2014

Assessing the impact of seasonal variations on the density structure of a weak freshwater plume

Kelsey-Wilkinson, D.

Kelsey-Wilkinson, D. (2014) 'Assessing the impact of seasonal variations on the density structure of a weak freshwater plume', The Plymouth Student Scientist, 7(1), p. 14-31.
http://hdl.handle.net/10026.1/14050

The Plymouth Student Scientist
University of Plymouth

Assessing the impact of seasonal variations on the density structure of a weak freshwater plume

Daniel Kelsey-Wilkinson

Project advisor: Phil Hosegood, School of Marine Science and Engineering, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA.

Abstract

Freshwater plumes are features of periodically intense salinity stratification created by an ebbing tide. The dynamics of these features are important for biological events, such as the spring bloom. Using an undulating towed Conductivity-Temperature-Depth (CTD) probe with a fluorometer attached, repeated sections were completed beyond Plymouth breakwater to a moored scientific station 9.6km offshore. These data were then gridded using linear interpolation and the density ratio; $R_\rho = \frac{\alpha \Delta T}{\beta \Delta S}$ was calculated at 3 positions: behind the plume, plume front and in front of the plume.
The ratios of influence which thermohaline properties contribute to the density structure of a water column under seasonal variations were investigated for the first time. A greater thermal input during spring induced strong thermal stratification in the shelf sea environment, but had little influence upon estuarine outflow. The thermohaline gradient between these two water bodies determines the rate of exchange experienced at the front. The spatial extent of the freshwater plume showed a strong negative correlation (-0.986, P-value<0.001) compared to the distribution of phytoplankton estimated using the fluorometer data. Therefore it was hypothesised that: the weak freshwater front is *too* weak to induce sufficient nutrient upwelling; therefore it cannot host high concentrations of phytoplankton in comparison to fresh plume waters.

Keywords: Freshwater plume; Estuaries; Tamar Estuary; Stratification; Spring Bloom

Introduction

Note that salinity is measured on the practical salinity scale, where values are stated to be dimensionless without the use of 'psu'.

Stratification is a fundamental aspect of shelf seas that controls the intensity of vertical mixing and the vertical fluxes of water properties such as: heat, salt, momentum and nutrients (Simpson, et al., 1990).

Seasonal and diurnal variations of vertical density structure in shelf seas are induced by thermohaline contributions. Freshwater outflow ejected from estuaries is a semi-diurnal feature that commonly produces freshwater plumes within shelf seas. The propagation of a plume can affect the distribution of nutrients into the euphotic zone. The euphotic zone is a level within the water column whose depth is limited by solar penetration. The high concentration of nutrients and heat, typically associated with the euphotic zone, are vital in limiting biological production. This zone is most active during the period of the spring bloom, where increased solar intensity and a high concentration of nutrients induce a 'bloom' of phytoplankton production.

The strength and growth of a plume, of an order of hours to days, is determined by both internal and external forces. However, there is little scientific literature to explain how plume behaviour is impacted by longer timescales of variability in the temperature field.

The aim of this study was to determine the impact of seasonal temperature variations within the Tamar estuary upon the stratifying characteristic of freshwater plumes and shelf seas. The objectives were to:

- Quantify over a horizontal scale of distance the plume front.
- Determine the density structure of the water column at three pre-determined locations relative to the fresh-water plume.
- Correlate the concentration of primary productivity with the spatial extent of the plume.

Estuarine dynamics

An estuary can be defined and classified differently depending upon the focus of study, be it physical, chemical or biological. The most accepted physical definition of an estuary produced by Pritchard and Cameron (1963) is: "a semi-enclosed, coastal body of water, with free communication to the ocean and within which ocean water is diluted by freshwater derived from land."

Pritchard's pioneering work on estuarine circulation (Pritchard, 1952, 1954, 1956) emphasized the importance of the density current within the tides (ebb and flood flow), controling the density structure of the water column. The ejection of estuarine outflow into shelf seas is commonly associated with the production of a freshwater plume. These freshwater plumes typically have a slainity value of 26-28, such as seen in the Columbia River plume, USA (Hickey, et al., 2005).

Estuarine features and processes

Narrow frontal regions of estuaries are dynamically 'active' where convergent flow, vertical circulation and horizontal salinity gradients are found (Largier, 1993). However, their short-lived, spatially vast presence has limited our ability to practically research and thus understand their internal processes.

A freshwater plume is “a periodic feature in estuaries which has been defined as a transient feature that develops spatially and temporally with mixing predominantly confined to the relatively narrow frontal region” (Pritchard & Huntley, 2002).

In the absence of external forcing, a plume forms during ebb tides (figure 1) assuming that there is sufficient fresh water exiting the estuary (Simpson, et al., 1990; Jay & Musiak, 1994). However, the behaviour, extent and dynamics of the resulting plume are subject to modification by a range of processees including tidal straining, wind stress and the surface waves that it generates (Fong, 1998), and near bed friction. Thus spatial extent and duration of these plumes is directly associated with the natural variations in the magnitude and timing of freshwater outflows, tides and meteorological conditions (Warrick & Fong, 2004).

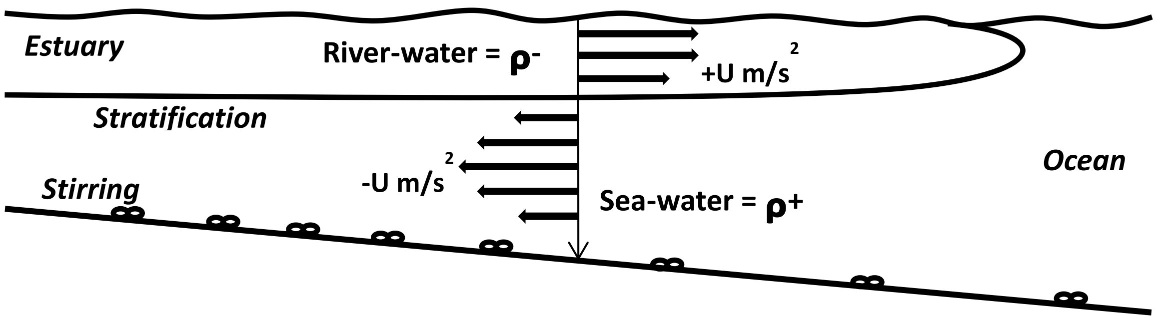


Figure 1: Schematic of ebbing freshwater stratification forming an estuarine plume in competition with bottom stirring. The estuarine circulation moves less dense surface water (ρ-) offshore and denser underlying water (ρ+) onshore.

Surface wind stress influences the spatial growth of a freshwater plume. During ebb tides, wind stress can either delay or progress the transport of freshwater from the river to the coastal plume (Geyer, 1997) depending on its direction and magnitude. The wind strength index (W_s) is the ratio of wind-driven and buoyancy-driven along-shelf velocities for a buoyant outflow (Whitney & Garvine, 2005). This can be used to determine the level of influence wind has upon a plumes growth. For example; when the wind stress is in the direction of the ebb flow, it increases the plume development speed by forcing surface riverine water further offshore. However when the wind stress is in the direction that opposes that of the plume, the growth rate decreases as the rate of onshore frontal mixing increases.

