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On the Possible Mechanisms for Saltening of the Bay of Bengal

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ABSTRACT

The Bay of Bengal (BoB) is a low saline basin owing to large influx of freshwater from precipitation and river runoff. To maintain the salt balance of the BoB, the incessant lowering of salinity is to be balanced by the inflow of saltier water into the basin. In the present work, various processes that contribute to the saltening of the BoB, viz. coastal upwelling, eddies and their interaction, lateral advection from Arabian Sea and tropical cyclones are discussed. In the near-shore regions, the coastal upwelling due to wind induced Ekman transport plays a dominant role in increasing the surface salinity. On the other hand, in the open ocean, the divergence induced by eddies and their mutual interaction contributes significantly to the salt water pumping. In the southern BoB, the advection from the Arabian Sea increases the salinity. The formation of cyclones in the BoB also leads to an increase in the surface salinity. However, the magnitude of saltening of the Bay due to these processes varies from north to south. The uplift of saltier water from subsurface levels increases the salinity in the surface layers thereby creating a salinity gradient and a salinity front.

Keywords: Bay of Bengal; Salt water pumping; Eddies; Upwelling; Cyclone

1. INTRODUCTION

It is well understood that the BoB receives excess precipitation (~2 m) and freshwater influx (1.6 x 10^{12} m^3yr^{-1}) from four major river systems viz. Ganges-Padma, Brahmaputra-Jamuna, Surma-Meghana and the Chittagong river systems[1]. Hence, the surface layer of the northern BoB is always fresher than other regions of the Indian Ocean, especially during and after the monsoon[2,3]. The influence of freshwater on the upper ocean dynamics of the BoB is many. To name a few, increase in the upper layer stratification at the head Bay[4,5], formation of barrier layers[6], formation of shallow mixed layer[7] thereby reducing the effects of storm-induced surface cooling[8,9], surface layer circulation[10,11] and biological productivity regimes[5].

To prevent the bay from continuous freshening due to freshwater influx and to maintain the salt balance, the entrainment of saltier subsurface water towards the surface plays a crucial role. These changes are forced or modified either in the upper ocean or at the air-sea interface by processes such as air-sea exchanges or vertical exchanges between the upper ocean and the interior, but their vertical exchanges with the deep interior occur at much lower rates. Vinayachandran[12], *et al.* noticed that one process by which saltier water enters the bay is through the summer monsoon current (SMC) from the Arabian Sea. Later, Akhil[13], *et al*. shows that vertical mixing of surface fresh waters with underlying saltier waters is the primary mechanism for salinity increase. More recently Chowdary[14], *et al.* emphasised the significance of accurate representation of vertical processes in general circulation models so that they simulate realistic surface and subsurface salinity structure in the BoB. Hareesh Kumar[15], *et al.* reported the uplift of saltier water towards the surface in the formation of thermohaline front in the BoB. The present work mainly addresses the pumping of saltwater into the surface layers of the BoB due to processes like coastal upwelling, eddies and their interaction and tropical cyclones.

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2. DATA AND METHODS

In the present study, the saltwater pumping is investigated using the Argo floats at the northern (Float nos. 2901336, 2901292), central (Float no. 6901558) and southern BoB (Float nos. 2902365) (Fig. 1). These are supplemented with data from RAMA buoy (15 ºN, 90 ºE), BOBMEX-99 (along 13 ºN, 81 ºE - 87 ºE) and World Ocean Circulation Experiment (WOCE) (Fig. 1) during February 1995 to further investigate the observed increase in salinity due to meso-scale eddies. To document the influence of cyclone on the saltwater pumping, data from nearby Argo float 2902114 during the passage of Hudhud in October 2014 and Argo float 290133 during the passage of cyclone Viyaru in May 2013 are utilised. The 7 day snapshots of the merged SLA from AVISO product having a spatial resolution of 0.33° x 0.33°[16] for the corresponding periods are presented to demarcate eddies. To study the meso-scale variability from SLA data, we used a high-pass filter for each grid point so that any variability with periods longer than 30 day is essentially removed to obtain a non-seasonal anomaly. After that, a boxcar filter was applied to the SLA data to remove any spatial in-homogeneity in the data. The wind

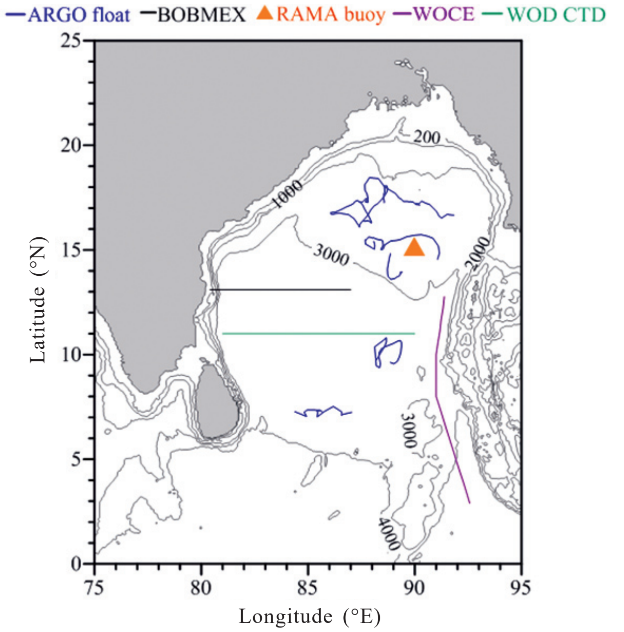

Figure 1. Study area with locations of data from various sources. Argo float (blue line), RAMA buoy (orange triangle), BOBMEX (black line), WOCE (violet line), and WOD CTD (green line).

stress curl is estimated from the weekly wind data acquired by ASCAT (spatial resolution of 0.25° x 0.25°) for the same period as the SLA data.

To identify eddies in the BoB, Okubo-Weiss parameter (W) is used[17,18]. W represents the balance between the magnitude of vorticity and deformation[19] and gives the relative contribution of these two parameters.

$$W = S_n^2 + S_s^2 - \omega^2 \tag{1}$$

here

$$S_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \tag{2}$$

$$S_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{3}$$

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{4}$$

S_n, S_s and ω are stretching deformation rate, shearing deformation rate, and vorticity respectively. The zonal (u) and meridional (v) geostrophic current components are estimated as

$$u = -\frac{g}{f}\frac{\partial \eta}{\partial y} \tag{5}$$

$$v = \frac{g}{f}\frac{\partial \eta}{\partial x} \tag{6}$$

where η is elevation, g is gravity and f is the Coriolis parameter. The equations (5) and (6) are used to compute S_n, S_s and ω. Regions with $W < 0$ are vorticity-dominated regions and correspond to the eddy core, while W > 0 indicates strain-dominated regions corresponding to the periphery of the eddy (circulation cell). Hence, W is used to identify the eddy core as interconnected regions of vorticity dominated over strain surrounded by a region of strain dominated over vorticity. The core edge is identified as closed lines with $W = 0$.

