Assessment of coastal density gradients near a macro-tidal estuary: Application to the Mersey and Liverpool Bay

M.J. Howarth, C.A. Balfour, R.J.J. Player, J. A. Polton

National Oceanography Centre

Joseph Proudman Building

6 Brownlow St.

Liverpool L3 5DA

UK

Tel: +44 151 795 4800

Corresponding author: john_howarth@rocketmail.com

E mails: Balfour, cabal@noc.ac.uk; Polton, jelt@noc.ac.uk

Abstract

Density gradients in coastal regions with significant freshwater input are large and variable and are a major control of nearshore circulation. However their measurement is difficult, especially where the gradients are largest, close to the coast, with significant uncertainties because of a variety of factors – time and spatial (horizontal and vertical) scales are small, tidal currents are strong and water depths shallow. Whilst temperature measurements are relatively straightforward, measurement of salinity (the dominant control of spatial variability for density) can be less reliable in turbid coastal waters.

The nearshore density gradients in Liverpool Bay are investigated using an integrated multi-year data set from an in situ buoy, instrumented ferry and HF radar. The ferry is particularly useful for estimating coastal density gradients since measurements are made right from the mouth of Mersey, where gradients are on average $3x10^{-4}$ kg $m^{-4}$. Using measurements at the single in situ site by the Mersey Bar, 17 km from land, density gradients can be estimated from the tidal excursion or by using ferry data; both giving average values of $5x10^{-5}$ kg $m^{-4}$. Nine years of surface salinity measurements there show no evidence of predominant periodicities, although there is a weak annual cycle, and no consistent relation with storms or floods, leading to the conclusion that the majority of the Mersey plume, for most of the time, lies closer to the English shore than the Mersey Bar. Liverpool Bay's circulation is the dominant factor, with wind forcing tending to reinforce it for wind speeds greater than 5 - 10 m $s^{-1}$. Near bed currents are consistently shoreward and near surface currents northward.

Keywords: Mersey plume, Liverpool Bay, Salinity, Ferrybox, HF radar

## 1. Introduction

The physical processes controlling the fate of fresh water river discharges in coastal seas are well understood, if complex and inter-related (Garvine, 1995; Yankovsky & Chapman, 1997; Simpson, 1997). However measuring, quantifying and predicting the resulting freshwater fluxes in particular cases is not straightforward since the real world does not generally conform to idealized conditions. The general construct is that river water forms a plume in the coastal sea whose features include:-

a) A thin near surface layer. Consequently salinity dominates horizontal and vertical density gradients. As a second order effect, density gradients are enhanced in summer when the river water is warmer than the receiving coastal water and in winter are weakened when the river water is colder than the coastal water (Hopkins & Polton, 2012, Polton et al., 2011).

b) In the Northern Hemisphere the Earth's rotation causes the plume to turn to the right, forming a coastal current.

c) A bulge can form in the vicinity of the estuary mouth, several times wider than the coastal current depending on the physical properties of the river discharge and coastal water (Yankovsky & Chapman, 1977).

d) If the coast is straight, upwelling favourable winds oppose the flow and can retard or block the plume causing it to spread offshore. Downwelling favourable winds can compress the plume against the coast (Howlett et al., 2013).

The dynamics of the plume are controlled by the wind and the density structure (both horizontal and vertical) which in turn is affected by the relative importance of mixing, principally by tides via bottom friction, but also by winds and waves. If mixing is weak the water column remains stratified and the plume is surface advected; if strong the water column is well mixed and impacted by the bottom boundary layer. Semi-diurnal tidal mixing dominates processes in the north-west European continental shelf seas and hence the latter case predominates. Mixing varies on semi-diurnal and spring-neap time scales so that the water column can be well-mixed, it can stratify on tidal time scales and it can remain stratified for periods of several days. Liverpool Bay, loosely defined as the region of the Irish Sea to the west of the United Kingdom shown in Figure 1a, is one extreme; it is a region with a large tidal range, up to 10 m at equinoctial spring tides, and with moderate fresh water input from several rivers. The maximum mean spring currents are twice those at neaps implying that on average tidal mixing varies by a factor of eight over the spring / neap cycle. The specific interest here is the interaction between a moderate freshwater discharge and a shallow receiving coastal sea where tidal mixing is large, in contrast to, for instance, the high discharge Columbia River into the straight and rapidly deepening Oregon / Washington shelf (Kilcher & Nash, 2010). The combined average discharge of the rivers Mersey, Ribble, Dee, Clwyd + Conwy is about 200 $m^3 s^{-1}$, respectively approximately 40%, 30%, 20% and 10% of the total (map Figure 1a). The coastline is 'L' shaped, on average east-west along the north Wales coast and north-south on the English coast. As a result Liverpool Bay encompasses the least saline water of the Irish Sea. Model studies have shown that Liverpool Bay is retentive, for instance with a flushing time exceeding 100 days (Phelps et al., 2013). In Europe, Liverpool Bay has some comparison with the German Bight – a similar shape into which with the river Elbe flows, although with a larger average rate (3.5 times the combined discharge into Liverpool Bay) and a lower tidal range.

There is a long history of studies of the Mersey and of Liverpool Bay but only a few have tried rigorously to connect the two. Studies in Liverpool Bay have identified different water masses based on their chemical composition, in particular a Mersey plume close to the

English shore (Abdullah & Royle, 1973; Foster & Hunt, 1977). Bowden & Sharaf El Din (1966a), Bowden & Gilligan (1971) and Prandle et al. (1990) showed that the salinity at the mouth of the Mersey is in the region 24 to 29 psu, that the water column there can be stratified by up to 4 psu and that the salinity is moderately correlated with the river discharge averaged over the previous 7 to 10 days.

The large scale circulation in Liverpool Bay is determined by the horizontal density structure (Heaps, 1972), which is principally freshwater controlled. This circulation has also been well studied - Bowden & Sharaf El Din (1966b), Ramster & Hill (1969), Halliwell (1973), Heaps & Jones (1977), Howarth (1984), Czistrom (1986). In particular Heaps & Jones (1977) postulate that wind effects on top of the density driven circulation introduce an additional mode – a clockwise density driven depth-averaged coastal circulation occurring when winds are less than 5 – 10 m $s^{-1}$ and an anti-clockwise coastal circulation occurring when winds are stronger. The current's vertical structure is discussed in Polton et al. (2013) as a result of a depth varying competition between horizontal density and sea surface slope induced pressure gradients. More generally, however, both bottom drifter (Halliwell, 1973) and ADCP measurements (Polton et al., 2011) show that the near bed mean currents are consistently shoreward, near surface current measurements are presented below.

The objective of this paper is to investigate the processes affecting the Mersey plume and the dependencies that determine the surface salinity. This analysis is based on a nine-year time series of measurements in Liverpool Bay, at a site in the transition zone between coastal and continental shelf waters. Understanding the salinity in the coastal near shore region is particularly important since density gradients are haline controlled and modulate the fate of the river discharges, which can introduce suspended particulate matter, nutrients and contaminants into the coastal waters.

A series of local propositions are investigated to provide structure as a means to gaining more general insight. The analysis is at a low level, seeking to establish whether simple relationships exist that can assist comprehension of a complex environment.

1) The Mersey discharge strongly influences the salinity at the Mersey Bar site, Figure 1b. Hence a meaningful time lag can be estimated between the mouth of the Mersey and the site.

2) There is a spring / neap cycle in salinity at the site, as a consequence of variations in tidal mixing impacting either the dynamics of the plume or horizontal advection in Liverpool Bay.

3) There is a significant seasonal cycle in salinity at the site, reflecting the annual variation in rainfall and river discharge which on average peaks between November and March and is a minimum from June to August, although there is much daily and year-to-year variability.

4) Large variations in the salinity at the site are driven by weather events – floods and storms.

5a) The dominant factor controlling the salinity at the site is Liverpool Bay's circulation. This is the converse of proposition 1, suggesting that the processes in the coastal region predominate.

5b) The average surface circulation in Liverpool Bay is clockwise and reversed if winds exceed 5-10 m $s^{-1}$, following Heaps & Jones (1977).

The measurement scheme is presented in section 2, followed by sections describing the time series of surface salinity at the Mersey Bar, including investigating periodicities (section 3), its relation to the freshwater river discharge (section 4) and to the circulation in the Bay (section 5) and the impact of storm and flood events (section 6).

## 2. Measurement scheme

A measurement campaign from 2002 to 2011 in Liverpool Bay comprised four main components - in situ sites, an instrumented ferry, HF radar surface current measurements and a regularly serviced CTD grid (Howarth & Palmer, 2011). All data are banked with the British Oceanographic Data Centre. This study exploits the first three – time series of surface salinity and winds from the in situ sites and of surface currents from the HF radar measurements, and nearshore surface gradients measured daily by the ferry. All measurement strategies are a compromise between the scientific requirements, site availability, logistic and resource constraints. Here we were especially fortunate in being able to deploy a mooring in relative safety, since Liverpool is a major port, in an anchor exclusion zone near to the mouth of the Mersey and to have access to a ferry with a daily schedule. Throughout the campaign no instruments were lost, a major achievement, although there were some data losses due to instrument malfunctions and fouling.

The focus of this paper is the time series of surface salinity (measured at 1 m depth) obtained at a site near the Mersey Bar Light Vessel by the Centre for Environment, Fisheries and Aquaculture Science, Figure 1b, (Mills et al., 2005). The salinity response at periods longer than a day is investigated. Effects at shorter, semi-diurnal tidal, time scales such as tidal straining have been well studied, for instance Verspecht et al., 2009a, b; Palmer, 2010; Howlett et al., 2011. The measurements every 30 minutes were reduced to daily means by averaging over 25 hours, to minimise tidal effects.

## 2.1 Mersey Bar Mooring

The site, at 53° 32′ N 3° 21.8′ W, is situated 17 km from the nearest land (Formby Point) and 24 km from mouth of Mersey, Figure 1b. The location is due west of the outflow from the Mersey which is partially constrained by training walls, ending 9 km to the east of the site. In the first half of the twentieth century training walls were built to stabilize the position of the shipping channel, which is regularly dredged to a minimum depth of about 12 m below mean sea level. The tops of the training walls are 3 m below mean sea level but on both sides there are shallow banks whose minimum depth exceeds mean sea level (Blott et al., 2006). The mean water depth at the site is 23.5 m. Tidal currents are rectilinear, approximately east-west, with a maximum surface speed at mean springs of 0.75 m $s^{-1}$, occurring at mid-tide. A surface buoyed mooring and a sea bed frame were deployed here. Near bed salinities were measured on the frame which also contained an ADCP, measuring currents at 1 m intervals from 2.7 m above the bed to 2 m below the surface. Starting later, sensors to measure salinity at 5 m (from December 2003) and 10 m below the surface (from March 2006) were mounted on the mooring.

## 2.2 HF radar array

Contextual information is needed to interpret these salinity measurements. Particularly relevant are residual surface currents in Liverpool Bay and salinity gradients between the mouth of the Mersey and the site. A phased array HF radar system recorded surface current data (an average over the top 1 m) every 20 minutes between August 2005 and November 2011 at 101 cells on a 4 km grid. The radar equipment was located at Llanddulas, on the North Wales coast, and just south of Formby Point. Figure 10 shows the positions of the radar sites and of the cells. Tidal currents were calculated using harmonic analysis and subtracted from the observations to give residuals which were then averaged into daily means. Short gaps are inherent in HF radar data – these do not pose a problem for harmonic analysis and taking daily means reduces the significance of gaps. In addition taking daily means reduces the impact of energy at tidal frequencies which inevitably is still present in the residuals and irrelevant for this study (see Brown et al., 2012). The surface current data are complemented by wind measurements obtained from Hilbre Island, at the mouth of the Dee, starting in April 2004. These measurements are representative of winds in Liverpool Bay, although the site is slightly sheltered by the Welsh mountains for winds from the southwest and winds from the southeast are channelled along the Dee estuary (Wolf et al., 2011, where 2.5 years of wind data from Hilbre Island are compared with data from the proposed site of the offshore Gwynt y Môr wind farm in Liverpool Bay, at 53° 28.83´N, 3° 30.42´W). In addition the HF radar system estimates wind direction (but not wind speed) at each of the cells from the ratio of the heights of the two Bragg peaks, on the assumption that the Bragg resonant wind waves are locally generated (Fernandez et al., 1997; Wyatt et al., 2006). Figure 2 shows a bivariate histogram of the differences between the wind directions measured at Hilbre Island and those estimated by the radar cell at the Mersey Bar site, plotted against Hilbre wind speeds. The two sites are separated by 17 km and the wind directions agree well for wind speeds above 5 m $s^{-1}$.

