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

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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 3×10^{-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 5×10^{-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.

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1. Introduction

The physical processes controlling the fate fresh of water river discharges in coastal seas are well understood, if complex and inter-related (Garvine, 1995; Yankovsky and 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 idealised 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 and 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 and Chapman, 1997).
(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., submitted for publication).

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

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shown in Fig. 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 and 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 Fig. 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 and Royle, 1973; Foster and Hunt, 1977). Bowden and Sharaf El Din (1966a), Bowden and Gilligan (1971) and Prandle et al. (1990) showed that the salinity at the mouth of the Mersey is in the region 24–29 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 7–10 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 and Sharaf El Din (1966b), Ramster and Hill (1969), Halliwell (1973), Heaps and Jones (1977), Howarth (1984) and Czitrom (1986). In particular Heaps and 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 9-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, Fig. 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 and Jones (1977).

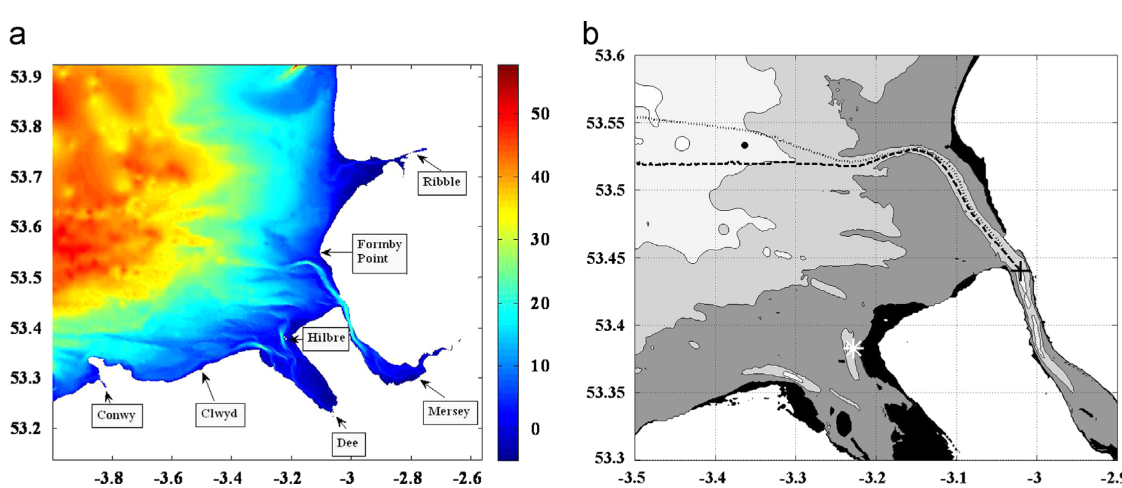

Fig. 1. Maps showing (a) Liverpool Bay and the positions of the major rivers; (b) the Mersey Bar site (dot), the ferry track and depth contours below mean sea level at 10 m intervals (black is above mean sea level). The dotted line indicates the average westbound ferry measurement track and the dashed 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.

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