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Impact assessment of advanced coupling features in a tide–surge–wave model, POLCOMS-WAM, in a shallow water application

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ABSTRACT

Tide–surge–wave interaction is important in determining the nearshore 3D-current profile and the total water elevation. Liverpool Bay, northwest England, is used to assess the impact of coupling the 3rd generation spectral WAve Model (WAM), modified for shallow water, to the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS), a tide–surge model, through 2-way interactions. Data are readily available from the Irish Sea Observatory to quantify the importance of each coupled term with the aim of producing the most accurate model setup for coastal forecasting. A storm event, 18th January 2007, has been hindcast to investigate extreme tide–surge–wave condition both offshore and inshore.

The coupled terms investigated include standard processes already included (bottom friction, surface stress and the Doppler shift of the waves by the depth-averaged current), as well as advanced coupling procedures: use of the 3D current in the wave physics and calculation of radiation stress and Stokes' drift. During storm conditions it is found that the radiation stress is the most important term in this shallow water application as wave-setup increases coastal flood risk. However, WAM runs in near real time, making this model only practical for research purposes. Further work is therefore required to simplify this model setup.

1. Introduction

In coastal waters nonlinear tide–surge–wave interaction is important in determining the 3D current circulation, wave field and the wave-setup contributions to the surge elevation. Policy makers require the most accurate modelling techniques upon which to base research-informed coastal management decisions (Esteves et al., 2009). Liverpool Bay, in NW England, has various management issues related to its estuaries and coastline. In this macrotidal location the mean spring tidal range is 8.22 m at Liverpool (Pye and Blott, 2008). Surges can exceed 2 m and waves can exceed 5 m offshore (Brown et al., 2010b). Wave-setup has been calculated to further increase the water level by up to 0.5–1.5 m in Liverpool Bay (Brown, 2010). The time of the maximum surge and setup levels are dependent on the tide–surge–wave interaction, so may not coincide with tidal high water. However, the elevated high water level provides the potential for coastal flooding by defence overtopping and breaching. Such extreme conditions also lead to significant sand dune erosion along the Sefton coast (Pye and Neal, 1994). Dune failure can expose additional areas to coastal flooding during a storm and possibly further tidal flooding once the storm has passed.

This region of gradually shoaling depths is used to investigate the impact of different modelling procedures within a coupled model framework both nearshore and offshore. The extreme conditions during a storm event are used for model assessment as such conditions are presently of interest to the Sefton Borough Council for coastal flood and dune erosion management issues (Esteves et al., 2009). Under storm conditions the water column is likely to be well mixed and thus the importance of baroclinic effects negligible. However the baroclinic influence is important for the long-term sediment transport pathways, which affect morphological change, and the net residual flows in Liverpool Bay. The findings from this research will therefore be used to setup a state-of-the-art wave-barotropic–baroclinic model with full atmospheric forcing for Liverpool Bay (Fig. 1) and identify the most relevant and efficient processes to take into account in operational modelling.

A tide–surge–wave model has previously been setup for the Irish Sea (Brown and Wolf, 2009). This modelling system has been applied to Liverpool Bay with additional features to improve the wave and surge predictions. These features include a wetting and drying scheme (Lane, 2008), improved wave prediction in shallow water by use of a relaxed wave-growth limiter (Brown, 2010), Stokes' drift, radiation stress and hence wave induced currents and wave-setup, and the Doppler velocity effect on the wave spectrum due to a 3D current field being implemented in the wave model (Bolaños et al., 2008, 2011). Previously, improved surge simulations have been found when accounting for wave-setup (e.g. Mastenbroek et al., 1993), a wave-dependent surface roughness (Moon et al., 2009) and a wave–current bottom roughness (Jones and Davies, 1998). The importance of these terms is explored in the shallow macrotidal regime of Liverpool Bay

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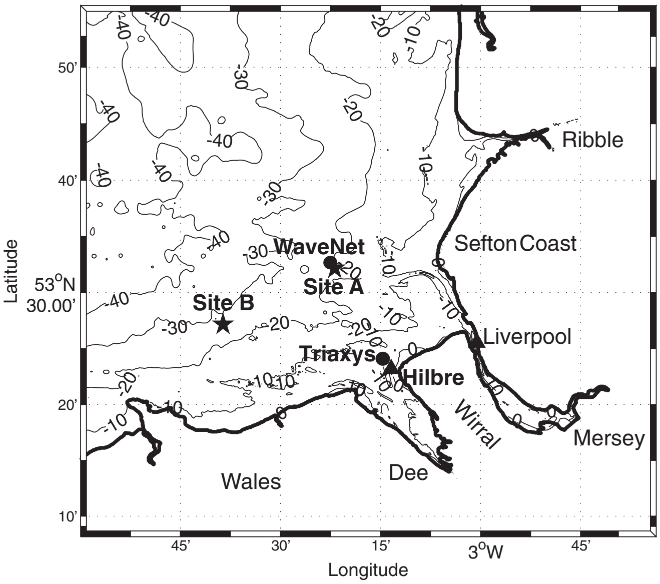

Fig. 1. Liverpool Bay location map, the depth is given below mean tidal level (MTL). Wave buoys are marked by circles, ADCP sites are marked with stars and the tide gauges with triangles.

and the added computational cost is also assessed. It is necessary to determine which features would be beneficial to an operational forecasting system and which features should be used for the sole purpose of research work due to high computational cost. The aim is to evaluate the predictive capability of the advanced-coupled Proudman Oceanographic Laboratory Coastal Ocean Modelling System and WAve Model (POLCOMS-WAM), which is a state-of-the-art shallow water tide–surge–wave coupled model. Results from this modelling system are used to describe the coastal circulation and waves in Liverpool Bay during an extreme storm event. An assessment of the implementation of the wave–current interaction is used to identify important coupling procedures required in coastal surge–wave forecasting within this region. Model run times are also assessed to determine if such a model could be used for operational forecasts. Finally the time occurrences of the peaks in storm parameters are compared with the wind forcing and the tidal levels to determine the strength of the interaction between the tide, surge, wave-setup and waves.

1.1. Data and environmental conditions

The Irish Sea Observatory (ISO, Howarth et al., 2006; http://cobs.pol.ac.uk) has been in operation since August 2002 and thus provides readily available near real-time data across the study area for model validation.

For validation purposes observations are obtained from: the coastal tide gauge at Hilbre and Liverpool, collected by the UK Tidal Network (https://www.bodc.ac.uk/data/online_delivery/ntslf/), current profiles, collected by ISO at offshore stations (A and B) in Liverpool Bay, and wave observations, obtained from the offshore Cefas WaveNet buoy (http://www.cefas.co.uk/data/wavenet.aspx) and the ISO nearshore Triaxys buoy (http://cobs.pol.ac.uk/cobs/fixed/#WaveBuoy), all located in Fig. 1.

Liverpool Bay is a macrotidal environment with a mean tidal range between 4.28 m (neaps) and 8.22 m (spring) depending on the phase of the tide (given by the National Tidal and Sea Level Facility, http://www.pol.ac.uk/ntslf/). The typical tidal velocities can reach up to 1 m/s during spring tide and are predominantly oriented east–west, the depth-averaged tidal ellipses being almost rectilinear (Palmer, 2010). Here, results are shown for the nearshore where depths are generally less than 30 m. The most extreme waves can reach 5.6 m offshore at the WaveNet location and the most extreme surges reach 2.4 m at the coast (Brown et al., 2010a). The worst wave–surge storm conditions result when Atlantic depressions (<1000 mb) track towards the northeast of Liverpool generating strong (>17 m/s) south-westerly winds, which veer west, over the Irish Sea (Brown et al., 2010b). The study period covers an extreme storm event, 18th January 2007, with offshore winds reaching ~22 m/s during a 6.7 m tidal range. The observed waves reached 5.22 m offshore while the observed surge due to meteorological forcing and wave-setup ranged from 1.94 m to 2.23 m along the coast, increasing with distance east and north. For hindcast maps of the wave and surge conditions for this event see Brown (2010). During this storm the east–west current velocity reaches typical values of 1 m/s, while the north–south component increases from a typical maximum value of 0.25 m/s observed a few days either side of the storm to 0.40 m/s during the storm.