## 2.3 Instrumented Ferry

In addition to the net movement of the sea surface, information on the outflow of the Mersey is required. A time series of salinity at the mouth of the Mersey would have been desirable but was not recorded. Instead measurements, at 3 m depth, have been obtained from an instrumented ferry on the route between Birkenhead and Dublin, passing close by the buoy, Figure 1b (Balfour et al., 2013). Instrumented ferry measurements provide coverage of the shallow near-shore region where measurements are exceedingly scarce. The ferry route had two advantages – first the ferry measured differences between the buoy site and the mouth of the Mersey and secondly the ferry measurements could be checked independently against the buoy measurements. The ferry does the round trip every day except Sundays and Mondays, when it sails one way; a total of 12 times per week. In port the ferry sensors are isolated by a valve, which reduces suspended particulate matter fouling. The valve was opened / closed at the mouth of the Mersey for west / east bound crossings and so there are measurements as the ferry steamed along the shipping channel and past the Mersey Bar site. Temperature and conductivity were recorded every 10 s (~100 m at 20 knots), although later analysis showed that the system had a time constant of about 5 minutes because the water flowed through a large sea chest. The record lasts between November 2007 and January 2011. One drawback with the data is that the ferry sailed at approximately the same time each day (either 10:00 or 22:00, Birkenhead and Dublin) so that over a 14 day period the time of sailing cycled from high to low water and back to high water. Hence nearshore variations due to the spring / neap cycle were masked by variations due to the ebb or flood state of the tide at departing and arriving, 6.4 hours later.

## 2.4 River gauges

Daily river flow values for the Mersey (and Conwy, Clwyd, Dee and Ribble) were obtained from the National River Flow Archive, based at the Centre for Ecology and Hydrology. Although the rivers have different catchment characteristics their flows are well correlated, correlation coefficients between 0.74 and 0.89 for the 9 year period. All correlations mentioned in this paper are statistically different from zero; of more relevance is the coefficient of determination (the correlation coefficient squared) giving the proportion of the variance of one variable that is predictable from the other variable.

## 2.5 Numerical Models

Numerical models complement measurements and are particularly valuable estimating spatial variability. However uncertainties will be largest near the shore because of the imprecise knowledge of fresh water, estuarine and ground water inputs; how best to introduce these into the model and also because of the lack of measurements to test the models. A model estimate of the annual mean salinity based on daily river flow values is shown in Figure 3, to provide background information for the paper. Note that the simulated salinity is too low at the measurement site (between 30.5 and 31 psu) whereas the measured mean salinity is in excess of 32 psu (see next section). The model indicates that at springs the plume is bottom attached, whilst at neaps it is surface advected, Polton et al., 2011, Figure 11.

# 3. Salinity at the Mersey Bar

Figure 4 shows 9 years of surface salinity measured at the Mersey Bar site, based on FSI high quality conductivity and temperature sensors. The site is in the transition zone between coastal and continental shelf waters, with daily values varying between 28.64 and 33.96 psu, the latter being typical of waters further offshore in Liverpool Bay. (Practical Salinity is used throughout the paper.) The overall mean salinity is 32.19 psu, which compares with the 1935-1961 mean of 31.94 psu based on measurements three times a week (Hughes, 1966).

The record is dominated by low frequencies as can be seen by the monthly averages, the black line in the figure. The spectrum of salinity variability is red (Figure 5), with no detectable peak at 0.068 cpd corresponding to the spring / neap cycle. In corroboration, the mean salinities at springs and neaps are virtually identical, respectively 32.17 and 32.16 psu, indicating no impact of variations in tidal mixing over the spring / neap cycle. The annual sinusoid explains only 6% of the variance (its amplitude is 0.21 psu) in marked contrast to temperature where typically more than 90% of the variance is explained by an annual sinusoid. The monthly median salinities are shown in Figure 6, together with the annual sinusoid calculated above. Monthly salinities are higher than average in August and November to January and lower in February to April. Hence proposition 2 (spring / neap cycle in salinity) is not supported and there is only a weak annual cycle in salinity (proposition 3).

The distribution deviates from normal since the skewness is -0.56 and the excess kurtosis of 1.4. Skewness, the third central moment of a distribution, is a measure of the distribution's asymmetry. Kurtosis, the fourth central moment, is a measure of the distribution's 'peakedness'. Both would be zero for a normal distribution. The negative skewness indicates there are more extreme low salinities, which can occur throughout the year, with a slight tendency for more in summer, and fewer extreme high salinities, all occurring in winter (emphasised by the outliers in Figure 6). Events are discussed in more detail in section 6. Hence this initial analysis indicates that to first order the best predictor for salinity is its overall mean value and this is slightly bettered by considering monthly means. This can only be improved if investigations described in the next two sections establish links between the salinity at the Mersey Bar and either freshwater discharges or the circulation in Liverpool Bay.

## 4. Fresh water discharged by the Mersey

Daily mean values of the fresh water discharge down the Mersey, Dee, Clwyd and Conwy are shown in Figure 7a for the three year period of the ferry measurements. There appears to be no coherent relation between this discharge and the salinities measured at the Mersey Bar (Figure 8). Indeed low salinities at the site are only observed for average river discharges and the highest discharge corresponds to a high salinity. Lagging the river discharge by time does not strengthen the relationship. Hence evidence in support of proposition 1 (Mersey discharge strongly influences Mersey Bar salinity) is absent.

The ferry provides an alternative approach which explains why the connection between the Mersey Bar and the Mersey discharge is so weak. Henceforth the two positions will be referred to as the mouth and the Bar and are indicated in Figure 1b by the plus sign and dot, respectively. Figures 7b and 7c show the comparison between the salinities measured by the ferry at the mouth, mean value 28.1 psu, and as it passed the Bar site, a distance of 24 km, taking on average 53 minutes. Studying differences from measurements taken a short time apart significantly reduces the impact of variations arising from whether the tide is ebbing or flooding. The water at the Bar site is always saltier than at the mouth; the median value of the salinity difference is 3.77 and its maximum 16.46 psu. The best fit line is

$$\text{Bar salinity} = 29.2 + 0.11 \times \text{mouth salinity}.$$

The coefficient of determination between the two data sets is 0.18, so that 18% of the variance of the salinity record at the Bar can be explained by variations at the mouth of the Mersey.

However, there is a wide variation in salinity values at the Bar site when the water at the mouth is relatively fresh. Similarly there is no relation between the salinity differences and the salinity at the Bar. This implies that the core width of any plume is usually less than 17 km and is confined to water less than 20 m deep. This is supported by estimates of the salinity gradient from the ferry, obtained by averaging each crossing's measurements into 1 km cells (Figure 9). The Mersey Bar site (3.36°W) is clearly outside the region of strong salinity gradient. Thus the ferry measurements show that the freshwater core from the Mersey is generally closer to the English shore than the Mersey Bar site and hence the Mersey discharge rate is not a strong control on salinity at the Mersey Bar site.

## 5. Circulation in Liverpool Bay

Since the core of the Mersey plume is shoreward of the Mersey Bar site what are the main controllers of salinity at the Mersey Bar? The mean currents at the site are consistently shoreward near the bed and northward near the surface (Polton et al., 2011). The surface circulation is particularly relevant for the extent of the Mersey plume and is principally driven by density gradients in Liverpool Bay, which are primarily the consequence of the freshwater input, and by winds. The mean surface currents measured by the HF radar system are approximately north-northeast, with speeds of about 0.05 m $s^{-1}$ (Figure 10). These surface currents are highly correlated with the wind - the correlation coefficient between the daily mean winds measured at Hilbre and the average of residual currents recorded at the 9 cells closest to the English shore is 0.81; with a factor based on linear regression of 0.011, at 24° to the right of the wind's direction. The offset calculated as part of the regression (i.e. the mean currents for weak winds) shows a slightly weaker value directed northward. The high correlation between the winds and the surface currents does not extend deeper into the water column. For the ADCP bin nearest the surface, at 18.7 m above the bed, 5 m below mean tide level, the correlation coefficient is 0.29, although the directions of the mean current are similar (north-northwest).

Figure 11a shows how the direction of the daily residual surface current relates to the wind's direction as measured by the HF radar system (current directions are towards, wind directions away in Figure 11b, as is standard for oceanography and meteorology). There are two regimes. For wind speeds less than about 5 m $s^{-1}$ there is no direct relation between the wind direction and the surface current direction. The weak wind can be blowing from any direction whilst the surface current is relatively constant towards the north, as for the overall mean. For wind speeds above 5 m $s^{-1}$ the surface current is approximately in the wind's direction, as indicated by the correlation. The link is particularly evident for winds from the southwest, the predominant direction during storms. Offshore currents (between northwest and southwest), which might be expected to lead to the plume spreading into Liverpool Bay, occur only 14% of the time and are associated with winds from the north. To test this salinity was plotted against current direction (Figure 12). The highest salinities occur when the current direction is in the quadrant towards the northeast (this is also the most frequently occurring current direction). Currents towards the west are relatively scarce and then salinities are lower than average. However really low salinities (<31 psu) can occur for any wind direction. Hence proposition 5a (circulation controls salinity at the Mersey Bar) is supported, Figure 12.

## 6. Events, storms and floods

Table 1 lists the 16 occasions when the daily averaged Mersey discharge exceeded 400 $m^3 s^{-1}$ and there were concurrent salinity measurements at the Mersey Bar. Note this covers only 11 separate events. The link between the river discharge and the salinity is tenuous and there is no consistent pattern to the delay between maximum discharge and minimum salinity at the Mersey Bar site during the succeeding fortnight, varying between 1 and 12 days. Previous studies have found a lag between river discharge in the preceding week and salinity at the mouth of the Mersey (Bowden & Sharaf el Din, 1966a). Clearly this does not extend further into the Bay and so proposition 4 (salinity variability at the Mersey Bar is driven by significant weather events) is not supported. The lowest salinity does correspond to significant discharge, at the end of January and beginning of February 2004, but the largest discharge which covers 4 days in a period of a week in January 2008 does not.

For three of these events (December 2007, January 2008 and September 2008) there were also ferry measurements (Figure 13) as well as wind data from Hilbre and HF radar surface currents (Figure 14). Two were in winter as part of sustained river discharges and one in summer, an isolated event. The daily river flows for these events are listed in Table 2. The salinity ferry measurements in Figure 13 show differences between the three events. (Although the ferry provides crucial information on nearshore gradients, interpretation of the measurements depends on the state of the tide (ebb or flood) for each sailing. The typical time between the end of one crossing and the start of the next is 6 hours, half a tidal cycle, hence the scatter in each of the panels in the figure.) In particular the January 2008 event (Figure 13b) not only had the highest daily discharge during the nine years but also was a period of sustained discharge over 20 days. High saline water (in this context above 33 psu) extended as far eastward as the Mersey Bar site (3.36°W) and consequently significant gradients were confined to east of 3.3°W. The reason can be seen in Figure 14 where for this period there were strong winds from the southwest and strong surface currents toward the northeast. In successive stages of reduced 'on-shore' wind (Figure 14) and reduced river discharge the December 2007 period (Figure 13a) also shows a high Mersey Bar salinity, though the reduced discharge rate means there is less freshwater to compress a sharp coastal salinity gradient. In September 2008 when the currents are directed off shore (Figure 14), the salinity at the Mersey Bar is reduced and the salinity gradient is again weak (Figure 13 c).

