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Impact of operational model nesting approaches and inherent errors for coastal simulations

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ABSTRACT

A region of freshwater influence (ROFI) under hypertidal conditions is used to demonstrate inherent problems for nested operational modelling systems. Such problems can impact the accurate simulation of freshwater export within shelf seas, so must be considered in coastal ocean modelling studies. In Liverpool Bay (our UK study site), freshwater inflow from 3 large estuaries forms a coastal front that moves in response to tides and winds. The cyclic occurrence of stratification and remixing is important for the biogeochemical cycles, as nutrient and pollutant loaded freshwater is introduced into the coastal system. Validation methods, using coastal observations from fixed moorings and cruise transects, are used to assess the simulation of the ROFI, through improved spatial structure and temporal variability of the front, as guidance for best practise model setup. A structured modelling system using a 180 m grid nested within a 1.8 km grid demonstrates how compensation for error at the coarser resolution can have an adverse impact on the nested, high resolution application. Using 2008, a year of typical calm and stormy periods with variable river influence, the sensitivities of the ROFI dynamics to initial and boundary conditions are investigated. It is shown that accurate representation of the initial water column structure is important at the regional scale and that the boundary conditions are most important at the coastal scale. Although increased grid resolution captures the frontal structure, the accuracy in frontal position is determined by the offshore boundary conditions and therefore the accuracy of the coarser regional model.

1. Introduction

A region of freshwater influence (ROFI) occurs where a river plume enters a shallow sea and the resulting stratification becomes influenced by the action of vertical mixing due to tides and winds (Simpson et al., 1993). A ROFI is one example of where exchanges between land and sea occur. Being able to represent ROFI dynamics accurately across temporal and spatial scales is therefore important for coastal management in relation to the transfer and fate of particles and nutrients in coastal seas. It is in this region that tidal and seasonal cycles influence sediment transport (e.g., Brown et al., 2015), pulses in primary productivity (e.g., Panton et al., 2012), and the trajectories of pollutants (e.g., Periáñez, 2005). To improve the understanding of physical processes within ROFIs, large scale observational campaigns (e.g., in the Rhine, de Boer et al., 2009) and modelling studies (e.g., in the Rhône, Reffray et al., 2004) are often employed. In this study observations (Howarth and Palmer, 2011) are used in combination with coastal models (Brown et al., 2015; O'Neill et al., 2012) to identify the main controls influencing the accuracy of an operational shelf sea model when applied in high resolution to a large dynamic ROFI.

The Liverpool Bay ROFI, which is used as our case study, is situated in the northwest UK (Fig. 1). The large tidal range (in excess of 10 m on spring tides) generates fast tidal currents (>1 m/s) that interact with the freshwater inflow complicating the dynamics of the region (Simpson et al., 1990). Stratification is promoted through surface heating and buoyancy input from river discharge and rainfall, while mixing is induced by tidal and wind stirring (Simpson and Bowers, 1981). The time-variation in the vertical stratification and remixing is important as it modifies the residual circulation that would occur under the barotropic conditions alone (Polton et al., 2013). The resulting residual circulation is a consequence of nonlinear tidal advection, lateral gradients in both density and sea surface elevation, frictional forces, the Coriolis effect and mixing

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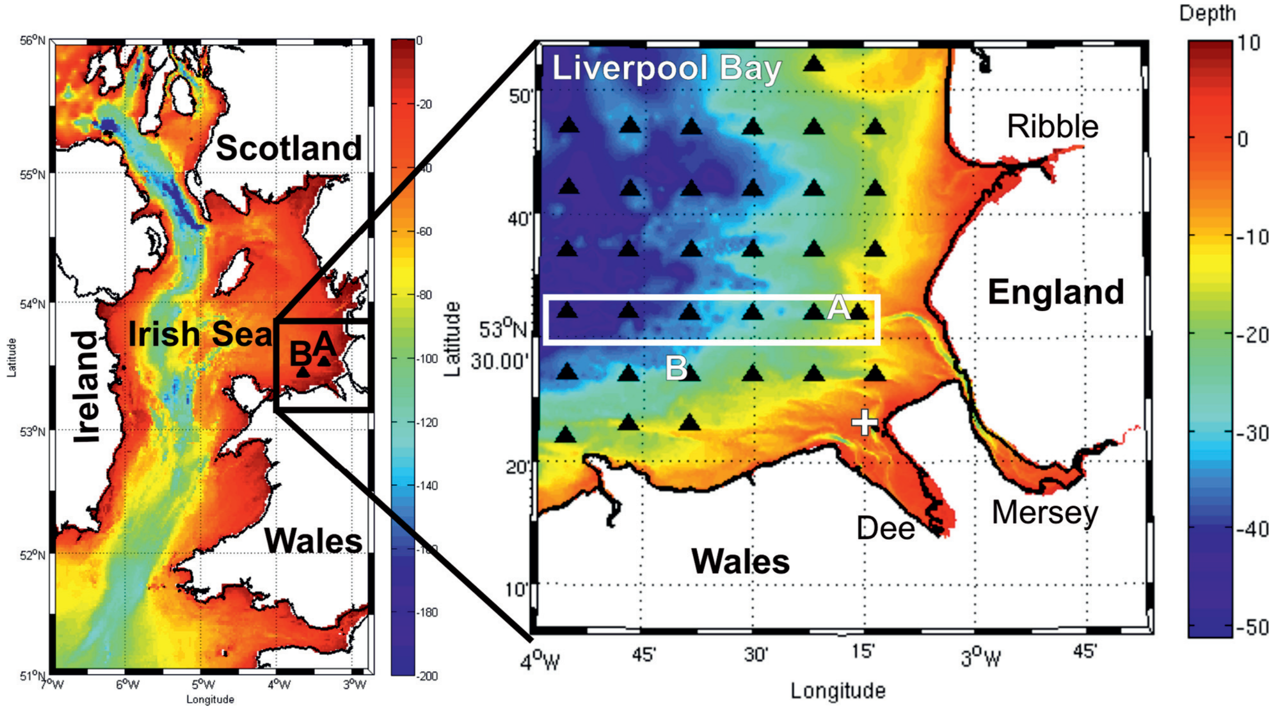