Horizontal forcing such as surface wind stress & coastal currents contribute to mixing via wave action. As waves break (Grant & Madsen, 1979), (Green, et al., 1997) the transfer of turbulent kinetic energy through the water column, via wave-driven mean currents, can cause increased near-bed shear (Mellor, 2008). The implications of this cause a vertical transfer of thermohaline properties through the water column and reduce the level of radial development.

The above processes all act together as one large dynamic system which regulates the development and growth of an ebbing buoyant outflow. However during the flood, turbulent processes (e.g. tidal straining) would result in homogenisation, the intensity of which would increase during periods of spring tides (Simpson, et al., 1990). This will inhibit plume formation as thermohaline properties will become well mixed throughout the water column removing stratification, and thus the presence of a plume front.

Tidal stirring is a vigorous turbulent motion induced by strong frictional forces at the seabed reacting to tidal dynamics (figure 3). This stirring competes with the buoyancy inputs form surface heating and freshwater to determine the structure of the density stratification in tidally energetic shelf seas (Simpson, 1998).

Thermal stratification and the density ratio

The transition of seasons cause the ocean to heat and cool periodically throughout the year, with the largest mean temperature contrast occurring between winter and spring (Sobarzo, et al., 2007). The process results in a thermocline within the first 10m which defines a shallow, warm, mixed epilimnion (upper layer) and a cooler, denser hypolimnion (underlying layer). The presence of this thermocline traps heat and nutrients within the epilimnion which are essential for the reproduction of primary biota (Simpson, et al., 1990).

A freshwater plume and thermal stratification both act to stabilise the water column (Simpson & Sharples, 1991). Thermally stratified shelf seas adjacent to an estuarine environment will experience large inputs of buoyant freshwater; a result of an ebbing tide. As a consequence, the predominant thermohaline property which will have the greatest effect upon the density structure will be undetermined.

The relative influence of changes in temperature and salinity on the density gradient can be quantified by the density ratio, R_ρ:

$$R_\rho = \frac{\alpha \Delta T}{\beta \Delta S} \qquad \text{Eq. 1}$$

Where

$$\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}$$

And

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial S}$$

Where; T = temperature (degrees), S = salinity (psu) and ρ = density (kg/m^3).

$$R_\rho = Salinity\ dependent < 1 < Temporally\ dependent$$

Alpha (α) and beta (β) (Eq. 1), represent the thermal expansion and haline contraction coefficient's, respectively.

The density ratio is defined to be the ratio of the relative effect of temperature and salinity on density (Rudnick & Martin, 2002). The value 1 represents equal effects by temperature and salinity; If R_ρ >1 density gradients will be temperature dependent, and if R_ρ<1 salinity will be the dominant characteristic to determine the water column stability (Schmitt, 1989).

This investigation aimed to identify the density structure of the water column at 3 locations relative to the plume front and how seasonal variations would impact this. Based on the literature, our hypothesis is that the density gradient, R_ρ, in plume waters will change from <1 during winter, indicating that the plume forms due to the excessive effects of salinity on the density gradient, to >1 during spring when rainfall decreases and air temperature increases, thereby increasing surface thermal stratification. Below the depth of thermal stratification during spring, waters are expected to approach or fall below the R_ρ critical value, thus indicating waters to become more salinity dominated.

The spring bloom

The dynamic interaction between the properties of density within two converging coastal bodies of water, make the development of an estuarine phytoplankton bloom a complex and intricate process. A phytoplankton bloom is a biological response to physical dynamics initiated by seasonal events (Lucas, et al., 1998). Shelf sea waters annually experience two blooms. The first to occur is the 'spring bloom'. Sverdrup (1953) described the mechanism for the spring bloom as 'a discrete change in the balance between phytoplankton primary production and loss when a shallow mixing layer (~10 deep) is formed above a seasonal thermocline'. The spring bloom can result in a rapid increase of chlorophyll of 10mg m^3, typically less than the summer concentration of 2mg m^3 (Cloern, et al., 1991). As phytoplankton quickly utilise the nutrients that are 'held' within the euphotic zone, the bloom transpires. The second annual bloom is a weaker, less obvious autumn bloom.

Enhanced growth or retention of biomass, with the presence of a freshwater plume, would occur within intermediate salinity waters that experience high levels of mixing (Lohrenz, et al., 1999). These waters are found at plume edges and frontal regions. An assessment of the spatial concentration of phytoplankton with respect to a freshwater plume during a spring bloom would expect to see highest concentrations at the front.

An assessment of the spatial concentration of phytoplankton with respect to a freshwater plume during a spring bloom would be conducted. Our hypothesis is that a higher concentration of chlorophyll will be found at the plume front where more intense mixing takes place.

Material and methods

Area of study

The Tamar Estuary, located to the west of Plymouth in the south west of the U.K (figure 2), has been defined as a coastal plain, partly mixed, flood dominant estuary, with tidal flows that appear to have the most effect on the water circulation (Mommaerts, 2009). The Estuarine Turbidity Maximum (ETM) is a very strong feature within the Tamar estuary, controlling both SPM concentrations and the location of the plume front (Uncles & Stephens, 1993). The ebb and flood tides are roughly equivalent to each other in terms of tidal strength (Uncles, et al., 1985) therefore the rate of freshwater input, due to runoff via meteorological conditions will influence the situation of its freshwater front. Precipitation leads to a downstream flow originating from Gunnislake. The residence time for runoff to reach the estuary is less than 5 days (Uncles & Stepthens, 1990).

Figure 2: A map of Plymouth, UK and the Tamar Estuary. The Circle represents L4, and the line is the 9.6km transect taken during data collection. Image is taken from Google maps.

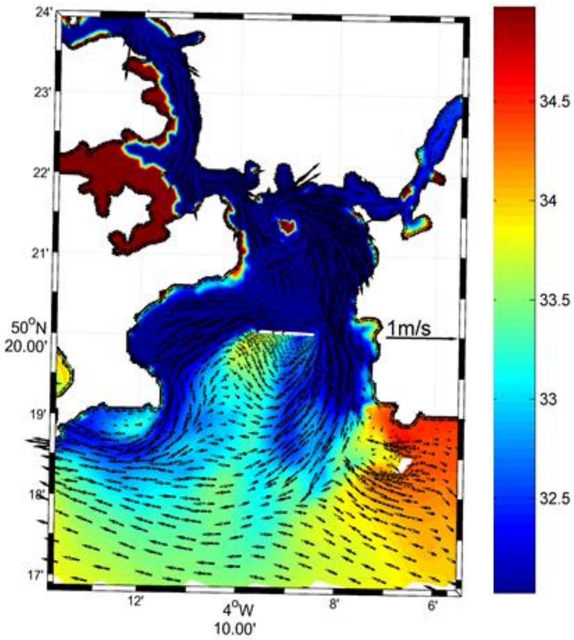


Figure 3: An image of the circulation within the Sound induced by the Breakwater during ebb flow. The model of which this image has been taken from runs with tides, realistic outflows and observed winds. However it is in early stages of production and therefore has some issues regarding model phase so the results need to be taken with caution but they are indicative nonetheless.
Credit is due to Ricardo Torres of Plymouth Marine Laboratories.

