

A summer monsoon pump to keep the Bay of Bengal salty

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The Bay of Bengal receives a large influx of freshwater from precipitation and river discharge. Outflow of excess freshwater and inflow of saltier water is required to prevent the bay from freshening. Relatively fresh water flows out of the bay along its boundaries and inflow of saltier water occurs via the Summer Monsoon Current (SMC), which flows eastward from the Arabian Sea into the bay. This saltier water, however, slides under the lighter surface water of the bay. Maintaining the salt balance of the bay therefore demands upward mixing of this saltier, subsurface water. Here we show that an efficient mechanism for this mixing is provided by upward pumping of saltier water in several bursts during the summer monsoon along the meandering path of the SMC. Advection by currents can then take this saltier water into the rest of the basin, allowing the bay to stay salty despite a large net freshwater input.

1. Introduction

The Northern Indian Ocean (NIO) shows a highly asymmetric salinity distribution. Strong evaporation and inflow from Red Sea and Persian Gulf makes the Arabian Sea, its western basin, much saltier than the surface water in the Bay of Bengal, its eastern basin [Antonov *et al.*, 2010; Chatterjee *et al.*, 2012], which experiences high precipitation and river discharge [Rao and Sivakumar, 2003]. Salinity increases from the northern Bay of Bengal to the northern Arabian Sea (Figure S1) and ocean dynamics plays an active role in maintaining this salinity gradient [Shenoi *et al.*, 2002]. The salinity of the Arabian Sea is maintained by inflow from the South Indian Ocean via the cross-equatorial Somali Current, from the Bay of Bengal via the westward-flowing Winter Monsoon Current (WMC) [Jensen, 2001, 2003; Schott and McCreary, 2001; Shankar *et al.*, 2002], high precipitation over the eastern Arabian Sea and the discharge from the numerous, small rivers that flow into it [Shankar, 1998; Fekete *et al.*, 2002; Dai *et al.*, 2009]. At the surface of the Bay of Bengal, climatological salinity [Chatterjee *et al.*, 2012] decreases from ~ 35 psu at the mouth to ~ 28 psu at the head (Figure 1). Therefore, the salt balance of the bay demands an export of freshwater. This export is accomplished by the East India Coastal Current [Shetye *et al.*, 1996] (EICC) and the WMC, which flows into the eastern Arabian Sea, and by an equatorward flow along the eastern boundary [Jensen, 2001, 2003; Han and McCreary, 2001; Sengupta *et al.*, 2006]. The water that exits the bay, however, has a salinity of ~ 34 – 35 psu (Figure 1) owing to the freshwater mixing with the surrounding saltier water on its way out of the basin. The net result is a freshening of the bay, implying the need for an inflow of saltier water to maintain the salinity of the basin.

This influx of saltier water is possible only via the SMC, which flows eastward from the saltier Arabian Sea into the southern Bay of Bengal during the summer monsoon [Murthy *et al.*, 1992; Vinayachandran *et al.*, 1999; Schott and McCreary, 2001]. Stability constraints, however, lead this saltier water to slide under the fresher and lighter surface water of the bay. As a result, the 35 psu surface is near the surface only near Sri Lanka, at the junction between the bay and the Arabian Sea (Figure 1). This surface deepens rapidly in the bay and flattens out at a depth of ~ 250 m around 15°N . Thus, mere advection of saltier, Arabian-Sea water into the bay cannot maintain its salinity. The saltier water has to be pumped upward in order to maintain the climatological surface salinity.

The three-dimensional salinity structure of the bay (Figure 1), with the 35 psu isohaline lying at a depth of ~ 250 m north of 15°N , makes it difficult to mix the saltier water with the fresher surface water in the northern bay. In the southern bay too, the eastern route of export of low-salinity water implies an east-west salinity gradient. Though this gradient is much smaller than the north-south salinity gradient, the 35 psu surface is located at a depth of ~ 150 m in the southeastern bay, again making it difficult to mix the sub-surface water with the fresher surface water. It is only in the southwestern bay, where the 35 psu surface lies close to the surface (Figure 1), that vertical mixing is likely to be efficient. In this paper, we use a new set of in situ CTD data from the southwestern bay, along with Argo profiles to show evidence of upward pumping of saltier Arabian-Sea water.

