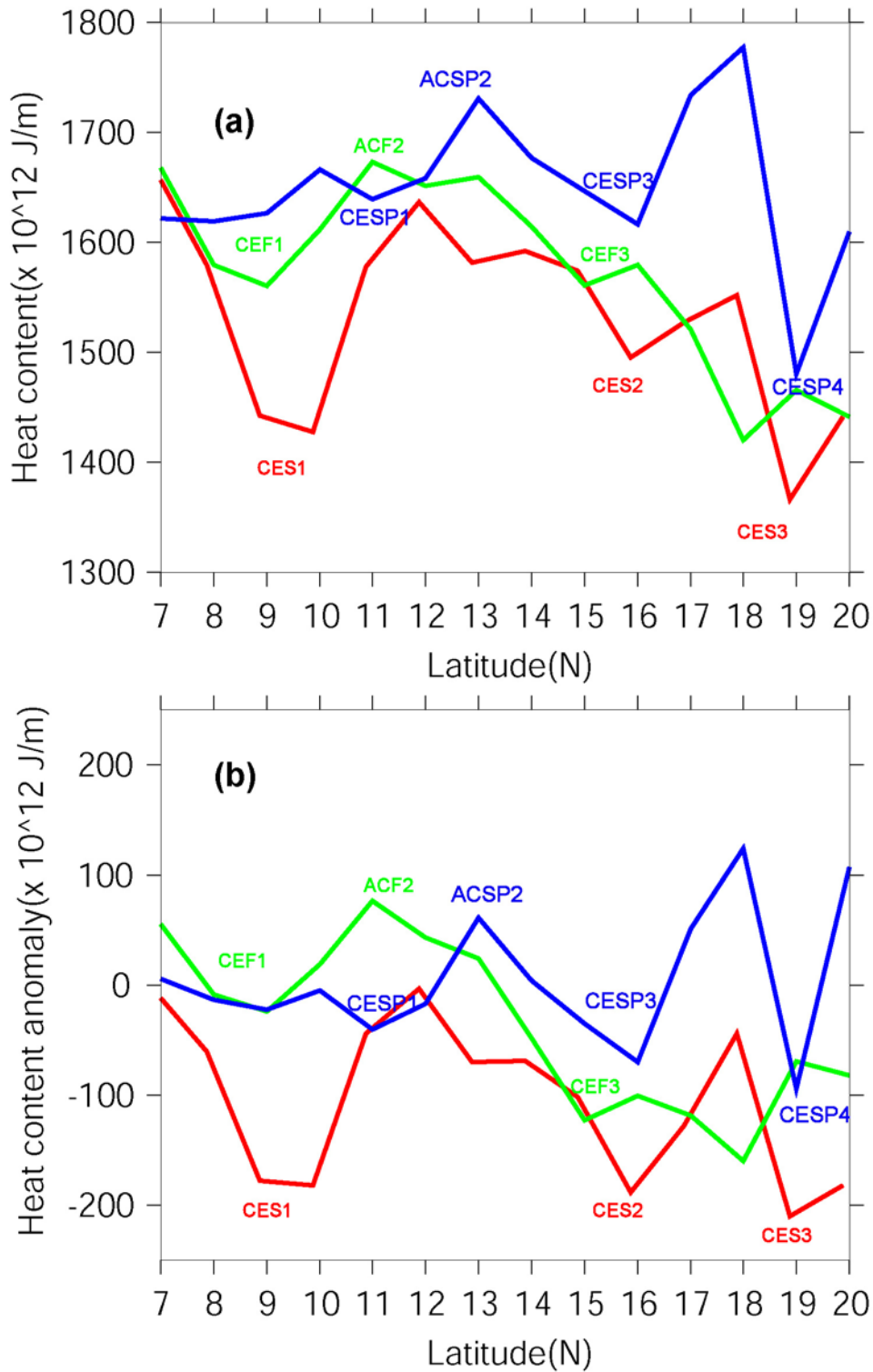


Figure 5.2.1. (a) Heat content and (b) heat content anomaly along the central (88°E) during — summer monsoon, — fall intermonsoon, — spring intermonsoon

