

## **Observed Variations in Stratification and Currents in the Zuari estuary, west coast of India**

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### **Abstract**

25-hour time series measurements of vertical salinity profiles and currents in Zuari estuary were conducted during both spring and neap tidal cycles of pre monsoon (April-May), southwest monsoon (June-September) and post monsoon (October-December) seasons during 2011 at four different stations along the estuary. Measurements were carried out at locations, near the mouth (called the Bay station), Lower middle estuary, Upper middle estuary and Upstream. Based on these observations, variations in stratification at different time scales (daily, spring-neap cycle and seasonal) are described. In the mixed tidal regime with semi-diurnal dominance, stratification at Higher Low water succeeding Lower High water is more intense than that of Lower Low water succeeding Higher High water over a tidal cycle. During pre monsoon, when river discharge is negligible, the spring-neap cycle hardly causes any change in peak stratification factor (stratification factor,  $\Delta S$ , is difference between the bottom and surface salinity), attained within a tidal cycle at the bay and upstream stations. However, during spring, the peak stratification factor ( $\Delta S$ ) of lower and upper mid-estuarine stations decreases by about 2 and 1 respectively. During monsoon at the lower middle estuary station, salinity value peaks only at high water which is similar to the pre-monsoonal conditions at the upstream station. High stratification observed during high waters at the lower middle estuary during monsoon, weakens marginally at the peak of the high waters, during both spring and neap phases. Due to the incursion of high saline downstream water along the bottom, the bottom water gets saturated slightly before the peak of high water. Because of this, the salinity of bottom layer remains constant for about 2-3 hrs while the surface salinity still continues to increase up to the peak of high water, resulting in the weakening of stratification. Moreover, during monsoon, the magnitude of the flood flow progressively reduced from mouth to upstream and no flood flow was observed at the upstream station. Variation of computed Potential Energy Anomaly is found to match with that of stratification factor ( $\Delta S$ ) closely.

**Key words:** Salinity Stratification, Spring-neap cycle, Mixed semi-diurnal tide, Monsoon, Salt wedge

## 1. Introduction

The Zuari estuary, a part of the Mandovi-Zuari estuarine system connected by 'Kumbharjua canal', is located on the west coast of the Indian peninsula. The length of the estuary is about 50 km and its width varies from about 5 km at the mouth to about 50 m at the head. The average depth of the estuary is about 5 m. The estuary can be divided into two regions, a broad bay, having about 5 km of width at the mouth, extending from mouth to about 12 km upstream, and a narrow channel, barely 50 m wide at the upstream station (Sanvordem) located at about 45 km from the mouth, extending further upstream (Fig. 1). The Kushavati river joins Zuari at about 38 km from the mouth. The upstream stretch of Zuari above the location marked Sanvordem is known as Sanguem and it has two tributaries at the head known as Uguem and Guloli rivers. Selaulim dam, with a capacity of 227 MCum is constructed in the Guloli river. The discharges from Selaulim dam, Kushavati and Uguem rivers count in altering the flushing rate. The copious rainfall received in the western ghats during the southwest (SW) monsoon with the peak rainfall occurring during July (Inset of Fig. 1) cascades down the slope and floods the estuary. This freshwater discharge at the head of Zuari during monsoon modifies the pre-monsoon characteristics of the estuary to such an extent that the saline water intrusion is observed to stop at the meeting point of channel and bay part of the estuary during some of the intense rainfall events. After monsoon, the freshwater discharge at the head decreases and the estuary starts recovering gradually to its original pre-monsoon condition.

The seasonal salinity cycle in Zuari estuary was studied and the annual salt budget was examined using a 1 D model (Shetye and Murty, 1987). With three day water level observations at 15 locations in the Mandovi-Zuari estuarine network using tide poles during dry and wet seasons, it was found that tidal amplitude is nearly constant up to 40 km. Even the meagre fresh water discharge at the head during pre monsoon is sufficient to cause dilution of salinity (Shetye et al., 1995). Later, a network model was developed to simulate tidal propagation in the Mandovi-Zuari estuaries to understand the dynamics of the above behaviour (Unnikrishnan et al., 1997). Sundar and Shetye (2005) studied tidal propagation by recording water level at 13 locations by using tide poles for a period of one month and determined the tidal harmonic constituents. Salinity variations over different seasons were described in a later work (Vijith et al., 2009) using salinity profile data from spot measurements collected once in a day at a fixed location and from profiles collected along the longitudinal section of the estuary. These salinity profiles were collected from a boat moving from the mouth to head, which could not resolve the estuarine variations occurring at high frequency. In the present work, we carried out time series measurements of salinity and currents at different locations to understand the estuarine variability in different time scales.

During pre-monsoon and post-monsoon seasons, the tide works relentlessly in transgressing

salt up the estuary through advection and diffusion processes. During monsoon, even though the tidal forcing is felt up to a distance of about 50 km from the mouth, freshwater discharge dominates in controlling the salinity field in the estuary by flushing salt out of the estuary. The perpetual tidal action and the seasonal fresh water discharge from catchment areas have their own effects on modifying the characteristics of the estuary at their own natural frequency of occurrence. The kind of tide observed here is mixed tide with semidiurnal dominance, with a higher high (HH), higher low (HL), lower high (LH), and lower low (LL) water in a diurnal cycle, which causes variations in the characteristics of the physical parameters of the estuary in a diurnal cycle. In Zuari estuary, the average tidal range during spring is about 2.5 m, while that during neap is about 1.5 m at the mouth. The two tidal asymmetries mentioned above in the diurnal and spring-neap cycles cause variations in the characteristics of the physical parameters of the estuary in various time scales ranging from daily and fortnightly (spring-neap cycle). The strong imprint of the SW monsoon causes variation in salinity characteristics in pre-monsoon, monsoon and post-monsoon seasons. To get a complete understanding of the physical processes in this estuary, it is required to study the diurnal, fortnightly and seasonal variations. Besides, there could be inter-annual variations, which is beyond the scope of the present study. In this work, we focus on the diurnal, spring-neap and seasonal variability of the physical parameters observed in the Zuari estuary.

In an earlier study made during February 1999, through time series observations of vertical profiles of temperature and salinity at a location (Old Goa) about 15 km from the mouth in the Mandovi estuary, it was suggested that the salt flux due to advection depends on the flow velocity, salinity and the two tidal asymmetries between flood and ebb and also spring and neap, permitting the net salt flux into the estuary (Shetye et al., 2007). In the present study, we have looked at the variability of stratification at various time scales from time series data collected at four locations along the length of the estuary.

There are a few studies made, using continuous observations of salinity in estuaries to describe the changes in stratification. Haas (1977) studied the effect of spring-neap tidal cycle on the salinity structure in lower York and Rappahannock estuaries in USA using surface and bottom salinity values and tide data and proposed that the salinity field is controlled more by the height of the tide than the magnitude of the tidal range. Stratification studies carried out in Cochin estuary, west coast of India suggested strong links of chemical and biological properties with it (Shivprasad et al., 2013). In an effort to study the composition and behaviour of heavy metals in Guanobara bay, Brazil, a tropical estuary, it has been shown that the observed stratification of the water column due to the presence of two water masses with different densities determined the residual transport of these metals during a tidal cycle (Gustavo et al, 2015). In a study to understand the impact of the salt water-fresh water interface due to sea level rise and ground water usage, the 'fresh water

discharge-salt water intrusion' phenomena into the estuary were also considered (Venkatesh et al, 2013). In the present study, during the monsoon period when the flow is high we observed formation of salt wedge, which is solely tide induced. It has also been shown during an observation in Tiber estuary, Italy, salt-wedge formation occurred even during high discharge rates, due to the wind effect (Fabio et al., 2014). Most of the salinity measurements made so far in the Mandovi-Zuari estuaries have been done by taking longitudinal sections during different time periods. In a recent paper, Anand et al. (2014) described the sub-hourly changes in biogeochemical properties in surface waters of Zuari estuary, Goa. This points out the need to study the processes in estuary at small time intervals. With a similar objective, simultaneous measurements of hydrography and currents for about 25 hours at chosen locations (Fig. 1) were done during spring and neap cycles of all three seasons in 2011. Using this data, daily, fortnightly and seasonal variation of stratification is described.

## **2. Methodology**

The observations were carried out from boats anchored midstream, at locations Dona Paula, Cortalim, Borim and Sanvordem, which hereafter are referred to as the bay station, lower middle estuary, upper middle estuary and the upstream station respectively. Dona Paula, Cortalim, Borim and Sanvordem are located at distances of about 1, 13.7, 20.5 and 45 km respectively from the mouth. The survey consisted of measurements of physical, chemical and biological parameters. In the present article, a discussion of variability of the physical parameters alone is made, which will help the chemical and biological oceanographers immensely in understanding the ecology of the estuary. Companion papers are being prepared on the variability of bacteria, zooplankton and phytoplankton. Portable CTDs of make Seabird Electronics Inc., USA of model 19plus having an accuracy of 0.005 °C in temperature and 0.005 in salinity measurements were operated from the anchored boats at every hour during observation period.