A numerical simulation using Finite Volume Coastal Ocean Model (FVCOM) has shown that the Breakwater, which lies 2km from the estuary mouth will induce a circualtion within the sound (figure 3). This circulation during ebb flow reduces the radial development of a freshwater plume and deflects westward to produce a more intense flow, which advects across the coastline (figure 3). The freshwater ejected from the estuary currently experiences an unknown degree of mixing before entering the shelf sea. Mixing of freshwater within the Sound does reduce the radial salinity gradient (figure 3) and result in a weaker freshwater plume expelled into the shelf sea; 33-33.5 (figure 3).

Instrumentation

MiniBat FC60, is a remotely controlled undulating towed instrument with a ‘Conductivity-Temperature-Depth’ (CTD) probe attached. CTD data was recorded to an accuracy of: conductivity ±0.01S/m, temperature ±0.005^{o}C, pressure ±0.05% FS. A GPS was attached to the vessel. A fluorometer was attached to the MiniBat during the last week of data collection. The fluorometer measured chlorophyll within the water column as a unit of voltage which represented the concentration of primary biota. All data were taken simultaneously, where CTD and GPS sample rates were 24Hz and 10Hz, respectively.

Data collection and analysis

Data were collected along transects within the Tamar estuary located Plymouth, South-West UK (figure 2). Deployment occurred just beyond the breakwater

(50°19°59'N, 4°09°56'W) and ended at approximately L4 (50°15'N, 4°13'W). The transect (figure 2) is a direct path from A to B. However commercial/naval shipping routes and oceanic conditions caused occasional deviations from the desired path.

The instrument was towed behind a vessel in a saw-tooth pattern between a minimum depth of 1m (surface) and a maximum depth of 10m. The surface depth varied between 1m and 2m depending on surface roughness to avoid overturning of the MiniBat by waves.

Deployment of the MiniBat occurred twice per week on a given day, once outbound and once upon return. The periods of data collection are indicated in Table 1. Preferred day and condition for deployment was Monday morning, weather permitting, during an ebbing tide.

The dates of the chosen profiles to be the focus of analysis were as follows: 21/11/11, 02/04/12 and 24/04/12 (table 1 – green fill). These dates were chosen as they all closely correlate to low water (LW), an ebbing tide (Table 2). Each profile was taken at approximately 8:30am and lasted until approximately 10:00am with the exception of 24/04/12, which was taken from 12:00pm until 1:30pm.

Table 1: Represents the periods of which data were collected over the two seasons - winter 2012 and spring 2013. Black filled blocks corilate to weeks that fieldwork took place. The green filled blocks show the dates of which the project focued profiles are found. The '|S|' denotes the timing of the spring bloom.

2011			2012			
October	November	December	January	February	March	April
						|S|

Table 2: Displays the time of LW with respect to the profiles of focus used within this study (table 1 – green fill). The time difference between LW and the initiation of a profile is given in minutes with respect to the time of LW. All tidal data has been provided by 'Mobile Geographic's'.

Date	Time of LW	Difference between time of LW and time of profile started (minutes).
Winter -21/11/11	7:39am	+52
Spring - 02/04/12	8:48am	-18
Spring bloom -24/04/12	2:30pm	-90

By gridding the CTD and fluorometer data using linear interpolation to a horizontal and vertical resolution of 2m and 0.5m respectively, a series of 'virtual profiles' were created at regular intervals along the ship's track. Salinity was measured using the practical salinity scale. The vertical density ratio (1) is then computed at 3 positions relative to the plume to quantify the relative role played by salinity and temperature in governing the vertical density gradient with respect to a weak freshwater plume. The 3 positions were: 1) Behind the plume, giving a freshwater profile; 2) In front of the plume, giving a seawater profile, and 3) within the frontal region.

Defining a weak freshwater plume front

A freshwater plume is commonly seen with a range of 26-36 (Hickey, et al., 2005) between two bodies of water. However, plumes ejected from the Plymouth Sound can be detected upon a salinity scale of 33.1-36 during winter conditions (figure 6A). Winter conditions impose the greatest salinity gradients between plume and ambient waters (Warrick & Fong, 2004). Therefore, a salinity gradient of 3 can hereby describe a weak freshwater plume. This weak salinity gradient may be a result of the circulation deflection which results in a net westward flow beyond the breakwater (figure 3); however more research is needed for confirmation of this.

In order to produce the density ratio profiles, the 3 locations had to be accurately defined. Freshwater and sea-water profiles were taken at mid-points inside and outside the plume with approximately constant salinities; less than a 0.5 change over 1km (figure 5A). The frontal profile was to be qualified within the 'frontal region'.

Figure 4 outlines the 3 bodies of water associated with the plume, in which the density ratio, R_ρ, depth profiles were taken. The frontal region is deemed an intermediate body of water and has been defined as: a salinity gradient of >0.4 between two adjacent water bodies (figure 5A). Within the frontal region the plume front exists within the last 0.5Km transitioning into ambient saline water. Figure 5B enlarges the last sharp salinity gradient within the frontal region. Using this, a weakly defined freshwater plume front has been quantified as: a 0.15 change in salinity over 420m±2m horizontally at a depth of 2m. The ±2m error is a result of the resolution during linear interpolation.

4A

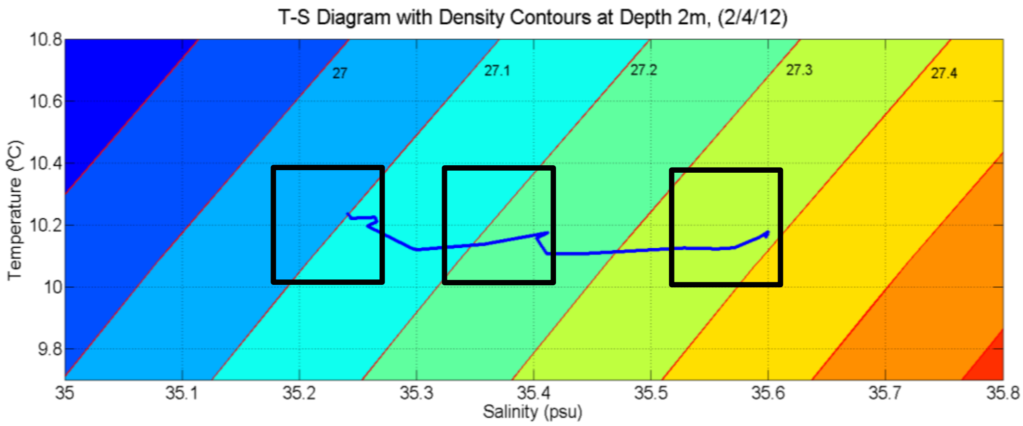


Figure 4: 4A – Outlines the presence of 3 bodies of water via the temperature and salinity properties of water on 2/4/12. The clusters of points (outlined) represent the freshwater, frontal region and ambient sea-water respectively from left to right. The coloured pycnoclines give the sigma density variations.