3. RESULTS AND DISCUSSION

In the BoB, any processes that lead to the uplift of subsurface water towards the surfaces increase the salinity in those regions and maintain the overall saltwater budget in the BoB. Now the question to be answered is which are the mechanisms responsible for the pumping of saltier water into the surface mixed layer? In general, the factors that lead to the pumping of saltier water from subsurface levels includes coastal and open ocean upwelling, presence of cyclonic/anti-cyclonic eddies and their interaction, lateral advection of saltier water from the Arabian Sea into the southern BoB through the SMC, passage of cyclones, etc.

3.1 Meso-scale eddies

The vertical exchanges of subsurface waters between the surface layers and interior of the ocean can be linked to processes occurring (i) at the interior of meso-scale eddies and (ii) at the interface between two strongly interacting eddies. The fomer considers the vertical exchange as purely a linear relationship which include eddy pumping concept whereas the latter deals with the vertical exchange produced by the eddy to eddy interaction. In the BoB, both these processes play a significant role in the vertical exchange of properties. Since the tracks of Argo floats cut across the cyclonic and anti-cyclonic eddies, the changes in the temperature and salinity field due to these eddies were captured. To probe into the role of eddies in increasing the surface salinity of the BoB; the vertical sections of temperature and salinity for the northern, central and southern BoB are separately presented.

(a) Northern Bay of Bengal

Case I: Argo float 2901336

The Argo float 2901336 located at 17.25 ºN, 88.6 ºE in January drift westward and reaches 16.4 ºN, 87.6 ºE in October 2012 (Fig. 2(a)). The SLA drops substantially along the track (upto -30 cm) during the period March-May (Fig. 2(c)), associated with a cyclonic eddy centered at 17 °N, 87 °E (Fig. 2(b)). The eddy is confirmed by negative divergence (Fig. 2(f)), positive vorticity (Fig. 2(g)) and negative values of Okubo-Weiss parameter (W) surrounded by positive values (Fig. 2(h)). Figure 2(d) shows that the prevailing low salinity water (< 33 psu) in the upper 50 m is replaced by water having salinity in excess of ~34 psu by end March, resulting in an increase of 1 psu in the surface salinity when the Argo float locates in the vicinity of the core (Figs. 2(d), 2(e)). The saltier water surfaces from a depth of 90 m and continue to exist till mid June. The uplifting of saltier water from the subsurface depths leads to a salinity front and hence lateral gradient.

The surface waters undergo warming during March-May and its effect is visible upto a depth of 30 m (Fig. 2(e)). The upper layer stratification due to the accumulation of heat may have opposing effect on the uplifting of subsurface waters towards the surface. Another possibility is that the marginal reduction in temperature due to uplift might have been offset due to the significant warming occur during this period.

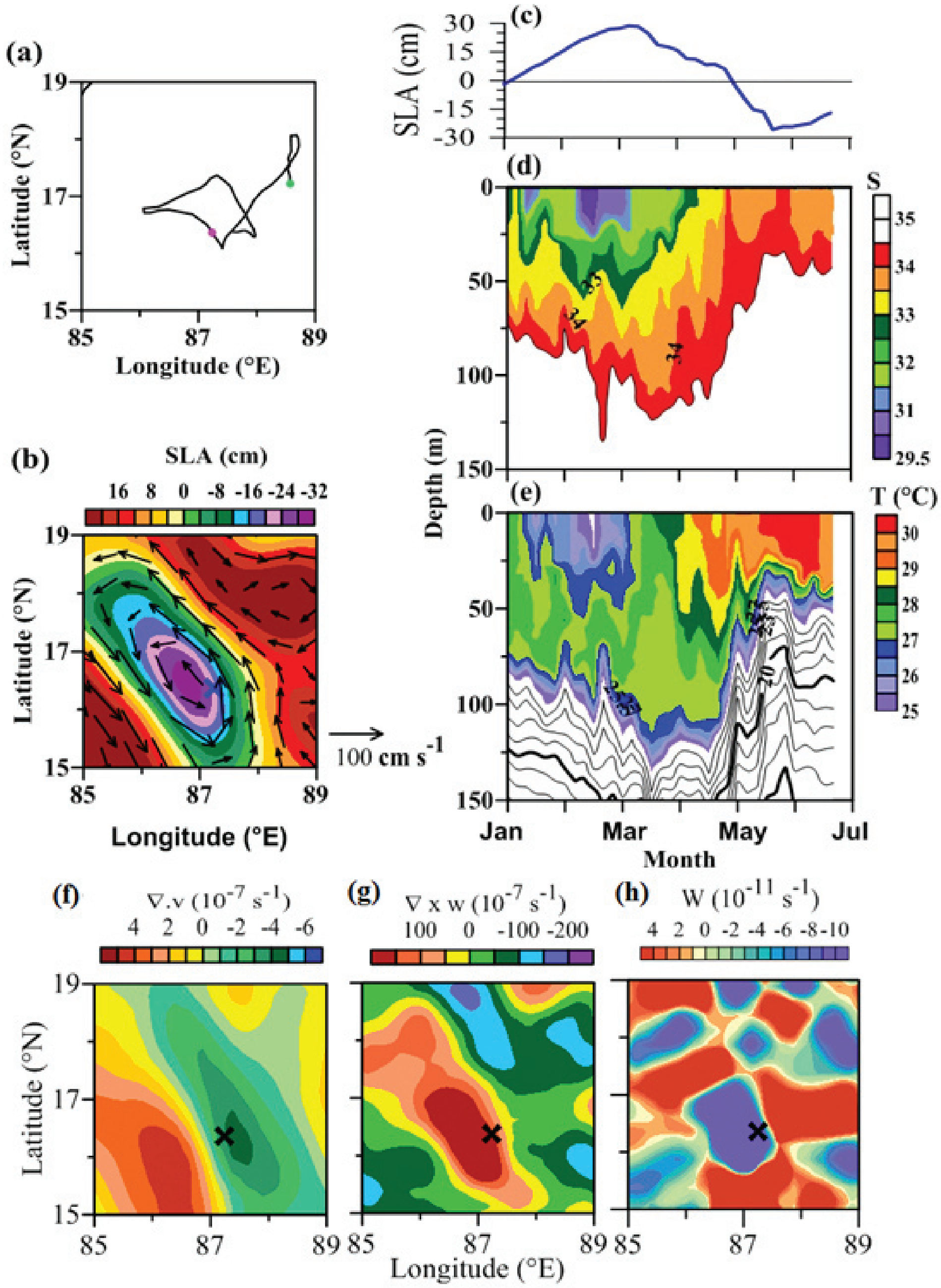

Figure 2. (a) Track of Argo float 2901336 (black line) in the northern BoB during January-October 2012. Green cross: Initial float position, Orange cross: Region of saltwater pumping, (b) Sea level anomaly (SLA) overlaid with geostrophic current on 15 May 2012; blue cross: float position, (c) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature, (f) Divergence (∇.v), (g) vorticity (∇xω) and (h) Okubo-Weiss parameter (W) on 15 May 2012. Positive values: yellow to red, negative values: blue to yellow. Black cross represent position of float on this day.