Flow at the four locations was observed and recorded at every 5 minutes using self recording current meters of Seaguard model of make Aanderaa Instruments, Norway. At bay and mid estuarine stations current meters were moored in the vicinity of the boat. At upstream station, due to shallow depth and narrow width of the estuary, and due to frequent barge movements, mooring of current meter could not be done. Instead, a current meter, with a tail fin attached for stability, was hung from the anchored boat and the stern end of the boat was tethered to the nearby bridge to eliminate rotation of the survey boat around its anchor during the turn of the tide. The speed and direction observed at all stations were resolved to 'u and v' components, which were rotated through appropriate angles depending on the angle of orientation of the channel at the station location, to get the flow along the channel and across the channel, known as the longitudinal flow and cross-shore flow respectively. The angle through which the u and v components were rotated at the bay

and the three channel stations, were about 85°, 84°, 58° and 72° respectively. They varied slightly in different sets of observation, as re-deployment of RCM mooring precisely at the very same spot is not possible. However, the range of variation of rotation angles is within 10° in all observations, which is well within the accuracy,  $\pm 10^\circ$  of the direction sensor of the instrument. The flow data were sub sampled to get hourly flow data to match with the hourly CTD observations.

Tidal harmonic constituents determined in an earlier study (Sundar and Shetye, 2005) at the sampling locations were used to generate the astronomical tides for the observation period for use in this study, using the TASK software from the Proudman Oceanography Laboratory, Liverpool (Bell et al., 1998).

River discharge data from Selaulim dam (Guloli river), Kushavati and Uguem rivers during the observation period were obtained from the Water Resources Department, Govt. of Goa, India. The river discharge patterns during the period of observations are shown in the 'inset' of Fig. 1.

### **3. Results**

In a shallow estuary, salinity variations affect density more than temperature variations do, thereby affect the stability and stratification of the water column. Hence we used the salinity data to describe the variation of stratification in the estuary. Knowledge of variability of salinity, tides and tidal currents from mouth to head helps in the study of the ecology of the estuary.

#### **3.1. Tide, Longitudinal flow and Salinity**

##### *3.1.1 Pre monsoon and Post monsoon*

During pre-monsoon and post-monsoon seasons, unlike the channel stations, tide and salinity variations with time at the bay station (Dona Paula) are found incoherent. This is probably due to the presence of cross-shore flow. The peak magnitude of which is about 15 cm/s, quite significant compared to the peak magnitude of the longitudinal flow of about 20 cm/s, during pre-monsoon observation. The longitudinal flow had a phase difference of about 90° with tide and salinity at all stations (Figs. 2 and 4).

The flood and ebb current magnitudes are found to be nearly same during both half tidal cycles of the pre monsoon and post monsoon at all stations (Table 1). But during monsoon, the flood and ebb flow magnitudes show marked difference due to freshwater discharge component added to them.

At all three channel stations, near-rectilinear flow is seen indicating that the flow is mostly longitudinal. The transverse flow is restricted at these stations owing to the narrow width of the

estuary. The orientation of the flow is observed to follow the orientation of the channel at the respective stations. The bay station alone exhibits unobstructed flow in all directions. In general, magnitude of current keeps increasing as one proceeds upstream from the mouth. The current at the lower middle estuary is found marginally stronger than the current at upper middle estuary, probably due to the geometry of the station location.

### 3.1.2 SW Monsoon

During monsoon, copious freshwater discharge at the head (Inset of Fig. 1) plays major role in altering the characteristics of the estuary over any other forcing such as tide, winds. Comparison of phases of longitudinal flow and tide at the lower middle estuary station (Cortalim) during monsoon observations shows, due to the weak tidal forcing at neap against heavy discharge of fresh water at the head, the three hours lag between flow and tide observed during pre monsoon reduced to about 2 to 2½ hrs and during spring the lag was 2½ to 3 hrs (Table 2). The diurnal inequality in tidal range of mixed tide with semidiurnal dominance has its effect in the phase lag between the tide and flow. Similarly, the successive phase lags between the peak flood flow and high water or peak ebb flow and low water are not the same. Hence there are two numbers for each column. There is only one number for three out of six upper estuary observations as one of the peak flow times could not be ascertained. The observation started sometime about the time of peak flood flow which posed uncertainty in judging the precise time of peak flood flow to calculate the phase lag with tide. At the upper middle estuary station (Borim), the lag is about 2½ hrs during both the neap and spring as the effect of spring phase gets damped in transit over a distance of 7 km from Cortalim to Borim. At the upstream station (Sanvordem), the lags during low waters are far less than the lags during high waters. During both the spring and neap highs the lags are about 2 hrs, while during neap lows, lags are about 25 min and 1 hr and during spring lows, are about 30 min and 45 min.

At the upstream location (Sanvordem), the time lag between the tide and flow of about 2.5 to 3 hrs (Table 2) during pre monsoon and post monsoon decreases to about 60 min and 25 min respectively during the two lows at neap tide and to about 45 min and 30 min respectively during the spring tide. This drastic change of phase lag is not seen at mid-estuarine stations (Cortalim and Borim), where the flow and tide phase difference is about two and a half hrs during neap and 3 hrs during spring. The higher range of tide and the resultant higher pressure head during spring tide helps to balance the discharge and thereby the spring phase offset is closer to the normal offset of 3 hrs.

Moreover, at all the three locations the magnitude and duration of ebb flow become higher than those of flood flow. The flood duration at the upper middle station (Borim) is less than the flood duration of the lower middle estuary station (Cortalim). At the upstream station (Sanvordem), only downstream flow is observed even though a tidal range of about 85 cm and 125 cm are observed

here during the neap and spring phase respectively. The strong river run-off alters the flood duration progressively as one proceeds towards the head of the estuary during the monsoon. Even though tidal wave reached the upstream station (Sanvordem), no salinity transgression takes place here. The water column at both the upper middle estuary station (Borim) and the upstream station (Sanvordem) are observed to be fresh.

During pre monsoon and post monsoon at the upstream station (Sanvordem), increase in surface salinity value, from near zero by a range of just less than 1, is observed only during highs (Figs. 2 and 4). The lower middle estuary (Cortalim) also manifests similar phenomenon of increase of salinity values of water column only during high waters during monsoon. During monsoon the dense saline water creeps all the way up the estuary along the bottom and thus the subsurface water in lower middle estuary is observed to be more saline than surface layer to cause high stratification during high waters. Due to its proximity to the mouth, the stratification developed at lower middle estuarine station (Cortalim) is phenomenal with every high water during monsoon (Figs. 3 and 6) enabling to exhibit a saltwater wedge. But during pre monsoon the saline water intrusion under the negligible river discharge conditions, travels 11 km in the bay and 33 km in the estuarine channel to reach the upstream station. This intrusion while moving upstream interacts with low saline upstream waters through turbulence and bottom friction due to shallow depth, to present only a small increase in salinity value at a well mixed water column at the upstream station. After monsoon, the salt wedge phenomenon observed at lower middle estuary location (Cortalim) moves upstream progressively and the high stratification breaks down to present marginally high saline mixed water column in the upstream region during the high waters.

#### 4. Discussion

Salinity stratification factor ( $\Delta S$ ) is taken as the difference between bottom salinity and surface salinity.

The potential energy anomaly (PEA) is defined as the amount of energy expressed in  $J/m^3$ , required to overturn the water column to a well mixed layer. The calculated PEA value is a good indicator of the intensity of stratification.

$$PEA = -\frac{1}{D} \int_{-z}^{\eta} gz(\rho - \bar{\rho}) dz \dots\dots\dots(1)$$

where D is the maximum depth, z is the height of the layer taken from the bed,  $\eta$  is the instantaneous tidal height, dz is the layer thickness,  $\rho$  is the density of the layer,  $\bar{\rho}$  is the mean density of the water column and g is the acceleration due to gravity. Thus when the layer thickness dz is constant, PEA is directly proportional to the height of the layer chosen from the bottom and the stratification parameter, which implies that PEA values depend the tidal phase and  $\Delta S$ .