2. Modelling and validation methods

2.1. The modelling system

The tide–surge–wave modelling system uses a coupled wave and tide–surge model. The wave module is based on a shallow water version of the 3rd generation WAve Model (WAM, Monbaliu et al., 2000), which was initially developed for global deep water simulations (Komen et al., 1994). This model considers the 2D spectral evolution due to energy input by wind, energy dissipation by whitecapping, bottom friction and depth-induced breaking, and non-linear quadruplet wave–wave interaction. When coupled to a hydrodynamic model, time varying depth-averaged current and elevation fields are also considered in the wave refraction computation as well as a Doppler shift of the wave propagation caused by the currents; otherwise the mean tidal level and zero currents are used. The above coupled and uncoupled model settings are all considered to be the standard WAM setup in this study and have recently been applied and tuned for accurate simulation in very shallow (estuarine) conditions (Brown, 2010). The tide–surge module is based on the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS). This 3D hydrodynamic B-grid model (Holt and James, 2001) has been developed to include a piece-wise parabolic method advection scheme, turbulence closure (Mellor and Yamada, 1982) modified to consider surface wave breaking (Craig and Banner, 1994) and a total variation diminishing (TVD) wetting and drying scheme. The model includes both barotropic and baroclinic processes arising from tides, rivers and meteorological forcing. Here the main interested is in the barotropic simulation influenced by the surge component due to wind, pressure and wind-waves. The coupled model has been under development since 2002 and can be coupled in 2-way, with both models interacting, or in 1-way, in which information is only passed to WAM from POLCOMS. The 1-way coupling includes refraction of waves due to time varying depth-averaged currents and depths, a Doppler shift of the waves due to the currents and a wave–current bottom friction (Madsen, 1994) in the wave model only. The 2-way exchange builds on the 1-way coupling passing information back to the hydrodynamic model. The additional coupling includes a wave-enhanced bottom roughness in POLCOMS, provided from the wave–current bottom friction method in WAM and a wave related surface roughness. Wave effects on the surface roughness are taken into account in POLCOMS through a Charnock (1955) relation, with a wave-age related Charnock parameter (Janssen, 2004) when coupled to WAM (Brown and Wolf, 2009). In the coupled system the bottom current is imported into WAM from POLCOMS. Wave–current bottom friction is then accounted for by the method of Madsen (1994) in WAM and the wave enhanced bottom roughness is imposed using the Blumberg and Mellor (1987) method in POLCOMS; otherwise the method of Madsen et al. (1988) is used for uncoupled

WAM simulations and a constant bottom roughness of 0.003 m is used in uncoupled POLCOMS simulations. In the coupled system standard WAM is the more expensive model, requiring 88% of the total computation time.

2.1.1. Advanced coupling procedures

The standard POLCOMS-WAM system (Section 2.1 above) has recently been modified (Bolaños et al., 2008, 2011) to include 3D current effects and applied to the (deep, microtidal) Mediterranean. Here its capability is assessed in a shallow coastal region under extreme storm conditions. Following the method of Mellor (2003, 2005), the 3D radiation stress and Stokes' drift at each vertical model level, including the vertical shear in the current profile, and also the 3D Doppler current velocity that modifies the observed wave spectrum are included. A detailed description of the models and their advanced coupling are given by Bolaños et al. (2008, 2011).

The radiation stress is defined as the excess flux of momentum due to surface waves (Longuet-Higgins and Stewart, 1962; Longuet-Higgins and Stewart, 1964). In shoaling conditions wave dissipation creates significant momentum gradients. Through the conservation of momentum the current field becomes noticeably modified. Under storm conditions, radiation stress cannot be neglected at the coast in certain locations since it produces a longshore drift and can contribute significantly to the total water level during a storm through wave-setup (e.g. Mastenbroek et al., 1993). The radiation stress is computed in WAM for each vertical model level of POLCOMS, generating the wave-induced current in addition to the barotropic current field. Stokes' drift is the mean surface drift due to the presence of waves (Longuet-Higgins, 1953). The Coriolis–Stokes' term affects the Ekman current profile (e.g. Polton et al., 2005; Rascle et al., 2006; Rascle and Ardhuin, 2009). The Stokes' drift can generate currents with magnitudes of 20–30% of the wind induced flow and 1.5% of the wind speed (Rascle et al., 2006). This drift velocity is calculated within WAM for each vertical level of POLCOMS, where it is included in the total velocity component. In the case of the standard (2D) WAM model the depth-averaged current is used for the refraction and Doppler shift and its inclusion can change the mean wave period (T_{m02}) by 20% (Osuna and Wolf, 2005). Additionally, the wind forcing is transformed to a moving frame of reference due to the surface current to produce an 'effective wind'. In the advanced (3D) WAM coupling the current velocity is integrated over a depth which depends on the wave frequency. This is used in place of the depth-averaged current to capture the vertical current structure when accounting for Doppler shift (Mellor, 2003; Kirby and Chen, 1989) and current refraction.

The updated methods of Mellor (2008) have also been coded and tested within Liverpool Bay for 3D radiation stress. However this procedure was found to be unstable in the offshore zone (depths 30–50 m) as a result of spurious current generation linked to the implementation of the E_D term in Mellor's (2008) method, within the numerical model. Bennis et al. (2010) go into further details of the problems with the Mellor (2003, 2008) methods. Since the Mellor (2003) method seems applicable in areas with low bottom gradients, as found within Liverpool Bay, and the focus of this investigation is not within the estuary regions, where steep gradients in the bottom topography can occur due to the channel-sandbank systems, this method is used. Inclusion of these advanced methods increases the simulation time of WAM such that more than 98% of the computation time is spent in the advanced (3D) wave model.

2.1.2. Model setup

This coupled modelling system is designed to run on parallel computers (Ashworth et al., 2004) allowing large scale application of high resolution modelling. Although POLCOMS-WAM is well designed for high performance computing WAM is computationally expensive when applied to shallow water regions. In WAM the source term time step (15 s) is set to be larger than the propagation time step (3 s) to improve efficiency. The POLCOMS model runs with a 3 s barotropic time step, updating the baroclinic properties and coupled parameters every 30 s. To allow quick computation of the high resolution 180 m Liverpool Bay hindcast the UK's supercomputing service: HECToR (High-End Computing Terascale Resource, http://www.hector.ac.uk/) is used. For this study 256 computer processors are used to allow a 1 day spin-up and a 1 day tide–surge–wave simulation for all model setups to complete within a total of ~12 h, the POLCOMS-WAM simulations requiring the full time and the POLCOMS-uncoupled simulation requiring less than 1 h.

In Liverpool Bay the surge generated externally, across the continental shelf in the Celtic and Irish Seas, contributes significantly to the total surge (Jones and Davies, 1998), while the waves are mainly generated in the northern part of the Irish Sea (Brown et al., 2010a) with maximum fetch to the northwest. A 1-way nested approach consisting of 3 model grids is used to capture the external surge. The low resolution model is the 1/9° by 1/6° (~12 km) operational Continental Shelf surge model developed at the National Oceanography Centre (see Flather, 1994) and run at the UK Met Office. This drives the offshore boundary of a 1.8 km medium resolution POLCOMS-WAM Irish Sea model (Brown et al., 2010a). In turn this model forces the offshore boundary of the 180 m high resolution POLCOMS-WAM Liverpool Bay model. The Liverpool Bay tide–surge boundary conditions are updated every 30 min, while the Irish Sea boundary conditions are updated every hour. The Irish Sea POLCOMS-WAM model also provides hourly offshore wave boundary conditions to the Liverpool Bay model. For all model resolutions hourly wind and pressure data, provided by the UK Met Office Northwest European Continental Shelf (mesoscale) model, with 0.11° (~12 km) resolution, were used to generate surge and wave conditions.

2.2. Validation procedure

To validate the model hindcast, hourly surge, wave and current observations have been used within Liverpool Bay (Fig. 1). The model output consists of 2D wave, 2D total elevation and 3D current fields at hourly intervals across the domain. To obtain the surge and surge plus wave-setup elevations the water level of a tide-alone simulation is subtracted from the water level hindcast by the tide–surge and tide–surge–wave model setups respectively. To obtain the wave-setup and/or Stokes' drift-induced elevation components in isolation from the surge the tide–surge total elevation was subtracted from the respective tide–surge–wave simulations. This method is not a direct measure of a modelled process, but provides a measure of the overall influence of a process following wave–tide–surge interactions. For example, Stokes' drift generates a current which will interact with the tide–surge current field and the wave field, which in turn interact with each other. Measured changes in the water level due to Stokes' drift will therefore be the consequence of the drift velocity and its' interaction rather than the drift alone. To validate the model data, *m*, the root-mean-square error (*RMS error*, Eq. 1) and the percentage error in the peak value during the storm event (*Perror*, Eq. 2) are calculated using the observed data, *o*.