Anyway, there is no visible evidence of a thermal front in Fig. 2(e). However, below 30 m, upward lifting of isotherms is noticed. The figures further indicate that the period of uplift is associated with the presence of cyclonic eddy centered at 17 °N, 87 °E (Fig. 2b). Therefore, it is concluded that the pumping of saltier water towards the surface is due to the divergence induced by the cyclonic eddy.

Case II: Argo float 2901292

The Argo float 2901292 after its initial northward displacement, drifts southeastward during March to May 2012 (Fig. 3(a)). In April, as the float enters the vicinity of a cyclonic eddy centered at 18 °N, 90 °E (Fig. 3b), SLA drop by nearly 30 cm along the track (Fig. 3c). This cyclonic eddy is corroborated by negative values of Okubo-Weiss parameter (Fig. 3h) and positive vorticity (Fig. 3(g)). At the same time, salinity (Fig. 3(d)) increases by ~2 psu up to a depth of 50 m (>33.5 psu) compared to its surrounding. The zone of saltier water is found sandwiched between fresher waters on either side (<31.5 psu), thereby creating a salinity front with lateral variation in excess of 2.5 psu. Figures 5(a)-5(c) shows that the increase in salinity is closely related to divergence (Fig. 3(f)) induced by the cyclonic eddy. In temperature (Fig. 3(e)) the eddy effect is perceptible below 15 m only, while the signal at the surface might have been masked by the opposing effect of stratification due to pre-monsoon warming.

(b) Central Bay of Bengal

Case I: Argo float 6901558

In the central BoB, a cyclonic circulation is observed during November-December 2015 centered at 15 °N, 88.5 °E (SLA for November is presented in Fig. 4(b)). The float (Fig. 4(a)) drifts westward from its initial position in the eastern Bay and cut across the cyclonic eddy in November. The float remains in the vicinity till the first week of December.

The SLA along the track of Argo float changes its sign from positive to negative in November (Fig. 4(c)) and reaches its minimum (-10 cm) by mid November. During this period, the float is located within the vicinity of the core of cyclonic eddy (Fig. 4(b), 4(c)), where normally upwelling occurs. Negative divergence, positive vorticity and negative W surrounded by positive values (Fig. 4(f)-4(h)) confirm the cyclonic eddy. Corresponding to SLA minimum, there is evidence of the uplift of saltwater from a depth of 50 m thereby creating a salinity front (Fig. 4(d)). The pumping centered at 15.2°N, 88.6°E increases the surface salinity by ~1 psu (32.5 to ~33.3 psu) and drop surface temperature by 0.5 °C (Fig. 4(e)). However, temperature changes are more visible below 50 m depth.

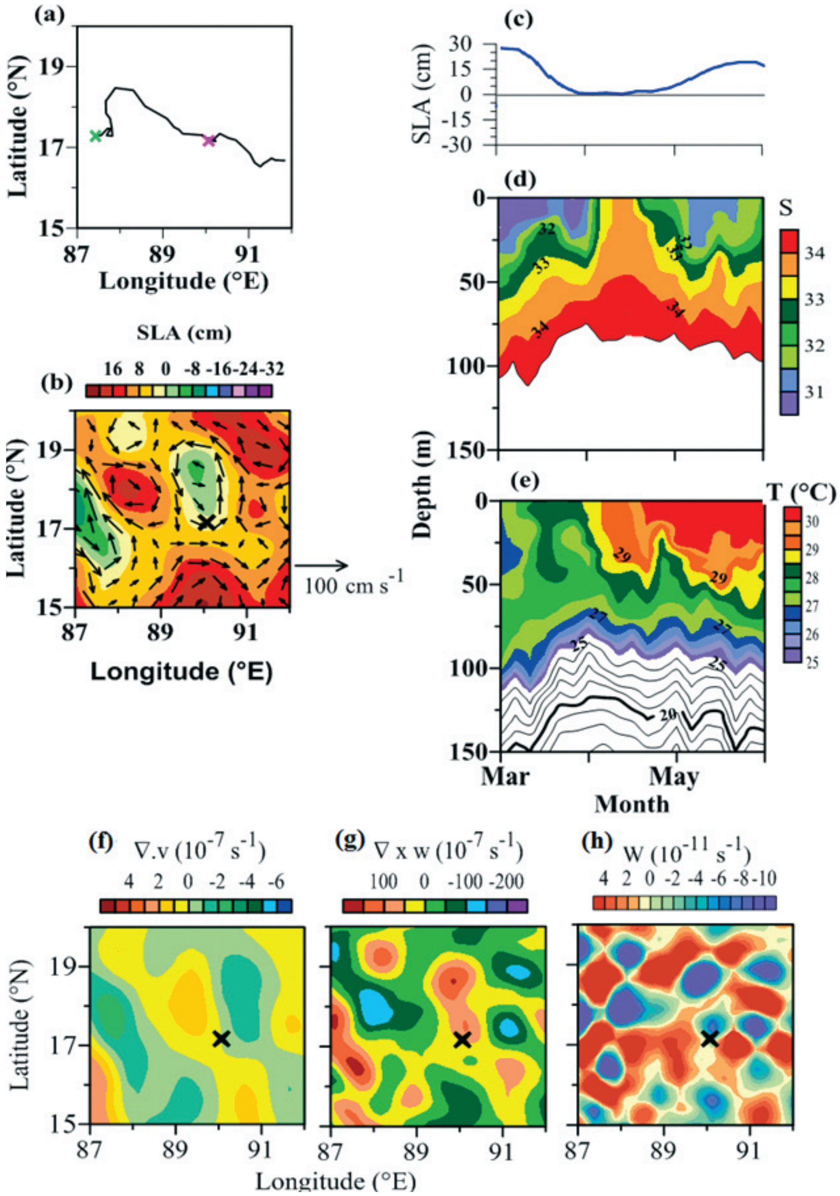

Figure 3. (a) Track of Argo Float 2901292 (black line) in the northern BoB during January-May 2012. Green cross: Initial float position, Orange cross: Region of saltwater pumping, (b) sea level anomaly (SLA) overlaid with geostrophic current for the period 23 April 2012; black cross: float position, (c) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature, (f) Divergence (∇.v), (g) vorticity (∇xω) and (h) Okubo-Weiss parameter (W) on 23 April 2012. Positive values: yellow to red, negative values: blue to yellow. Black cross represent position of float on this day.

Case II: RAMA buoy

RAMA is a network of buoys deployed in the BoB to obtain long time series measurements of atmospheric and oceanic parameters. The data collected from one of the buoy located at 15º N, 90º E over a period of seven months, i.e. December 2013 to July 2014 is utilised to probe into the uplift of saltier waters in the central BoB. The Fig. 5(c) shows two events of saltwater pumping, one in January and another in June of which the first event lasted longer. From the figures 5(c)-5(d), it can be seen that the existing water become more salty (by 1.25 psu, i.e. 32 psu to 33.25 psu) and cooler (1.5°C, i.e. 28.5° C to 27° C) due to the uplift, as the salinity in BoB increases with depth. Also, the saltier water is found to surface from a depth of around 40 m. The sigma-t indicates that the existing Transition Watermass (sigma-t: 19-21) is replaced by Southern Bay of Bengal Watermass (sigma-t: 21-22) (Fig. 5(e)). During rest of the period, salinity is less than 33 psu in the surface layers.