The portable CTD observes from about 50 to 80 cm below water surface to a level about 50 cm above the bed. The respective near surface and near bottom salinity values were taken as the surface and bottom salinity. To examine the  $\Delta S$  variations due to the diurnal inequality of tidal range, the mixed tide with semidiurnal dominance is divided into two half tidal cycles, one of higher tidal range containing the higher high (HH) and lower low (LL) phase and the other of lower tidal range containing the lower high (LH) and higher low (HL) phases. Maximum and minimum values of  $\Delta S$  within the half tide of higher range are marked with large and small filled circles respectively (Figs. 2-4). Similar notation is followed for the other half tide of lower range with filled triangles. These markers are shown on the tidal curves at the respective time of their occurrence.

#### **4.1 Diurnal Variations in stratification**

The Bay station (Dona Paula) being shallow and open to the sea, is also affected by wind and wave action besides tidal action, which breaks up development of any stratification resulting to a well mixed water column irrespective of the phase of the tide. It was found during this observation that the  $\Delta S$  maximum was less than 1 during pre monsoon and about 3 during post monsoon over 25 hrs. This station manifests coastal sea conditions while the influence of low saline upstream waters is seen in modifying the stratification during post monsoon. It is however believed that the influence of the upstream waters at Dona Paula must be more intense during monsoon. There was no observation carried out this time due to rough weather and hence no data to support this view. Typical wide bay circulation causes low saline low dense upstream waters to flow along the surface layers to the bay station region during ebb phase, which modifies the salinity profile causing a momentary spike in  $\Delta S$  value for a short duration of about < 2 hrs, immediately after low water (Figs. 4 and 7). But for these spikes observed at low waters, both the pre monsoon and the post monsoon diurnal  $\Delta S$  variations are well within about 1.

Lower middle estuary (Cortalim) location is at the entrance of the channel, where all westerly winds, waves and swells from the adjacent coastal seas reach unhindered. During the observation period, this location turned choppy caused by sea breeze during the afternoon. This apparently did not have any effect on stratification. Tide and flow alone seem to be the dominating factors in the mixing processes (Figs. 2-4). The water column in this location shows mixed, partially stratified and salt wedge characteristics under different conditions. The water column was observed to be well mixed during the high water phase of the tide and partially stratified during low water. Thus it is inferred that stratification was more intense during low waters than during high waters, which phenomenon is more prominent during neap. Low saline upstream water seen at the surface during low water (HL and LL) cause the stratification and in its absence during high water (HH and LH) only a mixed water column is observed. This indicates that at lower middle estuary, upstream water is instrumental in causing diurnal stratification variations during pre monsoon and post monsoon



(Figs. 5 and 7).

Larger  $\Delta S$  values occur during HL after the LH than at LL occurring after HH phase. This is due to the half tide of higher tidal range, comprising HH and LL, mixes the water column well, more than the half tide with lower tidal range. The higher tidal range and thereby the enhanced tidal flow, causes higher turbulence, which augments mixing. When the LL builds stratification over a well mixed column due to preceding HH phase, the HL builds stratification over a partially mixed water column due to preceding LH phase (Fig. 2). Thus the stratification at HL over the already partially stratified waters at LH is higher than the stratification at LL following a mixed column of water observed at HH. Similar phenomenon is observed during post monsoon also during neap (Fig. 4).

The rapid variation of stratification may also be caused by the 'tidal straining' phenomenon (Simpson, 1990). Longitudinal density gradients and vertical shear in tidal currents interact to generate an input to stratification. During ebb, lighter brackish water moves towards estuarine mouth with the leading edge acting on the water surface without affecting the high dense bottom waters, increasing the  $\Delta S$  values, leading to maximum stratification during the low waters. Similarly, during the HH phase of the tide, enormous amount of sea water displaces the brackish water at this location resulting to same surface and bottom water characteristics, leading to a low  $\Delta S$  value. The shallow water depth at the observation locations restricted measurement of flow to only one level, so that vertical shear in current is not understood, which causes tidal straining. We intend to carry out measurements at different vertical levels using ADCP moorings in the next study. The lower middle estuary (Cortalim) water is controlled by high saline downstream waters and the extent of salinity variability is influenced by the dilution of low saline upstream waters.

In upper middle estuary (Borim), similar to the location in lower middle estuary, high  $\Delta S$  values were observed at both the HL phases, which occurred after the LH phases and low  $\Delta S$  values were observed at high waters. The diurnal variation in the pattern of isohalines and  $\Delta S$  at the upper and lower middle estuary during neap phase of pre-monsoon and post-monsoon period are identical; even though the magnitude of  $\Delta S$  values were larger here.

At the upstream station (Sanvordem), water was found to be fresh with very weak salinity spiking, occurring only during high water phase of the tide. The  $\Delta S$  factor is found to be near zero during most of the observations. During spring high  $\Delta S$  reached a maximum of 1.

#### **4.1.1 Stratification and Potential Energy Anomaly**

The calculated hourly PEA values show, very obvious dependence of PEA over  $\Delta S$  by their quite similar variation patterns (Figs. 2-4). There are few instances observed, when  $\Delta S$  values became nearly constant the PEA curve matched well with the tidal curve. That means, even if the  $\Delta S$  values are same more energy will be required to overturn the water column, if the water column

depth  $z$  increased due to change of tidal phase.

The following two events are examples of such instances. In Fig 2 at Lower middle estuary, at 0300 hrs and 1300 hrs on 28<sup>th</sup> April, for same values of  $\Delta S$  and magnitude of observed flow, the PEA at 0300 hrs is nearly half of the PEA at 1300 hrs. This is due to low water depth at 0300 hrs and high water depth at 1300, which needs more energy at 1300 hrs to make the water column mixed. In Fig 4 at the Bay station, observed the  $\Delta S$ ,  $z$  and PEA parameters at 1800 hrs on 23<sup>rd</sup> October, 0200 hrs and 0800 hrs on 24<sup>th</sup> October. At 0200 and 1800 hrs, the  $\Delta S$  values are nearly same, but PEA is more at 1800 hrs and less at 0200 hrs, due to higher water depth at 1800 hrs. Similarly, the PEA at 0800 hrs is more than at 0200 hrs even though the  $\Delta S$  value at 0800 hrs is less. This is also due to higher tidal elevation and thereby higher  $z$  at 0800 hrs.

The PEA variability does not manifest any relation with the longitudinal flow variation in this observation.

#### **4.2 Spring-Neap Variations in stratification**

The spring-neap variability of  $\Delta S$  is caused due to the difference in tidal range between the two phases which is about 1 m at the mouth of Zuari estuary and the associated stronger tidal flow. At the Bay station, where the flow magnitude is the lowest of all locations, the velocity at neap and spring were observed as about 17 cm/s and 25 cm/s during pre monsoon and 20 cm/s and 30 cm/s during post monsoon respectively. The same at the lower middle estuary station were 45 cm/s and 65 cm/s during pre monsoon and 60 cm/s and 80 cm/s during post monsoon (Table 2). The spring phase velocity is more by about 25-30% of the neap flow. Higher velocity of spring flow enhances the turbulence, reducing the stratification of the water column more vigorously than the weaker neap flow. Hence the spring phase  $\Delta S$  values are observed to be lower than the neap values.

Figs. 2 and 4 show that mixed water column condition at the bay station (Dona Paula) does not change appreciably with the spring-neap phase of tide. During post monsoon, patches of low saline upstream water are seen at surface during HL and LL phase and during LL the patch lasted longer; for 2 hrs during HL and 4 hrs during LL respectively. These cause some peaks in  $\Delta S$  at low waters (Figs. 4 and 7). In spite of that,  $\Delta S$  values of spring are lower than the neap values showing less stratification. Very negligible increase in  $\Delta S$  maximum at the bay station is found during the spring than at neap during the pre monsoon. It should only be taken that during all observations, except at the upstream station during all seasons (Sanvordem) and at the upper middle estuary station (Borim) during post monsoon,  $\Delta S$  maximum decreases from neap to spring.  $\Delta S$  is found to be zero at upstream station (Sanvordem) during both the phases.

During neap, the  $\Delta S$  variations are seen similar at both the mid estuarine locations. High  $\Delta S$  during the lows and low  $\Delta S$  during the highs are observed. But during spring,  $\Delta S$  variation pattern is

found different from each other. At lower middle estuary station, it is inferred from the pattern of isohalines that almost well mixed water column exists during spring and only at mid tides some weak stratification is observed.  $\Delta S$  maximum is observed at mid tides at lower middle estuary and at slack water at upper middle estuary.

#### **4.3 Seasonal Variations in Stratification**

The copious rainfall and the resulting heavy freshwater discharge at the head of Zuari causes the salinity variations during monsoon in the Zuari estuary, leaving its strong foot print in all the estuarine phenomena observed.

The  $\Delta S$  values are zero at stations in the upper middle estuary (Borim) and upstream (Sanvordem) (Fig. 2) CTD has recorded zero salinity from surface to bottom.