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{n}(o_i - m_i)^2}{n}}, \tag{1}$$

where the data is provided as a time series consisting of $i = 1{:}n$ data. In this case $n = 25$, the number of inclusive hourly outputs between 18th January 00:00 and 19th January 00:00.

$$Perror = 100\frac{(\hat{m} - \hat{o})}{\hat{o}} \tag{2}$$

where ^ denotes the peak (maximum value) in a time series of data during the storm period investigated. A positive *Perror* indicates an overestimated peak by the model and a negative *Perror* indicates an underestimated peak by the model. An *RMS error* that is less than 20% of the range in the data is considered good, and a *Perror* less than 20% is also considered good. These metrics allow the maximum values during the storm (*Perror*) and the general model capability at predicting any time variation over the storm period (*RMS error*) to be investigated. The *RMS error* is considered to be the more important validation metric as it assesses the model performance over the full storm period, whereas the *Perror* only considers a single point in time.

3. Results

Results from the high resolution Liverpool Bay model are presented for a single day: 18th January 2007, when the storm event occurred. This period has been simulated such that spin up errors are not present at the onset of this analysis period. The model data is output hourly and compared with observation at the same time. The results show the interactive influence of each physical process studied not the direct influence of a process in isolation. The differences in the error metrics between each model simulation are small. Different coupling procedures therefore only refine the stand-alone model hindcasts, which are shown to already give good results using the above definitions (Eqs. 1 and 2).

3.1. The surge simulation

The *RMS error* for the POLCOMS uncoupled simulation (R01) is 12% of the range (maximum value–minimum value) in surge elevation at Hilbre and 14% of Liverpool range in surge elevation. The POLCOMS model therefore provides a good estimate of surge conditions at the coast (as seen in Fig. 2). Table 1 shows the impact of including isolated and combined wave effects on the surge results for both locations. The changes in the model hindcasts are mostly in the simulation of the peak value (*Perror*), the general trends (*RMS error*) are relatively unaffected by the changes in model couplings. This implies that within Liverpool Bay local interactions do not dramatically modify the external tide–wave–surge forcing. Generally the surge hindcast is better at Hilbre. The localised accuracy is likely to depend on the quality of the local bathymetry.

When wave effects are considered through surface stress coupling (R02) the overall surge simulation improves, although the peak value slightly worsens. The effect of including wave–current bottom friction leads to a worse surge prediction (R03 and R04). The influence of the bottom friction coupling is much smaller than the surface stress coupling. The inclusion of both surface and bottom couplings is a more physically sound method and does improve the general shape of the surge compared with the uncoupled model. The use of a 3D current field in WAM (R05, Fig. 2) has little impact on the surge compared with using the depth-averaged current in WAM (R04, Fig. 2); the main change is an improved representation of the maximum surge value. The addition of Stokes' drift (R06) further improves the simulation of the maximum value by increasing the elevation of the peak. Wave-setup, due to inclusion of radiation stress, contributes significantly to the peak level of the surge (R07, Table 1). However, the *RMS error* suggests that including radiation stress leads to a slightly worse simulation of the overall surge event. This is due to the advancement in time of the surge peak (previously shown by Brown, 2010). The maximum surge value is better represented at Liverpool for this simulation, although the over-prediction at Hilbre is slightly greater than the original under-prediction (R07 compared with R05, Table 1). Brown (2010) found the inclusion of radiation stress using 3D WAM and SWAN improved the peak elevation in the surge through wave-setup at Hilbre when compared to higher frequency (30 min) observations, which had a single point at a similar elevation to that hindcast by this model setup. This raised peak could have been due to noise in the data, making this value hard to assess. The Liverpool hindcast consistently under-predicts the peak surge level unless radiation stress is considered when it over-predicts the surge elevation. These findings imply that consideration of wave-setup is important close to the coast to accurately forecast the maximum surge elevation. Without radiation stress the surge peak is under-predicted at both locations. When Stokes' drift is combined with radiation stress the fully coupled advanced simulation becomes slightly worse (R08 compared with R07).

Only selected model runs are show in Fig. 2 since there is very little change in the surge results for the different coupling setups as seen in the error metrics presented in Table 1. The Liverpool Bay high resolution simulations are compared with previous model hindcast (Brown and Wolf, 2009) from the medium resolution Irish Sea model. The results (Table 1 and Fig. 2) show that the medium resolution model has a better level of accuracy at Liverpool and similar level of accuracy at Hilbre for prediction of the maximum surge level. This is discussed further in Section 4.

The model simulations (Table 1) are used to explore the current velocities in addition to the background tidal velocities due to the storm. These surge velocity residuals are obtained by subtracting the

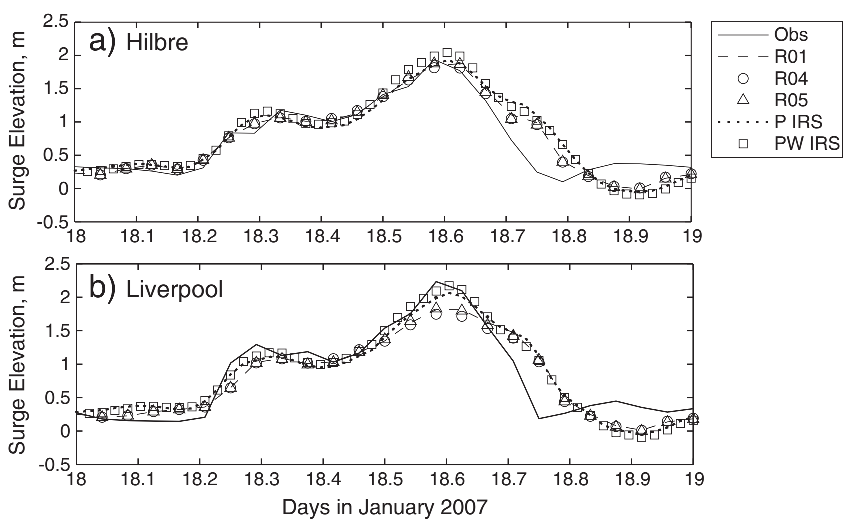

Fig. 2. Selected model hindcast surge elevations compared with observation (Obs) during the 24 h storm period at the Hilbre and Liverpool tide gauges. The tick marks fall at 2.4-hourly intervals starting on 18th January 00:00. The model runs shown in the legend can be identified in Table 1, where 'IRS' refers to the Irish Sea POLCOMS (P) and POLCOMS-2DWAM (PW) simulations performed by Brown and Wolf (2009).

Table 1
Validation of the high resolution Liverpool Bay model surge hindcast at Liverpool and Hilbre, for different 2-way POLCOMS-WAM model coupling through: surface stress (SS), bottom stress (BS), Stokes' drift (SD) and radiation stress (RS). Whether the 2D (depth-averaged) or 3D current field is imported into WAM is denoted by the dimension in the model name. The medium Irish Sea (IRS) model hindcast is also shown.

		Liverpool		Hilbre			
Model	Coupling	Surge *Perror*, %	*RMS error*, m	Surge *Perror*, %	*RMS error*, m	Run time	Run identification
POLCOMS	None	−18.75	0.29	−3.22	0.22	331 s (256 proc)	R01
POLCOMS-2D WAM	SS	−21.69	0.28	−6.35	0.21	9.76 h (256 proc)	R02
POLCOMS-2D WAM	BS	−37.24	0.35	−20.83	0.22	9.74 h (256 proc)	R03
POLCOMS-2D WAM	SS and BS	−21.76	0.28	−6.33	0.21	9.76 h (256 proc)	R04
POLCOMS-3D WAM	SS and BS	−18.01	0.28	−2.98	0.22	11.57 h (256 proc)	R05
POLCOMS-3D WAM	SS, BS and SD	−17.34	0.27	−1.96	0.22	11.65 h (256 proc)	R06
POLCOMS-3D WAM	SS, BS and RS	7.07	0.34	10.09	0.27	14.55 h (256 proc)	R07
POLCOMS-3D WAM	SS, BS, SD and RS	8.04	0.35	11.21	0.28	14.65 h (256 proc)	R08
POLCOMS IRS	None	7.19	−0.28	11.88	−0.31	0.11 h (64 proc)	Brown and Wolf (2009)
POLCOMS-2D WAM IRS	SS and BS	2.79	−0.27	6.83	−0.30	1.81 h (64 proc)	Brown and Wolf (2009)

tidal velocity (predicted by a tide only POLCOMS simulation) from the tide–surge(–wave) velocity near the tide gauge locations (Fig. 1). Without observations at these locations the current patterns cannot be validated, but since the surge elevations are realistic it can be assumed that the velocity patterns give a reasonable approximation to reality (at least when depth-averaged). In Section 3.3 the current is looked at in more detail at sites A and B, where observations are available. The current patterns at the surface and bottom are almost identical, with a stronger flow at the surface. Only the surface velocities are consequently presented (Fig. 3). The influence of stratification and river flow on the vertical current structure is not included here and is being investigated in other research (Bolaños et al., in press). The residual currents due to the surge are weaker (reaching 0.5 m/s at Hilbre) than the tidal currents (which reach maximum flows of ~1 m/s at the surface and ~0.8 m/s at the bottom in the Hilbre Channel). The maximum residual velocity at Liverpool is 0.18 m/s. A much smoother time series is produced at this location. As expected, the residual velocity patterns at Hilbre and Liverpool, located near the mouth of the Dee and Mersey Estuaries respectively, imply that the flow is into the estuaries (positive u-velocity and negative v-velocity components, Fig. 3) until the peak in the surge elevation (Day 18.6) and then out of the estuaries (negative u-velocity