In both cases, the SLA changes its sign from positive to negative and drop by ~10 cm (Fig. 5(b)). As in the previous cases, the SLA drops with the formation of a cyclonic eddy in the vicinity of mooring (Fig. 6(a)) as confirmed from positive values of vorticity and W in June (Figs. 6(b)-6(d)). Therefore, the uplift of the subsurface waters towards the surface is attributed to the divergence (Fig. 6(b)) at the core of this cyclonic eddy.

Case III: BOBMEX-99

The impact of cyclonic eddy (Fig. 7(a)) on thermohaline field is illustrated utilising BOBMEX data along 13 °N transect. The figure shows doming of isopleths (Figs. 7(c), 7(d)) between 84 ºE and 85 ºE causing uplifting of saltier and cold water from a depth of around 60 m. In the BoB, during the monsoon season, temperature decreases and salinity increases with depth. Consequently, the surface layers cools by 0.5 °C (28.5 °C to 28 °C) and surface salinity increases by 0.5 psu. The zone of saltier water is found sandwiched between comparatively warm and low salinity (<34.25 psu) water on either side. Southern Bay of Bengal Watermass ($21<\sigma_t<22$) occupies the upper 60 m in July (Fig. 7e).

The regions of isotherms doming coincide with the drop in SLA, where cyclonic circulation is noticed (Fig. 8(a)). Hareesh Kumar[15], *et al.* attributed the cooling of the water column in the western BoB to the southward elongation of a cyclonic eddy formed due to the baroclinic instability caused by the two opposing currents along the coastal periphery of the western BoB along with the wind stress curl. In the BoB, the cooling of the water column and increase in the salinity are possible when there is divergence at subsurface levels, in this case it is due to a cyclonic eddy. Therefore, the 0.5 psu increase in salinity in the surface layer results from the divergence (Fig. 7(b)) in presence of a cyclonic circulation, supported by positive values of vorticity (Fig. 7(c)) and negative W (Fig. 7(d)).

(c) Southern Bay of Bengal

Case I: Argo float 2902365

The track of Argo float (Fig. 9(a)) covers the southern BoB (around 7 °N) during May to September 2013. During its traverse, it encounters a cyclonic eddy in June centered

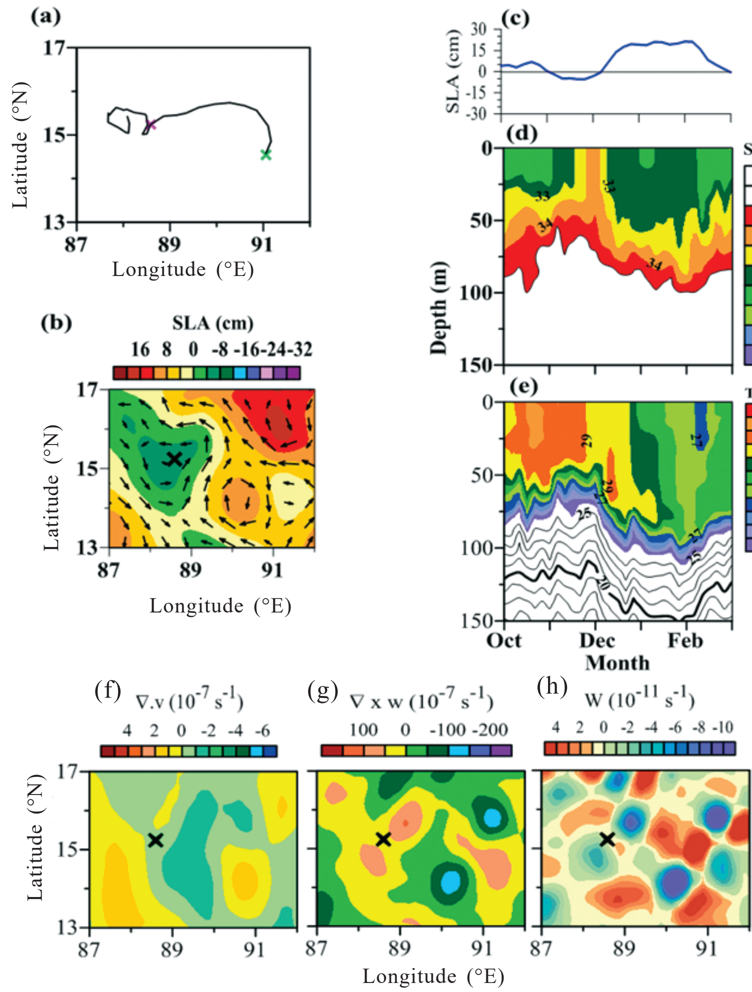

Figure 4. (a) Track of Argo float 6901558 (black line) in the central BoB during October 2015 to February 2016. Green cross: Initial float position, Orange cross: Region of saltwater pumping, (b) SLA overlaid with geostrophic current for the period 28 November 2015; black cross: float position, (d) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature (f) Divergence (∇.v), (g) vorticity (∇ x ω) and (h) Okubo-Weiss parameter (W) on 28 November 2015. Positive values: yellow to red, negative values: blue to yellow. Black cross represent float position on this day.

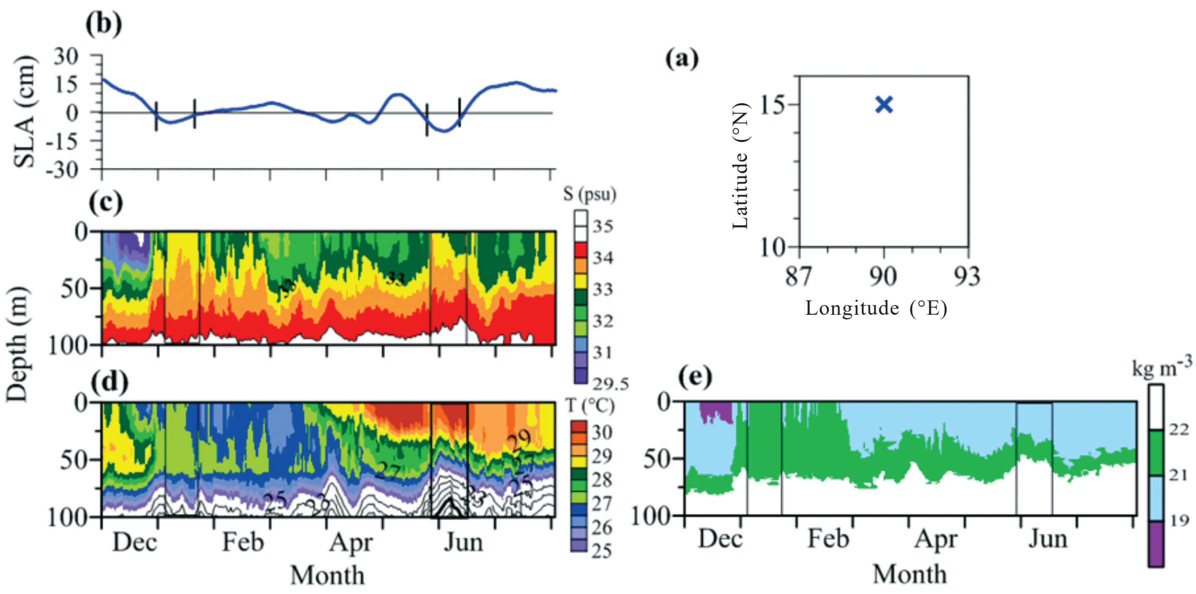

Figure 5. (a) RAMA buoy location (15 °N, 90 °E, Blue cross) (b) sea level anomaly at buoy location, vertical sections of (c) salinity, (d) temperature and (e) sigma-t during December 2013 to July 2014. The duration of uplift is indicated between vertical bars.