BOB showed a northward decrease of about  $200 \times 10^{12}$  J/m (Figure 5.2.1a), except during spring intermonsoon. Apart from this general south – north decrease, the heat content varied dramatically at locations where the presence of eddies were identified in the earlier chapters. During summer monsoon a heat content deficit of about  $200 \times 10^{12}$  J/m (Figure 5.2.2) was encountered at the location of cyclonic eddies CES1, CES2 and CES3. During fall intermonsoon, however, the heat content deficit exhibited by the cyclonic eddies was much smaller,  $\sim 50 \times 10^{12}$  J/m for CEF1 and  $\sim 100 \times 10^{12}$  J/m for CEF3. In the case of anticyclonic eddy ACF2 the heat content increased by about  $100 \times 10^{12}$  J/m. The general south – north decrease in heat content found during summer and fall intermonsoon was not discernable during spring intermonsoon. Again, unlike that during summer and fall intermonsoon, the heat content during spring intermonsoon did not exhibit any significant variability in the south (south of  $15^{\circ}\text{N}$ ), except that eddy ACSP2 has increased the heat content by about  $50 \times 10^{12}$  J/m. In the north the heat content deficit associated with cyclonic eddy CESP3 and CESP4 were  $\sim 70$  and  $100 \times 10^{12}$  J/m respectively. The northward decrease in the heat content during summer and fall intermonsoon is associated with the general northward shoaling of isotherms along with the occurrence of cyclonic eddies which dominate the thermohaline structure. Another striking feature is an increase of  $\sim 150 \times 10^{12}$  J/m in the heat content at  $18^{\circ}\text{N}$  associated with an anticyclonic circulation as inferred from the SLA. The heat content along the western boundary did not show any definite south-north trend as in the case of the central BOB. However, in spring intermonsoon the heat content showed a southward decrease of about 150 to  $200 \times 10^{12}$  J/m (Figure 5.2.2). The most prominent feature in the heat content distribution in any season is the heat loss in the north (north of  $16^{\circ}\text{N}$ ) in the upper 150 m under the influence of the cyclonic eddy NCE and heat gain in the south associated with high SLA.

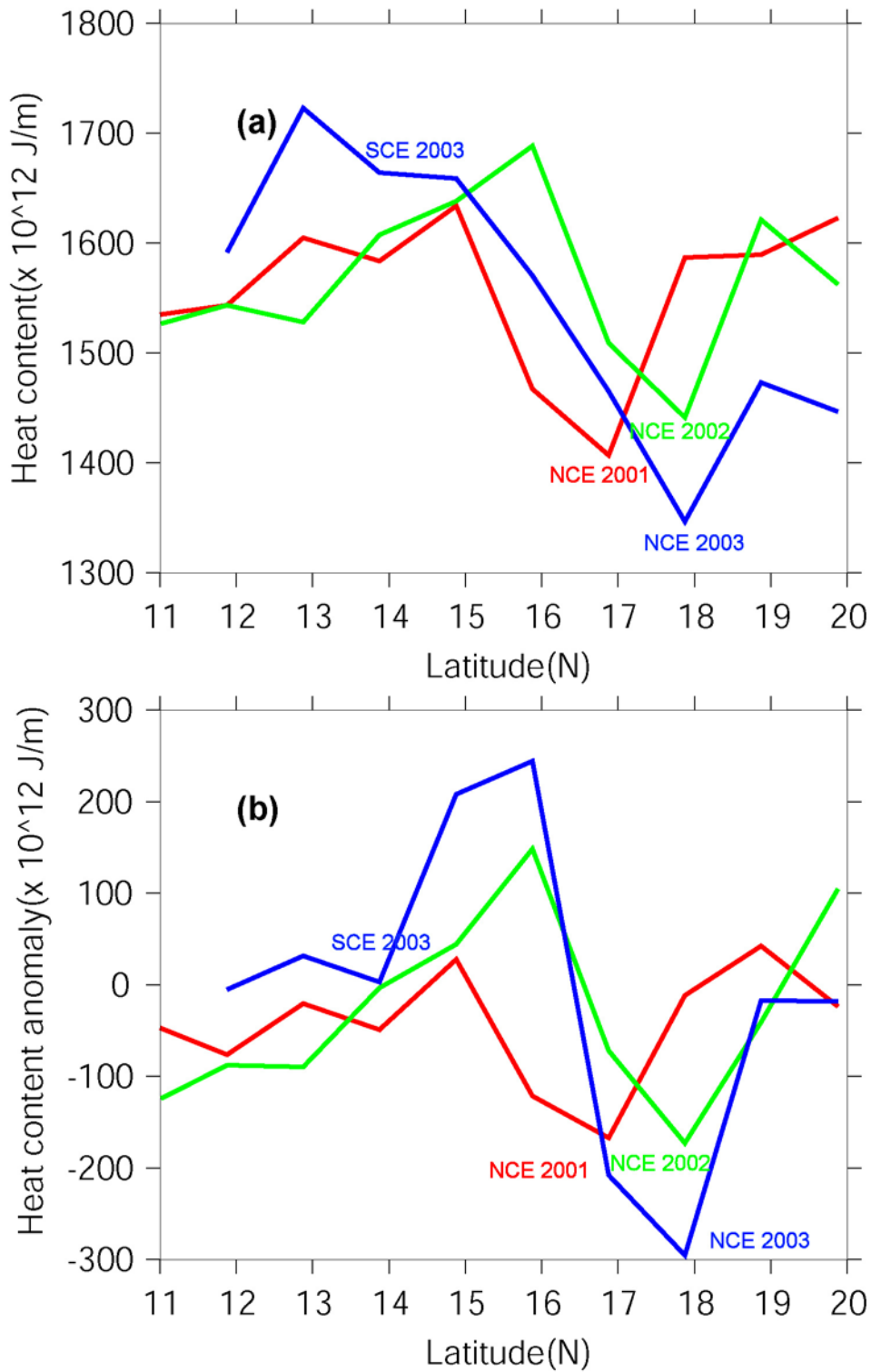


Figure 5.2.2. (a) Heat content and (b) heat content anomaly along the Western boundary BOB during — Summer monsoon, — Fall intermonsoon and — Spring intermonsoon.