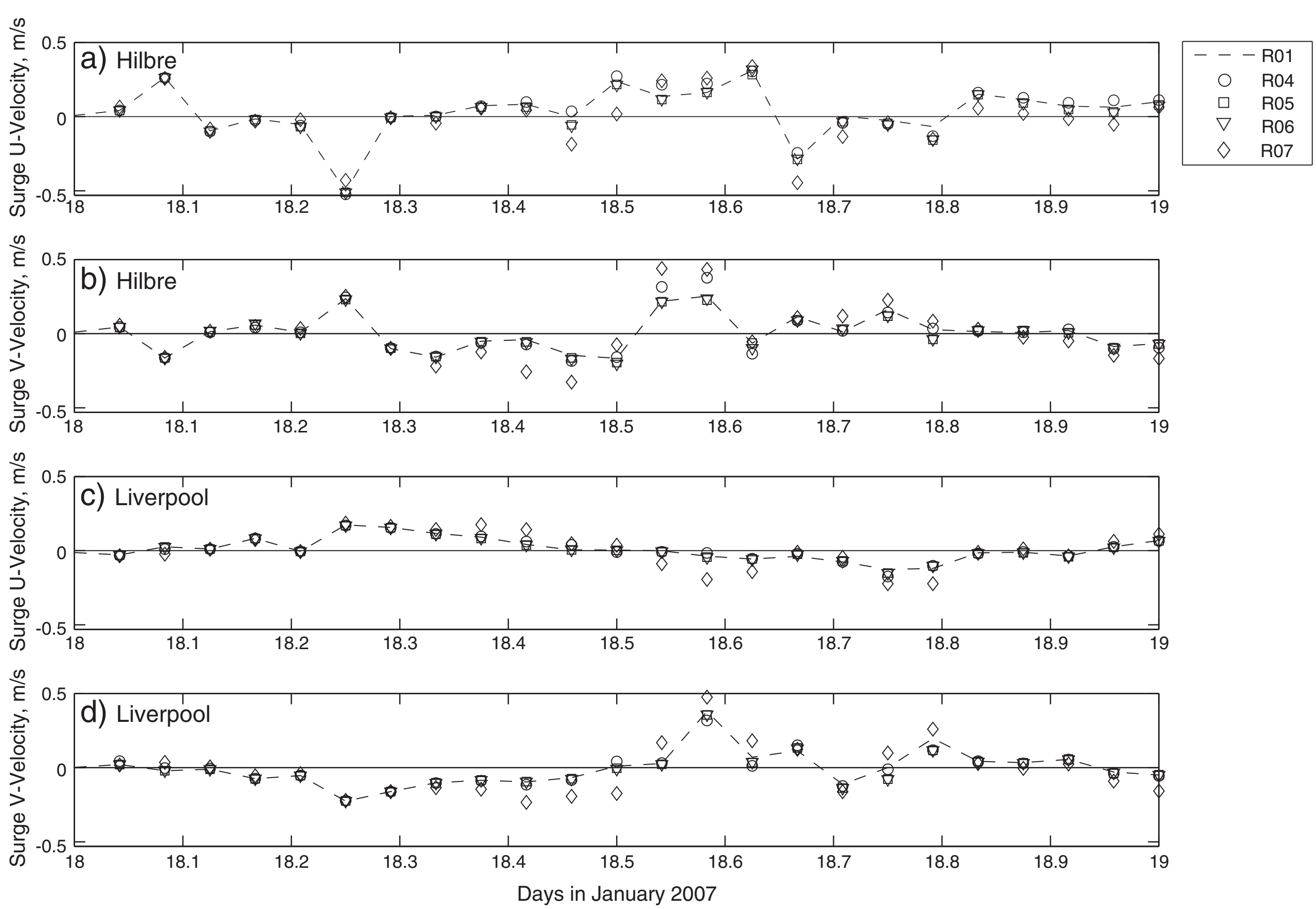

Fig. 3. The modelled surface surge velocity during the 24 h storm period at Hilbre and Liverpool tide gauges. The tick marks fall at 2.4 hourly intervals starting on 18th January 00:00. The u-velocity components are shown in the top panel for each location and v-velocity components in the bottom panel for each location. The model couplings, identified in Table 1, are shown in the legend.

Table 2
Validation of the significant wave height, H_{m0}, mean wave period, T_{m02} and peak wave period, and T_p, hindcast at the WaveNet and Triaxys buoys for different POLCOMS-WAM model couplings. The 1-way (1 W) coupling includes time varying elevation and currents within WAM and either a wave–current bottom friction (WCBF) or wave-alone bottom friction (WBF). The 2-way (2 W) coupling is the same as the 1-way but information is returned from WAM to POLCOMS through: surface stress (SS), bottom stress (BS), Stokes' drift (SD) and radiation stress (RS). Whether the 2D (depth-averaged) or 3D current field is imported into WAM is denoted by the dimension in the model name. Each Liverpool Bay model run performed here used 256 processors, while the Irish Sea (IRS) model was run on 64 processors.

Model	Coupling	WaveNet		Triaxys		WaveNet		Triaxys		WaveNet		Triaxys		Run time	Run identification
		H_{m0} *Perror*, %	H_{m0} *RMS error*, m	H_{m0} *Perror*, %	H_{m0} *RMS error*, m	T_{m02} *Perror*, %	T_{m02} *RMS error*, s	T_{m02} *Perror*, %	T_{m02} *RMS error*, s	T_p *Perror*, %	T_p *RMS error*, s	T_p *Perror*, %	T_p *RMS error*, s		
2D WAM	None	−15.61	0.97	−9.25	0.99	−9.38	1.99	−24.93	9.38	−12.48	1.83	−11.86	3.38	9.51 h	R09
POLCOMS-2D WAM	1 W (WBF)	−15.17	0.94	−25.56	0.80	−6.88	1.25	−20.25	2.00	−16.93	1.74	−3.05	3.10	9.55 h	R10
POLCOMS-2D WAM	1 W (WCBF)	−20.54	0.93	−33.37	0.89	−10.94	1.25	−45.49	1.76	−24.48	1.79	−11.86	3.34	9.75 h	R11
POLCOMS-2D WAM	2 W with SS	−19.84	0.92	−31.13	0.88	−9.80	1.25	−43.48	1.78	−24.48	1.84	−11.86	3.34	9.76 h	R02
POLCOMS-2D WAM	2 W with BS	−20.53	0.29	−33.37	0.89	−10.94	1.25	−45.49	1.76	−24.48	1.79	−11.86	3.34	9.74 h	R03
POLCOMS-2D WAM	2 W with SS & BS	−19.83	0.92	−31.12	0.88	−9.80	1.25	−45.49	1.78	−24.48	1.84	−11.86	3.34	9.76 h	R04
POLCOMS-3D WAM	2 W with SS & BS	1.13	0.85	−36.82	0.87	−5.89	1.03	−43.73	1.50	−16.93	0.99	6.64	2.16	11.57 h	R05
POLCOMS-3D WAM	2 W with SS, BS & SD	1.20	0.85	−36.71	0.87	−5.57	1.03	−43.65	1.50	−8.62	0.94	6.64	2.16	11.65 h	R06
POLCOMS-3D WAM	2 W with SS, BS & RS	2.76	0.59	−23.32	0.74	−1.30	0.73	−30.49	1.84	−8.62	1.05	6.64	1.97	14.55 h	R07
POLCOMS-3D WAM	2 W with SS, BS, SD & RS	2.93	0.60	−23.26	0.74	0.17	0.73	−30.32	1.83	−8.62	1.11	6.64	1.97	14.65 h	R08
POLCOMS-2D WAM IRS	2 W with SS & BS	−0.13	−0.58	−3.50	−0.88	5.23	−0.69	14.54	−2.18	16.93	−1.03	67.69	−14.25	1.81 h	Brown and Wolf (2009)

and positive v-velocity components, Fig. 3) after the peak in the surge. At Hilbre (Fig. 3a and b) the inflow occurs just before the peak and switches to outflow just after the surge peak for a short period. At Liverpool (Fig. 3c and d) the inflow switches to outflow just before the peak. The flow direction at Liverpool is consistently in one direction either side of the time at which it switches direction. At Hilbre the flow is more complex due to the wider estuary mouth with 2 channels, but the same general pattern is seen. The different model coupling procedures have very little influence on the flow patterns. The main changes occur during the surge peak (Day 18.4–18.7). Enhanced surface currents (Fig. 3) invoked by the surface and bottom couplings (R04) compared with the POLCOMS-alone hindcast (R01), are reduced when the 3D current is considered in WAM (R05). The impact of Stokes' drift is minimal at the surface during this storm event. Radiation stress generates the most noticeable change through the wave-induced current, but the accuracy is questionable, as remarked on earlier in this section.

