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Stratification in the presence of an axial convergent front: Causes and implications

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ABSTRACT

Flood tide salinity stratification in the presence of an axial convergent front is revealed with new data. The data were collected during sampling campaigns in the Conwy estuary, North Wales, the location of a previous study for axial convergent fronts. The stratification, with a maximum observed vertical density difference of 5 kg m^{-3}, begins as soon as the saline intrusion arrives and lasts throughout the flood tide. The flood stratification is shown to be caused by a tidal straining-type process. The along-channel shear is modified by cross-channel currents developed during the formation of the convergent front such that surface currents are smaller than those at mid-depth. The modified shear interacts with the horizontal density gradient to form the stratification on the flood tide. Implications for the turbulence and sediment transport regime in the estuary are discussed.

1. Introduction

Estuaries are the gateway between river and marine systems. Dynamics taking place in an estuary determine how much pollution is delivered to the marine environment (Elsdon et al., 2009). Rivers transport enhanced nutrient loading, heavy metal concentrations, faecal bacteria and pathogenic organisms from anthropogenic activities including agriculture and sewage discharge (Malham et al., 2014). In particular, it is well known that human microbial pathogens preferentially attach to sediment and in estuarine systems, the chemical and physical properties of the sediments mean that heavy metals become easily incorporated (see Wang et al. (2014) and references therein). Physical and chemical processes within the estuarine system determine the sediment, and thus pollutant, deposition and storage in bed sediments and subsequent resuspension and flushing during extreme events causing potential detrimental impacts to high risk coastal zones. Of key interest to current policies in a time when food security is high on the agenda, is what happens to these pollutants and what proportion of them is likely to be delivered to local shellfish beds.

Estuaries play host to three principal categories of frontal system: plume and tidal intrusion fronts; longitudinal or shear fronts and axial convergent fronts (O'Donnell, 1993; Largier, 1993). Fronts tend to be associated with bathymetric features and transverse circulation, typically occurring on small spatial scales and tidal timescales. Axial convergent fronts were first identified by Nunes and Simpson (1985; henceforth NS85) in the Conwy estuary and have since been reported in many other estuaries (Brown et al., 1991). The front, identified by the presence of a foam line on the water surface, is the manifestation of surface convergence which itself is the product of a complex interplay between bathymetry, cross-channel shear of the along-channel current and the along-channel salinity gradient (Turrell et al., 1996). Effectively, the bathymetry of the channel creates a cross-channel gradient of the along-channel current such that the along-channel current is faster in the channel centre than the sides. This differential advection causes a small cross-channel density gradient to develop which, in turn, drives a two-celled cross-channel flow due to the balance between the pressure gradient and internal frictional stresses. Cross-channel variations in bed roughness may also drive cross-channel circulations (McLean, 1981). In the Conwy, where along-channel currents >1 m s^{-1} occur, cross-channel currents have been observed to reach 0.2 m s^{-1} (Turrell and Simpson, 1988; Brown et al., 1991). Cross-channel circulations have been shown to have an impact on sediment and larval transport processes in the estuary (Trevethan and Chansen, 2007; Neill, 2009; Robins et al., 2012); specifically, Neill (2009) showed how the axial convergent

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front acts to sort grain size fractions laterally across the channel. Coriolis forcing (Scully et al., 2009; Huijts et al., 2009) and channel curvature (Geyer, 1993) can also generate cross-channel circulation though these processes are not considered here for reasons discussed at later.

Though the water column in the presence of an axial convergence front was originally described as well-mixed (NS85), here we will present new data which show the formation of salinity stratification on the flood tide. We will propose how this vertical stratification is formed via a tidal straining type scenario. Furthermore, we will examine implications for the turbulence and sediment transport regime in the presence of such flood-dominant stratification.

2. Sampling campaign

A site in the Conwy estuary, previously used by authors such as NS85 and Simpson et al. (2001), was chosen. The site is located in a relatively straight section of the estuary channel (making variations due to curvature minimal) and has been the focus of previous observations regarding the axial convergent front (see Fig. 1; "main site"). The channel is <100 m wide at this point (such that Coriolis forcing is negligible) with a mean depth of 3.5 m. The site is subject to semi-diurnal tides with a spring tidal range of 5 m and along-channel currents which reach 1.3 m s^{-1} during the flood. The tide is asymmetric due to shallow water effects with a spring flood tide lasting 2.75 h and an ebb 9.75 h. Ebb tidal currents are 70–75 % of their flood counterparts.