Note that both heat gain and heat loss is almost of the same magnitude. Thus, along the western boundary, the cyclonic eddy NCE which is seen in the SLA in all the 3 seasons reduced the heat content of the upper water column. The gain in the heat content in the north during spring intermonsoon was associated with the large-scale circulation while that in summer and fall intermonsoon was associated with anticyclonic circulation which was the reminiscent of spring intermonsoon.

The salt content in the central BOB showed a progressive decrease from south to north in all the 3 seasons, except during spring where an increasing trend was noticed towards the north from 16°N onwards (Figure 5.2.3). The salt content during summer and fall intermonsoon was about 5 to 10 x 10<sup>6</sup> kg/m higher than that during spring intermonsoon in the south. However, towards the north (north of 16°N) salt content did not show much variability with season. The salt content anomaly predominantly showed the variability associated with eddy. The eddy-induced variability was highest during spring intermonsoon followed by fall intermonsoon. The northward increase of salt content anomaly (~20 x 10<sup>6</sup> kg/m) during fall intermonsoon was the effect of fresh water. However, the magnitude of the anomaly appears to be too large and it is because the WOA 2001 salinity is too fresher.

The salt content along the coast also showed a southward decrease, but only during summer and fall intermonsoon [Figure 5.2.4]. In spring intermonsoon no definite south-north trend was discernible. Two regions of large variability was noticed one centered at