## 7. Discussion

The paper has concentrated on exploiting salinity measurements from a fixed site 24 km from the mouth of the Mersey to study the plume's extent and influences. Whilst salinity is useful as a tracer for freshwater it is also important dynamically because of its impact on density. Horizontal density gradients are primarily controlled by salinity both because a change of 1 psu in salinity to first order has the same effect on density as a change of 5°C in temperature and also because horizontal temperature gradients are relatively small. Even for vertical density gradients in coastal sites, where temperature gradients are larger, salinity still plays a principal role. However, estimation of gradients in coastal regions is challenging, since they vary rapidly in space and time. Ideally two or more separate sites are required, for instance this data set would have been enhanced by concurrent time series of salinity measurements at the mouth of the Mersey. As an alternative, data from the instrumented ferry have been used to fill the gap. Numerical models are also particularly useful at providing spatial context (O'Neill et al., 2012), although uncertainties can be large if (for example) the freshwater boundary forcing is not well known.

One approach to circumvent these difficulties is to estimate gradients from simultaneous single point measurements of current and density, by applying the continuity equation:

$$\partial\rho/\partial t + u\ \partial\rho/\partial x + v\ \partial\rho/\partial y + w\ \partial\rho/\partial z = 0 \quad (1)$$

where the x component is towards the east and the y component towards the north. In Liverpool Bay tidal currents are approximately rectilinear east-west so that both the north-south current component (v) is an order of magnitude less than u and the north-south density gradient is less than the east-west (Figure 3). Hence the north-south term can be neglected. The vertical term has also been neglected which is valid for homogeneous conditions but may be inappropriate during some stratified periods. The equation then reduces to

$$\partial\rho/\partial x = -a/u\ \partial\rho/\partial t, \quad (2)$$

Where a is 1 if the system is purely zonal and can otherwise be fitted to the data. Whilst the validity of this equation is difficult to verify from observations it is an easy diagnostic for a numerical model. Calculations applying one year's model data for the Mersey Bar site indicate the correlation is particularly robust for all but the largest gradients, i.e. valid for when $1/u\partial\rho/\partial t < 3.5 \times 10^{-4}$ kg m$^{-4}$, Figure 15. Above this value stratification may be significant. The slope of the fit is a = 0.78. Using the observed hourly values of currents measured with an ADCP and the density time derivative, the median east-west surface density gradient is calculated, applying equation (2), to be $-4.7 \times 10^{-5}$ kg m$^{-4}$. The median gradient was also estimated from the ferry as it passed the buoy to be $-5.6 \times 10^{-5}$ kg m$^{-4}$, in reasonable agreement.

The study has concentrated on a particular set of observations targeted at determining coastal density gradients and in the end has derived conclusions with wider relevance chiefly regarding measurement strategy. The principal data sets were several years of surface salinity at a fixed point and from an instrumented ferry. The latter in particular were unique and invaluable, providing estimates of gradients from the river mouth. Methodologies for measuring spatial gradients are much scarcer than those for obtaining time series. The combination with the mooring data was effective. In the future gliders may in part be able to replicate this capability; a trial deployment away from the shipping lanes, off the Ribble coming into depths of 15 m was successful (M. Palmer, personal communication). Coastal salinity variations are larger than in the open ocean, so that an accuracy of 0.01 psu would be acceptable, but even achieving this for time series employing high quality sensors is not always possible because of fouling and turbid water. It is found that a wide variety of background measurements, including HF radar for surface currents, river flows and winds, are also essential for interpretation of the salinity measurements. The HF radar current measurements proved more valuable than ADCP measurements since they included the near surface wind drift, relevant to the plume's movement. Whilst the measurement campaign provided much pertinent information, no strategy is perfect. With hindsight three developments worth considering are i) the duration, ii) the nearshore gradients and iii) the offshore winds. Firstly 9 years has proved to be too short for studying the low frequency temporal salinity variability. Secondly, the results have shown the largest gradients generally occurred shoreward of the Mersey Bar site. Hence, although gradients were estimated from the ferry measurements and via the tidal advection method, one or more additional inshore in situ sites would have greatly enhanced the study, although creating logistical problems – particularly finding safe, robust sites. Thirdly, surface currents respond to local wind forcing and shore-based wind measurements will always be affected by the local topography. Hence, offshore wind measurements would reduce uncertainty. Finally, an external consideration concerns the imprecision regarding data on freshwater flows. Firstly rivers are gauged somewhere up river and contributions below the gauging site can only be estimated. Secondly knowledge of the extent and importance of distributed groundwater is deficient.

As well as lessons for measurements strategies and the wide variety of observations needed to interpret a specific set of measurements, the study has demonstrated the unpredictable fate of river discharges into a particular, partially enclosed, coastal sea where tidal mixing is large. This is relevant more widely, for instance to much of the north-west European coast line, and further afield, where tides dominate the dynamics and the topography is often intricate. The failure to obtain predictability of near shore gradients from measurements alone, for which there are few techniques, indicates that a combination of long term measurements and models will be key.

## 8. Conclusions

The coastal near shore region is particularly important both because salinity and density gradients are large and because here river discharges, including suspended particulate matter, nutrients and contaminants, are introduced into coastal waters. However, measuring salinity and its gradient is challenging and uncertainties in model estimates can be large. Nine years' measurements of coastal salinity have formed the focus of an investigation into the lateral extent of the Mersey plume and influences on it. Tidal mixing in Liverpool Bay is large and as a consequence the plume can switch between bottom attached during spring tides and surface advected during neaps.

The propositions listed in the introduction are summarised and their level of applicability reviewed below:

1) The Mersey discharge strong influences the salinity at the Mersey Bar site and hence a meaningful time lag can be estimated from the Mersey to the site.

2) There is a spring / neap cycle in salinity at the site.

3) There is a significant seasonal cycle in salinity at the site.

4) Large variations in the salinity at the site are driven by events – floods, storms.

5a) The dominant factor controlling the salinity at the site is Liverpool Bay's circulation.

5b) The average surface circulation in Liverpool Bay is clockwise and reversed if winds > 5-10 m $s^{-1}$.

The evidence presented here is not sufficient to support the first four – there are no predominant periodicities, although there is a weak annual cycle, and no consistent relations with storms or floods - leading to the conclusion that the majority of the plume for most of the time is confined to be closer to the English shore than the Mersey Bar, 17 km from the land. The salinity (and density) gradient decreases by an order of magnitude between the mouth of the Mersey and the Mersey Bar.

The fifth proposition, that the Bay's circulation is the dominant factor, is supported and its second part is partially supported to the extent that wind forcing tends to reinforce the surface circulation at wind speeds greater than 5 - 10 m $s^{-1}$. However, near bed currents are consistently shoreward and near surface currents northward, so that there is no evidence of a clockwise circulation which is reversed at higher wind speeds. Hence this extensive measurement based analysis contradicts and enhances the modelling study of Heaps & Jones (1977). The wind's direction has an important impact on the westward extent of the plume as mentioned in the introduction concerning upwelling favourable winds. Although the strongest winds are predominantly from between southwest and northwest, reinforcing the mean flow, winds from the north can lead to lower salinities at the Mersey Bar site. These conclusions are generally negative but emphasise the importance of processes in the shallow coastal region to the plume behaviour.

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Table 1. The largest discharges of freshwater by the river Mersey and the minimum salinity in the succeeding 14 days at the Mersey Bar. Days are measured from 1 Jan 2002, day 1.

| Mersey Discharge ($m^3\ s^{-1}$) | Day | Day of minimum salinity | Time delay (days) | Minimum salinity (psu) | Date of river discharge |
|---|---|---|---|---|---|
| 911 | 2212 | 2213 | 1 | 32.16 | 21 Jan 2008 |
| 608 | 765 | 770 | 5 | 28.64 | 4 Feb 2004 |
| 586 | 2441 | 2442 | 1 | 30.88 | 6 Sep 2008 |
| 561 | 1052 | 1064 | 12 | 30.34 | 17 Nov 2004 |
| 546 | 761 | 770 | 9 | 28.64 | 31 Jan 2004 |
| 525 | 363 | 374 | 11 | 31.34 | 29 Dec 2002 |
| 508 | 2470 | 2482 | 12 | 31.30 | 5 Oct 2008 |
| 497 | 953 | 954 | 1 | 31.70 | 10 Aug 2004 |
| 495 | 2011 | 2020 | 9 | 30.78 | 4 Jul 2007 |
| 478 | 2211 | 2213 | 2 | 32.16 | 20 Jan 2008 |
| 466 | 2210 | 2213 | 3 | 32.16 | 19 Jan 2008 |
| 461 | 1844 | 1853 | 9 | 31.74 | 18 Jan 2007 |
| 458 | 968 | 981 | 13 | 30.29 | 25 Aug 2004 |
| 427 | 2167 | 2171 | 4 | 30.45 | 7 Dec 2007 |
| 424 | 2206 | 2213 | 7 | 32.16 | 15 Jan 2008 |
| 413 | 2440 | 2442 | 2 | 30.88 | 5 Sep 2008 |

Table 2. Freshwater discharge by the river Mersey between 30 November and 7 December 2007; 7 and 25 January 2008; 3 and 9 September 2008. Days are measured from 1 Jan 2002, day 1.

| 30 Nov - 7 Dec 2007 | | 7 – 25 Jan 2008 | | 3 – 9 Sept 2008 | |
|---|---|---|---|---|---|
| Day | Mersey discharge ($m^3$ $s^{-1}$) | Day | Mersey discharge ($m^3$ $s^{-1}$) | Day | Mersey discharge ($m^3$ $s^{-1}$) |
| 2160 | 117 | 2198 | 146 | 2438 | 105 |
| 2161 | 165 | 2199 | 135 | 2439 | 100 |
| 2162 | 264 | 2200 | 205 | 2440 | 413 |
| 2163 | 205 | 2201 | 380 | 2441 | 586 |
| 2164 | 143 | 2202 | 183 | 2442 | 254 |
| 2165 | 138 | 2203 | 155 | 2443 | 154 |
| 2166 | 300 | 2204 | 146 | 2444 | 119 |
| 2167 | 427 | 2205 | 156 | | |
| 2168 | 365 | 2206 | 424 | | |
| 2169 | 247 | 2207 | 378 | | |
| 2170 | 151 | 2208 | 294 | | |
| 2171 | 110 | 2209 | 357 | | |
| | | 2210 | 466 | | |
| | | 2211 | 478 | | |
| | | 2212 | 911 | | |
| | | 2213 | 269 | | |
| | | 2214 | 204 | | |
| | | 2215 | 176 | | |
| | | 2216 | 120 | | |

Figure captions

Figure 1. Maps showing (a) Liverpool Bay and the positions of the major rivers; (b) the Mersey Bar site (dot), the ferry track and depth contours below mean sea level at 10 m intervals (black is above mean sea level). The dotted line indicates the average westbound ferry measurement track and the dashed the eastbound. The plus sign marks the start of ferry measurements at the mouth of the Mersey. The maintained shipping channel out to 3.2°W is clearly visible. The position of the weather station on Hilbre Island is indicated by the white asterisk.

Figure 2. Bivariate histogram of the difference between wind direction measured at Hilbre Island and that estimated at the Mersey Bar radar cell, in 10° bins, against wind speed measured at Hilbre, in 1 m $s^{-1}$ bins. The contour intervals are every 0.5%.

Figure 3. Modelled annual mean salinity in psu, from Phelps et al., 2013. The position of the Mersey Bar buoy is indicated by a cross.

Figure 4. Surface salinity at the Mersey Bar site from November 2002 to September 2011, the vertical grid lines indicate years. Daily values are in grey; the monthly average is shown by the black line.

Figure 5. The salinity spectrum from 9 years of data, averaged into segment lengths of 512 days.