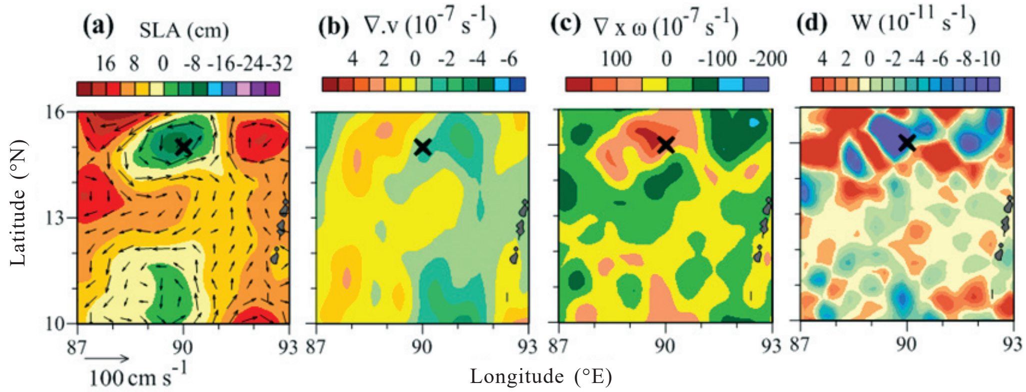

Figure 6. (a) SLA overlaid with geostrophic current, (b) divergence (∇.v), (c) vorticity (∇xω) and (d) Okubo-Weiss parameter (W) on 6 June 2014. Positive values: yellow to red, negative values: blue to yellow. Black cross represent RAMA buoy location.

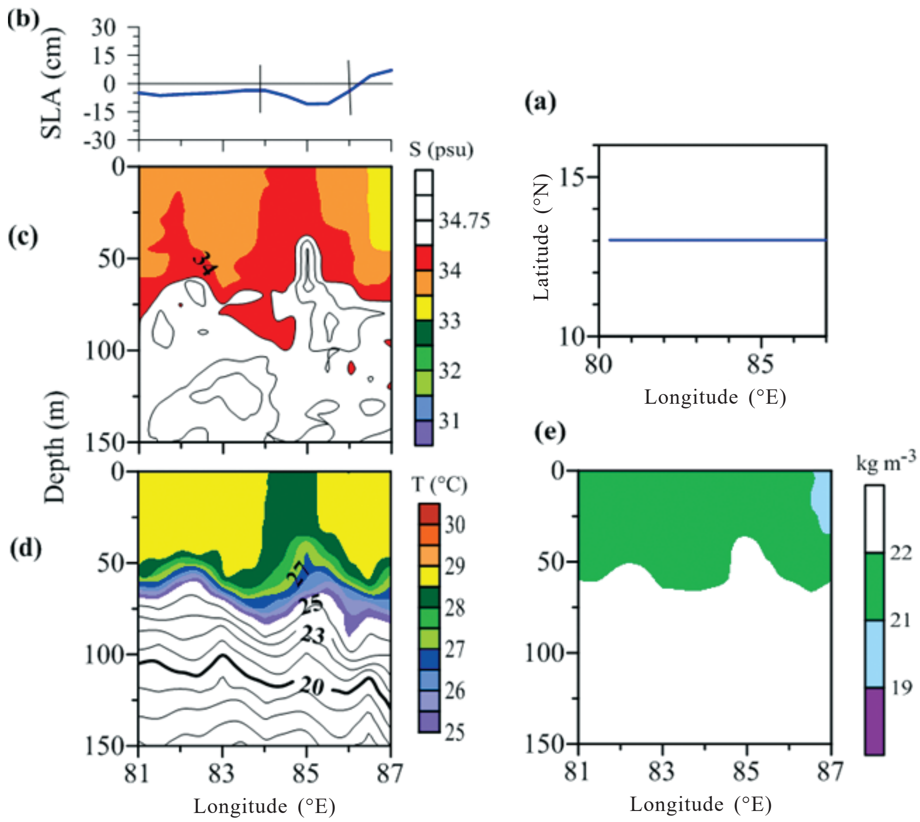

Figure 7. (a) BOBMEX track (Blue line) along 13°N,81-87°E during 28-30 July 1999, (b) sea level anomaly, vertical section of (c) salinity, (d) temperature and (e) sigma-t.

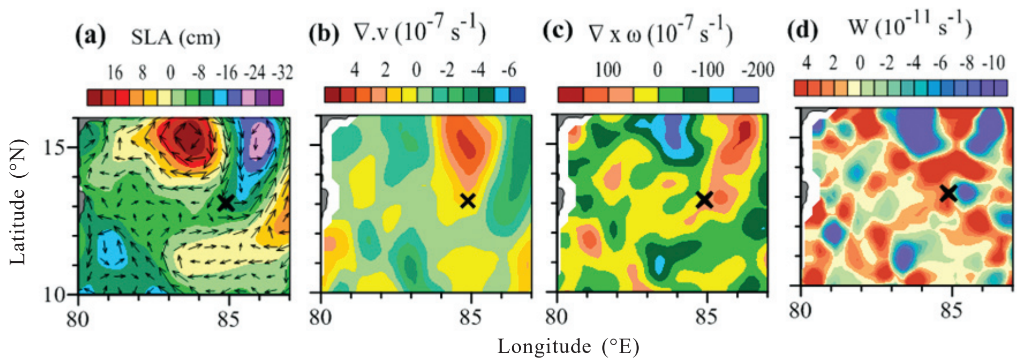

Figure 8. (a) Sea level anomaly overlaid with geostrophic current, (b) divergence (∇.v), (c) vorticity (∇xω) and (d) Okubo-Weiss parameter (W) on 29 July 1999. Positive values: yellow to red, negative values: blue to yellow. Black cross represent station location.

