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Impacts of high resolution model downscaling in coastal regions

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A B S T R A C T

The issue of appropriate resolution of coastal models is addressed in this paper. The quality of coastal predictions from three different spatial resolutions of a coastal ocean model is assessed in the context of simulation of the freshwater front in Liverpool Bay. Model performance is examined during the study period February 2008 using a 3-D baroclinic hydrodynamic model. Some characteristic lengthscales and non-dimensional numbers are introduced to describe the coastal plume and freshwater front. Metrics based on these lengthscales and the governing physical processes are used to assess model performance and these metrics have been calculated for the suite of downscaled models and compared with observations.

Increased model resolution was found to better capture the position and strength of the freshwater front. However, instabilities along the front such as the tidal excursion led to large temporal and spatial variability in its position in the highest resolution model. By examining the spatial structure of the baroclinic Rossby radius in each model we identify which lengthscales are being resolved at different resolutions. In this dynamic environment it is more valuable to represent the governing time and space scales, rather than relying on strict point by point tests when evaluating model skill.

1. Introduction

Increasing spatial and temporal resolution appears to be an obvious route for getting more accurate forecasts in operational coastal models. Also physical processes such as coastal baroclinic Rossby waves may need increased resolution (Garvine, 1995; Chant, 2011). However there are penalties for increasing resolution, for example the cost of running a higher resolution model may increase by several orders of magnitude, because if the resolution in 1-D is doubled the resolution in 2-D is 2^2, plus usually there will be a related reduction in time step which may lead to an order of magnitude increase in the model run time for the same period of real time. Another problem is the introduction of high-frequency variability which is not necessarily deterministic. Thus a flow may appear more realistic by generating eddies but the simple statistics like root-mean-square (rms) error and correlation may deteriorate because the model variability is not exactly in phase with the observations (Hoffman et al., 1995).

Traditional error metrics, such as least squares methods, are not necessarily the best choice to illustrate model accuracy, e.g. small errors in the location of a front are translated to large differences in least squares of intensities (Ziegeler et al., 2012). Spatial error metrics have been developed in a number of studies (Gilleland et al., 2009, 2010; Marzban et al., 2009), many of which are in the atmospheric modelling discipline. By examining model output in terms of the length and timescales of the dominant physical process, rather than naive statistical measures, we will address the question "Do coastal predictions improve with higher resolution modelling?".

In collaboration with the UK Met Office, the National Oceanography Centre runs a suite of nested models (http://cobs.noc.ac.uk/modl/). These Irish Sea Observatory (ISO) models provide predictions 36 h into the future, generating ocean forecasts of currents, waves, temperature and salinity on a variety of scales, ranging from 12 km to 1.8 km. The forecast area covers the Northwest European Shelf, with a focus on the Irish Sea, and information from the Met Office's FOAM model (a product of MyOcean http://www.myocean.eu/) is used as an open boundary forcing for the the outermost model in the system.

We have used the ISO nested modelling suite, together with a further model nest covering Liverpool Bay at 180 m resolution, to investigate the impact of dynamical downscaling. The MyOcean product is thus downscaled through the nested models, with the aim of adding value to the coastal forecasts generated by this coarser product. Boundary information from the MyOcean model will impact upon each level of model nest, and ultimately affect the results in the 180 m model. At local scales and in limited coastal domains such as Liverpool Bay, boundary conditions become particularly important since the simulated field may well be controlled by boundary information. The zone of boundary

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influence is dynamic and process-dependent and has received relatively limited research attention in oceanography (with some exceptions such as e.g. Sanchez-Arcilla and Simpson, 2002). Liverpool Bay is a region of freshwater influence (ROFI) and will be controlled by the land-ocean boundary forcing, as well as the open-boundary ocean forcing. Thus we choose to assess the position and strength of the freshwater plume and front between mixed and stratified water as our metrics.

In Section 2 we present the physical situation in the study area, and in Section 3 we discuss the dominant length and time scales which need to be resolved. In Section 4 the modelling tools are described together with the error metrics used to assess model accuracy. The results of model downscaling are presented in Sections 5 and 6 and discussed in Section 7 and some final conclusions are drawn in Section 8.

2. Case study for Liverpool Bay

Our study area covers a corner of the eastern Irish Sea extending from roughly 2.5°W–4.5°W and 53°N–54°N. Under the classification of Simpson (1997), Liverpool Bay is a corner source ROFI (region of freshwater influence) with strong horizontal density gradients. The bay is also strongly tidally dominated, with a high tidal range (mean spring tidal range 8.22 m) and extensive intertidal areas (Polton et al., 2011; Howarth and Palmer, 2011). Freshwater enters Liverpool Bay from several rivers, including the Mersey, Dee, Ribble, Conwy and Clwyd, which collectively maintain a strong salinity gradient. As part of their review paper, Simpson and James (1986) identify the eastern Irish Sea as a region where river inflow dominates the stratification.