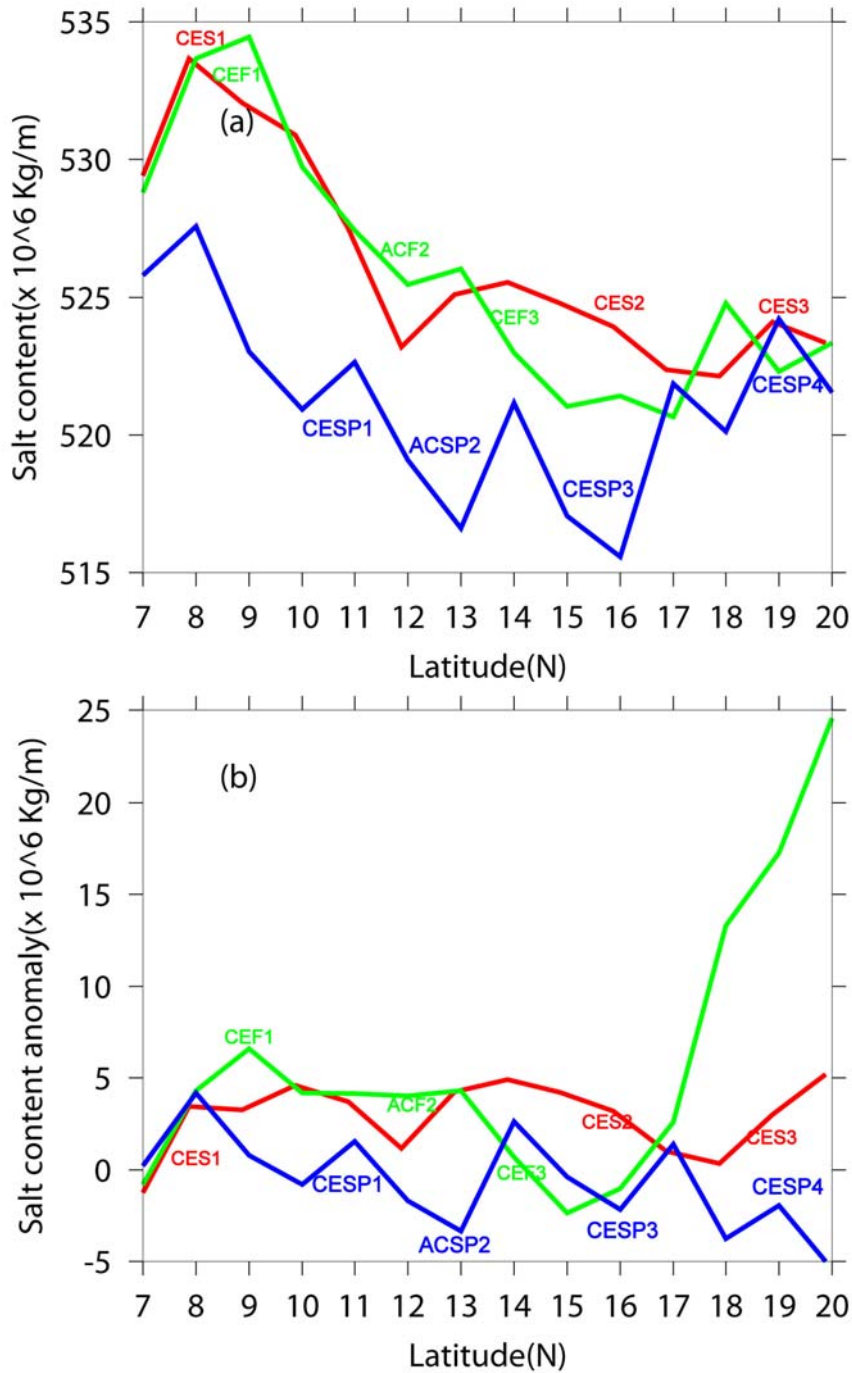


Figure 5.2.3. (a) Salt content and (b) salt content anomaly along central (88°E) BOB during — Summer monsoon — Fall intermonsoon and — Spring intermonsoon.

13°N and the other one at 17°N. From the salt content anomaly it is clear that eddy-induced variability was of lesser magnitude, unlike that manifested in the heat content anomaly. The reason for this lies in the fact that these cyclonic eddies are subsurface

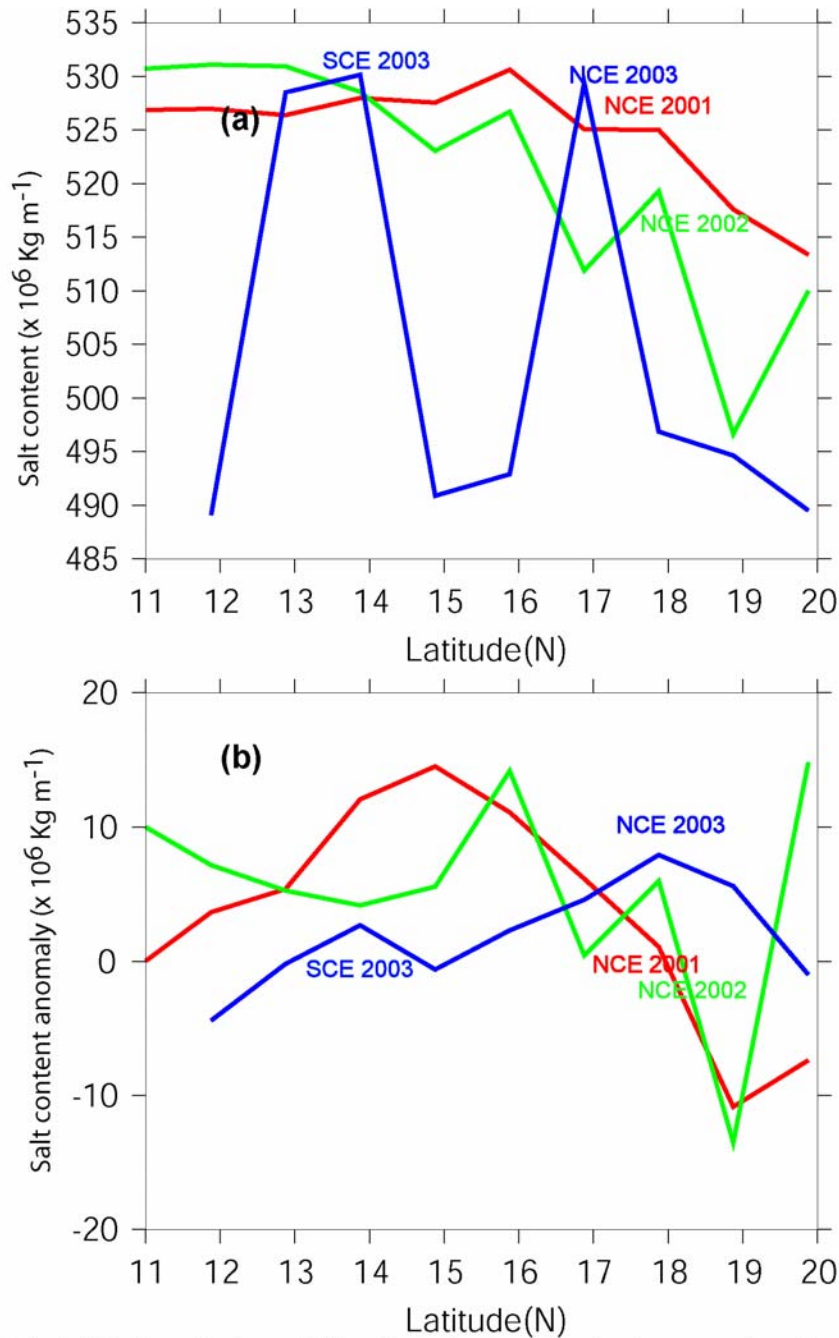


Figure 5.2.4. (a) Salt content and (b) salt content anomaly along western boundary of BOB during — Summer monsoon — Fall intermonsoon and — Spring intermonsoon.

features and lies below the upper halocline. Hence the up/down sloping of isohalines will not induce larger changes in the salt content of the water column due to eddy-pumping.