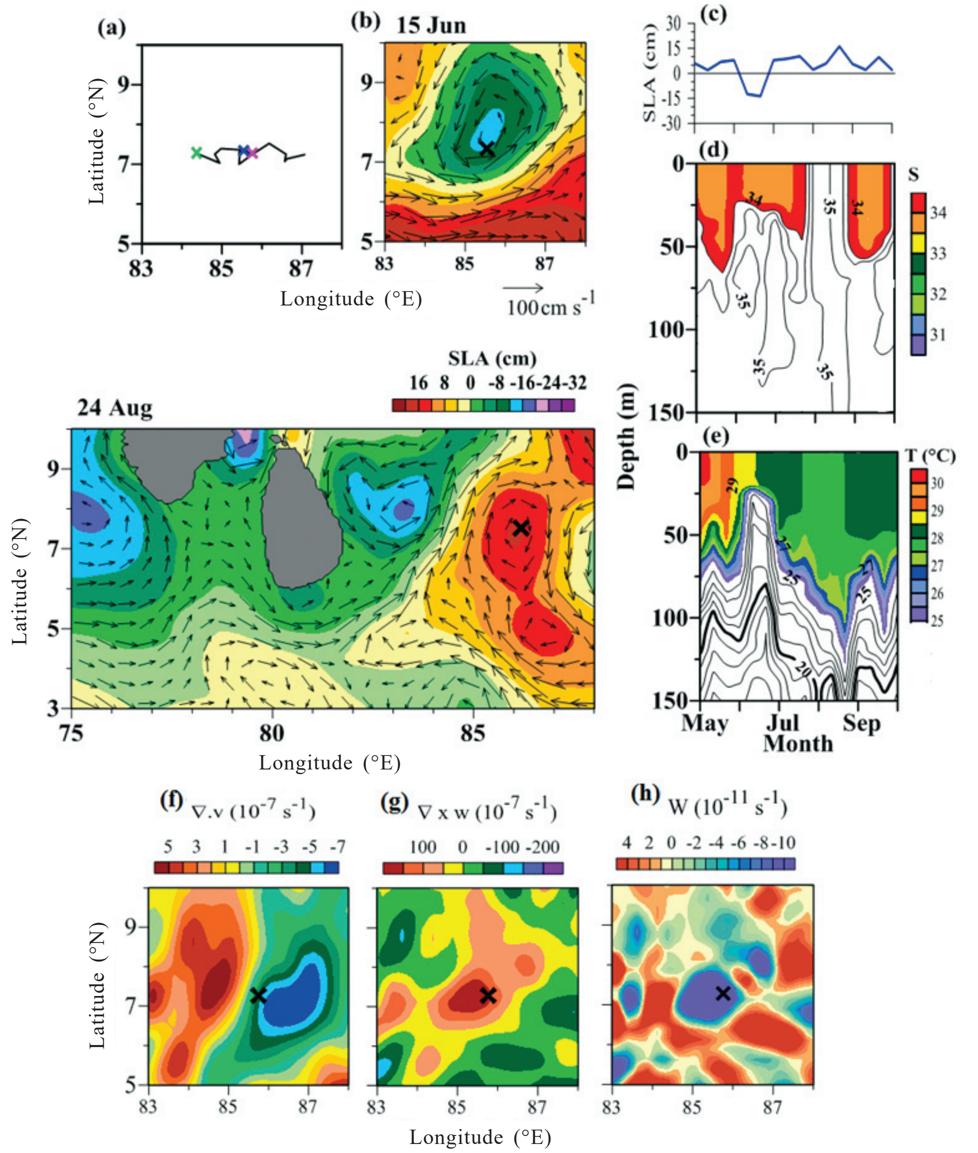

Figure 9. **(a) Track of Argo float 2902365 (black line) in the southern BoB during May-September 2013. Green cross: Initial float position, Blue and Orange cross: Regions of saltwater pumping, (b) sea level anomaly (SLA) overlaid with geostrophic current on 15 June and 24 August 2013; black cross: float position, (d) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature, (f) Divergence (∇.v), (g) vorticity (∇ x ω) and (h) Okubo-Weiss parameter (W) for the uplift on 15 June 2015. Positive values: yellow to red, negative values: blue to yellow. Black cross represent float position on this day.**

at 8 °N, 85 °E and an anti-cyclonic eddy in August at 6.5 °N, 86.5 °E. The most striking observation is the presence of saltwater in the region of these opposing cyclonic and anti-cyclonic eddies. As discussed in the previous sections, the cyclonic eddy (Fig. 9(b)) pump comparatively saltier water towards the surface, thereby increasing the salinity in the upper 50 m water column by 0.5 psu (Fig. 9(d)). The strong cyclonic eddy in June is evident from negative divergence, positive vorticity and negative values of W (Fig. 9(f)-9(h)). On the other hand, in the presence of an anti-cyclonic eddy, the upper 150 m water column becomes homogenous in salinity (~35 psu). This saltier water is advected from the Arabian Sea as observed by Vinayachandran[12], *et al.* The convergence of this water leads to downward displacement of isopleths. However, in the temperature field, the homogeneous condition is noticed only up to 100 m (Fig. 9(e)).

Case II: WOCE

The temperature and salinity section (Figs. 10(c), 10(d)) along the WOCE track (Fig. 10(a)) shows doming of isopleths in February 1995. Being south of 10°N makes the water saline (~33.75 psu) and the uplift further increases salinity by 0.5 psu (Fig. 10(c)). The sigma-t indicates the presence of Southern Bay of Bengal Watermass in the upper 60 m (Fig. 10(e)). The cyclonic eddy induced divergence (Figs. 10(g)-10(i)) leading to modification in thermohaline structure is evident from Figs. 10(c), 10(d).

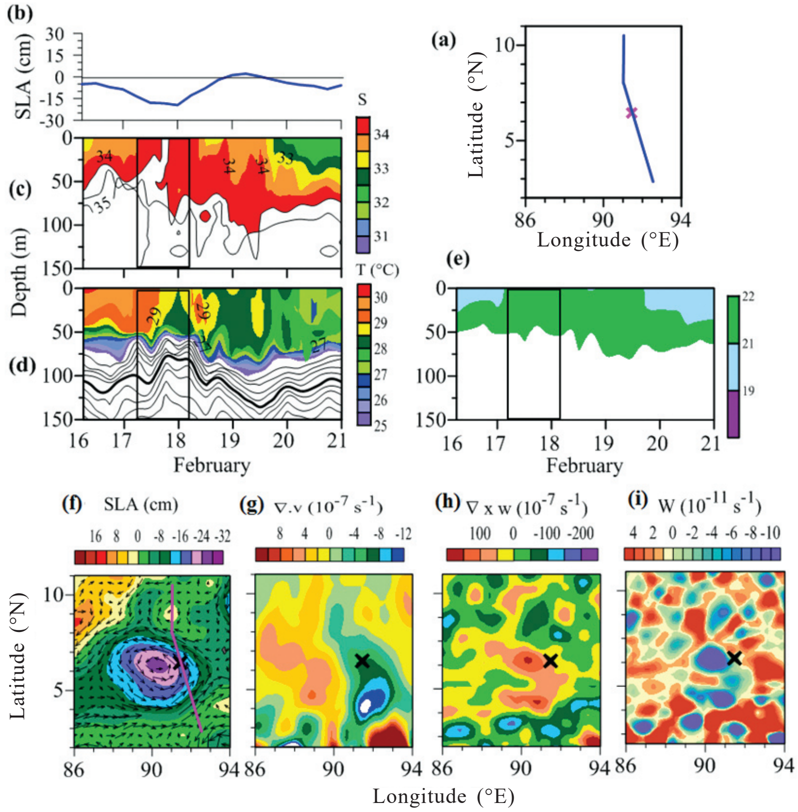

Figure 10. **(a) WOCE track (Blue line) during 16-21 February 1995 (Black cross: region of uplift), (b) sea level anomaly, vertical sections of (c) salinity, (d) temperature and (e) sigma-t along the WOCE track. The duration of uplift is indicated between vertical bars, (f) Sea level anomaly (SLA) overlaid with geostrophic current, (g) divergence (∇.v), (h) vorticity (∇xω) and (i) Okubo-Weiss parameter (W) for the uplift on 18 February 1995. Positive values: yellow to red, negative values: blue to yellow. Black cross represent position of float on this day.**

