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Wave–current interactions in a tide dominated estuary

R. Bolaños [a,*], J.M. Brown [b,1], A.J. Souza [b,2]

[a] *National Oceanography Centre, Denmark*
[b] *National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool, L3 5DA, UK*

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ABSTRACT

There is a need to understand the interactions of waves and currents in the nearshore and estuarine areas. By using observational data and an advanced model an assessment of the wave–current interactions was performed in a hypertidal estuary. The circulation model includes both barotropic and baroclinic processes arising from tides, rivers and atmospheric forcing. It is coupled to a spectral wave model and a turbulence model. Waves within the estuary are strongly modulated by the tide. Significant wave height and period are mainly controlled by time-varying water depth, but wave periods are also affected by a Doppler shift produced by the current. The major-axis depth-averaged current component is tidally dominated and wave-induced processes do not have a significant effect on it. However, the inclusion of wave effects, in particular 3D radiation stress, improves the depth-averaged minor-axis (transverse) current component. The residual currents show a clear two-layer system, indicating that the baroclinic river influence is the dominant process. The wave effects are second order, but their consideration improves the long-term modelled residual circulation profile, specially the along estuary component. The main improvement appears when a 3-dimensional radiation stress coupling is considered. The 3D version of radiation stress produced better results than the 2D version. Within the estuary, wave setup has little effect on the storm surge, while 2-way wave–current interaction improved the wave simulation. Using a 3D Doppler shift further improved the model compared with using a 2D version.

1. Introduction

Coastal waves and currents are highly variable and can have a significant impact on human activities and structures (Wolf et al., 2011). There is also a need to understand the interactions of waves and currents in the near-shore zone as nonlinear effects become more important. Waves can contribute to the circulation, which then modifies the waves creating a wave–current feedback mechanism. The impact of currents, waves and surges at the coast is closely linked (Brown et al., 2011; Jones and Davies, 1998) and thus the prediction of wind–waves and ocean currents is of great importance for the management (including navigation) of coastal areas.

There have been a number of research studies dealing with such interactions, e.g. wind–waves (Chen et al., 2013; Donelan et al., 2012; Fan et al., 2012; Janssen, 1989; Makin and Kudryavtsev, 1999, 2002) where the effects of waves on the wind boundary layer are studied. For a comprehensive review the reader is referred to a special issue in Journal of Geophysical Research (see Babanin et al., 2012). Wave–current interactions have also been the subject of several theoretical and practical studies (Ardhuin et al., 2008b; Jorda et al., 2007; Kumar et al., 2012; Mellor, 2003, 2005; Michaud et al., 2012). Andrews and McIntyre (1978a) have derived an exact theory for the interaction of waves with a Lagrangian mean flow including the wave momentum into the mean flow evolution. Mellor (2003, 2005, 2008) derived, in an Eulerian framework, a set of equations to be used in ocean models based on the linear wave theory, assuming a flat bottom. Sheng and Liu (2011) show Mellor's (later 2008) method is more accurate, than alternative 3D methods, at hindcasting wave-induced circulation. Mellor's formulations have been the subject of debate regarding some inconsistencies in the derivations (Ardhuin et al., 2008a; Bennis et al., 2011) and at the same time other approaches have been developed. Ardhuin et al. (2008b), following Andrews and McIntyre (1978a, 1978b), derived explicit wave-averaged primitive equations limited to second-order wave theory. McWilliams et al. (2004) derive a set of equations for use in finite water depth, which led to a Vortex force representation evaluated by e.g. Lane et al. (2007) and implemented in the ROMS-SWAN model (Kumar et al., 2012; Uchiyama et al., 2010). The main effects of waves on the mean flow commonly considered are due to radiation stress and Stokes drift, although interaction with turbulence and bottom stress can also be important (Babanin et al.,

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* Corresponding author. Present address: DHI, Agern Alle 5, Hørsholm 2970, Denmark. Tel.: +45 45169580; fax: +45 45169292.
E-mail addresses: rbol@dhigroup.com (R. Bolaños), jebro@noc.ac.uk (J.M. Brown), ajso@noc.ac.uk (A.J. Souza).
[1] Tel.: +44 151 795 4971; fax: +44 151 795 4801.
[2] Tel.: +44 151 795 4820; fax: +44 151 795 4801.