Fig. 1. The bathymetry (m below mean tidal level) for the nested Irish Sea (IRS) and Liverpool Bay (LB) model domains. The outer edge marks the model boundaries with the fixed mooring sites (A and B), CTD survey grid marked by triangular symbols and Dee met station marked by a cross.

processes (Fischer, 1976; MacCready and Geyer, 2010). Simulating these dynamics is not only important for water quality management, as in Liverpool Bay, but also, for example, where offshore industries are interested in the real-time ocean state (e.g., fishermen in Funka Bay, Japan (Nakada et al., 2012)).

Within Liverpool Bay the tidal ellipses are predominantly aligned east-west, with 50% of the amplitude accounted for by two dominant tidal components, the M2 and S2 constituents (Polton et al., 2011). The coastal front that forms within the bay moves between 5 and 10 km in response to semi-diurnal tidal straining and up to 35 km due to the spring-neap cycle. The fortnightly cycle in the frontal excursion of this particular front is much greater than other fronts across the northwest European Shelf (Hopkins and Polton, 2012). Stratification and remixing occurs over a large region ($\sim$ 30 km offshore $\times$ 20 km alongshore, Hopkins and Polton, 2012) making it important for the biogeochemical cycles and sediment transport, as it carries contaminants, nutrients and suspended particulate matter (Greenwood et al., 2011; Souza et al., 2013; Panton et al., 2011; Yamashita, et al., 2010). This site is therefore ideal to test model capability at simulating large scale spatial and temporal variability in frontal dynamics.

Tidal flow asymmetry, due to the shoaling depths causing the flood flow to be on average a factor of 1.2 faster than the ebb flow, leads to asymmetric tidal mixing (Polton et al., 2011) in addition to the typical strain induced periodic stratification (SIPS) (Simpson et al., 1990). During the ebb tide, the vertical shear in the current profile advects the surface freshwater layer further offshore from the coast. Low water stratification creates a baroclinic circulation with a northerly surface flow of $\sim$ 4.0 cm/s and southerly near bed flow of $\sim$ 2.4 cm/s. On the flood tide stratification is broken down creating a well-mixed water column at high water (Palmer and Polton, 2011). This baroclinic flow, although weak in comparison to the tides, is approximately 4 times faster than the maximum (coastal) residual tidal current, making it a major contributor to the residual sediment transport pathways within this system (Brown et al., 2015).

Over an annual cycle Liverpool Bay shows no seasonal cycle in estuarine and river influence, receiving a mean freshwater discharge of 233 m^3/s (Polton et al., 2011). Peak flows can however, be an order of magnitude larger (Palmer and Polton, 2011). Although the freshwater buoyancy input continually exceeds that of the seasonal solar heating (Palmer and Polton, 2011), there is evidence for seasonality in the occurrence of enduring stratification, with a greater likelihood in the summer months (Polton et al., 2011). There is also a seasonal cycle in storminess with higher waves between October to March (Wolf et al., 2011). The winds associated with storms are typically from southwest to northwest (Wolf et al., 2011), straining the front towards the English coast while locally generated waves act to increase mixing.

Due to the coastal geography of Liverpool Bay, the large freshwater plume naturally moves north along the English coastline (Howarth et al., 2014) due to the Coriolis effect in the Northern Hemisphere (Garvine, 1987). Wind influence acting on the ROFI can strain the vertical density gradient (Scully et al., 2005), either enhancing (offshore winds) or reducing or even reversing stratification (onshore winds). In addition, under stratified conditions, upwelling winds typically spread the plume offshore, while downwelling winds compress the plume towards the coast (Whitney and Garvine, 2005). In Liverpool Bay winds that allow the plume to spread into the bay are associated with a northerly direction and occur for only 14% of the year (Howarth et al., 2014). A wind with a southerly component restricts the movement of the front offshore, while a wind directly from the east promotes the northerly along-coast transport.

Previous modelling studies (at 1.8 km, Polton et al., 2011; Palmer and Polton, 2011) have investigated the long-term time-average of the spatially varying horizontal density gradient. Here we extend this research with a higher horizontal resolution model to identify problems using a nested model setup for large dynamic ROFIs. A high ($\sim$ 180 m) resolution model, designed to be part of a preoperational system combining real-time observation and model forecasts (Howarth et al., 2010), is applied to assess its capability