At lower middle estuary (Cortalim), high  $\Delta S$  values at high waters and zero  $\Delta S$  values at low waters are observed during both the spring and neap phases of monsoon season. This is the reverse of the condition seen at this location during pre monsoon and post monsoon. During both spring and neap phases of monsoon,  $\Delta S$  value peaks and coincides with high waters and the duration of  $\Delta S$  spike from the zero to maximum and back to zero is about 8 hrs (Fig. 3). The water is highly stratified only during the flood phase.

During neap, the  $\Delta S$  peak of LH is seen undisturbed while that of the HH has a dip immediately after the peak flood flow (Fig. 3). During spring,  $\Delta S$  curves of both LH and HH have dips. These manifest weakening of stratification. On comparing the figs. 3 and 6, it is observed that the duration in hours of the dip in  $\Delta S$  observed in Fig. 3 matches with the duration in hours of saturation of the salinity of the bottom water (Fig. 6). During high water, the bottom water reaches the maximum salinity value it can attain early and stabilizes, when the surface salinity continues to increase. This phenomenon causes the dip at  $\Delta S$  peak (Fig. 3). The  $\Delta S$  maxima at HH and LH phases are 7.56 and 8.87 during the neap and 10.34 and 14.87 during the spring of the diurnal cycle respectively. During the HH phase the surface salinity values are higher than that of the LH phase. Hence are the lower  $\Delta S$  maximum values at HH than at LH.

Even though the features of the salinity field observed during pre monsoon and post monsoon at the four locations appear to be similar (Figs. 5 and 7), on closer look, lower salinity values are observed and the range of salinity variation is also higher during post monsoon than at pre monsoon. Though the copious discharge at the head of the estuary has stopped during post monsoon, still a meagre amount of constant discharge keeps taking place (Inset of Fig. 1), which is sufficient to keep the water at upstream fresh. Due to tidal excursion, each station gets low saline upstream water and high saline downstream water oscillating about it with the relentless tide. After monsoon, with the transgression of salt due to tidal advection, salinity values all along the estuary start rising and the

salinity gradient becomes progressively less while moving upstream from mouth. During pre monsoon, the salinity gradient upstream from mouth is low and hence is the smaller range of salinity variation and during post monsoon higher salinity gradient in the estuary causes the high range of salinity variation at each station over a tidal cycle.

Knowledge on stratification, currents and tides during a tidal cycle is useful in understanding the variability of bio-geochemical parameters, distribution of organisms and to study the ecology of the estuary.

## **5 Summary and Conclusions**

Stratification variability at four locations in Zuari over a tidal cycle, during both spring-neap phases of pre monsoon, monsoon and post monsoon has been discussed using  $\Delta S$ , tide and longitudinal flow. The bay station is observed to exhibit the characteristics of a shallow coastal station that the waters are well mixed and only a change of 0.5 in the  $\Delta S$  value over a tidal cycle is observed. The mean salinity change from spring to neap is only 0.37. At the upstream station, always fresh water column is observed. At mid estuarine stations, stratification conditions changed with phase of the tide. The stratification is observed to be high during low waters and low during high waters. Higher  $\Delta S$  values occurred at HL phase after LH and lower  $\Delta S$  values at LL phase after HH phase. Due to turbulence and bottom friction,  $\Delta S$  during HH phase is lower than  $\Delta S$  at LH phase. The stratification at HL over already partially stratified waters at LH is more intense than stratification at LL after a mixed column of water observed at HH. Similar phenomenon is observed during post monsoon. This rapid variation of stratification within a tidal cycle is due to the phenomenon known as 'tidal straining'. The ebb tide moves lighter brackish water towards the mouth with the leading edge acting on water surface without affecting the high dense bottom waters, increasing  $\Delta S$  values. This explains why maximum stratification is observed during the low waters. Similarly during HH phase of the tide, enormous amount of sea water displaces the brackish water at this location resulting to same surface and bottom water characteristics and to a low  $\Delta S$  value. Stratification conditions observed in the channel stations are different than the bay station at same phase of the tide.

During monsoon at the upstream location, the normal phase lag of about 3 hrs between the current and tide reduces to about 30 min to 1 hr. During spring tide, the phases of current and tide almost became same. The flood and the ebb durations in the estuary change progressively from mouth to head. The flood duration decreases and the ebb duration increases to such an extent that, at upstream station only ebb flow is observed even though the tidal wave reached the location. The advancing tidal wave only diminishes the magnitude of the ebb flow and does not carry any salt upstream.

Rectilinear flow is observed at the three channel stations. The Bay station alone shows some cross shore flow. The flow orientation is observed to follow the orientation of the channel at the respective stations.

The lower middle estuary exhibits mixed, partially stratified and salt wedge conditions during various seasons of the year. The salt wedge formation observed during monsoon is found to be of transient feature occurring twice in a tidal cycle. It appears with the transgression of high saline water along the bottom during high water and disappears with low water. The salinity peaking at high waters is due to the intrusion of high saline downstream water along the bed and is clearly indicated in the salinity contour plots (Figs. 3 and 6). The dip in the  $\Delta S$  values in the peaks is explained as follows. During the flood phase, high saline water from downstream keeps creeping up increasing the salinity of bottom water. At some stage bottom salinity values almost stabilize and do not change appreciably. But surface salinity values continue to rise. This causes the dip in  $\Delta S$  values. Immediately after the passage of the high water the surface salinity values start falling, with the bottom salinity values staying steady for a while, before they themselves start decreasing. Hence is the rise in the  $\Delta S$  values after the dip. This reasoning is consolidated by comparing the duration of the constant salinity value of the near bottom water seen in the salinity contour plots with the duration of the dip in the  $\Delta S$  values in Figs. 3 and 6. The bottom salinity value has stayed constant for 4 hrs during the neap and 5 and 3 hours during the spring phase. During monsoon, the intensity of stratification is found directly proportional to the range of the tide so that  $\Delta S$  during spring is higher than at neap during monsoon. But, due to this phenomenon,  $\Delta S$  at LH phase was observed to be higher than at HH phase within a tidal cycle during both neap and spring.

Fig. 8 illustrates the pattern of variation of stratification parameter ( $\Delta S$ ) in Zuari estuary over a tidal cycle during the spring-neap phases of pre monsoon, monsoon and post monsoon. In general, higher  $\Delta S$  during neap phase of the tide and lower during spring is observed. During monsoon, the estuary has fresh water from the head to the lower middle estuary with a salt wedge showing up as a transient feature only during high waters. Weakening of stratification at peak of high waters is also noticed by corresponding low  $\Delta S$  values. This was observed in three occasions out of four salt wedges.

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This is NIO contribution number xxxx.

### **Legends of the Figures**

1. The location map of Mandovi-Zuari estuarine system. The bay station (Dona Paula) is located very close to the mouth of Zuari, Cortalim is at the entrance of the channel, Borim is a mid estuarine station and Sanvordem is located upstream in the estuary. They are located at a distance of 1, 13.7, 20.5 and 45 km respectively from the mouth. The inset gives the discharge rates of Selaulim dam, Kushavati and Uguem rivers ( $\text{m}^3/\text{s}$ ) at the head of Zuari estuary during July-November 2011.
2. Variation of stratification parameter ( $\Delta S$ ), tide, alongshore flow, surface salinity and bottom salinity observed at the four locations and the calculated Potential Energy Anomaly over 25 hrs during spring and neap phases of pre monsoon, 2011. ( $\Delta S = \text{Bottom salinity} - \text{Surface salinity}$ ). For better clarity each panel is subdivided to top and bottom halves. The top panel contains  $\Delta S$ , PEA and tide. The lower panel contains salinity of surface and bottom layers and flow. The positive flow indicates flood phase and negative flow indicates ebb. As per the range of variation of salinity at the location, salinity axis is modified in the panels to illustrate salinity variations with the change of tide and flow clearly. Maximum and minimum values of  $\Delta S$  within the half tide of higher range are marked with large and small filled circles respectively. Similar notation was followed for the other half tide of lower range with filled triangles. These markers are shown on the tidal curves at the respective phases of their occurrence. The numbers written right above the markers are the respective  $\Delta S$  values.
3. Same as above during the spring and neap phases of SW monsoon.
4. Same as above during the spring and neap phases of post monsoon. PEA curve mostly follows the  $\Delta S$  curve during both spring and neap phases; with the exceptions at 1800 hrs on 23<sup>rd</sup> October, 0200 hrs and 0800 hrs on 24<sup>th</sup> October at Dona Paula during neap and at 2000 hrs on 29<sup>th</sup> October and 0300 hrs on 30<sup>th</sup> October at Dona Paula during spring.
5. Time-Series of hourly salinity profiles observed over 25 hrs, during spring and neap phases of pre monsoon at the four locations. The depth values include tidal height. The line with dots interspersed on it, gives the tidal heights and the dots give the time of observation.
6. Same as above during the spring and neap phases of SW monsoon period
7. Same as above during the spring and neap phases of post monsoon period
8. Variation of stratification parameter ( $\Delta S$ ) in Zuari estuary over a tidal cycle during spring-neap phases of the three seasonal cycles. D, C, B and S indicate Dona Paula, Cortalim, Borim and Sanvordem locations shown at their respective distances from the mouth in the Y axis.