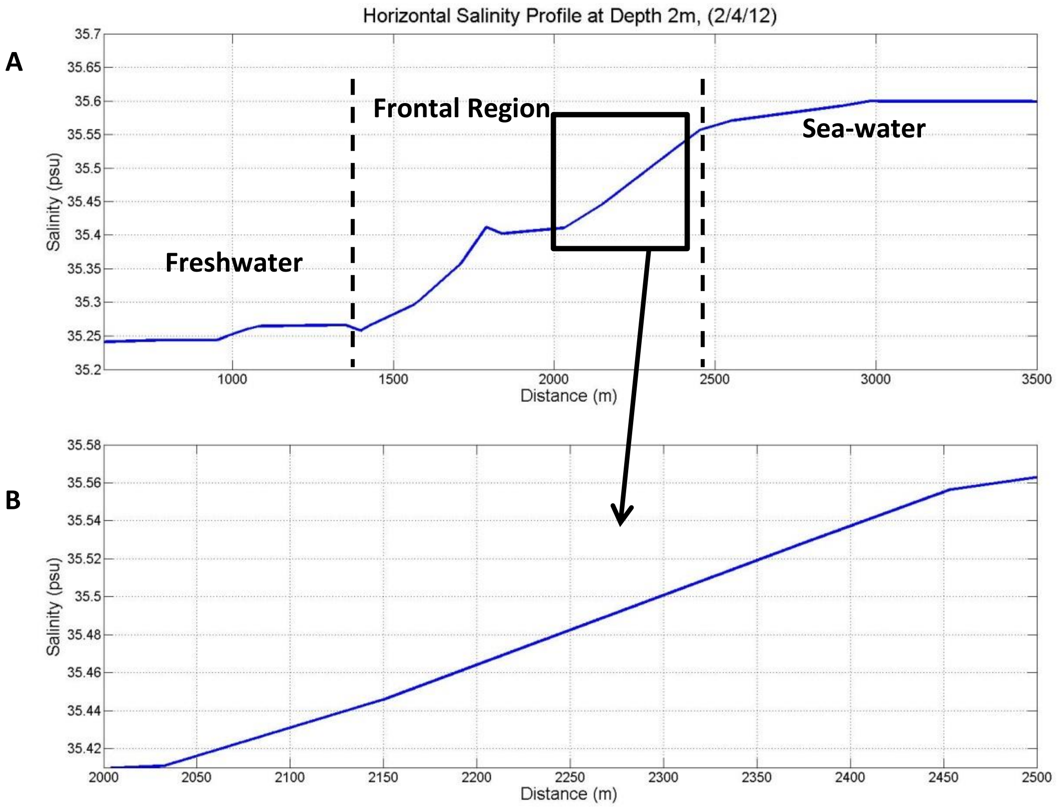
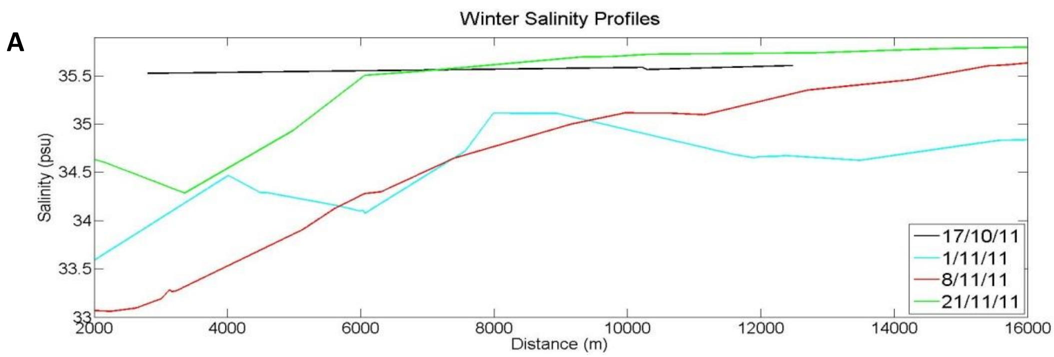


Figure 5: 5A and B show a horizontal salinity profile at a depth of 2m, from Plymouth breakwater to L4, on 02/04/12. '5A' is the complete profile and outlines the 3 bodies of water. '5B' is an enlarged image of the outlined section, the last sharp salinity gradient, within the frontal region.

Results

Overview of transects

An alteration between the winter and spring seasons (table 2) has clearly influenced the spatial growth and magnitude of a freshwater plume (figure 6). The salinity range during the winter season (figure 6A) is much greater than that experienced during the spring season (figure 6B); 33.1-35.9 to 34.9-35.5 respectively. During winter, the frontal region can be clearly observed due to this large salinity range. However, the spring frontal region is much more subtle and occurs over shorter distances; on average: 3.75km & 1.5km, winter – spring respectively.



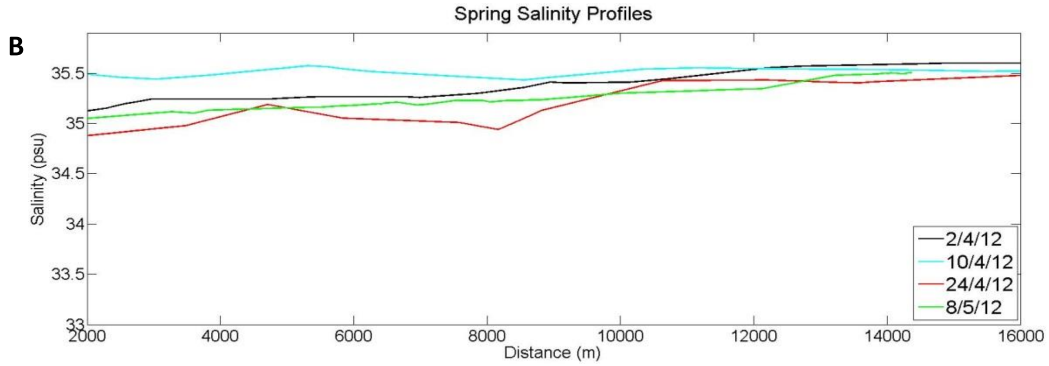


Figure 6: Two horizontal salinity profiles at 2m depth, which show an overall summery of all transects which occurred during both winter (A) and spring (B) periods. The salinity scale: 33 – 36 and the horizontal distance are taken from 0Km to 10Km; where 0km is the breakwater and transect deviations had caused an increased net horizontal distance.