During summer and fall intermonsoon the fresher water layer extends up to 15-16°N, while during spring intermonsoon it is confined to the north. Thus, the eddy-induced



changes were more pronounced in the heat content changes rather than salt content changes and the reason for this lies in the characteristics of the BOB.

Apart from the eddy-induced vertical motions and associated changes in the heat and salt contents, there can also be changes in the water column due to horizontal advection of water. To understand this, volume transport along the central and western boundary of the BOB was computed and discussed below.

Volume transport due to wind-driven Ekman drift was much smaller compared (Figure 5.2.5 a & c) to the transport due to geostrophic currents, both along the central and the western boundary (Figure 5.2.5 b & d). The geostrophic volume transport (zonal) showed alternate bands of eastward and westward transports along the central BOB track (Figure 5.2.5d). These alternating bands are associated with the cyclonic/anticyclonic circulation of eddies as could be seen from their location. During summer monsoon enhanced transport of 7 Sv eastward and 5 Sv westward was noticed between 8 and 10°N. Another major fluctuation in the volume transport was noticed between 18 and 20°N. Both these locations coincides with the locations of eddies CES1 and CES3. During fall intermonsoon the eastward transport associated with CEF1 located at 9°N was less compared to the summer monsoon period. However, the westward transport was comparable to that of summer. Enhancement of transport can also be seen between 12 and 13°N, and 14 and 15°N, both coinciding with the location of eddies ACF2 and CEF3