Corresponding tide variation is given in each diagram. Grey area shows no data. The Selaulim dam discharge rates are negligible during pre monsoon. The discharge rates in units of m<sup>3</sup>/s, were 84.48 and 85.90 on 1<sup>st</sup> and 2<sup>nd</sup> of August, 61.07 and 50.61 on 9<sup>th</sup> and 10<sup>th</sup> of August, 11.50 and 11.20 on 23<sup>rd</sup> and 24<sup>th</sup> of October and 10.62 and 10.60 on 29<sup>th</sup> and 30<sup>th</sup> of October respectively.

## References

1. Bell, C., Vassie, J.M., Woodworth, P.L., 1998. POL/PSMSL Tidal Analysis Software Kit 2000 (TASK2000). Permanent Service for Mean Sea Level, Proudman oceanographic Laboratory, Merseyside, UK.
2. Fabio Manca, Giuseppe Capelli, Francesco La Vigna, Roberto Mazza, Annalisa Pascarella 2014. Wind-induced salt-wedge intrusion in the Tiber river mouth (Rome–Central Italy). *Environ. Earth Sci.* (2014) 72:1083–1095, DOI 10.1007/s12665-013-3024-5
3. Gustavo Vaz de Melo, Jose Antonio Baptista Neto, Olaf Malm, Marcos Antonio dos Santos Fernandez, Soraya Maia Patchineelam (2015). Composition and behaviour of heavy metals in suspended sediments in a tropical estuarine system. *Environ. Earth Sci.* (2015) 73:1331–1344 DOI 10.1007/s12665-014-3491-3
4. Haas, L.W., 1977. The Effect of the Spring-neap Tidal Cycle on the Vertical Salinity Structure of the James, York and Rappahannock Rivers, Virginia, U.S.A. *Estuar. Coast. Mar. Sci.* 5, 485-496.
5. Shetye, S.R., Gouveia, A.D., Singbal, S.Y., Naik, C.G., Sundar, D., Michael, G.S., Nampoothiri, G., 1995. Propagation of tides in the Mandovi-Zuari estuarine network. *Proc. Indian Acad. Sci., Earth Planet. Sci.* 104(4), 667-682.
6. Shetye, S.R., Michael, G.S., Vishwas, P.C., 2007. Mixing and intrusion of salt, Chapter 4, *The Mandovi and Zuari Estuaries* ISBN 978-81-7525-872-3.
7. Shetye, S.R., Murthy, C.S., 1987. Seasonal variation of the salinity in the Zuari estuary, Goa, India. *Proc. Indian Acad. Sci. Earth Planet Sci.* 96, 249-257.
8. Shivprasad, A., Vinita, J., Revichandran, C., Reny, P.D., Deepak, M.P., Muraleedharan, K.R., Naveen Kumar, K.R., 2013. Seasonal stratification and property distributions in a tropical estuary (Cochin estuary, West coast, India). *Hydrol. Earth Syst. Sci.* 17, 187-199.
9. Subha Anand, S., Anju, K.J., Mathew, D., Dileep Kumar, M., 2014. Sub-hourly changes in biogeochemical properties in surface waters of Zuari estuary, Goa. *Environ. Monit. Assess* 186: 719-724.
10. Sundar, D., Shetye, S.R., 2005. Tides in the Mandovi and Zuari estuaries, Goa west coast of India. *J. Earth Syst. Sci.* 114(5), pp 493-503.
11. Venkatesh Uddameri, Sreeram Singaraju, E. Annette Hernandez (2014). Impacts of sea-level rise and urbanization on groundwater availability and sustainability of coastal communities in semi-arid South Texas. *Environ. Earth Sci.* (2014) 71:2503–2515 DOI 10.1007/s12665-013-2904-z
12. Vijith, V., Sundar, D., Shetye, S.R., 2009. Time Dependence of Salinity in monsoonal estuaries. *Estuar. Coast. Shelf Sci.* 85, 601-608.
13. Unnikrishnan, A.S., Shetye, S.R., Gouveia, A.D., 1997. Tidal Propagation in the Mandovi-Zuari Estuarine Network, West Coast of India: Impact of Freshwater Influx. *Estuar. Coast. Shelf Sci.* 45, 737-744.
14. Simpson, J., J. Brown, J. Mathews, G. Allen, 1990. Tidal straining, density currents, and stirring in the control of estuarine stratification. *Estuaries*, 12, 125-132.

Table 1: Peak magnitude of longitudinal flow (cm/s) during flood and ebb phases. During monsoon, at Sanvordem only downstream flow is observed in a tidal cycle due to the high freshwater discharge rate. The negative sign during flood phase indicates that the flow direction is only downstream.

Season	Phase of the tide	Dona Paula ( Bay)		Cortalim (Lower middle)		Borim (Upper middle)		Sanvordem (Upstream)	
		Flood (cm/s)	Ebb (cm/s)	Flood (cm/s)	Ebb (cm/s)	Flood (cm/s)	Ebb (cm/s)	Flood (cm/s)	Ebb (cm/s)
Pre monsoon	Neap	17/15	22/16	40/41	52/46	33/34	39/30	47/32	44/45
	Spring	25/14	28/29	60/61	63/77	61/52	57/57	69/53	58/69
Monsoon	Neap	No observation		18/49	41/53	13/29	45/65	-33/-13	79/84
	Spring	No observation		89/75	107/92	34/43	97/83	-29/-34	100/89
Post monsoon	Neap	18/21	22/20	52/55	77/71	46/50	55/49	42/32	49/42
	Spring	15/27	39/22	56/69	92/75	65	71/61	65	40/28



Table 2: Comparison of phase lags between longitudinal flow and tide using the time of occurrence of peak flood (ebb) flow and high (low) water. The two values shown correspond to time (hrs) from maximum velocity during flood (ebb) to time (hrs) at high water (low water) in the mixed semi-diurnal tidal regime.

Season	Phase of the tide	Dona Paula ( Bay)		Cortalim (Lower middle)		Borim (Upper middle)		Sanvordem (Upstream)	
		Peak Flood flow to High water (hrs)	Peak Ebb flow to Low water (hrs)	Peak Flood flow to High water (hrs)	Peak Ebb flow to Low water (hrs)	Peak Flood flow to High water (hrs)	Peak Ebb flow to Low water (hrs)	Peak Flood flow to High water (hrs)	Peak Ebb flow to Low water (hrs)
Pre mon soon	Neap	3.0/2.0	2.7/1.0	3.0/2.0	2.7/2.5	2.5/2.0	2.7/2.0	2.7	3.0/2.5
	Spring	2.0/3.5	2.5/3.0	2.0/2.5	2.5/2.5	2.5/3.0	2.5/2.5	2.2	2.2/3.5
Mon soon	Neap	No observation		1.0/3.0	2.0/2.5	2.3/2.5	2.5/2.8	2.0/1.8	1.0/0.4
	Spring	No observation		3.0/2.5	3.0/2.5	2.0/3.5	3.0/3.0	2.0/2.0	0.5/0.75
Post mon soon	Neap	4.0/2.3	3.5/3.0	3.5/3.5	3.0/3.3	3.0/2.5	3.5/3.0	3.5/4.0	3.0/3.0
	Spring	2.5/2.5	3.0/2.0	2.0/2.5	3.0/2.0	2.5/2.5	3.0/2.0	4.0	3.0/2.0