In the nearshore river discharge creates a plume of freshwater, which flows out over saltier water while remaining close to the coast. The front is defined as the point at which stratified coastal plume meets the tidally well-mixed shelf waters. In the nearshore there is strong vertical stratification and the front will be salinity controlled. The strength and extent of the stratification are governed by the stratifying influence of freshwater discharge injecting buoyancy into the system, and the de-stratifying effect of tidal and wind mixing. When the water column is well mixed, the sea surface temperature (SST) will match the bottom temperature. During periods of high discharge, or at slack water when tidal mixing is low, freshwater at the surface can spread further in the horizontal and the front may become detached from the bottom. The SST can be a tracer for the salinity stratification, which is useful as this can be detected in satellite images. Proper resolution of a front requires identifying the straining leading to filaments, as well as capturing the strong density gradients forming the front. Conversely the models must also contain accurate representation of turbulent mixing which break down these gradients.

Previous modelling studies of the Liverpool Bay ROFI have found the salinity particularly difficult to represent. O'Neill et al. (2012) evaluate the performance of POLCOMS models at 12 km and 1.8 km resolution in Liverpool Bay. When compared against observed temperature and salinity from CTD profiles and ferrybox data, POLCOMS was found to over-estimate the salinity range. They also found that, at these resolutions, POLCOMS displayed high errors in the region of the Mersey plume. In our study the freshwater plume front has been modelled at a range of resolutions. Fig. 1 shows snapshots of the modelled salinity from 17th February 2008. The horizontal extent of the plume, and the width and position of the freshwater front are affected by model resolution.

3. Lengthscales and timescales

The behaviour of freshwater plumes and fronts has been reviewed by Simpson and James (1986), and Garvine (1995) classifies the behaviour of buoyant plumes based on principal lengthscales. Two dominant lengthscales must be considered when we examine the freshwater plume. The first lengthscale to consider is the first baroclinic Rossby radius. This is the natural scale of baroclinic motion in the ocean, often associated with boundary currents, eddies and fronts (Gill, 1982). The Rossby radius (R_n) is the scale at which rotational effects become as important as buoyancy effects, defined as

$$R_n = \frac{c_n}{|f|}, \quad \text{where } n = 0, 1, 2, \dots \tag{1}$$

The first mode, $n=0$, is only applicable for a barotropic ocean, but the next modes are baroclinic ones. The first baroclinic mode, $n=1$, is the most important one as regards mesoscale motions. Here we will use only the first baroclinic Rossby radius (i.e. for $n=1$) where

$$c_1 = \frac{1}{\pi}\int_{-H}^{0} N(z)\, dz, \tag{2}$$

which will be calculated as $L_R = NH/f$ where f is the Coriolis parameter, H the water depth, and N the Brunt–Väisälä frequency, defined as

$$N = \sqrt{\frac{-g}{\rho_0}\frac{\delta\rho}{\delta z}} \tag{3}$$

The second important lengthscale is the extent of the freshwater plume in the horizontal. L is defined as the extent of the freshwater plume along the coast. Garvine (1995) define the extent of plume away from the coast as γL, where $1/\gamma$ represents the 'slenderness' of the plume. This plume width, γL, is measured from both models and observations and listed in Table 3. These two lengthscales can be combined through the Kelvin number, defined as a ratio of γL and L_R:

$$K = \frac{\gamma L}{L_R} \tag{4}$$

Garvine (1995) separates plumes into non-notating (of small or zero Kelvin number) and rotationally controlled (Kelvin number of order 1). Bolanos et al. (2013) use these, and other non-dimensional numbers to characterise properties within the tidal channels of the Dee estuary. However, in these channels the lengthscale will be constrained by the channel geometry, while the freshwater plume will be free to extend more widely before coming under rotational control.

Though the freshwater front itself is a persistent feature, its mean position displays considerable spatial and temporal variability. This variability includes a regular tidal excursion studied by Hopkins and Polton (2012) in which the front can move as much as 10 km over a flood–ebb cycle. The freshwater entering Liverpool Bay also has an 'age' defined as a time-scale for freshwater entering from rivers to be flushed out of the system. The bay has a flushing time of approximately 136 days and mean residence time of approximately 103 days (Phelps et al., 2013). Water exchange in the region is impacted seasonally by both thermal stratification and wind action, for example Dabrowski et al. (2010) found considerable seasonal variability in the residence time of the Irish Sea, which was found to range from 386 days in the summer to 444 days in the winter.

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