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2009; Rascle and Ardhuin, 2009; Rascle et al., 2006). Several numerical, experimental and observational investigations have been carried out to understand wave processes in upper ocean dynamics. Ardhuin et al. (2009) used radar measurements to estimate Stokes drift showing that typically it is between 0.6% and 1.3% of the wind speed (the direct wind induced current is about 1–1.8% the wind speed). Weber et al. (2006) showed that the Eulerian and Lagrangian approaches for the fluid motion produce the same mean wave induced flux in the surface layer: for their simulations the wave-induced stress constituted about 50% of the total atmospheric stress for moderate to strong winds. Coupled 2D current–wave models have shown the importance of considering wave effects when modelling water levels due to a hurricane in the Gulf of Mexico and a storm in the Adriatic Sea (Roland et al., 2009), and for storm surges in the Irish Sea (Brown et al., 2011; Brown and Wolf, 2009). Osuna and Wolf (2005) and Wolf et al. (2002) studied the effects of waves on the hydrodynamics of the Irish Sea; further work by Brown et al. (2013) studied the effects of 2D radiation stress formulation on a 3D hydrodynamic model showing the benefit of including these processes without compromising computational time. Tang et al. (2007) implemented wave–current interaction in a 3D ocean model (POM) and a spectral wave model (WAVEWATCH III) following Jenkins (1987) and evaluated the model by comparison with surface drifters. They showed that Stokes drift is a dominant effect for surface drift speed with a contribution of about 35%. They also showed a reduction of momentum transfer from wind to currents if waves are taken into account. Wave–current interaction

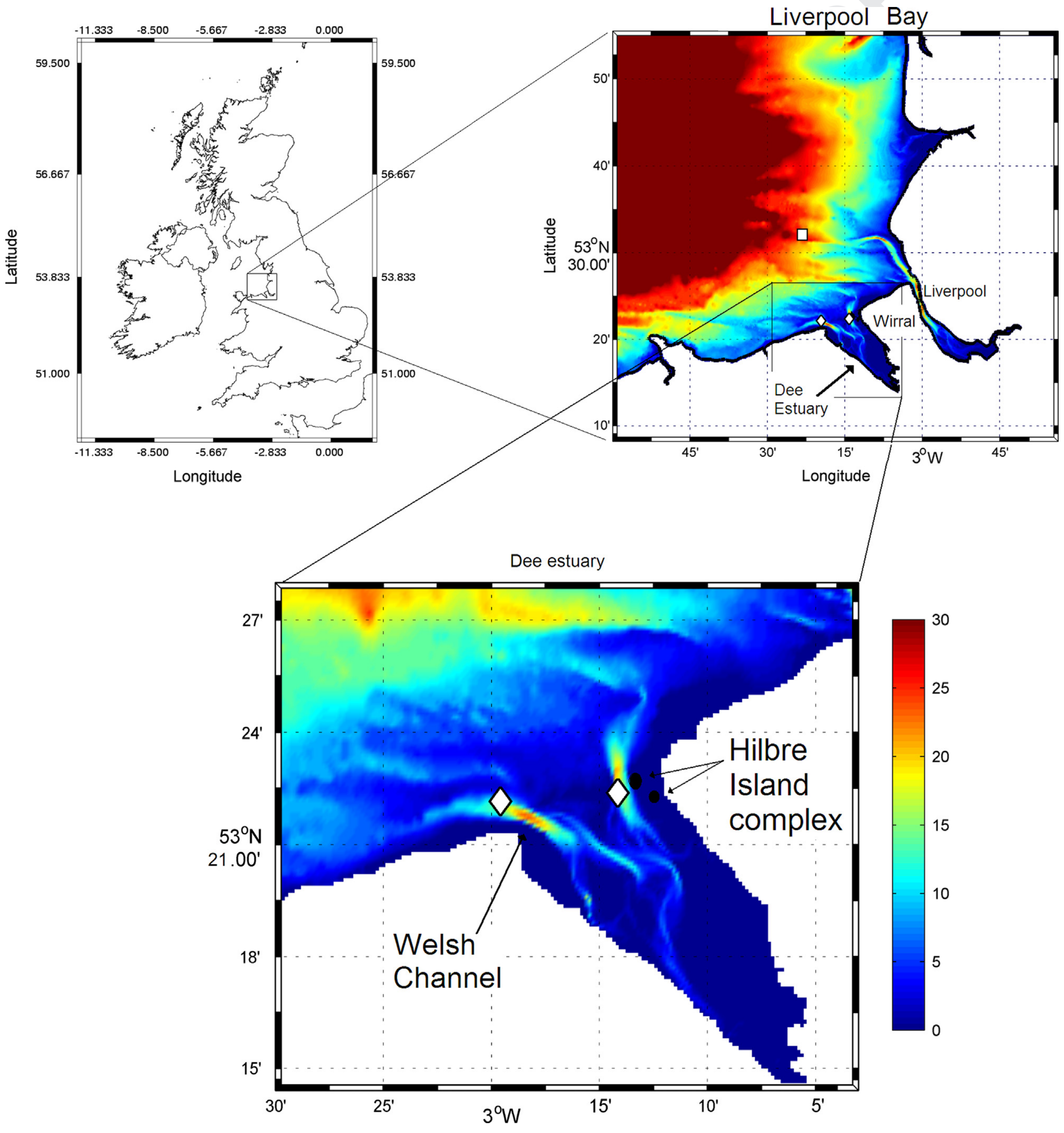

Fig. 1. Location of the Dee estuary in Liverpool Bay showing the model domain bathymetry and the location of the measured data. The white diamonds show the mooring locations in the Welsh channel (west) and Hilbre channel (east). The white square shows the WaveNet buoy position.

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