Figure 6. Box plot of the surface salinity at the Mersey Bar site by month, showing the median (red), 25 and 75 percentiles (blue); the whiskers show 99% data coverage for normally distributed data; outliers beyond this are shown by crosses. Superimposed is the annual cycle in grey.

Figure 7. Surface salinity measured by the ferry at the mouth of Mersey and the Mersey Bar between November 2007 and January 2011. a) Daily river flow – Mersey (black); Mersey, Dee, Clwyd and Conwy combined (grey); b) time series of salinity at the Bar (blue); mouth (red) and difference (black); c) scatter plot of salinity at the Bar and the mouth.

Figure 8. Scatter plot of salinity measured at the Bar site against River Mersey discharge.

Figure 9. The salinity gradient as measured by the ferry averaged in 1 km cells. The black line is the median value and the dashed line the 95 percentile.

Figure 10. The mean surface currents from 6 years of HF radar measurements. The horizontal bar indicates 0.1 m $s^{-1}$; the two crosses indicate the radar sites.

Figure 11. A) Difference between daily mean HF radar wind and current direction v Hilbre wind speed. B) HF radar current direction (oceanographic) v wind direction (meteorological). Red dots for wind speeds <= 5 m $s^{-1}$.

Figure 12. Daily mean salinity at the Mersey Bar plotted against surface current direction.

Figure 13. Salinity measured by the ferry: (a) 30 November – 13 December 2007; (b) 9 – 21 January 2008; (c) 3 – 12 September 2008.

Figure 14. Progressive vector diagrams based on daily means for 30 November – 13 December 2007 (15 days; blue); 9 – 28 January 2008 (20 days; red); 3 – 12 September 2008 (10 days; black). Asterisks mark midnight. (a) HF radar residual surface currents at the Mersey Bar site; (b) winds measured at Hilbre Island.

Figure 15. Plot of $1/u \, \partial\rho/\partial t$ against $\partial\rho/\partial x$ from one year of model calculations. The blue line is the least squares fit through the origin. The red dots are for values of $1/u \, \partial\rho/\partial t > 3.5 \times 10^{-4}$ kg m$^{-4}$.