2. Data

We carried out intensive CTD profiling on board *ORV Sagar Nidhi* in the southwestern part of the Bay of Bengal from 16 July to 19 August 2009 under severe summer-monsoon conditions, when the SMC was at its peak strength (Figure 2). The observations included hydrographic measurements along zonal and meridional sections and at two time-series locations (TSLs), surface meteorological measurements, and hull-mounted-ADCP (Acoustic Doppler Current Profiler) measurements of currents. Both TSLs lay well within the core of the SMC, which flowed anticyclonically with a surface speed of $\sim 0.7 \text{ m s}^{-1}$ around a high in sea level during the observation period (Figure 2). The first TSL (TSL1) was located to the east of this high and the second (TSL2) to its north.

The research vessel *ORV Sagar Nidhi* sailed from Chennai on 16 July 2009 to the oceanic region east of Sri Lanka and returned on 19 August 2009. Time series observations were collected at (86°E, 6.25°N) (TSL1) from 22–27 July 2009 and at (85°E, 8°N) (TSL2) from 29 July to 8 August 2009 at 2-hourly intervals during the day (0700 to 1900 hours Indian Standard Time) and approximately 3-hourly intervals during night (1900 to 0700 hours). Temperature and salinity profiles were measured using an SBE 19Plus Seacat CTD. Observations were also made along zonal sections along 4°, 6° and 8°N at one - degree intervals. Surface meteorological observations were recorded using an automated weather system installed on board the ship. The velocity measurements were made using, a 37 kHz, vessel-mounted ADCP (Ocean Surveyor, RD Instruments). A 4 m vertical bin or depth interval was used with about 100 bins, providing a depth range of about 400 m. A 3-beam solution was obtained. The ship was made to run for a minimum period of 20

minutes at a speed of ~ 4 knots for ADCP data recording in between CTD measurements at both TSLs. The ship's velocity was calculated from Global Positioning System and heading was obtained from the ship's gyro platforms. The data were initially averaged over 10 minutes and were discarded when the ship accelerated, i. e., it either turned (changed heading or course) or changed speed.

In addition to the CTD data, we have used Argo profiles (see www.coriolis.eu.org), surface currents from OSCAR [*Bonjean and Lagerloef, 2002*], winds from QuikSCAT (<http://www.ifremer.fr/cersat/en/data/data.htm>) and cyclone track data from JTWC (<http://www.usno.navy.mil/JTWC/>), etc.

3. Salt Pumping

Vertical sections of salinity measured along three latitudes capture the high-salinity core of the SMC (Figure 3a–c). The 4°N, 6°N and 8°N sections were located to the south, in the middle and towards the northern edge of the SMC, respectively. One striking feature of these sections was a low-salinity (< 34.5 psu) cap in the top 50–75 m, below which lay a core of saltier (> 35 psu) water of Arabian Sea origin carried by the SMC. This core was most prominent along the 6°N section between 50–150 m, sandwiched between two layers of lower salinity, of which the upper layer was fresher than the lower. These observations confirm the sliding of the Arabian-Sea water under the lighter Bay-of-Bengal water.

The core of this high-salinity water was located between 100–150 m at TSL1 and between 50–100 m at TSL2 (Figure 3d). The CTD data show that this saltier water erupted upward intermittently from its sub-surface abode to mix with the fresher surface water. The time-series observations captured two such events during 22 July to 8 August 2009

(Figure 3d), the first during 25–27 July and the second during 2–5 August. During both events, surface salinity exceeded 35 psu owing to the entrainment of saltier, Arabian-Sea water from the sub-surface, high-salinity core into the surface mixed layer.

Are these events isolated, or do they occur throughout the summer monsoon? Additional evidence for this intraseasonal *salt pump*, spanning the entire season, was obtained from two Argo floats that profiled in this area during 2009 (see tracks in Figure 2). Both floats show an increase in salinity with the progress in season as well as with depth (Figure 4a,b). The coarse vertical resolution of the Argo profiles does not resolve the alternating salinity layers as clearly as the CTD, but the high-salinity core and its upward surges are captured fairly well. Float 2900106 (Figure 4a) showed three events of upward pumping of high-salinity water during June–September 2009, of which the second and third events reached the surface. The surface salinity increased from 33.5 to 35 psu by the end of July and dropped by about 1 psu between these pumping events (Figure 4a). Float 2900883 (Figure 4b) recorded a salinity of 34.12–35.13 psu, with the peak value on 14 June 2009. The intermittent upward surges of the high-salinity core of the SMC and its dilution by the less saline water from the north is captured well by this float as well.