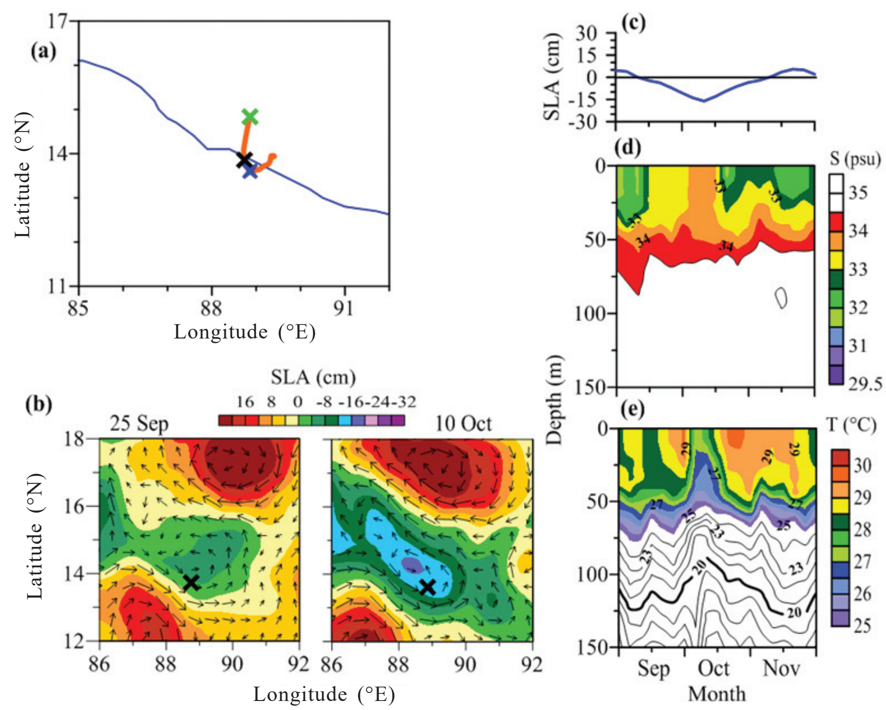

Figure 11. **(a) Track of Argo float 2902114 (Orange line) during September to November 2014 and cyclone Hudhud (Blue line) formed in the BoB during October 2014; Green cross: Initial float position, Black and blue cross: Regions of saltwater pumping, (b) Sea level anomaly (SLA) overlaid with geostrophic current on 30 September and 10 October 2014; black corss: float position, (c) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature.**

3.2 Tropical Cyclone

Case I: Cyclone Hudhud (Argo float 2902114)

In September 2014, a cyclonic eddy is noticed in the central BoB centered at 14 °N, 89 °E. Under its influence, SLA drops to -15 cm (Figs. 11b, (c)) and saltier water is uplifted towards the surface from a depth of 40 m resulting in an increase of 0.25 psu in the surface salinity (Fig. 11(d)). But in the temperature field, such uplift is not perceptible, probably because of the fact that the water is isothermal up to 50 m (Fig. 11(e)).

On 7th October 2014, the cyclone Hudhud, referred to as Hoopoe bird in Arabic, was formed as a low pressure area over Andaman Sea and upgraded as "very severe cyclonic storm" on 10th October, when it was centered near 15ºN and 86.8ºE around 470 km east-southeast of Visakhapatnam (Fig. 11(a)). Thereafter the system moved in a north-westward direction. The cyclone is evident from strong positive wind stress curl (Fig. 12(d)), negative value of divergence and positive vorticity (Figs. 12(a), 12(b)). The availability of Argo float 2902114 in the vicinity of Hudhud track helps to understand its impact on the thermohaline variability. The vertical sections (Figs.11(d), 11(e)) show cooling of the surface waters in excess of 2 °C and increase in salinity by more than 0.5 psu when Hudhud was at its maximum intensity. In this case, Hudhud cause not only the saltwater pumping in the upper 60 m but significant cooling in the water column and a thermohaline front. The subsurface water with temperature ~27 °C surfaces, replacing warmer water of ~28.5 °C (Fig. 11(e)).

Case II: Cyclone Viyaru (Argo float 2901331)

Cyclone Viyaru, formerly known as Mahasen, was a relatively weak tropical cyclone (Fig. 13(a)). It originated from an area of low pressure over the southern BoB in early May 2013, slowly consolidated into a depression on 10th May. As in the previous cases, negative divergence, positive vorticity and negative W enclosed by positive values confirm cyclonic circulation (Figs. 13(f)-13(h)). The Argo float 2901331 in the vicinity of the cyclone track show increase in salinity by 0.75 psu and marginal drop in surface temperature (Fig. 13(c), 13(d)) when cyclone was at its maximum intensity. In this case, the cyclone causes only the saltwater pumping in the upper 50 m without significant cooling in the water column leading to the formation of a haline front.

3.3 Coastal Upwelling

Near the coast, the upwelling is one process that causes uplift of subsurface waters towards the surface. The upwelling variability involves many factors such as wind stress, the sharp bathymetry along the east coast of India, large-scale circulation, and eddies. The data collected onboard Sagar Kanya along 11 °N, 81-82 °E during 11-15 July 1993 (www.nodc.noaa.gov) shows upsloping of isolines in the upper 60 m towards the east coast of India signifying the coastal upwelling (Fig. 14(b), 14(c)). Sil and Chakraborty[20] also reported upwelling in the western BoB during May-September. In the western BoB, the coastal upwelling is mainly driven by the Ekman divergence induced by the southwesterly monsoon winds. As a consequence of strong divergence, cooler and saltier water advect upward from its sub-surface domain towards the surface and cools the surface layers (upper 75 m) by 0.5 °C (28.5 °C to 28 °C) and increase the salinity by 0.5 psu (33.5 to 34 psu).

4. CONCLUSIONS

In this work, the saltwater pumping in the BoB and various causative mechanisms are described utilising the data from Argo floats, RAMA buoy and dedicated field experiments like BOBMEX and WOCE. Primarily, saltwater pumping varies spatially and temporally. In the western boundary of the BoB, the prevailing southwesterly wind during summer monsoon causes coastal upwelling, which result in the salt water pumping. However in the open ocean, saltwater pumping occurs owing to the cyclonic eddy as water diverges at its centre. In addition, eddy to eddy interaction also leads to divergence and subsequent salt water pumping. The analysis indicated that the uplift of saltier water from subsurface levels increases the surface layer salinity thereby creating a salinity gradient, which varies from north to south. During the monsoon season, the advection of saltier water from the Arabian Sea also leads to an increase in the salinity in the surface layers. The formation of tropical cyclone during pre- or post-monsoon season also increases surface salinity of the BoB.