Fig. 1

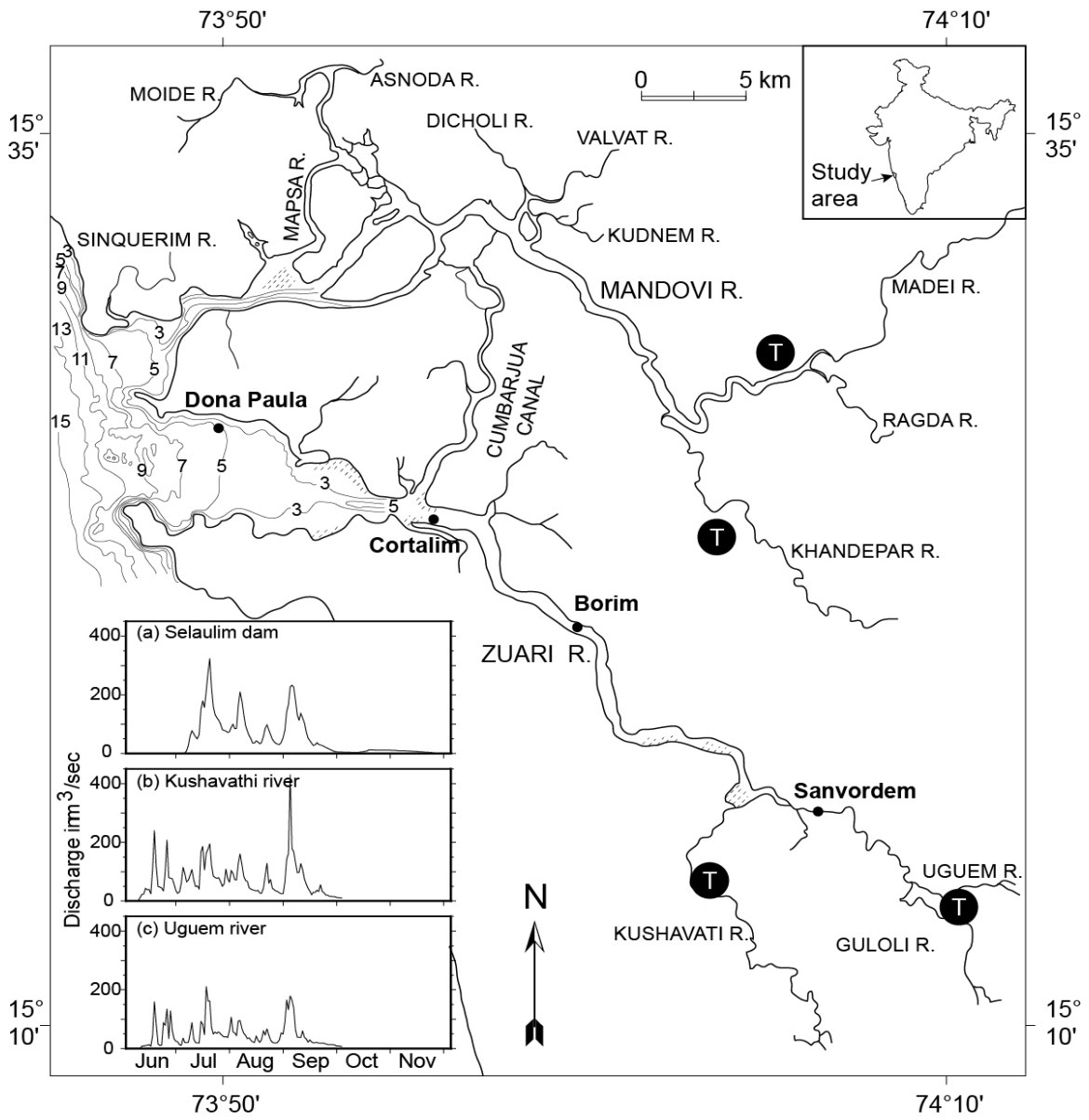


Fig.2

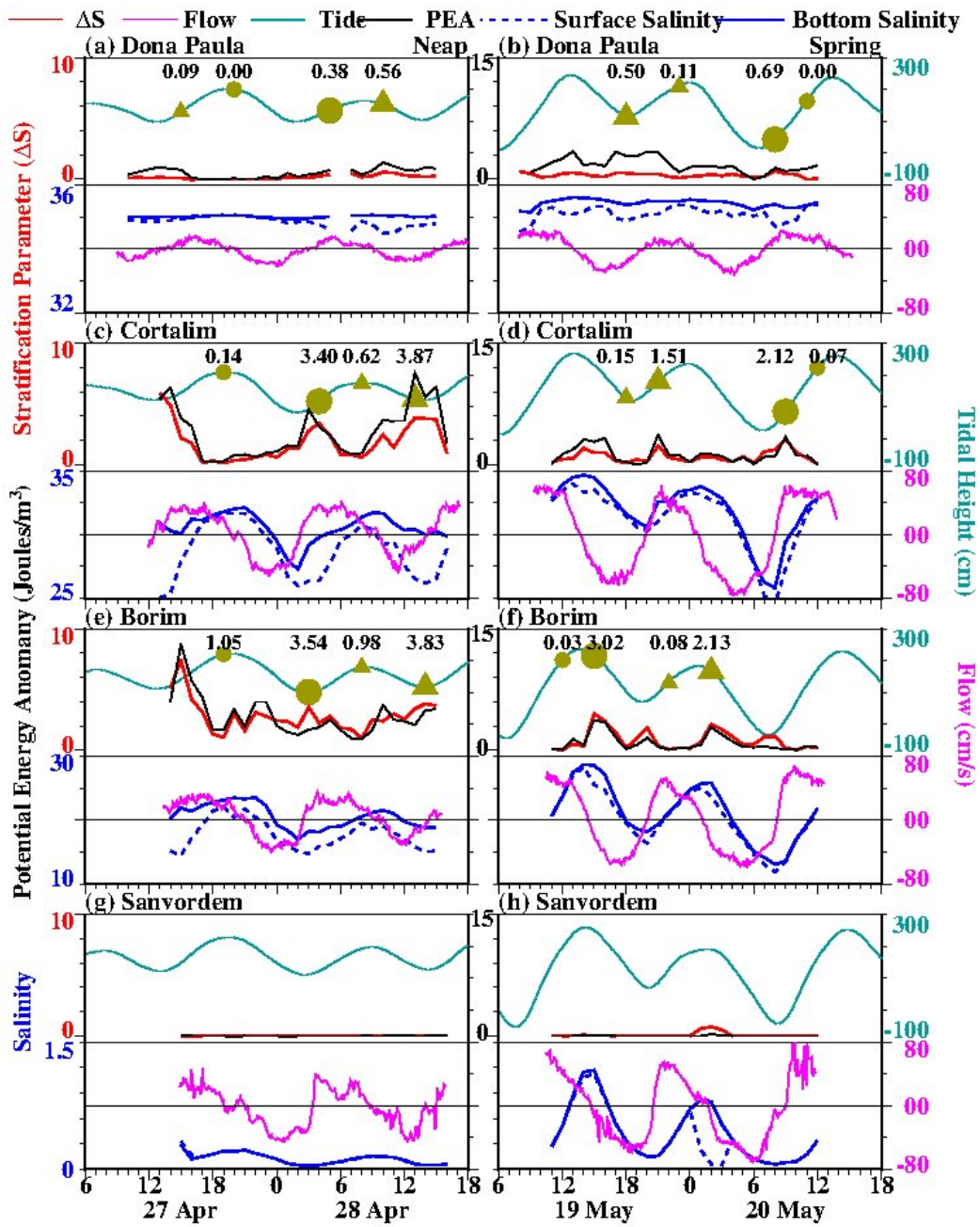


Fig 3