The only other mechanism that has the potential to pump up saltier water is a tropical cyclone. Cyclones cross the southern Bay of Bengal during October–December, following the withdrawal of the summer monsoon [IMD, 1979] (Figure S2). Data recorded by an Argo float (2901284) during the passage of cyclone *Jal* (Figure 5a) during 4–8 November 2010 provide evidence for the upward pumping of saltier, sub-surface water (Figure 5b). That this saltier water is located between 150–200 m, whereas cyclones entrain water from

50–100 m, implies that the salinity of the upwelled water is lower (~ 34.3 psu) than that pumped along the SMC track in summer. A similar pumping event was also recorded during the passage of cyclone *Thane* (25–31 December 2011) by Argo float 2901329 (Figure 5c). Argo profiles collected from the southern bay during the passage of several cyclones of different intensities and at varying distances from the cyclone tracks indicate that the pumping is restricted to regions close to the cyclone tracks. On an average, one severe cyclone blows across the southern Bay of Bengal each year (Figure S2), limiting the amount of salt that can be pumped into the surface mixed layer. Moreover, the cyclone has to be located near Sri Lanka to act as an efficient pump.

In contrast, several intraseasonal pumping events occur during a summer monsoon, each typically lasts a few days. Repeated occurrence of these events increases the salinity of the surface mixed layer from less than 34 psu to more than 35 psu during June–September (Figure 4b). The coarser temporal resolution of the Argo float suggests that an event may last up to 10 days, with breaks of a similar duration between the events. The CTD time-series data, however, suggest that a pumping event is shorter (~ 5 days), with breaks of a similar duration between the events (Figure 3d). The pumping events during the observations were accompanied by bursts in the wind (Figure 3e,4c,d) or fluctuations in current (Figure 3f). Therefore, the proximity of the SMC to Sri Lanka and the frequent bursts in the wind and current in the regime of the SMC make these intraseasonal bursts more efficient at pumping the saltier, Arabian-Sea water into the mixed layer than the cyclones.

Other possible mechanisms include coastal upwelling during the summer monsoon, but upwelling in the bay is too weak and the high-salinity core too deep (Figure 1) for the saltier, sub-surface water to break the stratification at the base of the surface mixed layer [Shetye *et al.*, 1991]. The western boundary current that exists during spring [Legeckis, 1987; Shetye *et al.*, 1993] is also not a viable mechanism because the inflow of the saltier, Arabian-Sea water begins only as this boundary current weakens with the onset of the summer monsoon [McCreary *et al.*, 1993].

4. Discussion

The intraseasonal pumping events in the SMC region are clearly seen in the CTD and Argo data. Although the physical cause of this pumping is not as apparent, several processes, either independently or in conjunction, could be responsible for this intermittent pumping. An examination of the time series for winds and currents during the CTD and Argo periods show that they tend to be stronger during these events. For example, both pumping events observed in the CTD data occurred when winds fluctuated between 8–12 m s⁻¹. The wind speed surged from ~ 6 m s⁻¹ to 12 m s⁻¹ during the first event and it was ~ 10 m s⁻¹ during the second event (Figure 3e). The cause-effect relationship is weak, however, because a one-to-one correspondence between the two variables is not observed: the pumping receded after 5 July even though the winds did not slacken, and the strongest wind burst on 1 July led to but a weak pumping event. There were similar wind bursts during the pumping events seen in Argo data, but a one-to-one correspondence was lacking (Figure 4b). Likewise, current measurements show bursts in the SMC during the pumping events in the CTD data, but the strength of the current is not directly

proportional to that of the salt pump (Figures 3f and 4). Local Ekman pumping (Figure 3e) favored upwelling during the first event in the CTD data, but not during the second event.