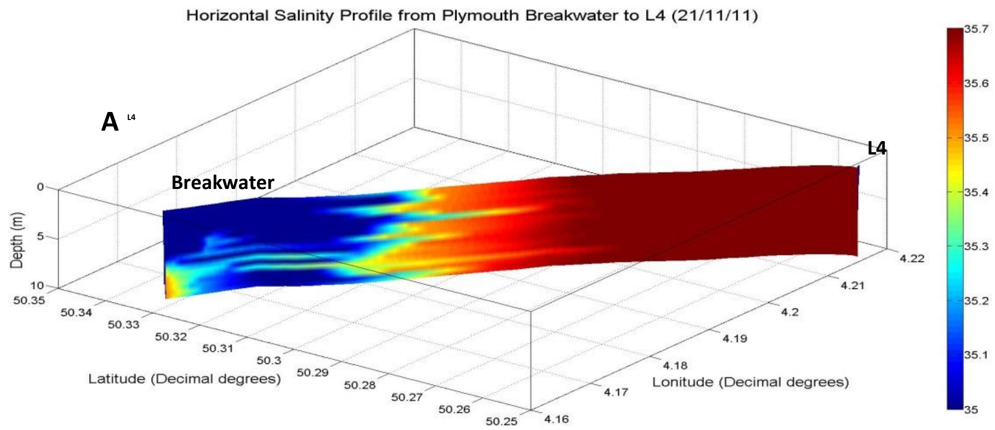
Seasonal meteorological influence upon a freshwater plume

Table 3: Values of the 5 day mean rate of freshwater outflow (m^3/s) from Gunnislake which flows down into the Tamar Estuary. The mean meteorological conditions which chosen transects (table 2) were exposed to over the period of data collection; 1.5 hrs. The following are mean values taken over the 1.5hr period of data collection: wind speed (m/s), its direction (Degrees North), solar insolation (W/m^2) and precipitation (mm). The level of solar insolation is a rate of heat flux per second ($J/s^{-1}m^{-2}$). The outflow data was provided by Hugh Smith of the University of Plymouth and the meteorological condition data was provided by the Fitzroy Meteorological Station, Plymouth UK.

Date	Mean Freshwater outflow from Gunnislake (m^3/s)	Mean Wind Speed (m/s)	Mean Wind Direction (Degrees)	Solar Intensity (W/m^2)	Precipitation (mm)
Winter -21/11/11	16.71	2.5	141.8^o	42.32	36.4
Spring - 02/04/12	5.19	1.7	79.4^o	214.03	0
Spring Bloom – 24/04/12	26.316	3.6	255.2^o	862.86	0

The winter profile (figure 7A) displays a large development spatially and vertically relative to the spring profile (figure 7B). Both of these profiles occur relative to a LW (Table 2), with positive wind directions relative to the direction of the plume motion (Table 3). However, the spatial development of the winter profile is exposed to stronger wind conditions of a 2.5m/s magnitude.

The frontal region, seen as the yellow intermediate water mass (figure 7), is seen to change spatially with respect to the tides (Table 2). The ebbing spring profile (figure 7B) exhibits a spatially developed frontal region. In contrast the flooding winter profile (figure 6A) results in a sharp frontal region in which shoreward perturbations occur with depth.



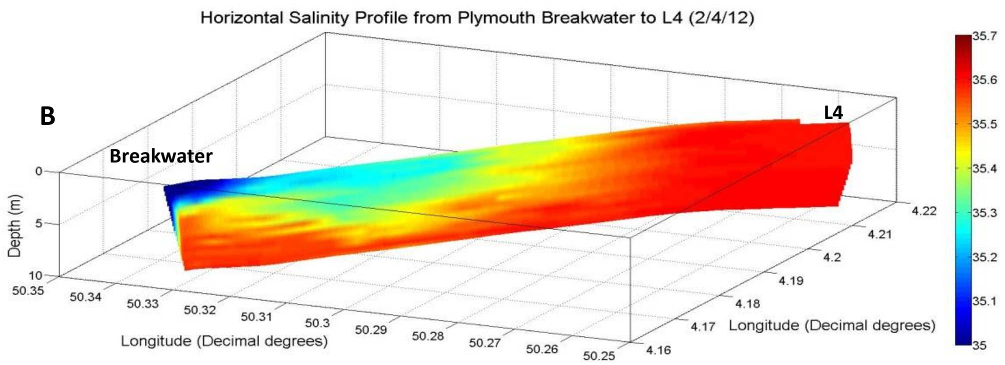


Figure 7: Salinity transects taken during winter (21/11/11) (7A) and spring (02/04/12) (7B) respectively. The colorimetric scale is a measure of salinity set between 35 – 35.7, allowing a visual interpretation of the 3 water masses. The plume front can be seen as the sharp yellow region, where blue equals freshwater and red is sea-water. Transect begins just beyond the Plymouth breakwater (marked) and ends at approximately L4 (marked) (figure 2).

Seasonal variation within the density structure of a weak freshwater plume

Thermoclines can be seen in both winter (figure 8C) and spring (figure 8F), at depths of 2.5m and 3m respectively. These are represented by the density ratio values found at these depths, R_ρ = 8 and 33.5 respectively. The difference in solar insolation between the two seasons is 171.71W/m^2.

The surface 2m during the winter profile (figure 8C) is a result of recent precipitation (Table 3). This has therefore produced a slightly more buoyant saline surface layer. Below the depth of thermal stratification the density structure of the water column becomes predominantly salinity dominated.

The winter R_ρ profiles of plume and shelf-sea waters remain predominantly below the critical value, therefore being salinity dominated (figure 8A & C). This has resulted in a low rate of R_ρ fluctuation, with respect to the density dependence throughout the frontal water column (figure 8B).

A larger degree of R_ρ fluctuation is found in the frontal profile (figure 8E) of the spring season, where freshwater (figure 8D) and thermally stratified shelf sea water (figure 8F) meet. The surface 2.8m remain below the R_ρ value of 1. This indicates a buoyant surface water mass. Below this depth the value of R_ρ fluctuates greatly about the critical value with a slight trend towards the positive.