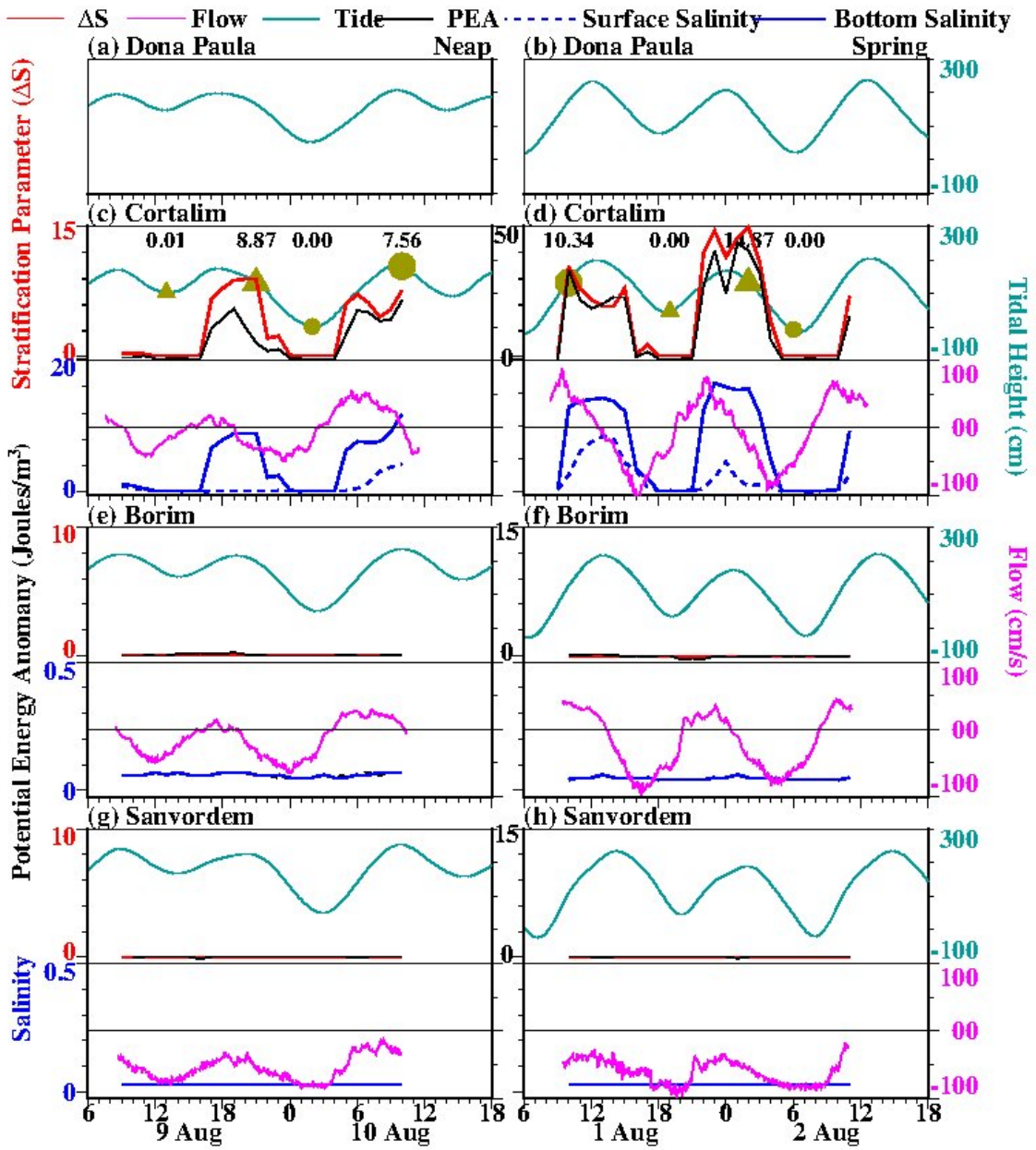


Fig 4

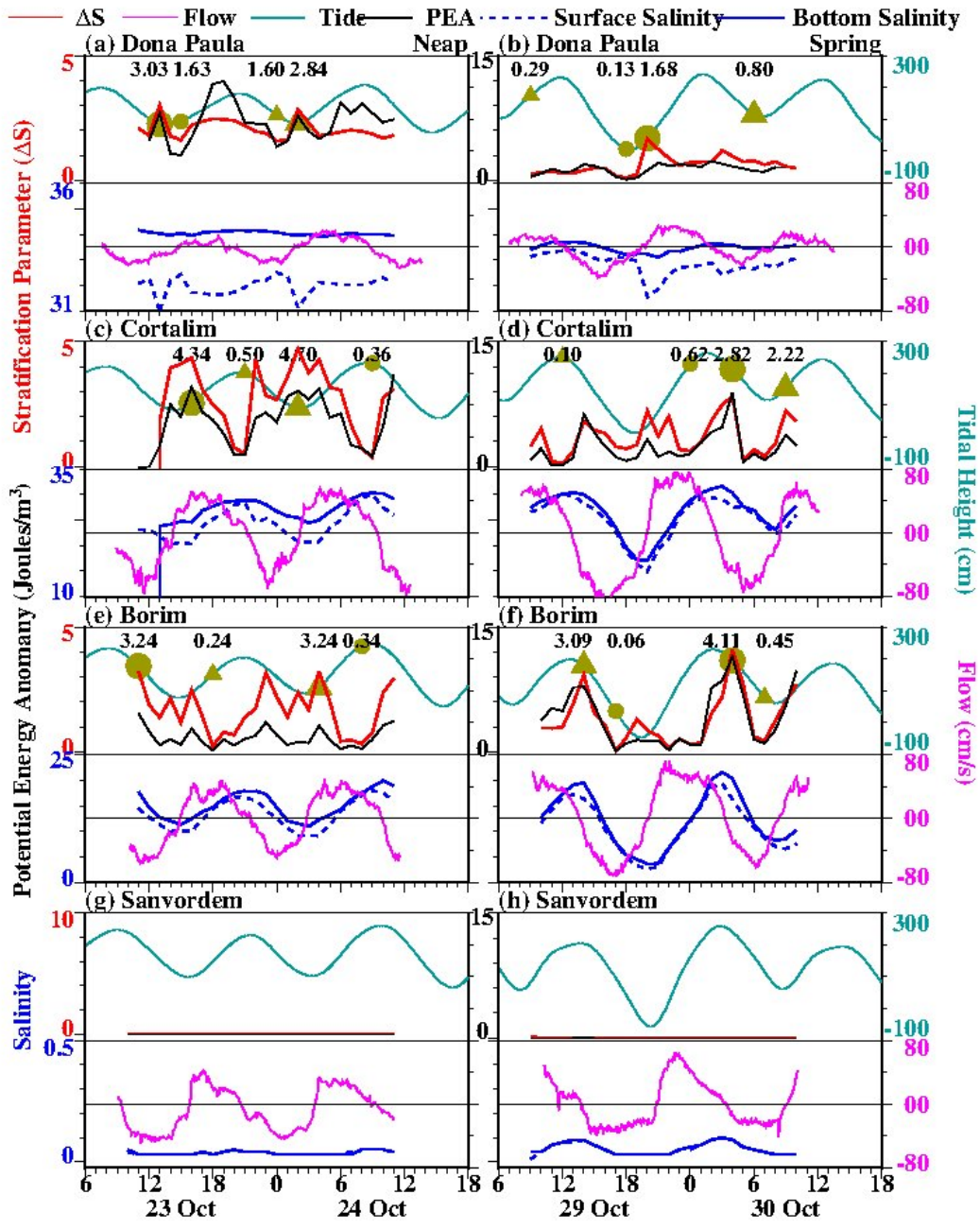


Fig 5

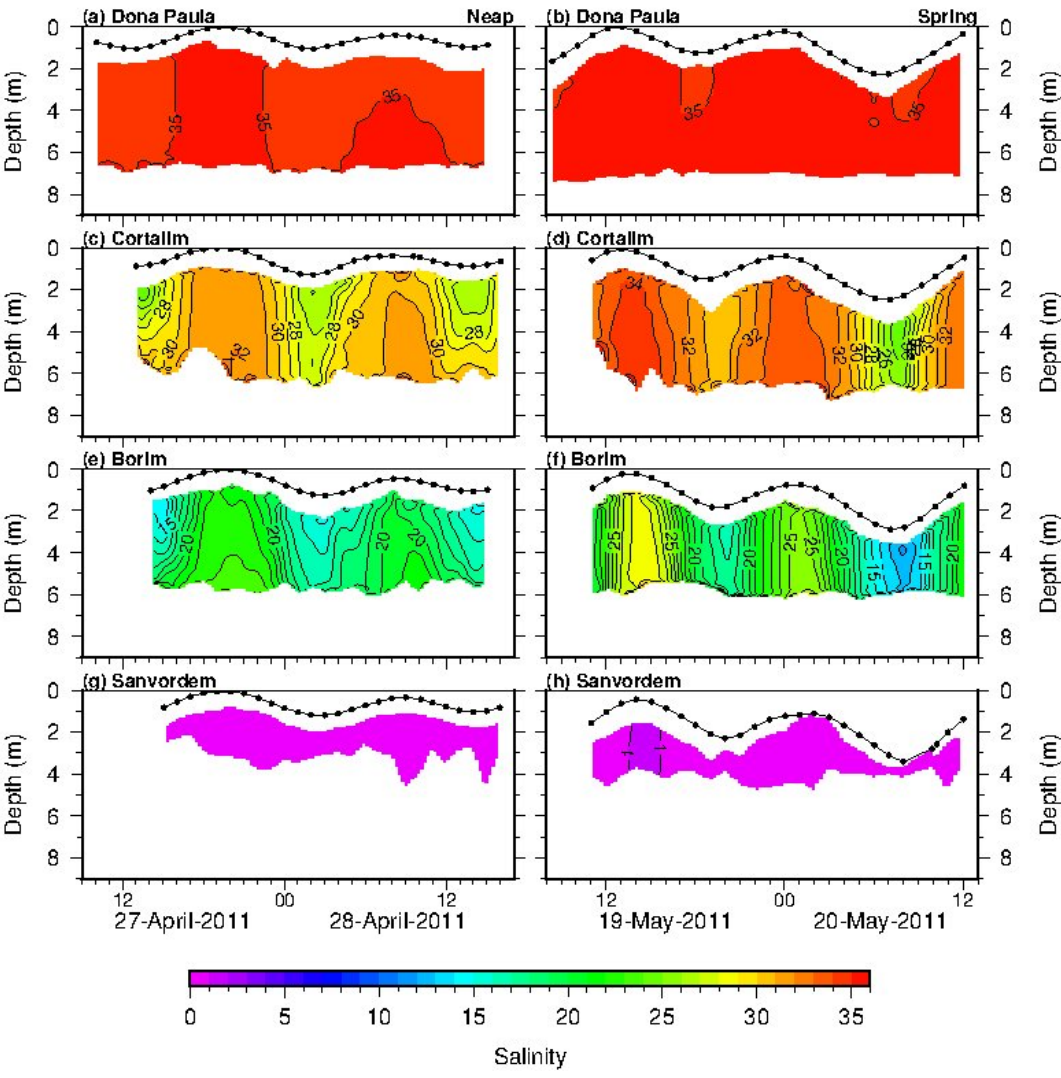