3.2. The wave simulation

In shallow water the waves become significantly modified by time varying elevations and currents. Offshore (depths >25 m) the waves are less affected and an uncoupled wave model suffices (Brown, 2010). The improved accuracy in the significant wave height, H_{m0}, hindcast when using a coupled modelling system in the nearshore is shown in Table 2, along with error metrics for the peak wave period, T_p, and the mean wave period, T_{m02}. It is found that the changes are more dramatic in the hindcast of the peak value (*Perror*), while the general trends (*RMS error*) show little change for the different model couplings (Table 2). The data presented for the Triaxys buoy is to be treated with caution. An error in the software incorrectly measuring very low frequency waves is currently under investigation. This means the total energy and therefore the wave height observations should be accurate, but the wave periods may not as a result of an incorrect frequency distribution.

The wave model is a good predictor offshore and an acceptable predictor in the nearshore (Fig. 4, Table 2) when model settings are optimised (Brown, 2010). The standalone model (R09) gives a better hindcast of the maximum wave height than the standard coupled model (R04), although tidal modulation is not captured. This phenomenon is significant in the nearshore. Once the 3D current is considered in WAM the advanced coupled offshore results improve while the nearshore results remain at a similar level of accuracy (Fig. 4, R05). This offshore improvement is related to a better representation of the shape of the peak in storm wave conditions. At this deep location the waves only feel the currents over a limited depth below the surface so using a current representative of this depth by considering the 3D profile is better than using the depth-averaged current in WAM. In shallow water the waves may penetrate to the bed and the depth-averaged current is a reasonable approximation to use in WAM, as seen by the small difference in the error metrics between R04 and R05 at the Triaxys buoy. In shallow water the accuracy of the wave simulation will affect the depth of the current field felt by the waves and therefore the accuracy of implementing the 3D current.

Offshore, 1-way coupling reduces the accuracy of the wave simulation (R11 compared with R09, Table 2), especially when a wave–current bottom friction is considered in WAM (R10) and demonstrates that the tidal range has negligible impact on the waves at these depths. Combined with the fact the 3D current significantly improves the simulation (R05, Table 2) and that the wave–current bottom friction has little affect over the study period (*RMS error* of R10 compared with R11, Table 2), the reduced accuracy observed offshore, is due to using the depth-averaged current in WAM. Since the uncoupled hindcast provides a good result the depth-averaged current must have a stronger influence on the waves than the actual

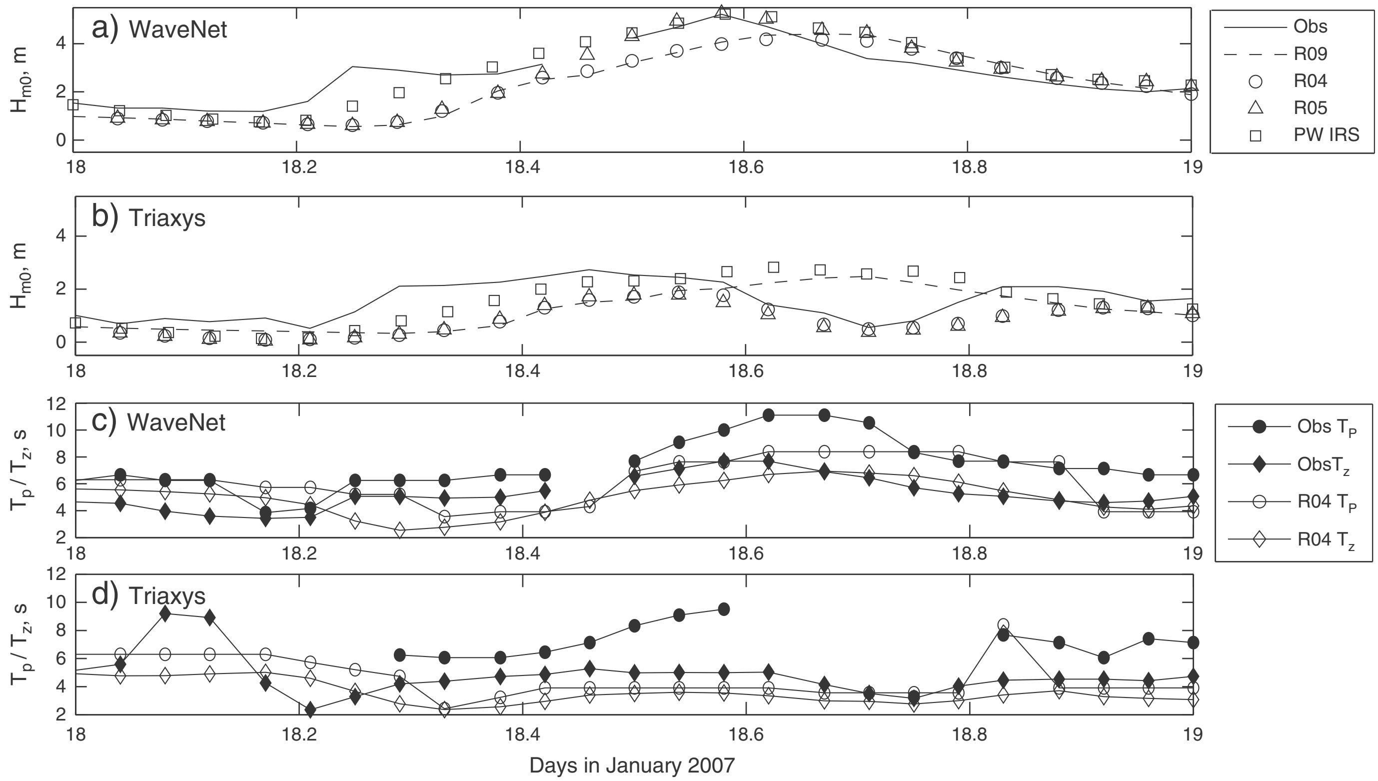

Fig. 4. The model hindcast significant wave height, H_{m0}, compared with observation (Obs) during the 24 h storm period at the WaveNet and Triaxys buoys (panel a and b). The tick marks fall at 2.4-hourly intervals starting on 18th January 00:00. The model couplings, identified in Table 1, are given in the top legend, where 'IRS' corresponds to the Polcoms-2DWAM (PW) Irish Sea model hindcast by Brown and Wolf (2009). Panels (c and d) show the observed peak, T_p, and mean, T_z, wave periods at the WaveNet and Triaxys buoys along with the standard WAM hindcast values.

currents experienced by the waves. Moreover, the wave-alone bottom friction does improve the hindcast of the maximum value (*Perror* of R10 compared with R11, Table2). A wave-alone bottom friction improved the nearshore hindcast (R10), demonstrating the importance of using an accurate friction predictor in shallow water. It is also found that small changes in the hydrodynamics have an impact on the wave hindcast. The slight changes in the hydrodynamics due to Stokes' drift leads to a slightly worse wave simulation while consideration of radiation stress in the hydrodynamics improves the hindcast. The raised water levels through wave-setup increase the peak in the significant wave heights at both locations. Nearshore wave-setup is important, increasing the total water level within the estuary and improving the wave simulation. Methods to include radiation stress therefore require further attention and are discussed in Section 4. Comparing the Liverpool Bay model results with the Irish Sea model hindcast (see Brown and Wolf, 2009, Table 2) shows that the medium resolution model is better at simulating waves offshore, when a depth-averaged current is considered in WAM. This is further discussed in Section 4. However, in the nearshore little tidal modulation is present in the hindcast (Fig. 4) making the high resolution model the preferred option.