While the role of the wind in mixing the saltier, sub-surface water with the fresher surface water is easy to understand, the role of the currents is not as clear. In model simulations (see supplementary material), the saltier water is advected into the Bay of Bengal. It does not sink under the fresher bay water, but replaces it. The data, whether from the CTD or Argo floats, do not indicate such a role of advection. The observed currents (Figure 3f) do not show any change in direction during 30 July – 7 August suggesting a direct role of advection in causing the pumping during 2–5 August. The SMC advects saltier water into the bay, but it sinks below the fresher bay water, and has to be pumped upward, a process that occurs several times along the SMC’s track during the summer monsoon. Altimeter and OSCAR data (Figure 2) show that the SMC meanders along its track across the southern bay. Its seasonal cycle is associated with Rossby-wave radiation from the east [*McCreary et al.*, 1993], but nonlinear interactions [*Vinayachandran and Yamagata*, 1998] and eddies are likely to be important at the shorter scales associated with the meanders. Eddy-driven vertical mixing due to horizontal or vertical current shear may play a role in these meanders [*Klein and Lapeyre*, 2009]. Future studies using models and new observations are needed to determine relative importance of each of these processes.

5. Concluding Remarks

We hypothesize that salt-pumping events in the SMC regime constitute the main mechanism for pumping saltier water of Arabian-Sea origin into the surface mixed layer of the Bay of Bengal, enabling the bay to stay salty. We have unravelled a fundamental process at work in the NIO to define its hydrography and regional climate. This finding has implications for present as well as future climate. The difference in salinity between the eastern and western basins of the NIO (Figure S1) is matched by the difference in precipitation. Precipitation decreases westward across the Indo-Gangetic plains (Figure S1). A warm ($>28^{\circ}\text{C}$) ocean surface [Gadgil *et al.*, 1984] is a necessary condition for organized atmospheric convection in the monsoon regime and stratification controlled by salinity keeps the Bay of Bengal warm [Bhat *et al.*, 2001; Shenoi *et al.*, 2002; Vinayachandran *et al.*, 2002]. In a warming climate, the global hydrological cycle is amplifying and, consequently, the Bay of Bengal has been freshening in recent decades, while the Arabian Sea is becoming more salty [Durack and Wijffels, 2010; Durack *et al.*, 2012]. Since individual components of oceanic freshwater budgets are far more complicated to measure, monitoring the SMC and the boundary currents could be a simpler alternative to detect long-term changes in the salt and freshwater budgets of the Bay of Bengal.

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Figure 1. Sliding of saltier Arabian-Sea water under the fresher surface water of the Bay of Bengal. The top plane shows sea-surface salinity (psu) for July (colour scale on top). The perspective view shows the depth of the 35 psu isohaline (colour scale at the bottom). Data used are monthly climatology for July [*Chatterjee et al.*, 2012].

Figure 2. The Summer Monsoon Current and observation locations. Sea level anomalies [*Ducet et al.*, 2000] (cm, colour scale) and surface currents [*Bonjean and Lagerloef*, 2002] (vectors in m s^{-1}), averaged during 22–27 July 2009, are shown. The line segments with black dots show the locations where CTD profiles were measured along zonal sections at 4°N, 6°N, and 8°N. The blue and black stars denote the locations of time-series measurements during 22–27 July 2009 (TSL1: 86°E, 6.25°N) and 29 July to 8 August (TSL2: 85°E, 8°N), respectively. The blue and red squares with white cores indicate locations where Argo floats with identification numbers 2900883 and 2900106, respectively, sampled during June–September 2009. From its location to the south of Sri Lanka on 4 June, Float 2900883 (blue) sailed eastward along with the SMC measuring profiles once in every 5 days. Float 2900106 (red) sampled northwestward across the SMC from 8 June at an interval of 10 days.

Figure 3. Shipboard observations of the salt pump. The three panels at the top show vertical sections of salinity (psu) along (a) 8°N, (b) 6°N, and (c) 4°N. (d) Time series of salinity measured at TSL1 (86°E, 6.25°E, blue star in Figure 2) from 22–27 July and at TSL2 (85°E, 8°N, black star in Figure 2) from 29 July to 7 August. Salinity > 35 psu is highlighted by contours. (e) Time series of wind speed (m s^{-1}) measured by an automated weather system on board *ORV Sagar Nidhi* during 22 July to 7 August 2009 (black curve), the wind speed measured by the QuikSCAT scatterometer (blue curve) and curl of the wind stress (Pa m^{-1} , red curve). (f) Currents (m s^{-1}) averaged over the upper 50m measured by an ADCP mounted on the ship.