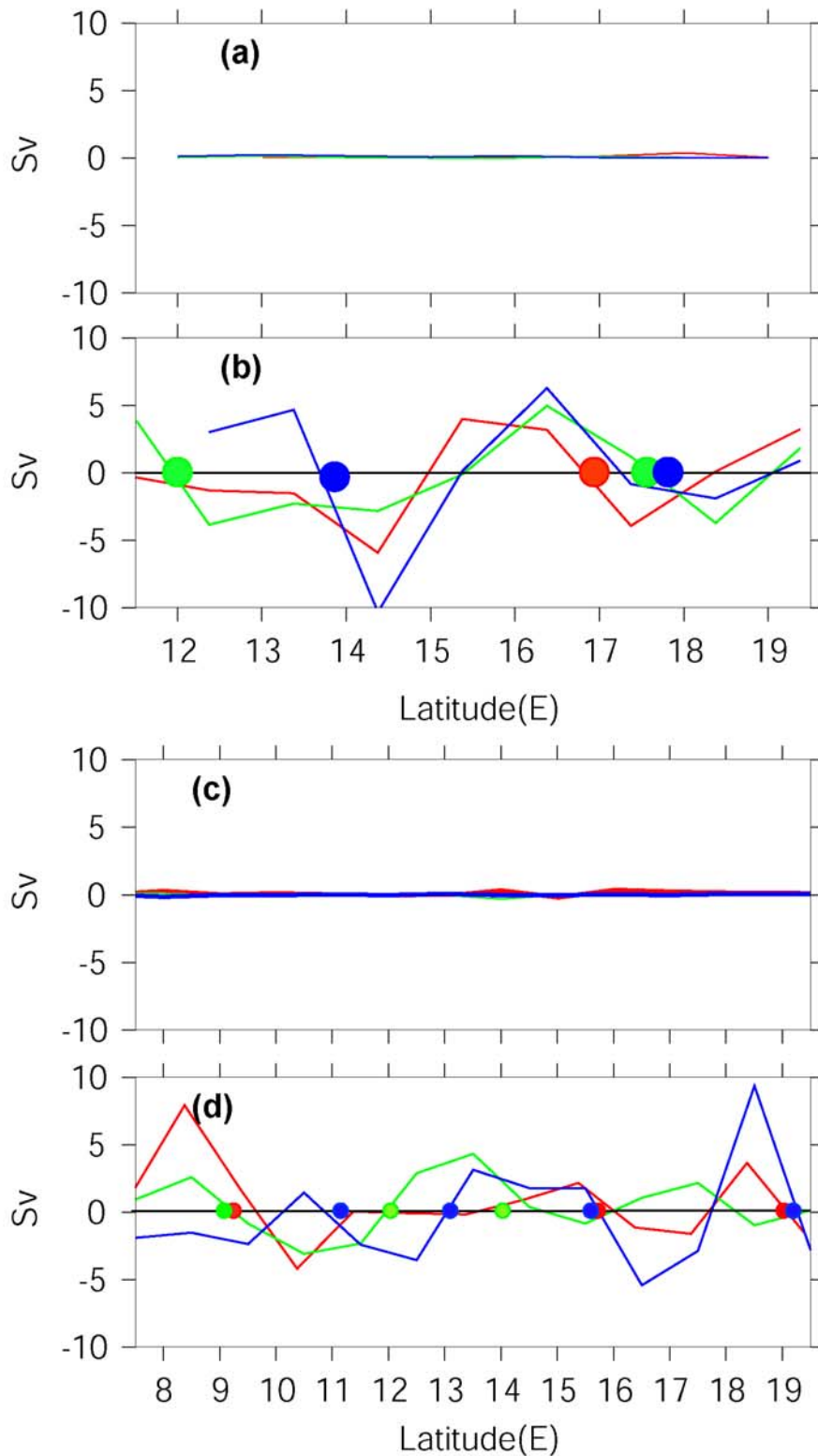


Figure 5.2.5. Volume transport integrated upto 150 m along central BOB(d), along the western boundary (b) along with the ekman transport along central BOB(c) and along the western boundary (a) during — summer monsoon, — fall intermonsoon and — spring inter monsoon. coloured circles indicate the centres of eddies during each season.

respectively. During spring intermonsoon, an increase in transport was found in the north between 18 and 20°N coinciding with the location of CESP4. Here the eastward transport was higher (~8 Sv) than the westward transport (~3 Sv). Another fluctuation in transport can also be found between 15 and 17°N coinciding with the location of CESP3. Along the coast (Figure 5.2.5b) also fluctuations can be seen w.r.t the center of NCE which had an eastward transport during spring (~2 Sv) and fall (~3 Sv) intermonsoons.

Another enhanced region of westward transport was found between 14 and 15°N during spring intermonsoon and summer. During spring intermonsoon this was associated with an anticyclonic circulation, which later developed into an anticyclonic eddy (see figure 3.3.1.4). There was another large variability in volume transport in the north between 13 and 14°N, associated with cyclonic eddy SCE. During summer also this onshore transport was noticed because of another anticyclonic circulation which persisted in the BOB from spring intermonsoon 2001 onwards (see figures 3.3.2). Thus, during all the seasons the geostrophic transport was dominated by eddies.

The heat and salt transport also followed the pattern of high variability (Figure 5.2.6) seen in the volume transport associated with eddies. The maximum heat transport in the open ocean transect (Figure 5.2.6b) was in the vicinity of CES1, CES3 during summer, and CESP4 in spring intermonsoon. CES1 had an eastward transport of about  $600 \times 10^{12}$  J/m/day and a westward transport of about  $300 \times 10^{12}$  J/m/day, whereas CES3 had an eastward and westward transport of about 300 and  $100 \times 10^{12}$  J/m/day respectively. In summer, the cyclonic eddy CES2 had an almost equal eastward and westward transport of  $100 \times 10^{12}$  J/m/day.