An instrumented mooring frame was deployed in the centre of the channel at the site in September–October 2013, January 2014, March 2014 and July 2014. Amongst other instruments which are not used in the analysis here, the frame was instrumented with an RDI 1200 kHz ADCP. The ADCP recorded in burst mode 12 with a vertical resolution of 0.1 m generating an ensemble average every 5 min. The site was also manned using a small boat for up to a tidal cycle (12.5 h) on two consecutive days whilst the moored instruments were in place; the boat was only available in October 2013, March 2014 and July 2014 so further discussion will centre around these manual-sampling campaigns. The boat was moored in the centre of the channel to obtain CTD casts and surface water samples every 20–30 min. Subsequently, CTD profiles and suspended sediment concentration (SSC) are available at the site for 12.5 h each day on 5–6 October 2013 and for 7.7 h each day on 31 March to 1 April 2014 and 29–30 July 2014. In October, the profiles were obtained from late ebb to late ebb whilst in March and July profiles were obtained from low water to mid-ebb.

3. Observations of stratification in the presence of an axial convergent front

The conditions observed during each of the manual sampling campaigns are summarised in Table 1. On all occasions, there was little wind present during the sampling. The river flow discharge (obtained from Natural Resources Wales for Cwm Llanerch river gauge station) range during, and several days prior to, the manual sampling campaign is also listed. July 2014 was particularly dry with very low flow rates compared to the mean (18.5 m^3 s^{-1}); March 2014 also had fairly low flow rates while October 2013 experienced both below and above average flow rates. The axial convergent front was visible, due to the presence of thick foam and other detritus, on the flood tide on all occasions the site was manually sampled. In October, the foam line tended to coalesce closer to the north-western bank whilst in March and July it was present in the centre of the channel. Once the tide turned, the foam dispersed and collected at the sides of the channel where it was advected downstream.

The stratification observed during the two sampling days is also summarised in Table 1 and shown in Fig. 2 relative to water depth. Stratification is shown as ϕ, the potential energy anomaly, which is calculated as:

$$\phi = \frac{g}{h}\int_0^h (\overline{\rho} - \rho) z \mathrm{d}z, \quad (1)$$

where g is gravitational acceleration, h is the surface height above the bed, ρ is density (with the over-bar denoting a depth-averaged quantity) and z is height above the bed. ϕ is useful as it describes the amount of energy required to overturn a stratified water column. In all cases, stratification was present on the flooding tide with magnitude ranging from 8 to 20 J m^{-3} (equivalent to $\Delta\rho$ of 2–5 kg m^{-3}). In the October and March cases the stratification broke down slightly in the approach to high water before strengthening just after high water when velocities were near-zero; in July, however, the stratification did not increase again after its

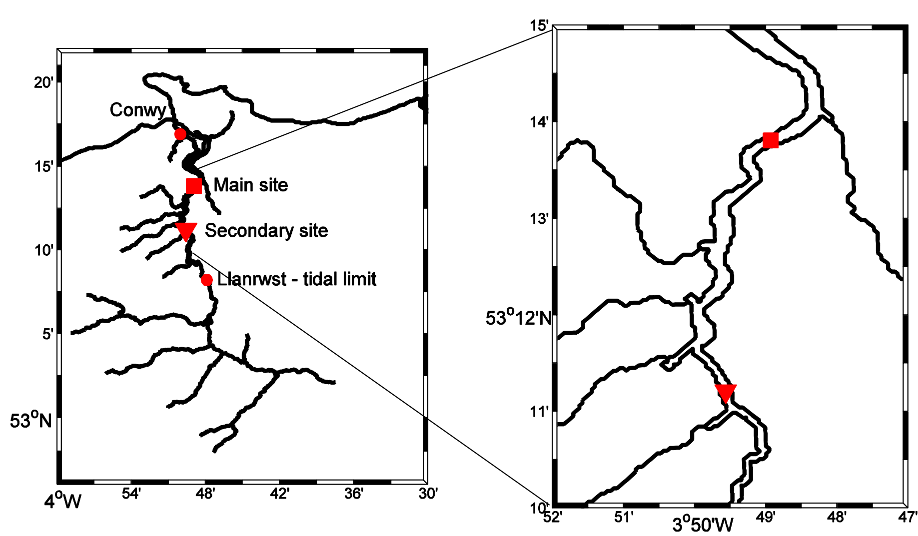

Fig. 1. Map of the Conwy catchment showing two mooring locations. The site represented by the square is the main site, for which most of the discussion herein will centre; a second site, highlighted by the triangle, is located further upstream. The tidal limit at Llanrwst is located 20 km from the estuary mouth at Conwy.