The observed peak wave period at the Triaxys location has many gaps, providing little data for validation (Fig. 4c). The mean period at this location has an initial peak (Day 18.1), which is larger than the maximum period generated during the peak of the storm (Day 18.6). This initial peak is therefore used in the *Perror* metric as it is the maximum value during the storm period. Poor simulation of this initial peak gives rise to a poor *Perror* value for the mean period at the Triaxys location, even though the mean wave period is well simulated during the main storm period after this point in time. At the WaveNet location the modelled periods (Table 2) are more valid and the data more robust.

The wave heights are more often modelled with higher accuracy than the wave periods (Table 2). The *RMS error* in the significant wave height is 15–23% and 34–44% of the range in values observed, offshore and nearshore respectively. The wave periods achieve *RMS errors* of 17–29% and 13–43% of the range (maximum value–minimum value) in observed mean and peak period offshore and 21–33% of the range observed in the mean period nearshore. Due to lack of nearshore peak period observation, the actual range is unknown. Using the measured range (maximum recorded value–minimum recorded value), which misses the actual maximum value, the *RMS errors* are overestimated as 21–33% of the range in peak period observed.

3.3. The vertical current structure simulation

The importance of the wave–current coupling on the 3D current field is investigated using observations from the permanent moorings at Sites A and B (Fig. 1). A time series of the observed 3D current structure is found to be well described by POLCOMS-alone (R01, Fig. 5). The storm event has little effect on the current field at these offshore locations. The most noticeable influence is enhancement of the v-velocity component at Site A during the falling tides (~15 h). Analysis of the vertical current profiles at both sites at hourly (model output) intervals demonstrated little change in the currents due to the different coupling procedures. The vertical current profile hindcast by POLCOMS was slightly improved by the inclusion of surface and bottom couplings with WAM. The inclusion of radiation stress however, led to a less accurate vertical profile being simulated producing large current velocities (e.g. a 50% increase in the north velocity component occurred at both sites, in addition to flow reversal in the east velocity component at Site A). This therefore highlights the presence of errors in the Mellor (2003, 2005) method. Since no significant vertical structure to the water column is present during the

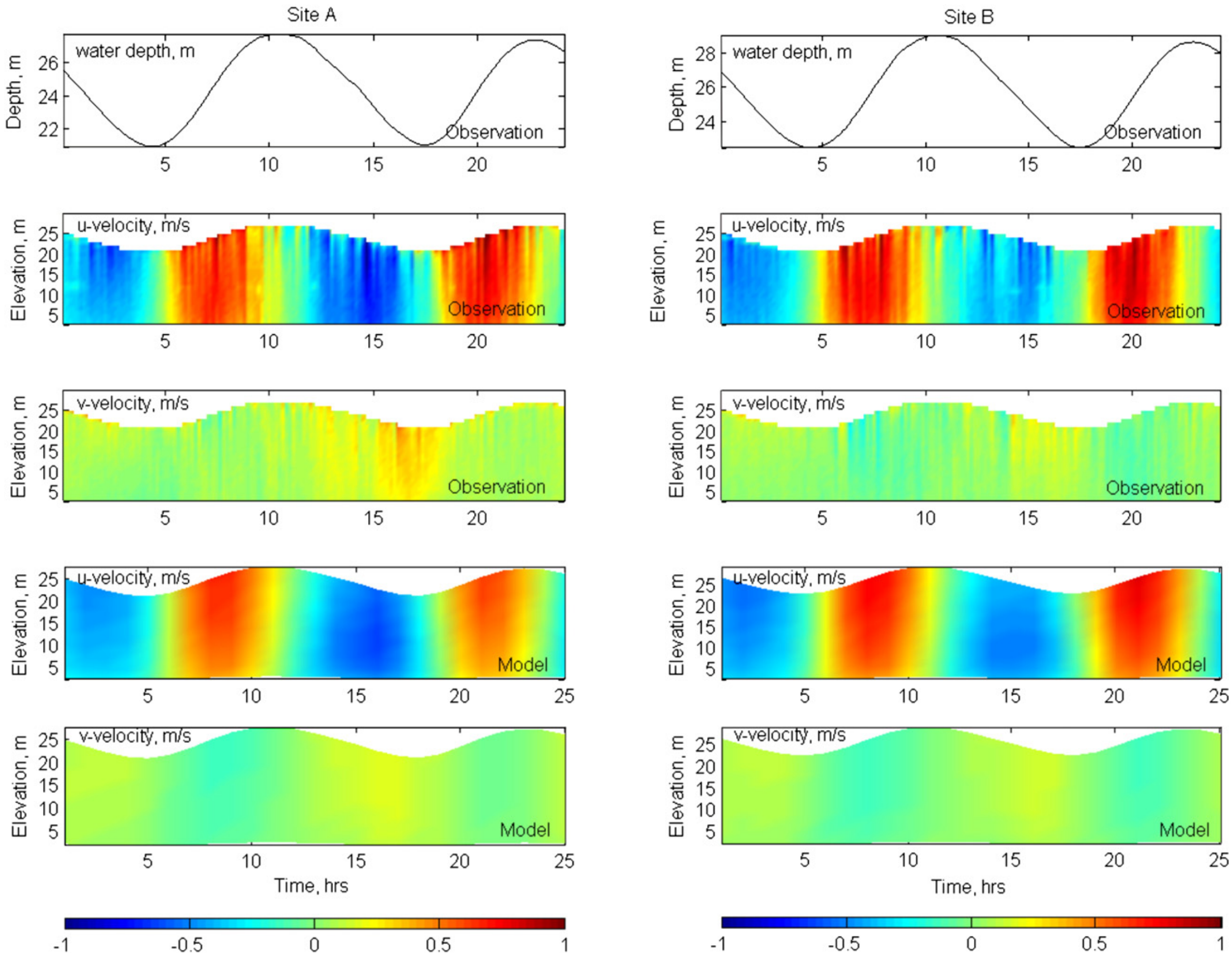

Fig. 5. The 3D hydrodynamic conditions observed and modelled by POLCOMS-alone (R01, Table 1) at the permanent mooring sites. The times are given in hours from 01:00 18th to 00:00 19th January 2007. Site A is shown as the left column and Site B as the right column. The colour scale represents the velocity (m/s). The first 3 rows are from observation and the last 2 from model hindcast. The u-velocity component is shown above the v-velocity component in both cases and the surface elevation is also provided from observation.

storm the model couplings are validated against the observations using a time series of depth-averaged current at each location (Table 3).

The POLCOMS hindcast (R01) of depth-averaged currents agree well with observation (Fig. 6). Both velocity components are well simulated, the most noticeable disagreement being at Site A in the northerly component (v-velocity, Fig. 6). For the different coupling procedures only small changes in the depth-averaged currents are observed (Table 3). The *RMS error* in the u-velocity and v-velocity components is between 1–10% and 8–28% of the range in the velocity components respectively. Surface and bottom couplings improve the model hindcast, while the use of a 3D current in WAM has little influence and Stokes' drift and radiation stress make the hindcast slightly worse (see Table 3). The best current hindcast is achieved with 2-way coupling (R04 and R05). Since the waves are improved when the 3D current is considered in WAM this model setup is preferable for a good tide–surge–wave hindcast.

Table 3
The *RMS error* metrics for the depth-averaged current components (U and V) in m/s at Sites A and B, located in Fig. 1, for each Liverpool Bay model hindcast identified in Table 1.

Site		R01	R02	R03	R04	R05	R06	R07	R08
A	U	0.03	0.03	0.02	0.03	0.02	0.03	0.18	0.18
	V	0.08	0.08	0.12	0.08	0.08	0.09	0.09	0.08
B	U	0.04	0.02	0.06	0.02	0.03	0.04	0.02	0.02
	V	0.03	0.03	0.04	0.32	0.03	0.03	0.03	0.04

3.4. Tide–surge–wave interaction

A time series of modelled storm parameters at Hilbre and the WaveNet location are used (Fig. 7) to qualitatively describe the tide–surge–wave interactions that occur in Liverpool Bay during an extreme storm. During the storm event (Fig. 7) the offshore wave climate responds directly to the wind forcing, while the inshore waves are modulated by the tide. The surge elevation peaks close to the maximum in wind speed, which occurs close to low tide. However there is a dip in the surge elevation (Day 18.4) at high tide, a result of increased water levels reducing the local effect of the wind over the water column. This surge shows weak tide–surge interaction, unlike observed in other events (e.g. the November 1977 storm, Jones and Davies, 1998), as a result of the maximum winds occurring close to low water. The peak in the elevations induced by Stokes' drift occurs at a similar time to the maxima in the offshore wave heights (and therefore wind speed) and shows no tidal modulation. The wave-setup peaks at a similar time to the nearshore wave heights, following the tidal level in similar fashion to the nearshore waves.