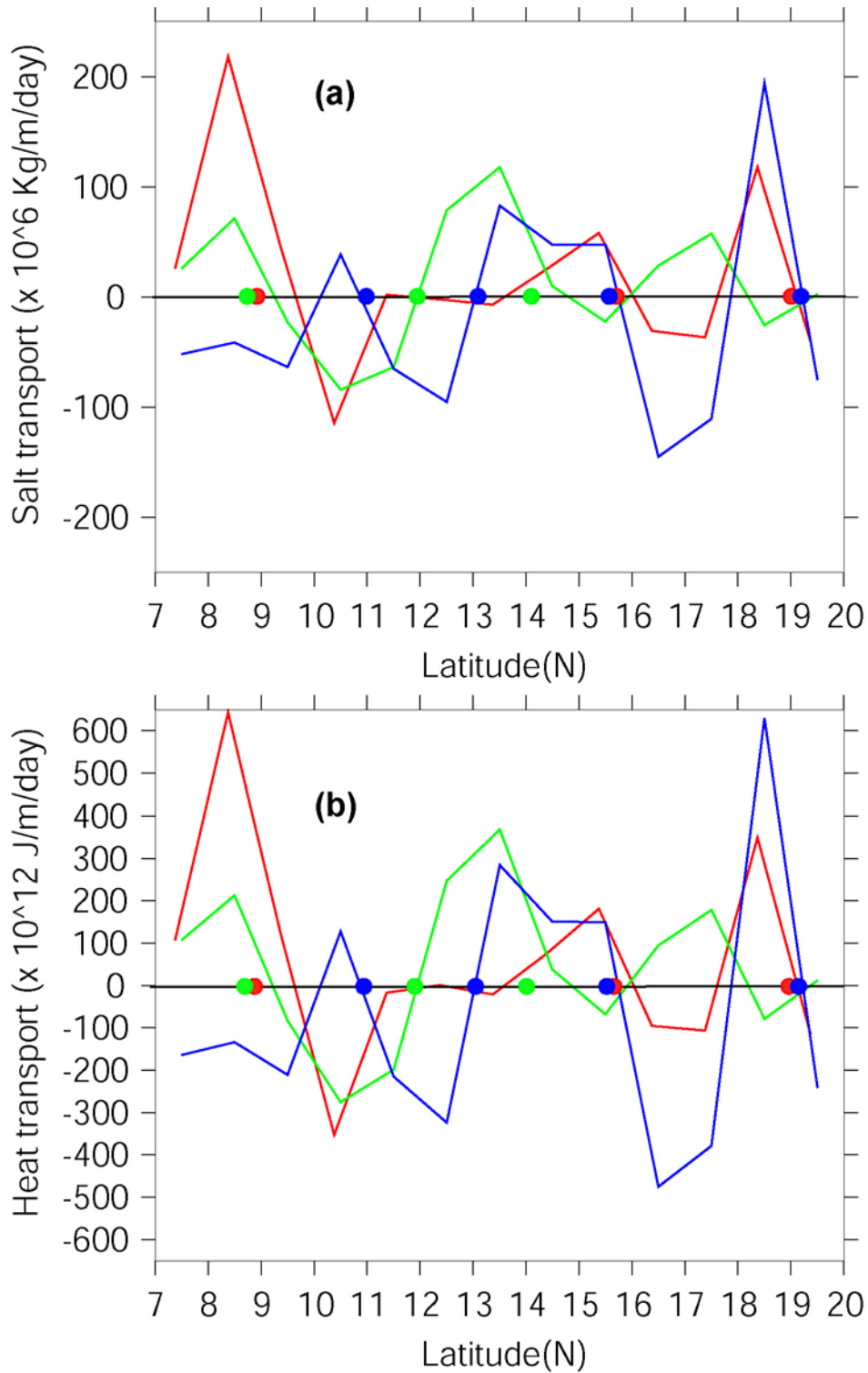


Figure.5.2.6. (a) Salt transport and (b) Heat transport along the central BOB during — Summer monsoon, — Fall inter monsoon and — spring intermonsoon. The coloured circles shows the approximate locations of eddies during each season.

During fall intermonsoon the eastward transport by CEF1 ( $200 \times 10^{12}$  J/m/day) (both eddies were formed by the same mechanism) was lesser than CES1 of summer, but the westward transport remained the same ( $300 \times 10^{12}$  J/m/day). Similarly, the heat transport associated with the anticyclonic eddy ACF2 was  $\sim 300 \times 10^{12}$  J/m/day. The highest heat transport was noticed during spring intermonsoon with the cyclonic eddy CESP4, which had an eastward and westward transport of  $600$  and  $300 \times 10^{12}$  J/m/day respectively. The pattern of salt transport (Figure 5.2.6a) was exactly similar to that of heat transport. The maximum values occurred during summer monsoon in the south and during spring intermonsoon in the north. In summer monsoon an eastward salt transport of  $\sim 200$  kg/m/day was associated with cyclonic eddy CES1 ( $9^\circ\text{N}$ ) while during spring intermonsoon it was with CESP4 ( $19^\circ\text{N}$ ).

Along the coast also the heat and salt transports were greatly influenced by the presence of eddies (Figure 5.2.7). During spring intermonsoon the cyclonic eddy NCE had an offshore heat and salt transport of  $\sim 400 \times 10^{12}$  J/m/day and  $100 \times 10^6$  Kg/m/day respectively. During summer and fall intermonsoon also the transport of heat and salt associated with NCE was the dominant with values of  $\sim 300 \times 10^{12}$  J/m/day and  $100 \times 10^6$  Kg/m/day respectively. The large variability in the south ( $\sim 13^\circ\text{N}$ ) in spring intermonsoon was associated with the cyclonic eddy SCE which was situated adjacent to an anticyclonic circulation as revealed from the SLA (Figure 3.3.1.3).