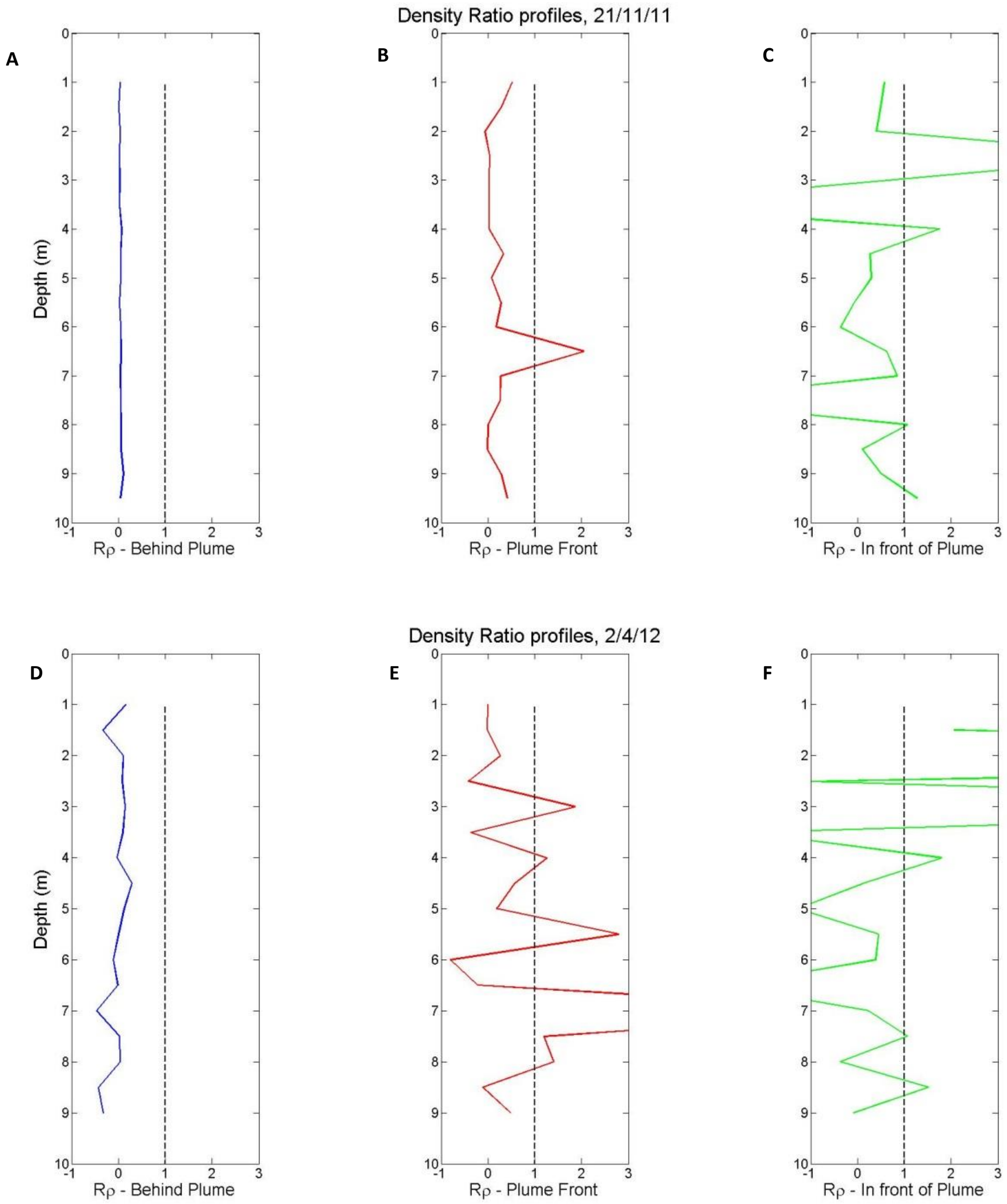


Figure 8: Vertical density ratio, $R_{\rho,}$ profiles with respect to the freshwater plume for the winter season, A,B,C, (21/11/11) and spring season, D,E,F (02/04/12) respectively. The density ratio is used to assess the thermohaline characteristic of water column stability. A value above the 'critical value' of 1 represents a thermal dependency; while below this value the density depends upon salinity characteristics. The larger the value, the more intense its reliance upon that property becomes. Each profile represents a position relative to the plume front. A, D = behind the front, B, E = the plume front, and C, F = In front of the front.

Concentration of primary productivity during the spring bloom with respect to a freshwater plume

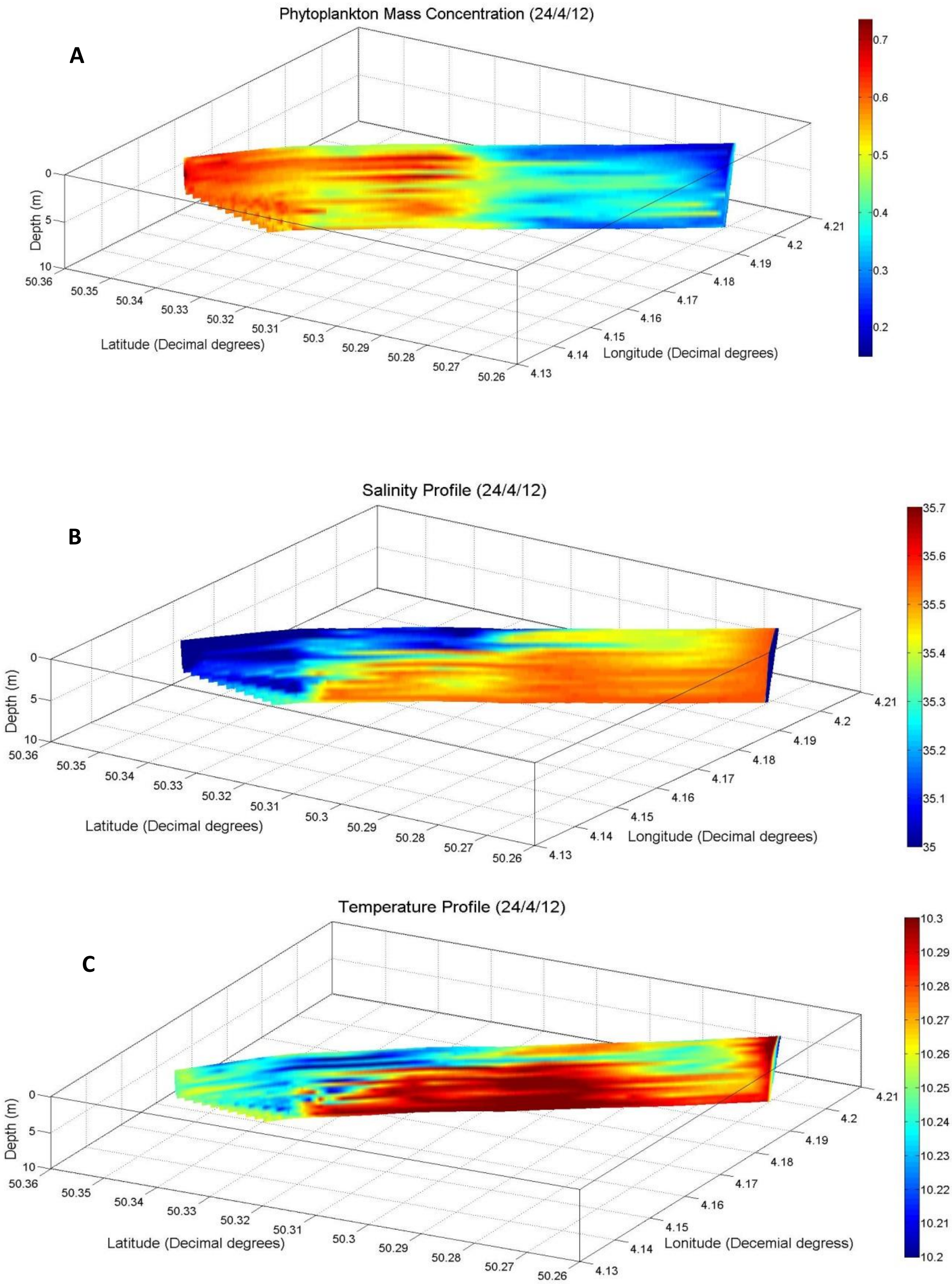


Figure 9: A = Horizontal profile of the concentration of florescence from the Breakwater to L4 on 24/4/12. Florescence is represented as a unit of voltage. B and C = Two horizontal profiles which show the spatial influence of thermohaline properties, salinity (A) and temperature (B). All profiles were taken simultaneously with each other; on the 24/4/12.