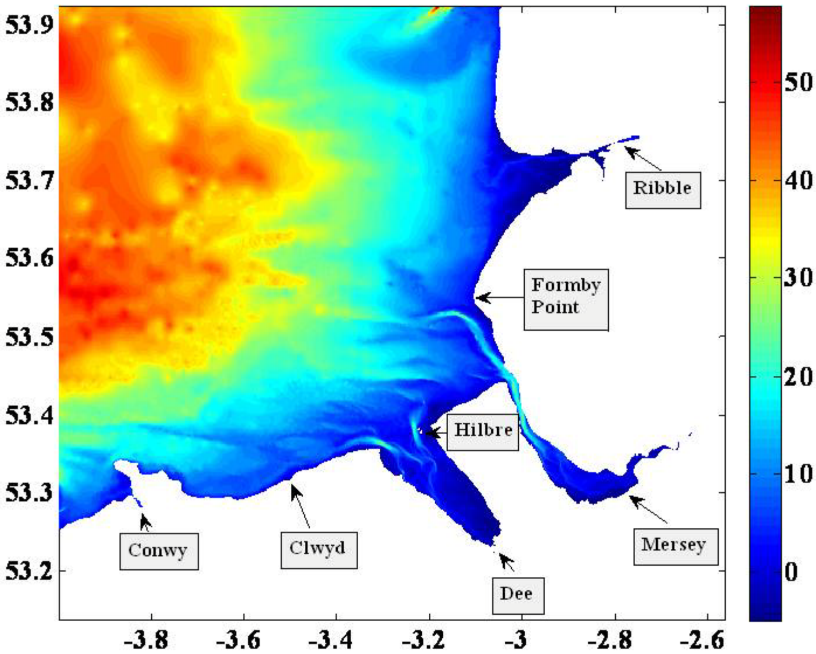


Figure 1A

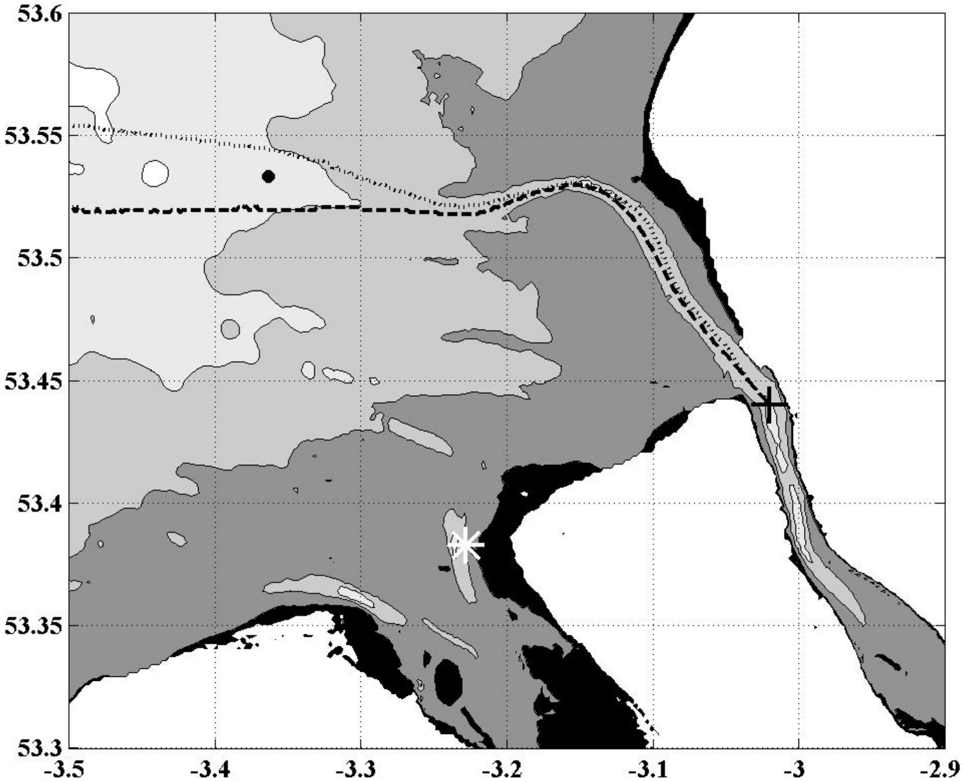

Figure 1B

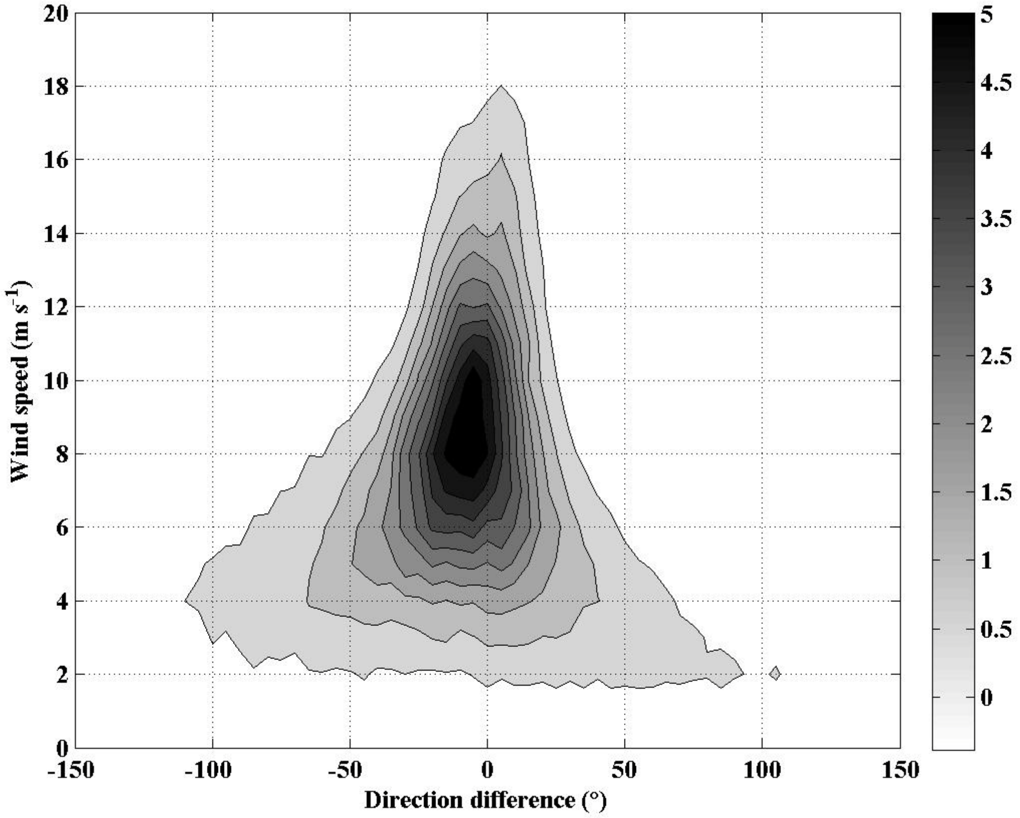


Figure 2

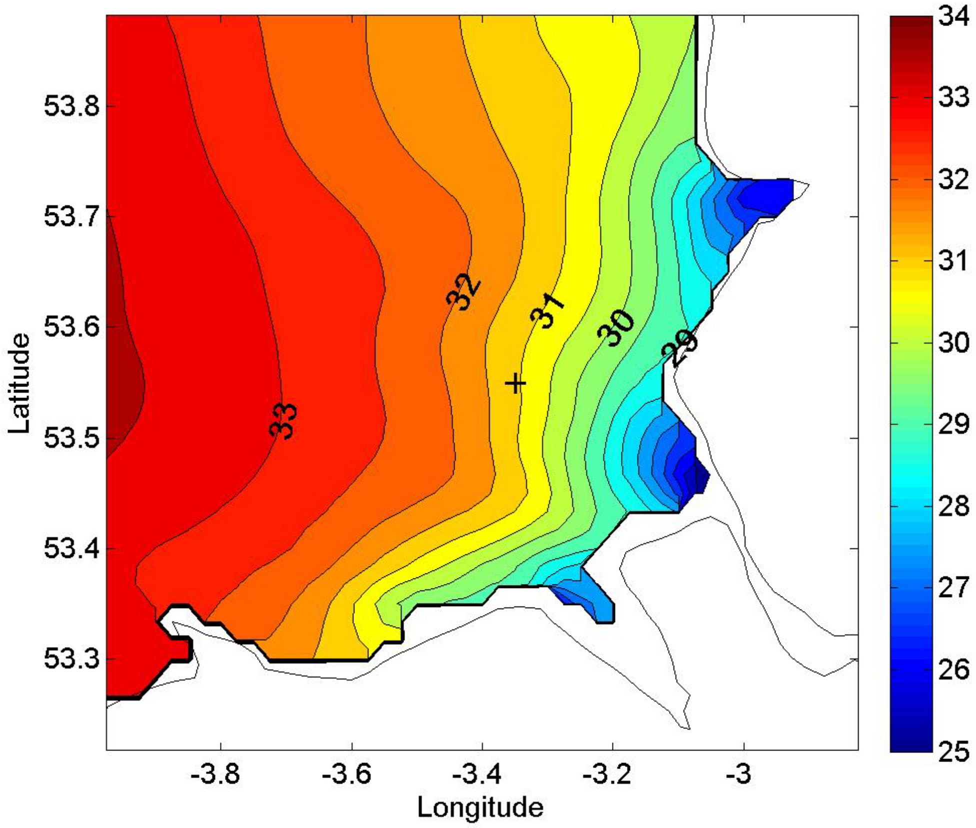


Figure 3

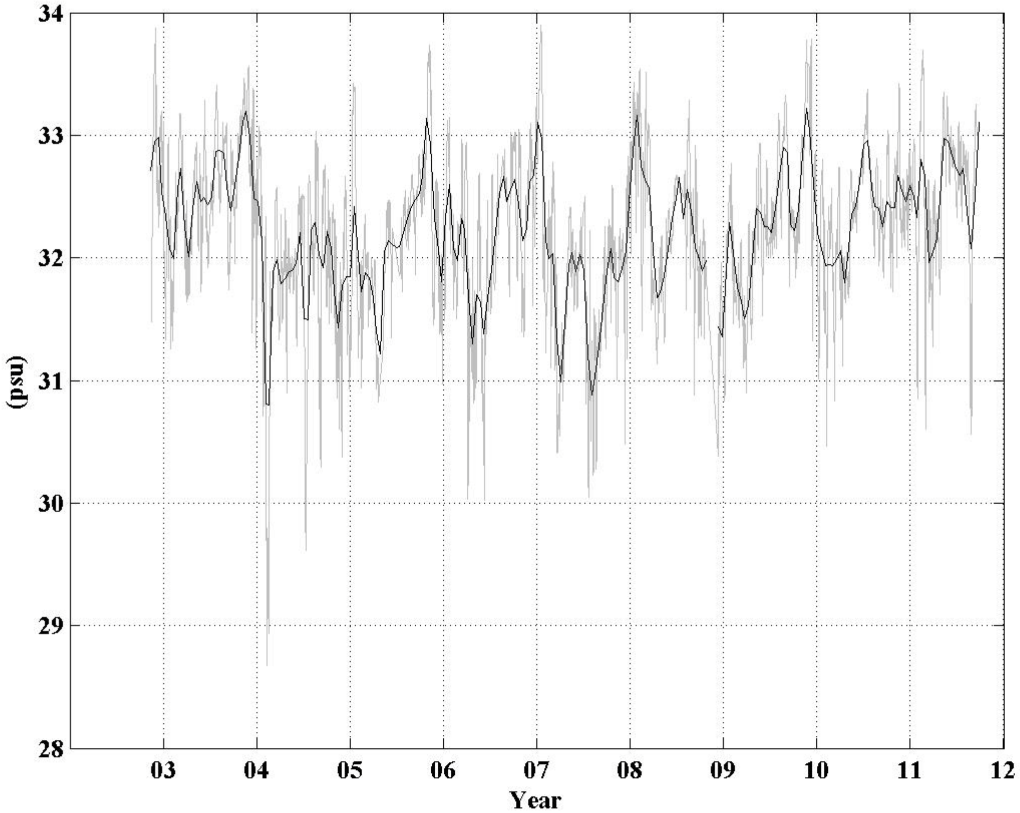


Figure 4

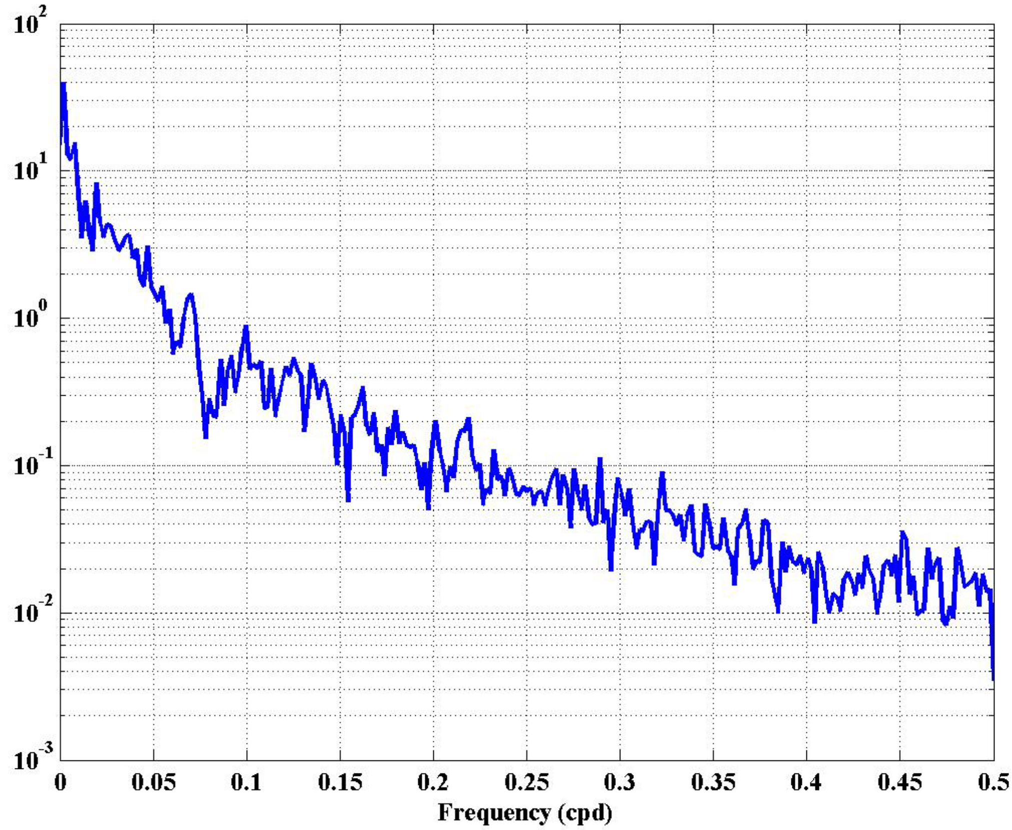