Figure 4. Argo profiles of the salt pump. Time-depth sections of salinity from Argo float (a) 2900106 (top left) and (b) 2900883 (top right) for June–September 2009 based on profiles measured at locations shown by the red and blue squares, respectively, in Figure 2. The bottom panels show wind speed (m s^{-1}) from QuikSCAT at space and time coordinates nearest the profiles of Argo floats (c) 2900106 and (d) 2900883.

Figure 5. Salt pumping by cyclones. (a) Trajectories of Cyclones *Jal* (black line) and *Thane* (blue line,). (b) Salinity measured by Argo float 29001284 that sampled during the passage of *Jal* at locations shown as red stars in (a) and (c) salinity from Argo float 2901329 at locations shown as green stars in (a).

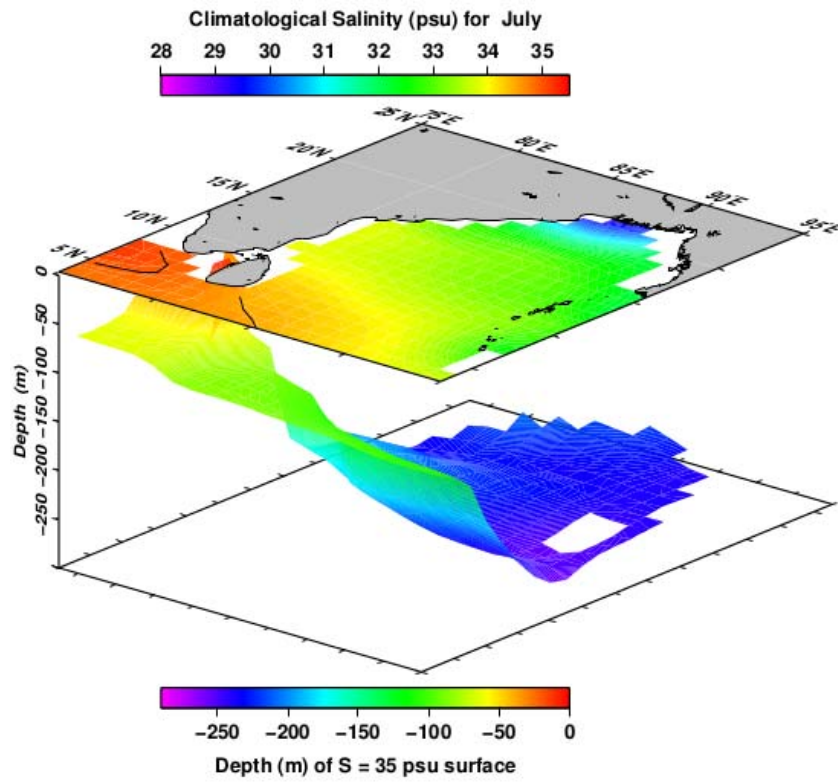


Fig -1

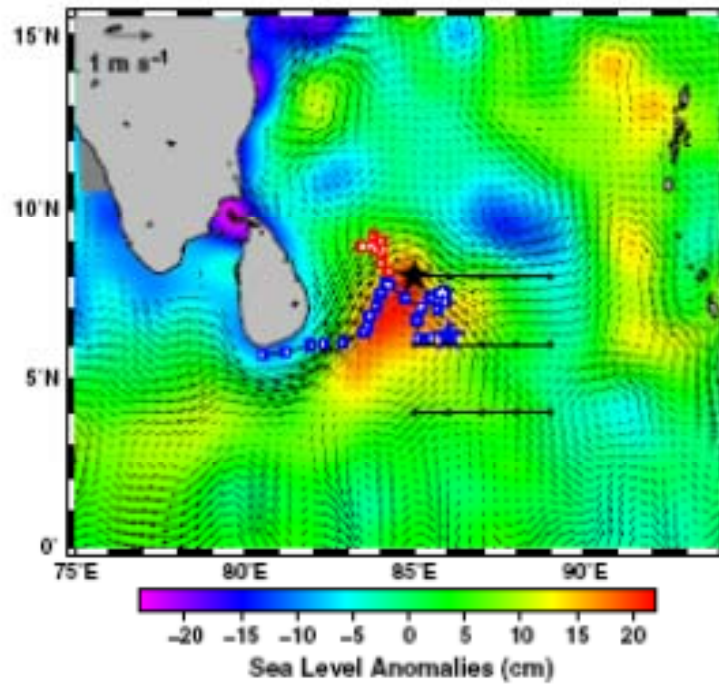


Fig -2

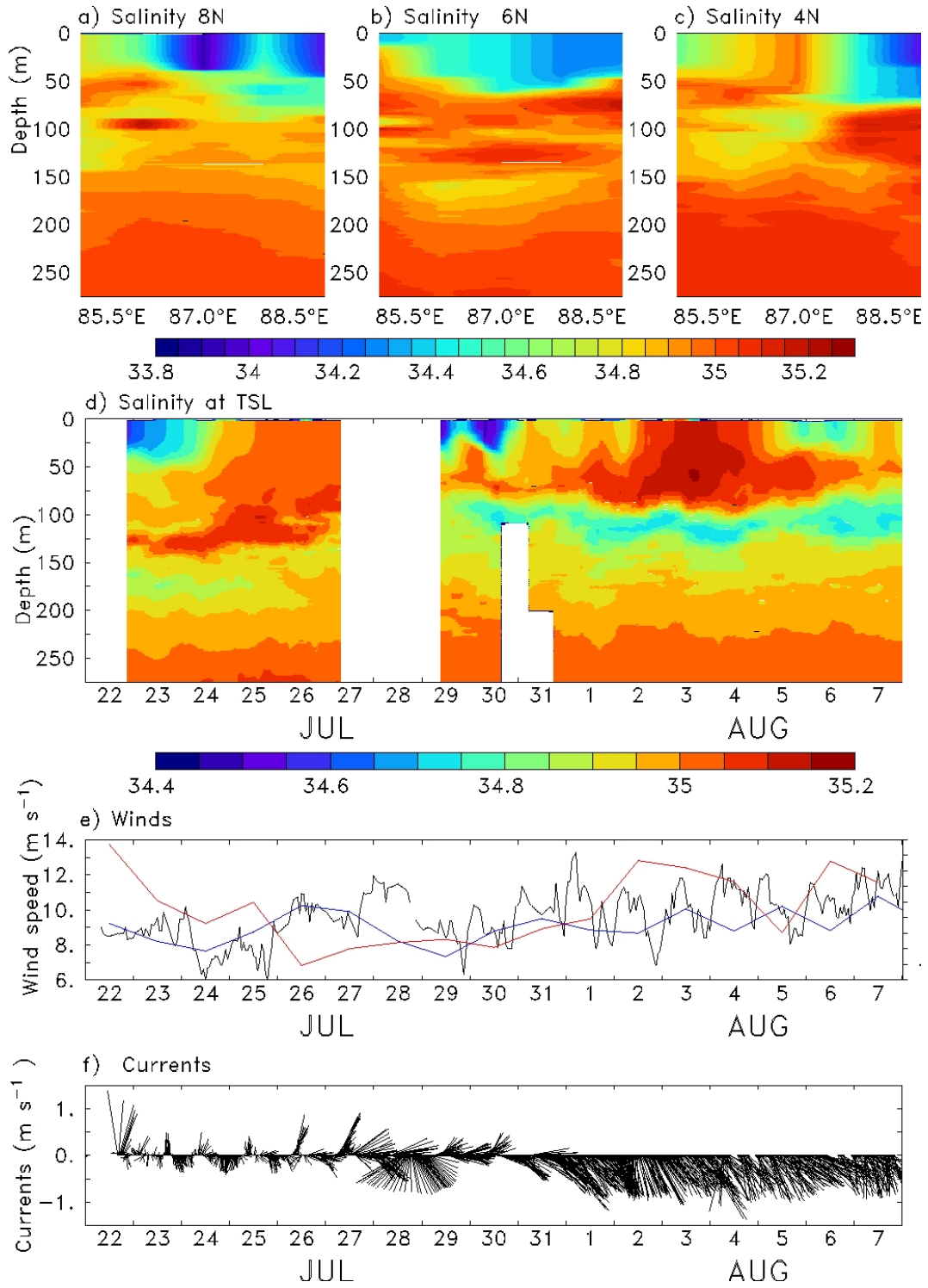


Fig -3

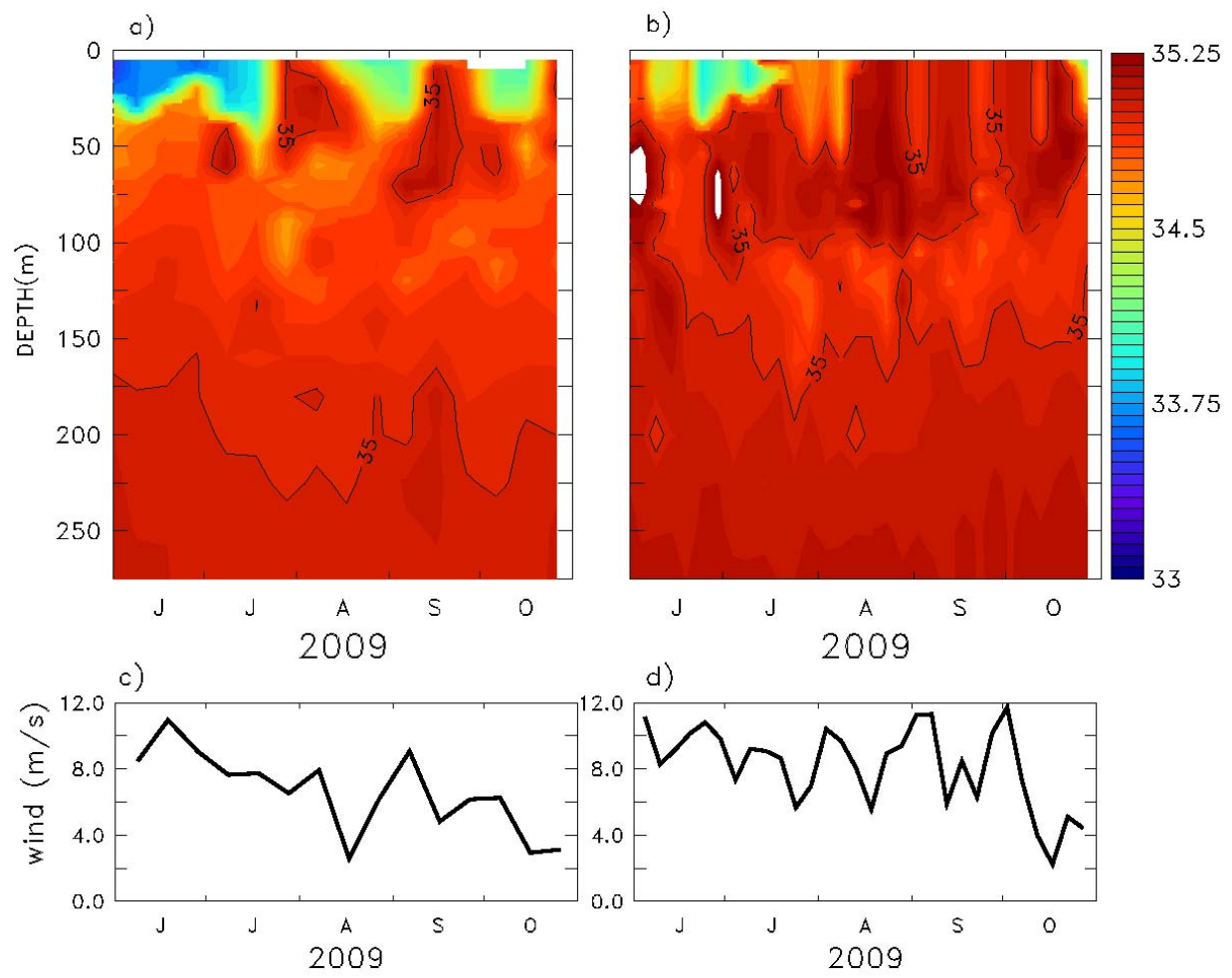


Fig -4