The concentration of chlorophyll increases proportionally with the concentration of primary biota. Therefore figure 9A is representative of the concentration of phytoplankton. The spatial extent of biota and distance covered horizontally by the surface layer (3m) of the freshwater plume (figure 9A and 9B) shares a -0.986 correlation with a P-value <0.0001. A P-value below 0.05 is deemed statically significant. A higher concentration of chlorophyll exists within the plume, whereas concentrations decrease by half beyond the frontal region.

Horizontally a -0.796 correlation with a P-value < 0.001 between temperature and chlorophyll is found. The spatial extent of temperature in the first 3m (figure 9A and 9C) is found to decrease as chlorophyll increases. However, the vertical penetration of temperature is greater than the salinity concentration within a weak freshwater plume (figure 9B and 9C). An increase of 0.1^{o}C below the plume waters reaches to the full depth range, 10m.

Discussion

The strength and spatial extent, in the horizontal and vertical, of a freshwater plume seem to relate to the meteorological forcing it is exposed to. Freshwater outflow from the Tamar, produced by mean catchment precipitation over 5 days, may have the greatest influence upon the density structure. However this outflow is weakened by a westward deflection produced by the breakwater. The radial expansion, commonly associated with freshwater plume ejection (Hickey, et al., 2005), is disturbed and results in the presence of a weakened plume, overlaying the shelf sea. A weakened plume has been defined as having a salinity gradient of less than 3. The result of a weakened outflow is that the frontal region between two water masses is much less defined and therefore a weak plume front was quantified as: a 0.15 change over 420m±2m. The error of ±2m was produced due to the horizontal resolution of linear interpolation. Quantitative identification of this weak front was essential as it indicated one of 3 water masses to be analysed; within the plume, the frontal region and the shelf-sea water.

The density structure of shelf sea waters reacts differently from plume waters under the same meteorological conditions (Table 3). The seasonal temperature variations between two contrasting seasons, winter and spring, were represented by the exposure of mean solar insolation at the sea surface; 42.32W/m^2 and 214.03W/m^2 respectively. The influence of salinity and heat were used to assess the density structure of the water column.

Plume waters are constantly flowing, influenced by the tides and surface wind stress. This constant movement inhibits the ability to absorb and retain heat at the surface. Therefore, the density structure of plume waters despite being exposed to high levels of solar insolation during the spring, remain dominated by their saline characteristics. However, shelf sea waters are steady with respect to plume waters, and are more efficient with the uptake of heat which acts to stabilise the water column by producing a thermocline.

Thermal stratification occurs at the surface during both seasons at depths of 2.5m and 3m respectively. An increase of 171.71W/m^2 in the solar heat flux at the surface between winter and spring had only increased the depth of the thermocline by 0.5m, however the strength of stratification increased greatly; R_ρ= 8 to 33.5. Therefore the intensity of solar insolation has a much greater effect upon the strength of thermal stratification than deepening the depth of the thermocline.

The frontal region is the interface between two bodies of water. These locations exchange thermohaline properties by diffusive processes (Archetti & Mancini, 2012); where the rate of exchange is defined by the thermohaline gradient. In this respect the thermal property had the greatest influence upon water column stability below depths of plume influence (2m). The winter season resulted in a low thermal contrast between water masses and therefore little thermal exchange occurred (figure 8B). However the greater level of heat available during spring (Table 3) resulted in a thermal gradient which induced intense turbulent mixing (figure 8E).

The spring bloom is a period in which there is a rapid increase of phytoplankton concentration and is the biological response to seasonal temperature variation. This process occurs within the euphotic zone and is enhanced with nutrients. Estuarine plumes transport runoff nutrients into the shelf sea which are then utilised. It is found that higher concentration of phytoplankton can be found around plume edges (Lohrenz, et al., 1999). This study has revealed a strong negative correlation (-0.986, P-value < 0.0001) between the level of chlorophyll, produced by primary biota, and the spatial extent of the freshwater plume; contradictory to literature.

Within weak freshwater plumes, double the concentration of phytoplankton can be found with respect to the ambient shelf seas. This is where the spatial extent of this phytoplankton plume is limited to the extent of the freshwater outflow (figure 9A and 9B). It has been found that up-estuary surface waters, salinity = 0-5, appear to be rich with nitrate and ammonium, 1.75mg/l and 0.7mg/l respectively (Uncles, et al., 2002). However, a linear decrease occurs towards the shelf, which results in very low concentrations of these nutrients to be utilised, 0.3mg/l and 0.05mg/l respectively, at salinity concentrations >34.

In comparison to the typical ~7 salinity gradient (Hickey, et al., 2005) a 0.7 gradient may prove to be too ‘weak’ to upwell settled nutrients from the lower water column (Bowman & Iverson, 1978).This leads to the postulation that a weak freshwater front is *too* weak to induce sufficient nutrient upwelling to host high concentrations of phytoplankton with respect to fresh plume waters.

The vertical penetration of a phytoplankton plume appears to be limited by the thermal exposure to surface waters. However, to accurately state this more data and a greater vertical resolution are required. With further research upon the physical dynamics and implications of seasonal temperature variations of plume and shelf-sea waters a greater understanding of the biological responses to these adjustments can be achieved.

Conclusion

The aim of this project was to determine the impact of seasonal temperature variations within the Tamar estuary upon the stratifying characteristic of freshwater plumes and shelf seas. This involved analysing both the physical modifications of the density structure of the water column between two contrasting seasons, winter and spring, and the biological responses to these modifications. Physical analysis involved calculating the vertical density ratio (R_ρ) at 3 positions relative to the freshwater plume: within the plume water, the frontal region and the shelf-sea water; for both seasons. The density ratio determines the ratio of influence temperature and salinity has upon density structure of a water column. The location of the weak freshwater plume front was quantified as a 0.15 change over 420m±2m.

The density structure of surface water is dependent upon thermohaline properties. At the interface between two independent bodies of water, an exchange of these properties does occur. The rate of exchange of each of these properties is dependent upon both the thermal and salinity gradient between the two bodies.

The biological phenomena known as the 'spring bloom' spatially correlates to weak freshwater plumes and its haline properties. The spatial extent of phytoplankton is limited to the spatial extent of the weak freshwater plume, where the frontal salinity gradient is too weak to induce sufficient nutrient upwelling. The vertical penetration of this phytoplankton plume appears to be limited by temperature. However further research is required to prove this hypothesis.