Figure 5

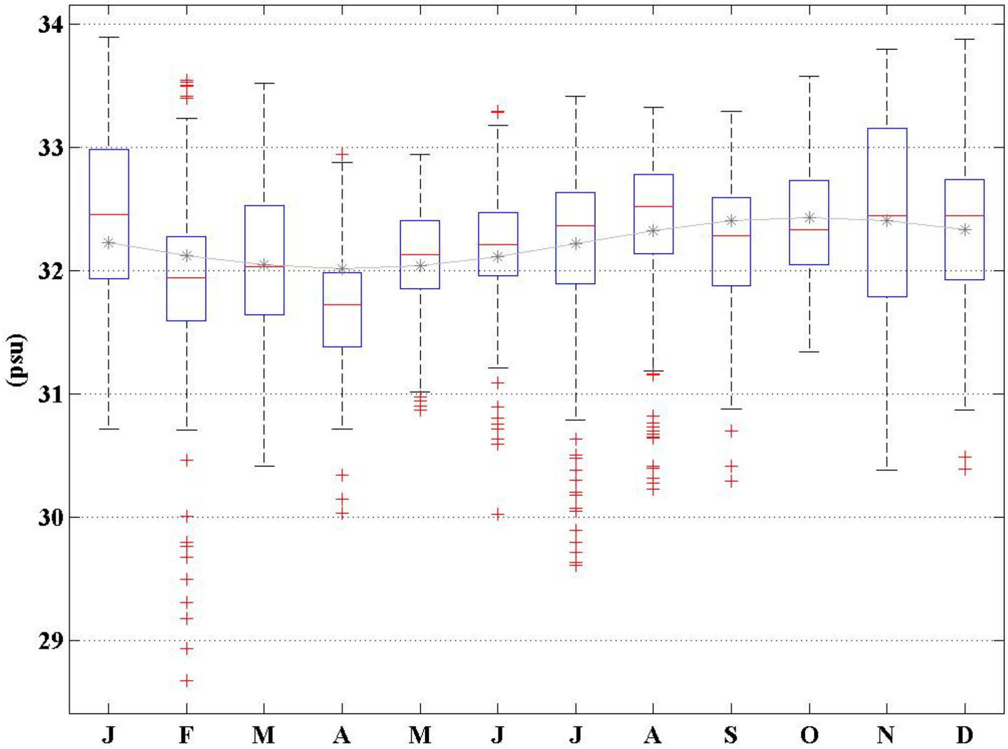


Figure 6

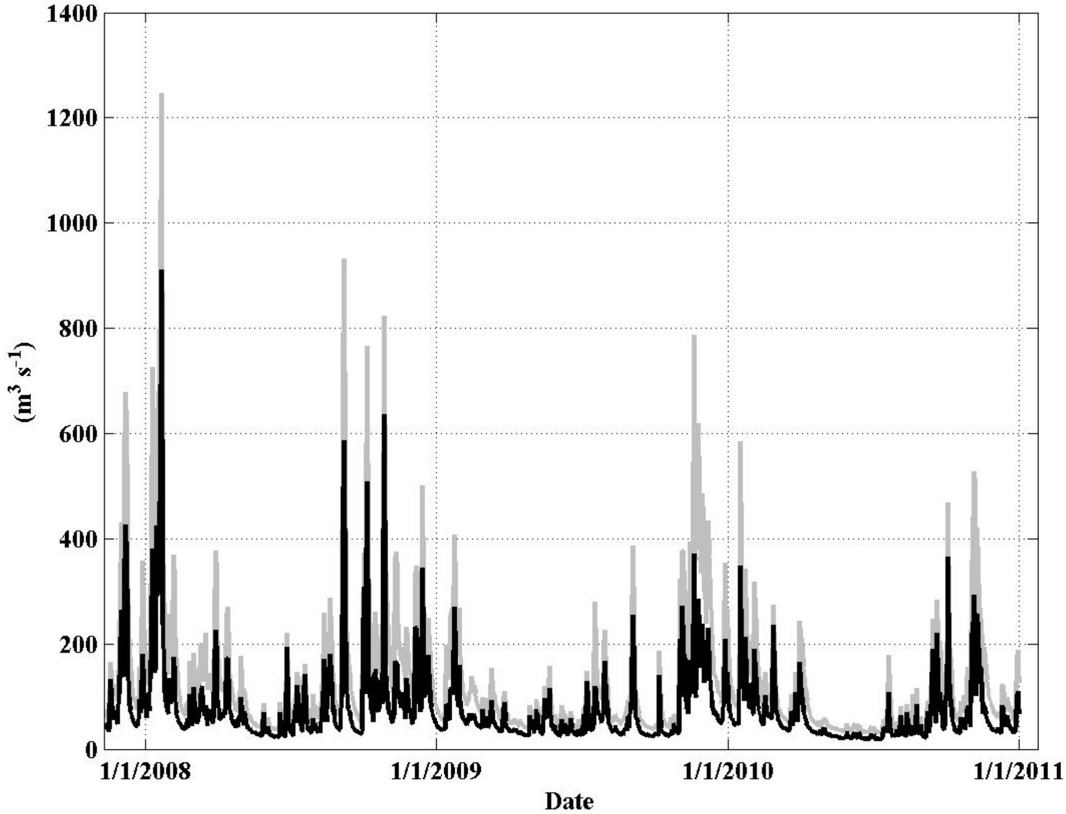


Figure 7A

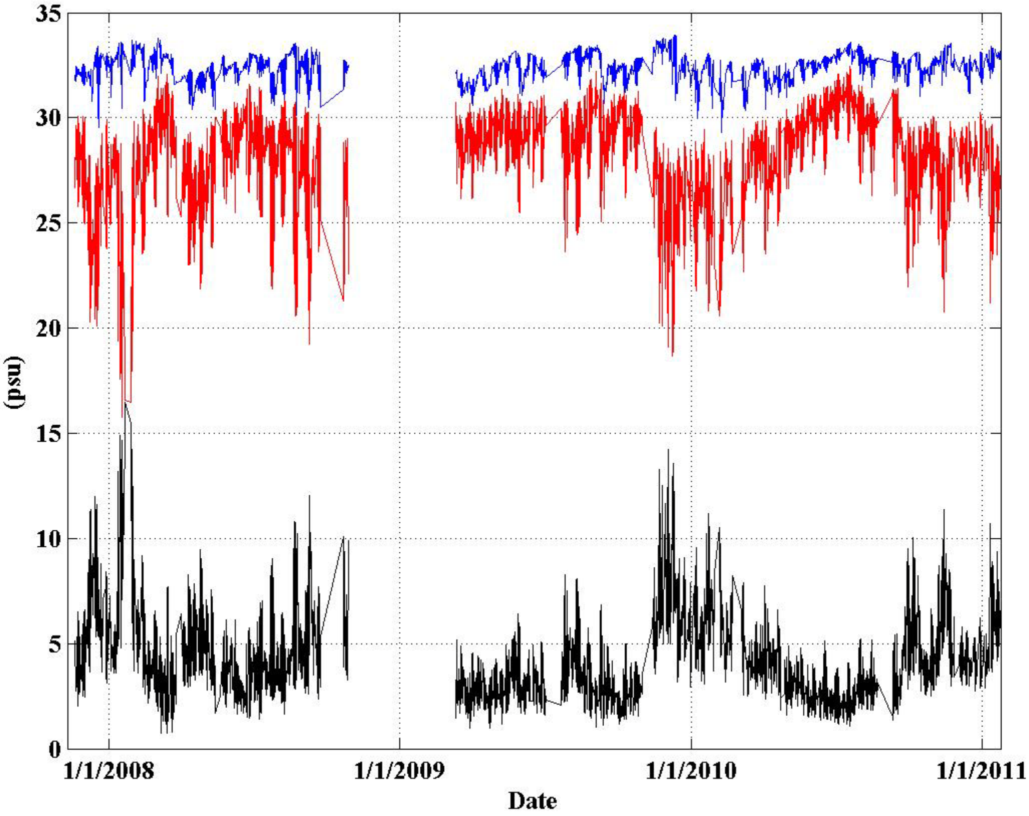


Figure 7B

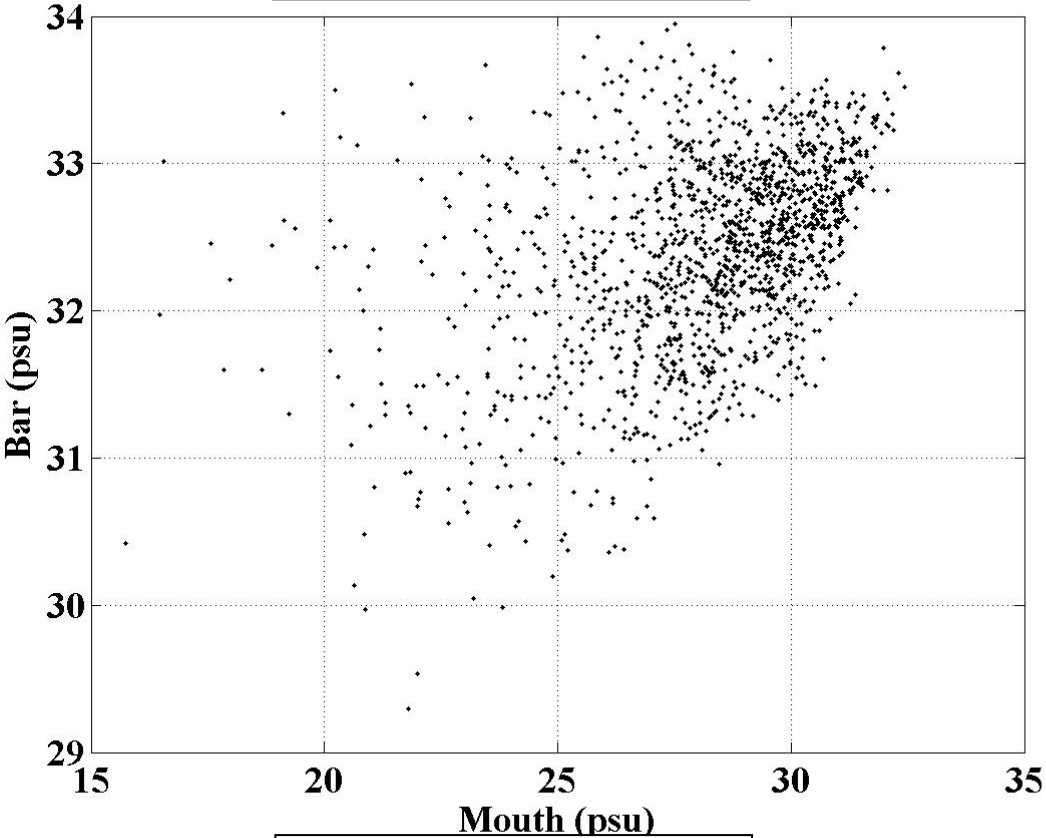


Figure 7C

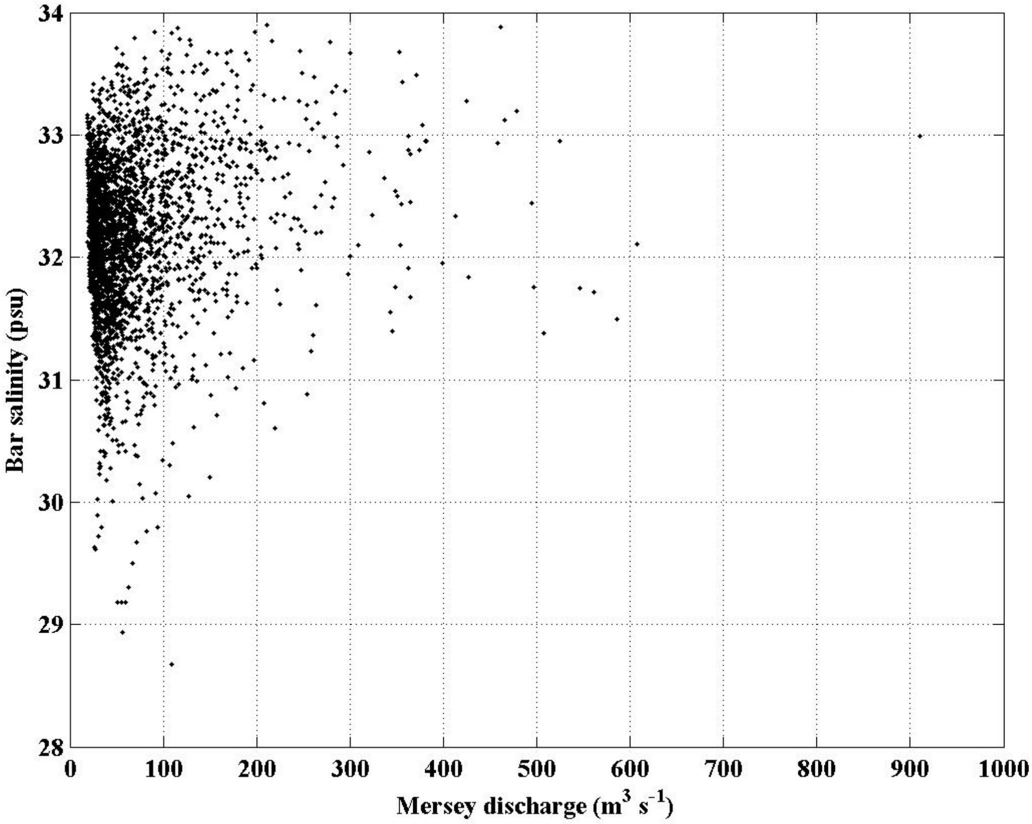


Figure 8