The interactions modelled during this storm show that the offshore waves depend only on the wind, while the nearshore waves are affected by wind and tide. Stokes' drift is related to the offshore wave field and seems unaffected by the tide nearshore. The local surge is influenced by

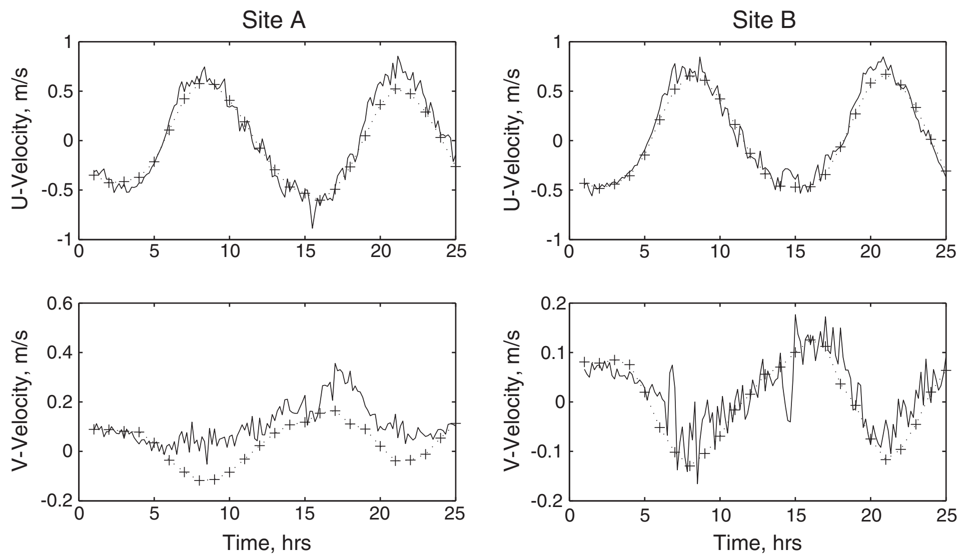

Fig. 6. The depth-averaged velocity components at Site A (left column) and Site B (right column), located in Fig. 1. The east (u-velocity, top row) and north (v-velocity, bottom row) components are presented for the observed data (solid line) and for the uncoupled POLCOMS (R01, Table 1) model data (dashed line with plus symbols). The times are given in hours from 01:00 18th to 00:00 19th January 2007.

wind and tide, although the external surge to Liverpool Bay, controlled by interactions between the tide and the propagation of the low pressure system over the continental shelf and the influence of surface roughness due to waves, dominates the total elevation. Finally radiation stress is controlled by the nearshore wave field. Between the offshore and nearshore there is a noticeable (~2.5 m) attenuation in wave height, which is increased further during low water, therefore the radiation stress is also influenced by the tidal elevation.

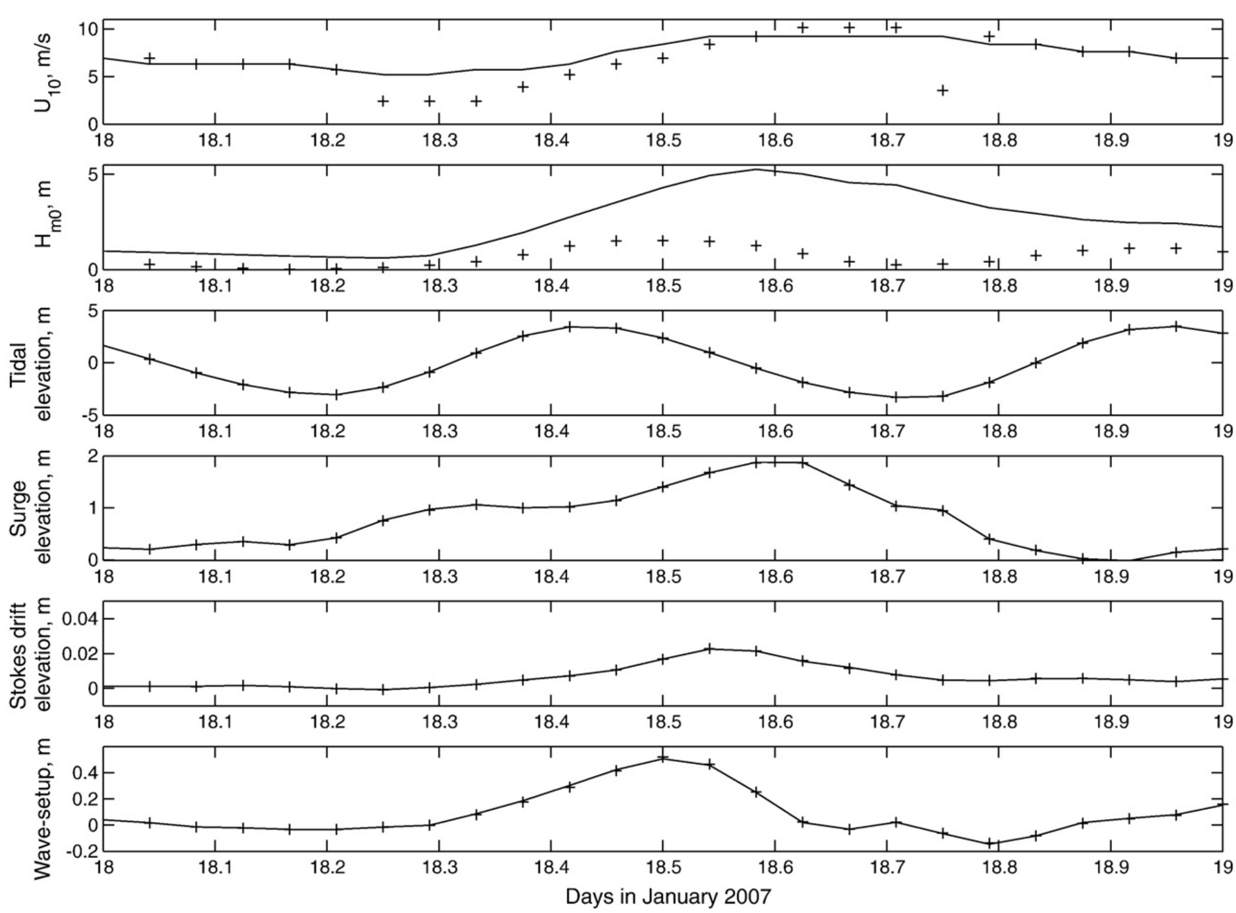

Fig. 7. Hourly model hindcast at the WaveNet (solid line) and Hilbre tide gauge (addition symbols) locations. The 10 m wind speed, U_{10}, is hindcast by the mesoscale model, the significant wave height, H_{m0}, tide and surge are hindcast by R05, and the elevation due to Stokes' drift and radiation stress are hindcast by R06 and R07 respectively. The vertical scales vary to provide clarity of the changes in storm parameters, which have quite different magnitudes.

Compared with the tide (6.7 m range), the surge (2 m maximum) and the wave-setup (0.4 m maximum) also contribute significantly to the total water level. In contrast Stokes' drift causes a minimal (0.02 m) increase in level. A considerable likelihood of flooding and morphological impact occurs close to high tide (Day 18.45). This is in response to the combined tide–surge–wave-induced water elevations and nearshore wave heights being at their maximum levels.

4. Discussion

POLCOMS-WAM has been applied to an extreme storm event to investigate the importance of model coupling procedures towards identifying important wave–current interactions for forecasting systems. A wave-dependent surface stress computation has previously been found to noticeably improve the surge simulation in the medium resolution (1.8 km Irish Sea) model (Brown and Wolf, 2009). Here, the small changes in the error metrics for surge and waves (Table 1 and 2) imply that the boundary forcing from this model has most influence in determining the wave–surge conditions in Liverpool Bay, and the local effects due to tide–surge–wave coupling are small. A single run without any wave or surge boundary conditions led to an under-prediction of the maximum surge value by about 60% and the maximum wave conditions by 65%. Although no sensitivity tests were performed here on the Liverpool Bay boundary conditions, Jones and Davies (1998) demonstrate the boundary conditions to the eastern Irish Sea dominate in the total observed surge while Brown and Wolf (2009) found that the waves in Liverpool Bay were locally generated within the northern Irish Sea. For the smaller Liverpool Bay domain the locally generated surge and waves are expected to be less than the wave–surge conditions generated locally within the Irish Sea.