A suggestion for improvements to further advance this study would be to produce an annual data set of greater depth. This enlarged data set would allow for a greater analysis of the thermal implications seasonal variations can have upon freshwater plumes and shelf seas; including sea surface cooling between autumn-winter and the biological response that would occur. Another improvement would be to collect water samples along transects relative to the 3 locations of the freshwater plume. Nutrient analysis of these water samples would provide accurate and up-to-date data which can be used to enforce the hypothesis that 'a weak freshwater front is *too* weak to induce sufficient nutrient upwelling to host high concentrations of phytoplankton'. One last improvement would be to attach a backscatter probe to the MiniBat. This probe would measure the concentrations of SPM held and transported by plume waters under various meteorological conditions. This is an important aspect to understand for predicting the location and movement of seabed features and improving the accuracy of hydrographic equipment.

Acknowledgements
The author would like to acknowledge PML for allowing this project use of their vessel and Riccardo Torres from PML for early access to numerical output regarding the Tamar outflow. Acknowledgement is also to Phil Hosegood for being my supervisor and loan of the MiniBat.

References

Alvarez, O. et al., 1999. The Influence of Sediment Load on Tidal Dynamics, a case study: Cadiz Bay. *Estuarine, Coastal and Shelf Science,* Volume 48, pp. 439-450.

Archetti, R. & Mancini, M., 2012. *Freshwater Dispersion Plume in the Sea: Dynamic Description and Case Study,* Rijeka, Croatia: INTECH.

Bowman, M. J. & Iverson, R. L., 1978. Esturaine and Plume Fronts. In: M. J. Bowman & W. E. Esaias, eds. *Oceanic Fronts In Coastal Processes.* New York: Springer Berlin Heidelberg, pp. 87-104.

Cheng, R. T., Ling, C. H., Gartner, J. W. & Wang, P. F., 1999. Estimates of bottom roughness length and bottom shear stress in South San Francisco Bay, California. *Journal of Geophysical Research,* 104(C4), pp. 7715-7728.

Cloern, J. E., Elliott, M. & Ducrotoy, D., 1991. *Annual variations in river flow and primary production in the South San Francisco Bay,* Fredensborg, Denmark: Olson and Olson.

Figueroa, H. A., 1996. World Ocean Density Ratios. *Journal of Physical Oceanography,* Volume 26, pp. 267-275.

Fong, D. A., 1998. *Dynamics of Freshwater Plumes: Observations and Numerical Modeling of the Wind-forced Response and Alongshore Freshwater Transport,* Massachusetts: Woods Hole Oceanographic Insitution.

Geyer, W. R., 1997. Influence of Wind on Dynamics and Flushing of Shallow Estuaries. *Estuarine, Coastal and Shelf Science,* Volume 44, pp. 713-722.

Grant, W. D. & Madsen, O. S., 1979. Combined Wave and Current interaction with A Rough Bottom. *Journal of Geophysical Research,* 84(C4), pp. 1797-1808.

Green, M. O., Black, K. P. & Amos, C. L., 1997. Control of Estuarine Sediment Dynamics by Interactions between Currents and Wavesat Several Scales. *Marine Geology,* Volume 144, pp. 97-116.

Hickey, B., Geier, S., Kachel, N. & MacFadyen, A., 2005. A bi-directional river plume: The Columbia in summer. *Continental Shelf Research,* 25(14), pp. 1631-1656.

Largier, J. L., 1993. Estuarine Fronts: How Important are they?. *Estuaries ,* 16(1), pp. 1-11.

Lentz, S., 2004. The Response of Buoyant Coastal Plumes to Upwelling-Favorable Winds. *Journal of Physical Oceanography,* Volume 34, pp. 2458-2469.

Lohrenz, S. E. et al., 1999. Nutrients, irradiance, and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume. *Continental Shelf Research,* Volume 19, pp. 1113-1141.

Lucas, L. V. et al., 1998. Does the Sverdrup critical depth model explain bloom dynamics in estuaries?. *Journal of Marine Research,* Volume 56, pp. 345-415.

Mellor, G., 2008. Oscillatory Boundary Layers. *Journal of Physcial Oceanography,* Volume 32, pp. 3075-3088.

Mommaerts, J. P., 2009. On the distribution of major nutrients and phytoplankton in the Tamar estuary. *Journal of the Marine Biological Association of the United Kingdom,* pp. 749 - 765.

Pritchard, D. W., 1952. Salinity Distribution and Circulation in a Chesapeake Bay Estuarine System. *Journal of Marine Research,* 11(106-123), p. Journal of Marine Research.

Pritchard, D. W., 1954. A Study of the Salt Balance in a Coastal Plain Estuary. *Journal of Marine Research ,* Volume 13, pp. 133-144.

Pritchard, D. W., 1956. The Dynamic Structure of a Coastal Plain Estuary. *Journal of Marine Research ,* Volume 15, pp. 33-42.

Pritchard, M. & Huntley, D. A., 2002. Instability and mixing in a small estuarine plume. *Estuarine, Coastal and Shelf Science,* Issue 55, pp. 275 - 285.

Rudnick, D. L. & Martin, J. P., 2002. On the horizontal density ratio in the upper ocean. *Dynamics of Atmospheres and Oceans,* 36(1-3), pp. 3-21.

Schmitt, R. W., 1989. On the Density Balance in the Central Water. *Journal of Physical Oceanography,* Volume 20, p. 900.

Simpson, J. H., 1998. Tidal processes in self seas. In: *The sea.* New York: 10Wiley, pp. 113-150.

Simpson, J. H., Brown, J., Matthews, J. & Allen, G., 1990. Tidal Straining, Density Currents and Stirring in the Control of Estuarine Stratification. *Estuaries,* 13(2), pp. 125-132.

Simpson, J. H. & Sharples, J., 1991. Dynamically-active models in the prediction of estuarine stratification. *Estuaries and the coastal Zone. New York*, pp. 101-113.

Sobarzo, M. et al., 2007. Coastal upwelling and seasonal cycles that influence the water column over the continental shelf off central Chile. *Process in Oceanography,* 75(3), pp. 368-382.

Sverdrup, H. U., 1953. On conditions for the vernal blooming of phytoplankton.. *Journal of marine science,* Volume 18, pp. 287-295.

Uncles, R. J., Elliott, R. C. A. & Weston, S. A., 1985. Dispersion of Salt and Suspended Sediment in a Partly Mixed Estuary. *Estuaries Vol. 8 No.3,* pp. 256 - 269.

Uncles, R. J. et al., 2002. The prediction of nutrients into estuaries and their subsequent behaviour: application to the Tamar and comparison with the Tweed U.K.. *Hydrobiologia,* Volume 475, pp. 239-250.

Uncles, R. J. & Stephens, S. J., 1993. The Freshwater-Saltwater Interface and its Relationship to the Turbidity Maximum in the Tamar Estuary, UK. *Estuaries Vol. 16 No. 1,* pp. 126 - 141.

Warrick, J. A. & Fong, D. A., 2004. Dispersal scaling from the world's rivers. *Journal of geophysical research,* 31(L04301), p. doi:10.1029/2003GL019114.

Whitney, M. M. & Garvine, R. W., 2005. Wind influence on a coastal bouyant outflow. *JOurnal of Geophysical Research,* 110(C03014), pp. 1-15.