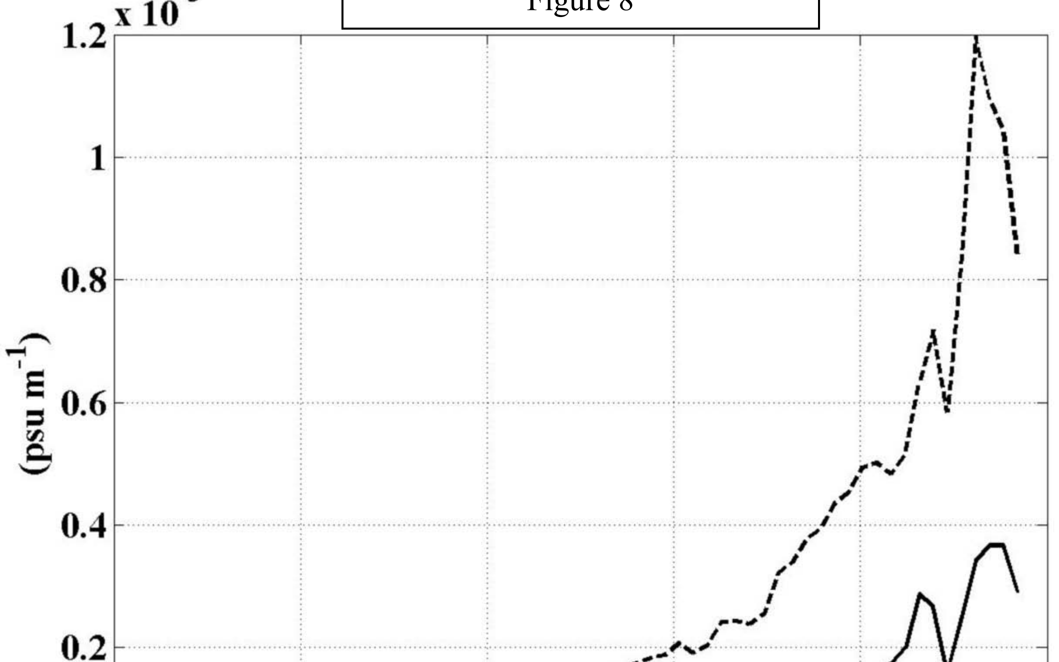


Figure 9

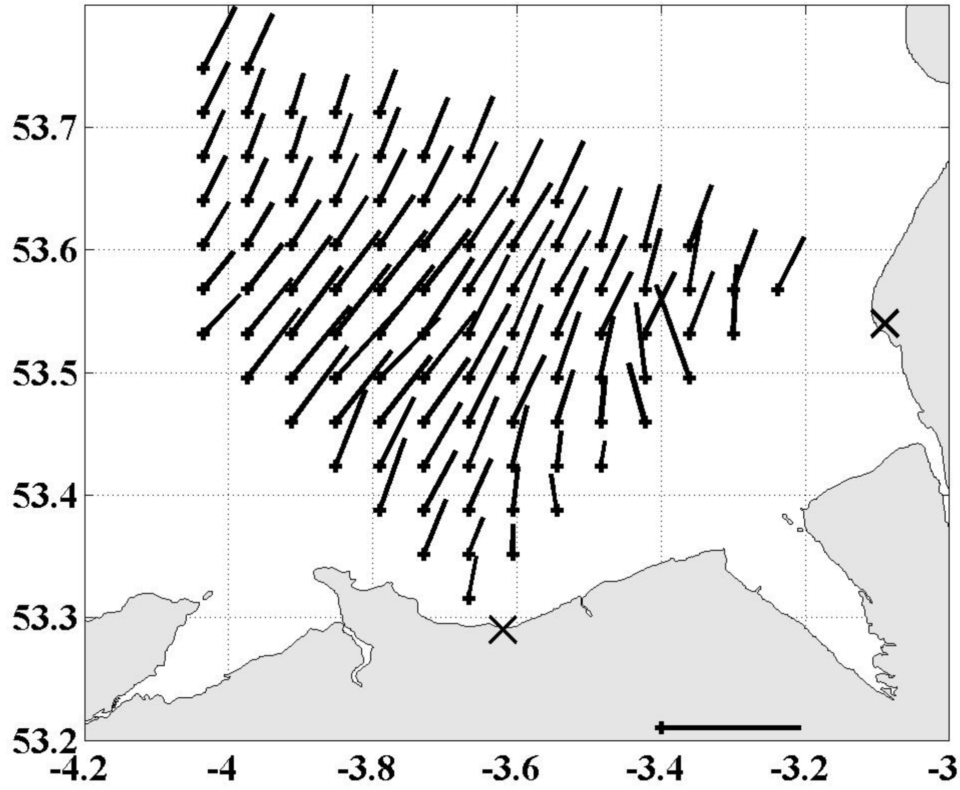


Figure 10

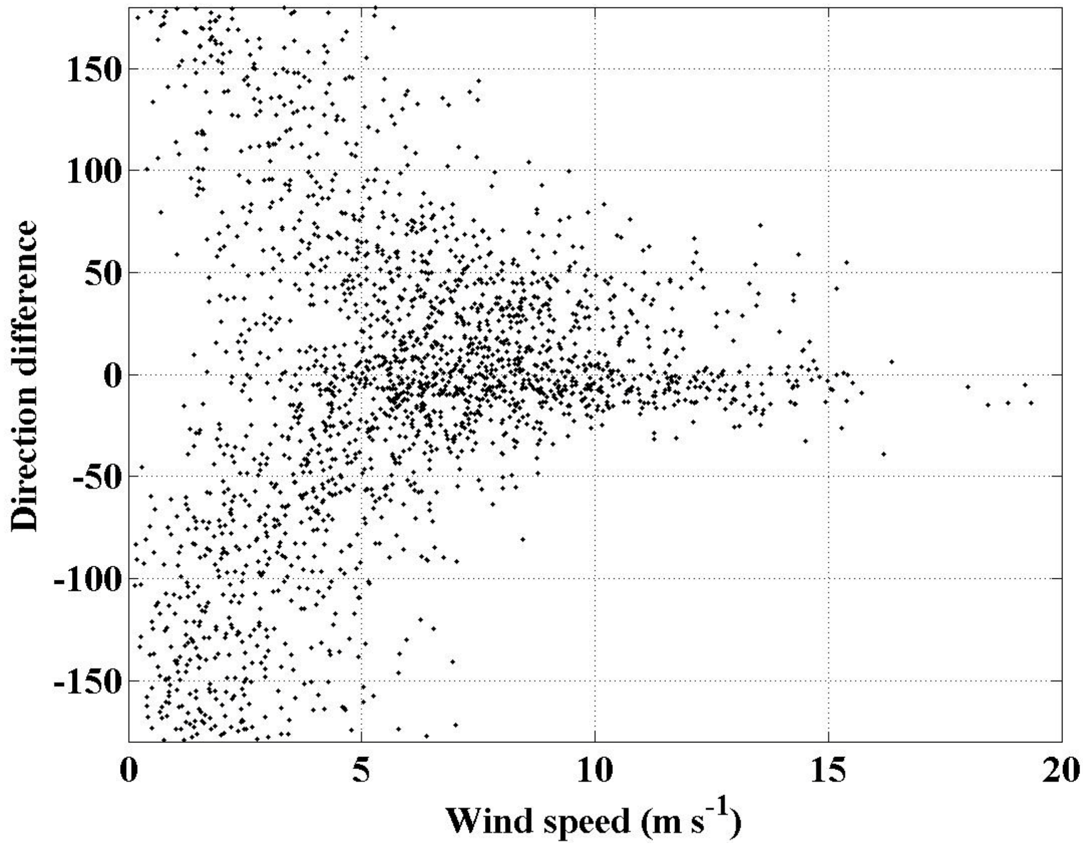


Figure 11A

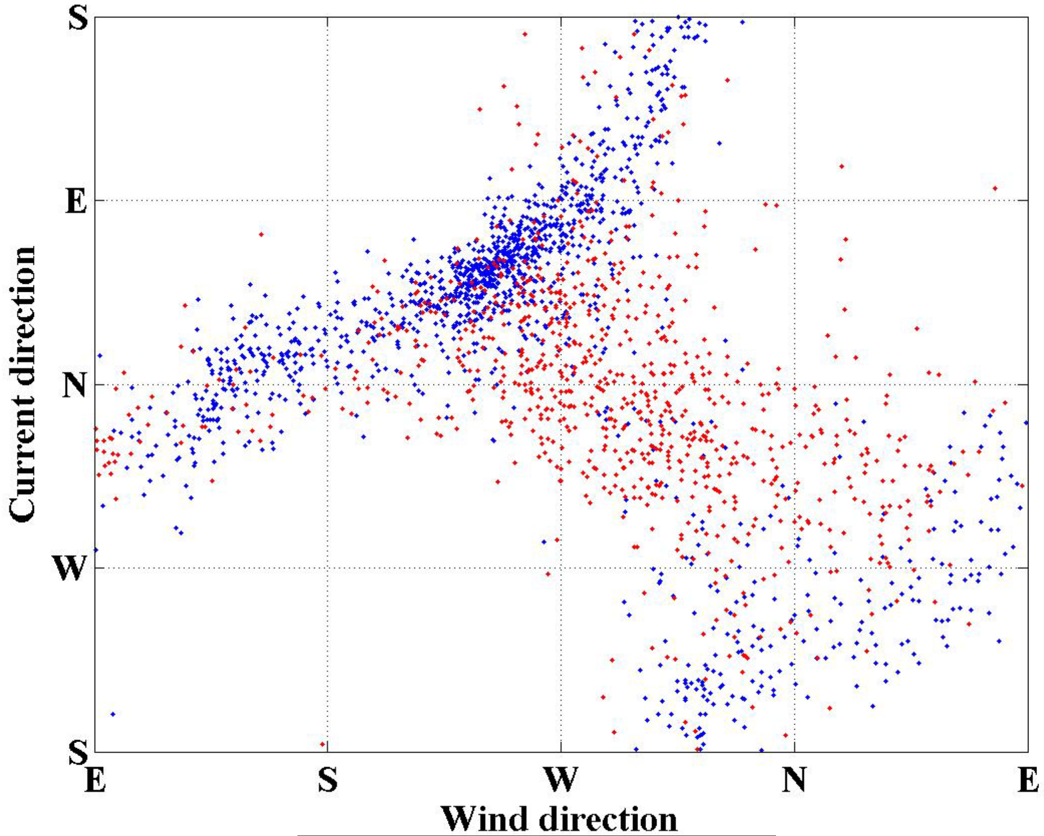


Figure 11B

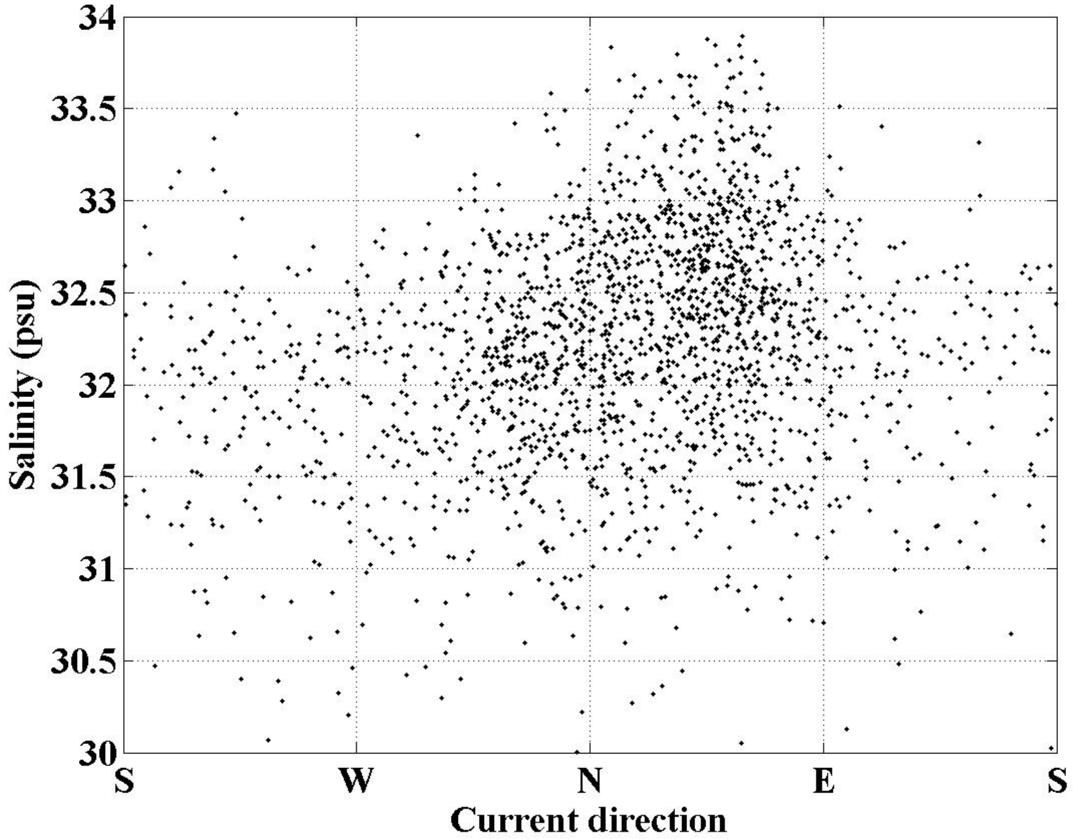


Figure 12

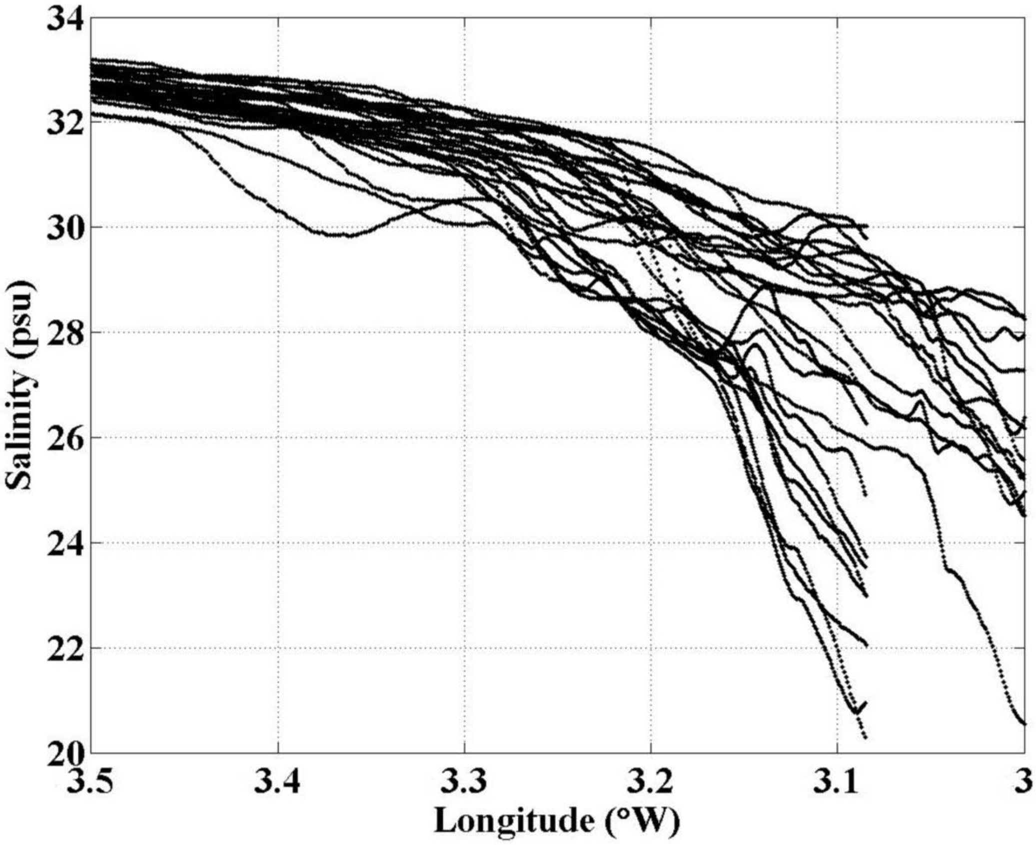