Fig 6

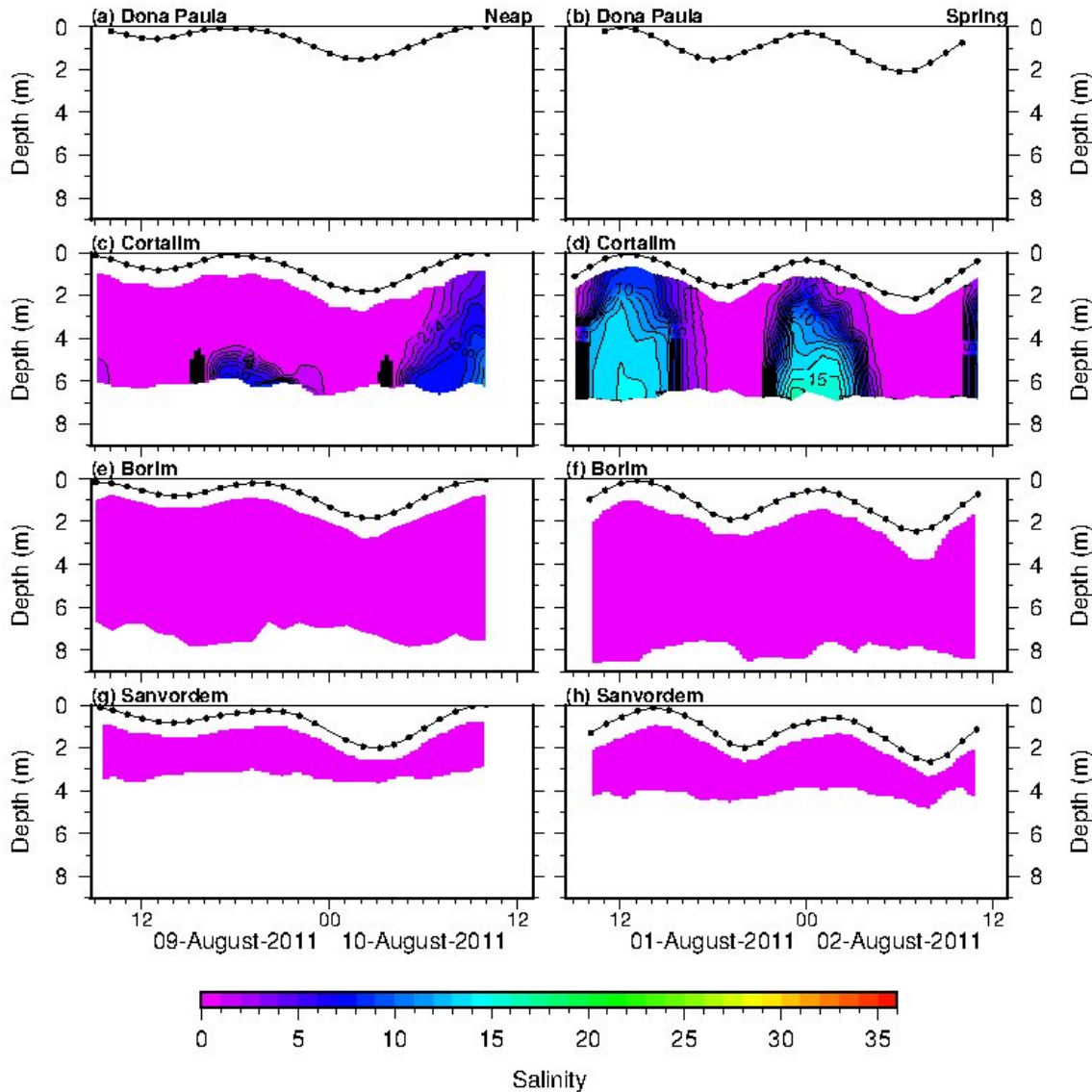


Fig 7

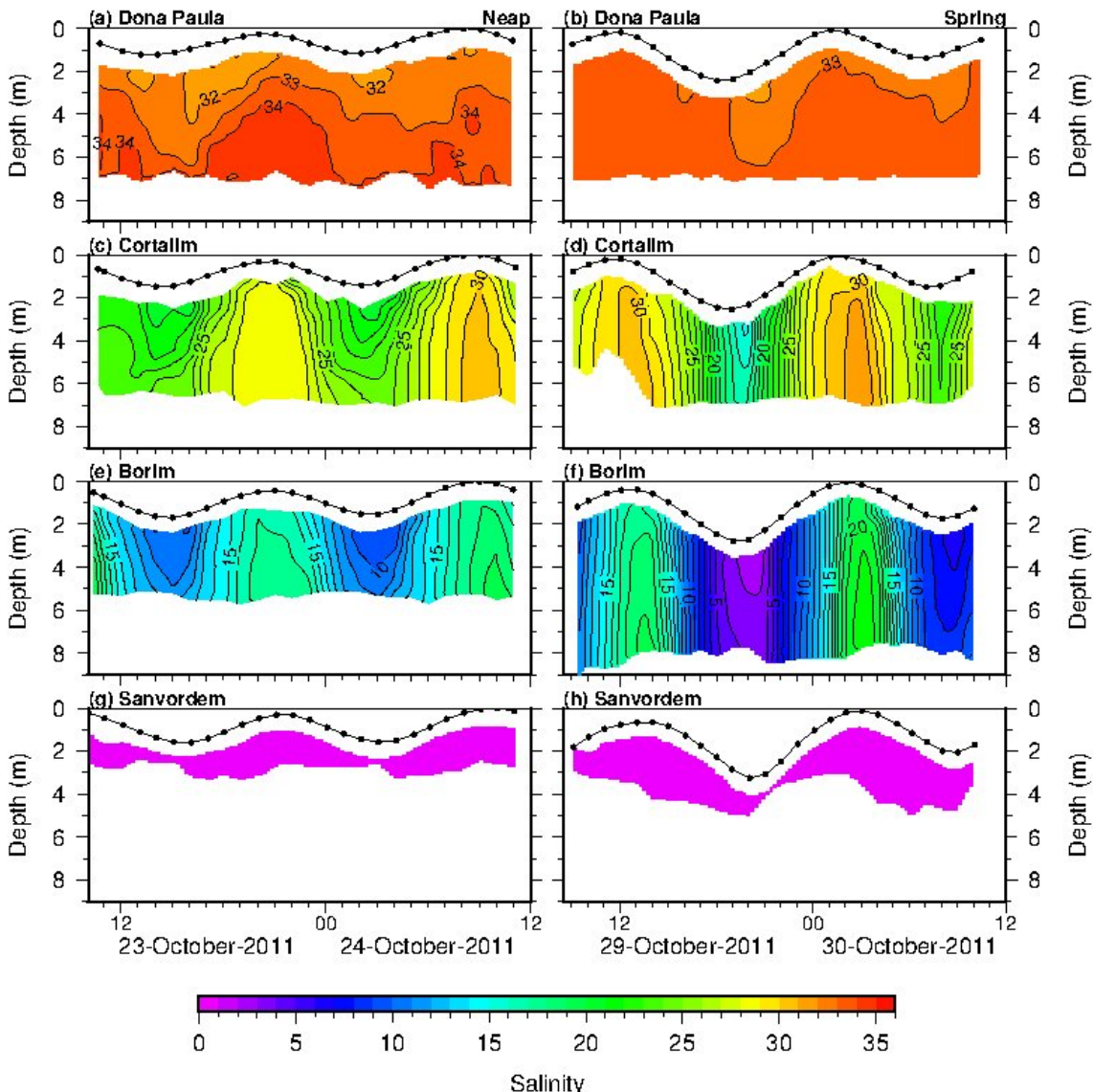




Fig 8