The medium resolution model performs as well if not better than the high resolution model for surge and offshore waves. It is speculated that close to the coast differences in the surge hindcast are related to the integrated (averaged) effect of the bathymetry over the grid cell and the inclusion of the intertidal zones in the high resolution model instead of a minimum (5 m) depth as applied in the medium resolution model. In shallow water the medium resolution model does not provide the best wave hindcast, since wave breaking is not considered and smaller scale bathymetric features are unresolved. However this model gives a better wave hindcast in the presence of a depth-averaged current offshore. This is attributed to the relaxation of the wave-growth limiter term, which restricts the rate of change of the wave spectra during a model time step, to allow tidal modulation to occur in the nearshore simulation (see Brown, 2010 for details). This relaxation delays the onset of wave growth reducing the accuracy of the wave hindcast offshore. The 3D current needs to be considered in high resolution wave applications to increase the level of the maximum wave conditions to obtain similar accuracy to the medium resolution model when the wave-growth limiter is applied (R05, Table 2). For this event it is demonstrated that increased resolution requires improved physics as the simplified 2D physics become a potential source for inaccuracy. Offshore, the high resolution localised modelling therefore adds little value to the wave hindcast. Using a medium resolution tide–surge–wave model (the 1.8 km Irish Sea model in this case), with low computational cost, to drive a local tide–surge model is more efficient and as accurate (for depths >15 m) as using a nested high resolution tide–surge–wave model (e.g. Liverpool Bay model), which is computationally demanding, for forecasting. Within an estuarine environment a higher resolution model is however required to capture important morphological features and improve the wave simulation.

In a deep microtidal region, using the methods applied in this case study Bolaños et al. (2011) has shown Stokes' drift to have a relatively important impact on the current field, while radiation stress is thought to be of little importance. It is found that in a shallow macrotidal regime, radiation stress has the largest impact on the surge level and wave heights nearshore, while Stokes' drift has a minimal impact on the hydrodynamic field. However, the reliability of the vertical distribution of the radiation stress hindcast is questioned. It is thought that wave-setup should have a significant contribution to the surge elevation in very shallow (coastal) environments. Thus further investigation of this part of the coupling is required using robust 2D computations for the radiation stress (Mastenbroek et al., 1993) incorporated into a 3D circulation model. Furthermore, Stokes' drift is considered to have low importance in Liverpool Bay during extreme storms. Investigation of the impact of Stokes' drift and radiation stress during a calm period (Bolaños et al., in press) combined with the extreme conditions presented here, finds that overall Stokes' drift has low impact while radiation stress has high impact within this region. The role of Stokes' drift is likely to have an increased effect in areas where swell can penetrate.

Further validation of the radiation stress is required within the estuary environment. The inaccuracies in the timing of the surge prediction are likely to be due to inconsistencies in the method to calculate the vertical flux term using Mellor (2003). This method can generate unrealistic currents in deep water (Mellor, 2008). At the offshore sites (A and B) the 3D currents were larger when radiation stress was considered; this could explain the increased water level and time shift during the surge hindcast at the nearshore Hilbre location. This raises the question: if the depth-integrated 3D radiation stress was implemented in the barotropic component of the code, such that the vertical flux is not included as it integrates to zero, rather than applying the stress at each vertical depth level within the baroclinic code, as done by Warner et al. (2008), would an improved solution result? Previously, Brown (2010) found that wave-setup predicted by 2D radiation stress using SWAN linearly added to the surge did not give rise to timing errors in this event. The source of error could therefore be in the theoretical or coupling procedures. Alternative approaches to the questionable methods of Mellor (2003, 2008) are required for testing. One option would be to develop the theoretical method of Ardhuin et al. (2008) for application within a numerical model. Another option is to implement the radiation stress in 2D, as done by Mastenbroek et al. (1993). Applying the 2D stress terms in the barotropic component of the hydrodynamic model would avoid the problem of describing the vertical profile of radiation stress which is still disputed. The methods to include radiation stress require further attention as a robust and acceptable method is fundamental in shallow water for improved surge–wave simulation during storm conditions.

The time series of each storm parameter (Fig. 7) show that the tide–wave interaction is important at the coast in Liverpool Bay. The tidal elevation impacts the magnitude of the surge, the nearshore wave heights and radiation stress. Offshore, the waves are relatively unaffected by the tide as is Stokes' drift. The main, and most important, influence of the waves on the surge is through the surface roughness coupling. Use of a 3D current field within the wave model noticeable enhances the accuracy of the wave simulation, through more realistic representation of the current field. For waves (Table 2) the different coupling methods applied locally have a noticeable influence nearshore, where tidal modulation is very important, while offshore the uncoupled model would suffice. Since the wave model requires most of the total computation time, the added benefit of coupling to a tide–surge model does not detriment computation efficiency. Using a 3D current instead of a 2D (depth-averaged) current increases the computation time by 1 h per simulated day. The best coupled results are achieved in this study when 2-way surface and bottom couplings are implemented with 3D currents imposed in WAM. Brown (2010) has previously found that a tuned wave-alone friction formulation improves the performance of WAM in very shallow water. The surge results presented here (R03 and R04, Table 1) suggest that a current-alone bottom friction gives a better hindcast in the nearshore. These studies raise the question as to what bottom friction methods should be implemented in both POLCOMS and WAM. Here, focus has been on the tide–surge–wave interaction, but work is also underway (Bolaños et al., in press) to include baroclinic effects due to river sources, surface heating and spatial temperature and salinity distributions. In this application a global ocean turbulence model (GOTM) is also activated to use the full POLCOMS-GOTM-WAM coupling. This will provide the best 3D hydrodynamics before sediment and morphological modules are included within this system.

It has been shown that the wave model is the most computationally expensive part of the coupled system. For surge forecasting the uncoupled POLCOMS provides an acceptable and efficient operational model. WAM provides an acceptable offshore wave forecast and a good approximation of the nearshore wave field, but with the settings used here, to forecast beyond 2 days would not be realistic due to the slow computation times. In comparison to the model runtimes presented (Tables 1 and 2) the tide alone takes 300 s on the same modelling system. Adding the surge component to this system requires little additional expense (30 s), while adding waves significantly increases the expense (by nearly 10 h). Using a 3D current field in place of a 2D current field only slightly increases the computation cost (by 1.8 h), while noticeably improving the simulation. The inclusion of Stokes' drift has little impact on the simulation time so can be included for completeness although it not necessary for accurate simulation. 3D radiation stress increases computation cost further (by nearly 3 h), making a more efficient (2D) method desirable as model results show that it plays an important role within the nearshore.

5. Conclusion

A fully coupled tide–surge–wave model (POLCOMS-WAM) has been assessed using an extreme storm event in a shallow macrotidal region, namely Liverpool Bay. This modelling system has been found to be robust under such extreme storm conditions both nearshore and offshore, providing valid hindcast data. The standard coupling procedures, which include wave–current bottom and surface roughness and a Doppler wave shift, have been extended to account for a 3D current field within the wave model, Stokes' drift and radiation stress. Time variation in tidal elevation is important in accurately simulating the nearshore current and wave fields. Assessment of each coupling component, within the wetting and drying models presented here, highlights the most important wave–current interactions for coastal storm forecasting in shallow macrotidal regions. These are: the use of a wave-dependent surface roughness to generate the surge; the implementation of a 3D current field within the wave model; and the inclusion of radiation stress to enhance the surge–wave-setup peak. To further develop this research an alternative (2D) radiation stress method will be investigated as well as the influence of these coupling procedures (under the influence of temperature and salinity driven stratification) on the model performance under less extreme conditions.

For the present application the same model time steps were applied in each simulation. In consequence of including all of the 3D coupling procedures the simulation time was increased by approximately 2 h per modelled day. Operationally, the improvement in accuracy is not so beneficial for accurate forecasting when taking into consideration the reduced efficiency, which is large compared with the overall computation time (~4.5 h per modelled day with no 3D effects). For operational use this modelling system requires a super computer to facilitate feasible computation time. To forecast further into the future or include radiation stress more computer processors than the 256 used here would be required. Further investigation into the optimum model time steps for each coupling procedure is required to ensure minimal computation times are achieved without loss of accuracy. However, it is shown that the Irish Sea model with medium resolution (~1.8 km) provides an accurate and efficient tool for operational use in Liverpool Bay. Due to the integrated effect of wave–surge interaction local model coupling is not as important as large scale coupling at the medium resolution.

Acknowledgments

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