Figure 13A

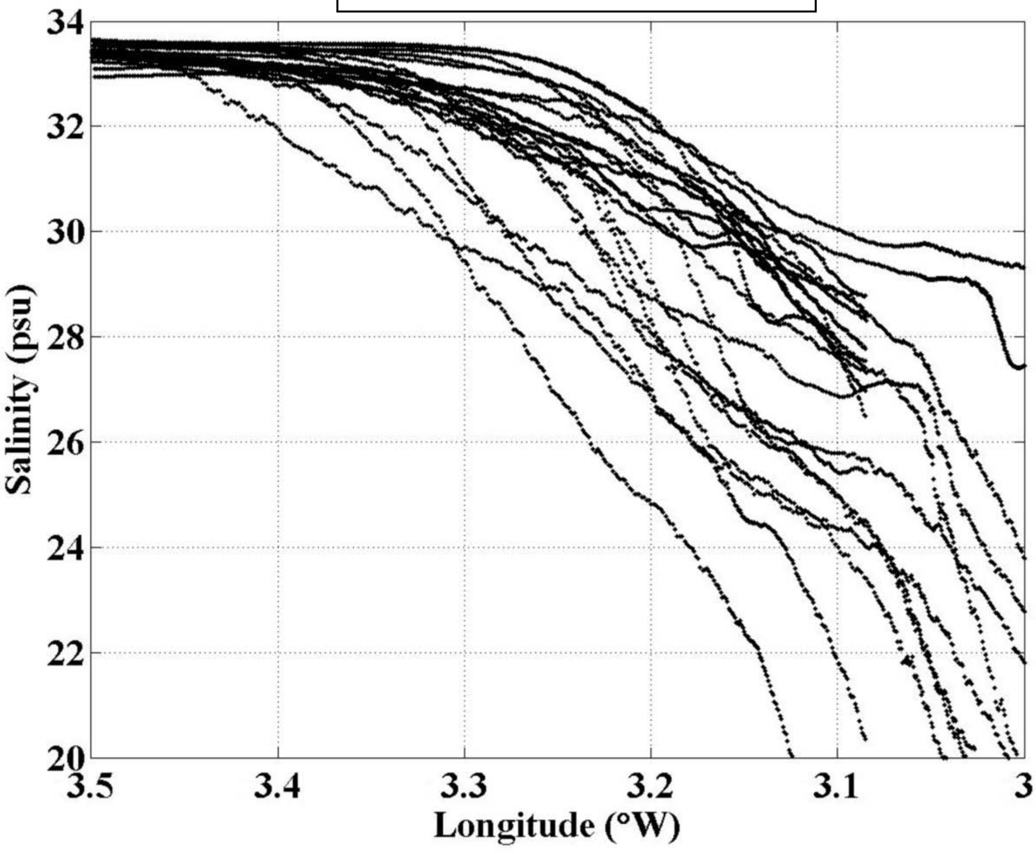


Figure 13B

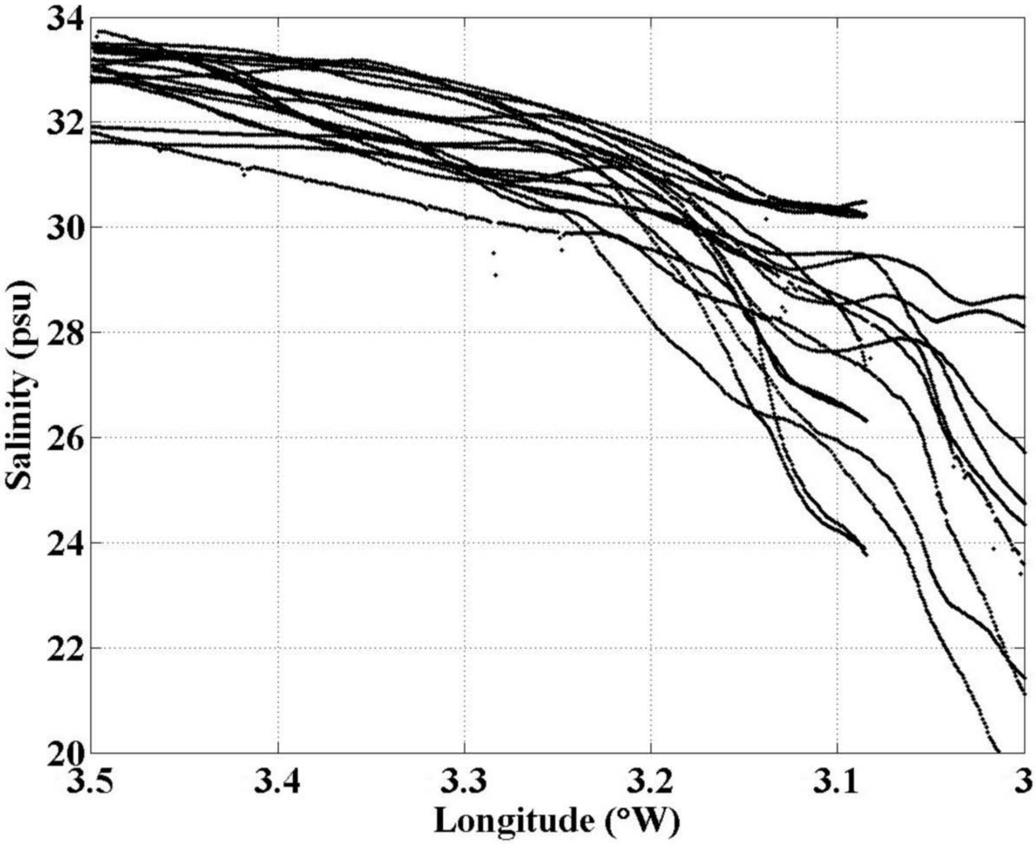


Figure 13c

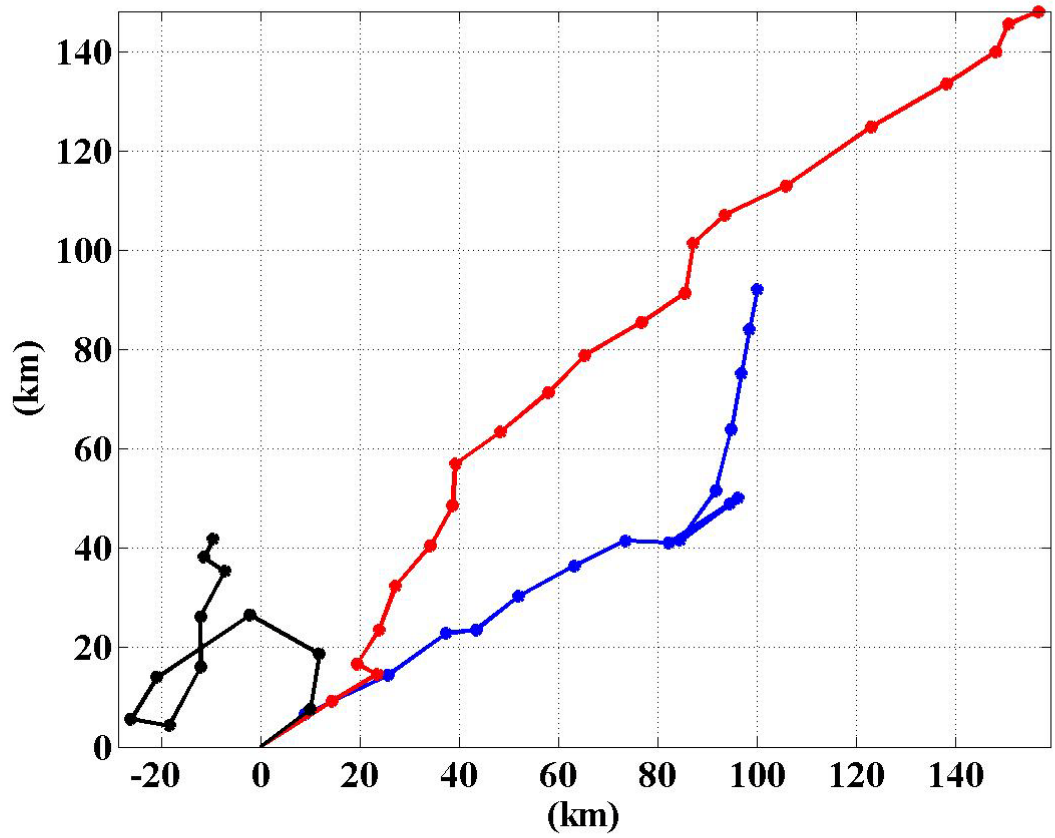


Figure 14A

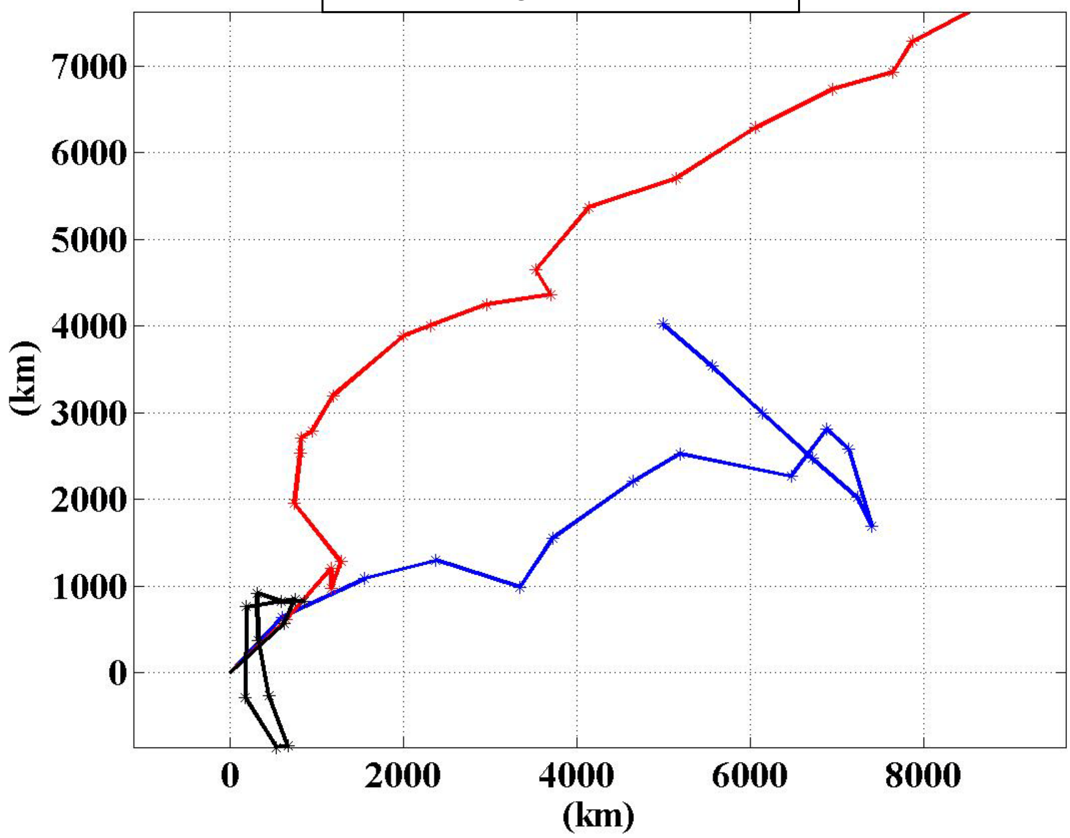


Figure 14B

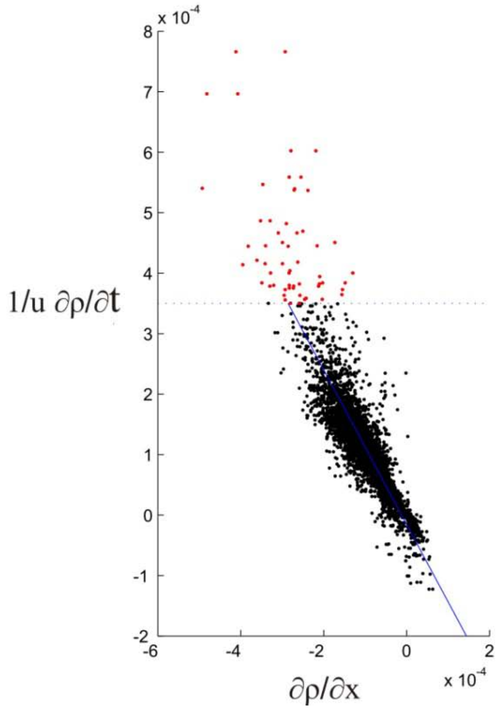


Figure 15