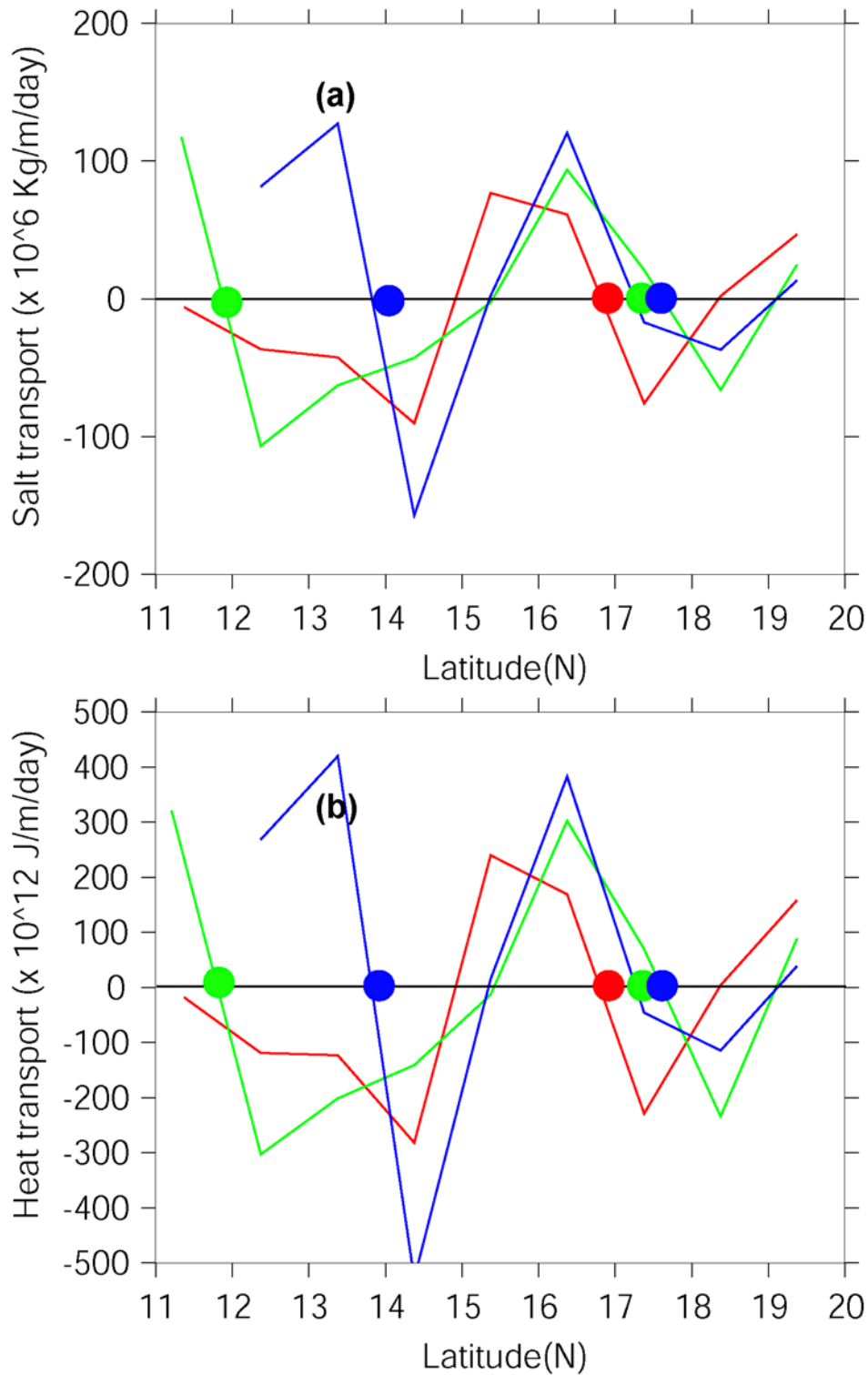


Figure.5.2.7. (a) Salt transport and (b) Heat transport along the western boundary during — Summer monsoon, — Fall inter monsoon and — spring intermonsoon. Coloured circles indicate the centres of the NCE observed during the three seasons.

### 5.3. Summary

The heat content in the upper 150 m of the water column along the central Bay of Bengal showed a northward decrease of about  $200 \times 10^{12}$  J/m in summer and fall intermonsoon. This was associated with the northward shoaling of thermocline seen in the thermal structure. However, along the western boundary the heat content did not show any definite trend as in the case of central BOB, except in spring intermonsoon. During spring intermonsoon the northward decrease of heat content by a bout  $200 \times 10^{12}$  J/m was also associated with the thermocline shoaling. The most dominant change in the heat content, in addition to the south-north variability, was associated with the cyclonic/anticyclonic eddies. The salt content along the central and western BOB showed a progressive decrease from south to north in all the 3 seasons except in spring intermonsoon along the western boundary. This northward decrease is associated with the freshening of the northern BOB under the influence of precipitation as well as river discharge. The dominant variability in the salt content was associated with eddies,  $\sim 5 \times 10^6$  Kg/m, especially during spring intermonsoon. However, the eddy-induced changes were more pronounced in the heat content changes rather than salt content changes. The reason for this lies in the characteristics of the BOB. The BOB has a very strong halocline in a very thin upper layer and 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 also showed the influence of eddies as alternate bands of eastward and westward transport in the region of eddies. The eddy-induced volume transport 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  $650 \times 10^{12}$  J/m/day, while the salt transport varied from 20 to  $200 \times 10^6$  Kg/m/day. Thus, from the above it is clear that eddy plays an important role in the east-west exchange of heat and salt in the BOB.