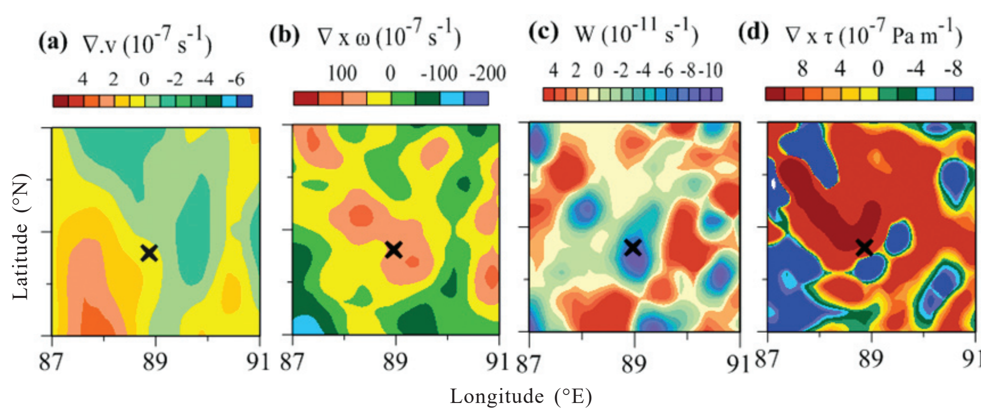

Figure 12. **(a) Divergence (∇.v), (b) vorticity (∇ x ω) and (c) Okubo-Weiss parameter (W) for the uplift on 10 October 2014 and (d) Wind stress curl (∇ x τ). Positive values: yellow to red, negative values: blue to yellow. Black cross represent float position on this day.**

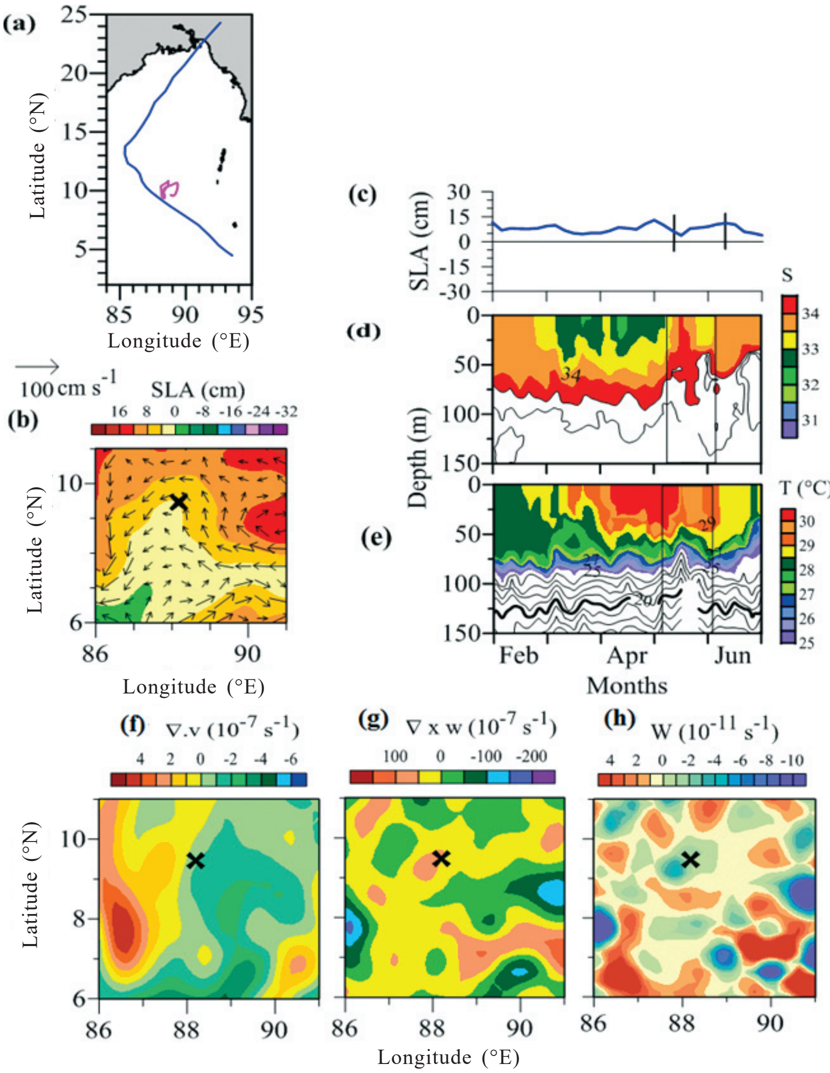

Figure 13. (a) Track of Argo float 2901331 (Orange line) during February-June 2013 and cyclone Viyaru (Blue line) formed in the BoB in May 2013, Green cross: Initial float position, Black cross: Regions of saltwater pumping, (b) Sea level anomaly (SLA) overlaid with geostrophic current on 15 May 2013, black cross: float position (c) SLA along the track of Argo float, vertical section of (d) salinity and (e) temperature. The duration of uplift is indicated between vertical bars, (a) Divergence (∇.v), (b) vorticity (∇x ω) and (c) Okubo-Weiss parameter (W) for the uplift on 15 May 2013. Positive values: yellow to red, negative values: blue to yellow. Black cross represent position of float on this day.

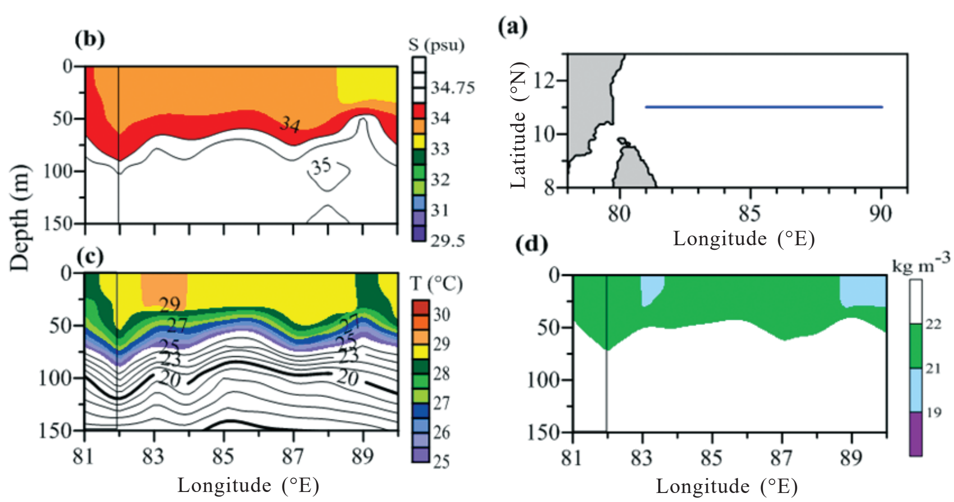

Figure 14. (a) Track along 11°N from 81° to 90°E during 11-15 July 1993, vertical section of (b) salinity, (c) temperature and (d) sigma-t. Vertical bar: upwelling zone.

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