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A case study of combined wave and water levels under storm conditions using WAM and SWAN in a shallow water application

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A B S T R A C T

Extreme storm events in Liverpool Bay, UK, are under investigation. A recent storm, 18th January 2007, has been used to investigate different modelling approaches to accurately simulate wave–surge conditions in shallow water.

In Liverpool Bay wave and surge influence and their interaction are often considered in many studies. The tide–surge–wave interaction has been modelled in the Irish Sea using the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) coupled to the state-of-the-art 3rd generation spectral WAve Model (WAM). Waves are locally generated in Liverpool Bay, while the surge is locally and externally generated. To include the external surge the 1.8 km Irish Sea model has been nested, using a 1-way approach, into the 1/9° by 1/6° operational Continental Shelf surge model. To investigate the performance of POLCOMS–WAM in shallow water a 180 m Liverpool Bay model has been nested within the Irish Sea model. For this high resolution model the state-of-the-art 3rd generation Simulating WAves Nearshore (SWAN) spectral model is used to further develop WAM, modified for shallow water. A POLCOMS–WAM and POLCOMS–SWAN (1-way) coupled model has been implemented to assess the effects of tide–surge–wave interaction at the coast.

Investigation of the significant wave height and surge elevation reveals that when modified for shallow water WAM performs as well as SWAN. Two-way coupling between POLCOMS–WAM allows wave-setup to be included in the surge prediction greatly improving the hydrodynamic result. A drawback to using WAM is the computational expense, making SWAN more suitable for simulations exceeding a few days in duration.

1. Introduction

Extreme storm events leading to significant dune erosion and flood risk are under investigation in Liverpool Bay. The Coastal Flooding by Extreme Events (CoFEE) project and Morphological Impacts and COastal Risks induced by Extreme storm events (MICORE) project are assessing past, present and future storms within Liverpool Bay, UK, due to extreme events (Brown et al., 2010; Wolf et al., 2008). These studies are focused on the Sefton coast (Fig. 1), with the largest British dune complex extending between Liverpool and Southport. The dunes can reach 30 m high nearshore and have a maximum system width of 4 km. The dune system provides a barrier from coastal flooding for a large area of low-lying hinterland (Pye and Blott, 2008). During storm surges (>1.0 m), raised water levels enable waves to break onto the frontal dunes, sometimes for a number of sequential tides resulting in large scale erosion. The worst erosion occurs when strong south-westerly winds coincide with high spring tidal levels (range >9 m) generating extreme water levels. If the wind then veers to the west extreme wave conditions ($H_s > 2$ m) occur on top of the storm tide (Pye and Neal, 1994). Dune erosion poses a significant management problem. Property requires protection from flooding and erosion, while the natural habitat needs to be preserved. Through CoFEE and MICORE the Sefton Metropolitan Borough Council are using the best knowledge available for long-term (future) management planning (Esteves et al., 2009). To determine what storm conditions (wave and water levels combined) pose most threat to Sefton coast coupled modelling systems have been utilised (e.g. Brown et al., 2010).

The meteorological conditions during the storm of the 18th–19th January are used to investigate and improve wave modelling methods in Liverpool Bay. Both nearshore and offshore wave data are available for this event along with surge observations. This previously modelled and validated (Brown and Wolf, 2009) storm event was the result of a depression moving east to the north of the eastern Irish Sea. A veering south-westerly to westerly wind peaked at 22 m/s in this region. Such a storm provides extreme surge (2.23 m nearshore elevation) and wave (4.95 m offshore H_{m0}) conditions likely to cause significant dune erosion. This storm

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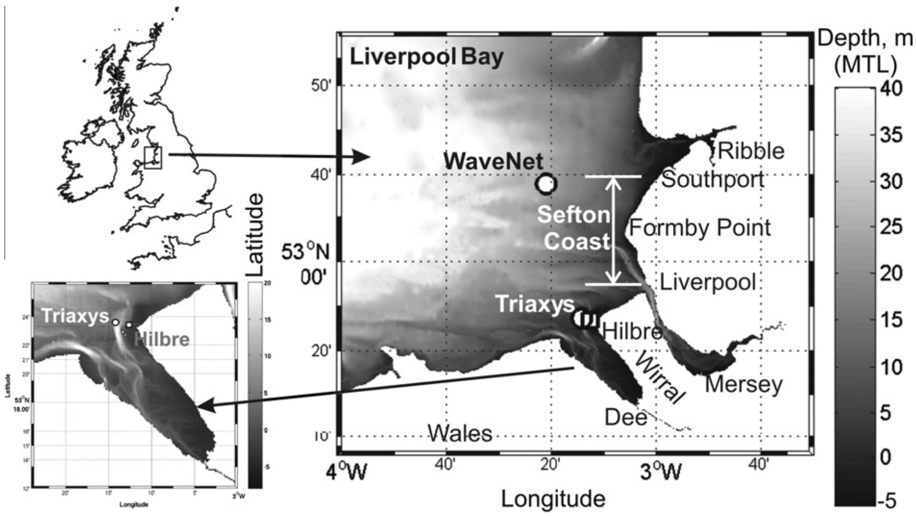

Fig. 1. Sefton coast situated in Liverpool Bay (UK). The model bathymetry is given below mean tidal level (MTL) and the wave buoy (○) and tide gauge locations (□) are shown.

event provides a good basis to assess model performance. Through the use of advanced modelling systems, a wave–surge hindcast has been performed for the shallow water conditions (<50 m) in Liverpool Bay (Fig. 1). This study area has significant tide–surge interaction (Woodworth and Blackman, 2002). The aim, here, is to assess the tide–surge–wave interaction. The accuracy of the global WAve Model (WAM, cycle 4) modified for shallow water (ProWAM) is examined both offshore and within the mouth of the Dee Estuary. To this end observations and the Simulating WAves Nearshore (SWAN, version 40.72) model have been used for validation purposes. SWAN has been used as a benchmark in addition to measurements as it is considered to be a state-of-the-art shallow water wave model. For ProWAM to be an acceptable shallow water model it must perform with at least a similar accuracy to that of SWAN. The main aim here is to verify whether POLCOMS–ProWAM performs well in coastal areas. This research assesses the effects of variable water levels and currents in ProWAM, and the importance of including radiation stress in POLCOMS when applied in shallow water. Further contributions to improve the predictive capability of ProWAM in this shallow water application include: modifying the limiter, a comparison of bottom friction expressions and the inclusion of a 3D current field in ProWAM. The effect of time varying elevation and current fields are found to be important in the modulation of the significant wave height nearshore, while the effect of wave-setup significantly enhances the peak surge and high water elevations. We focus on the significant wave height, wave-setup, surge elevation and total water elevation as these quantities are most important with regard to coastal defence management issues. Wave-setup describes the wave-induced increased sea level and surge describes the wind- and pressure-induced increase in sea level. Wave-setup can contribute up to 0.3 m of additional water level along the coastline in Liverpool Bay, especially within the estuaries (Wolf, 2008). In this study the surge component is defined as the water level in addition to the predicted astronomical tide due to meteorological forcing and tide–surge interaction (i.e. the total water level minus the predicted tidal level). Based on the POLCOMS–ProWAM model results, the spatial surge–wave-setup patterns and maxima in Liverpool Bay are quantified.

The coupled POLCOMS–ProWAM system has been under development at the Proudman Oceanographic Laboratory since 2002 (Wolf et al., 2002). Here, this system is further developed for application to a coastal 180 m Liverpool Bay model (Fig. 1). Model-data and model-model validations are performed for the wave related part of this modelling system to evaluate its performance when applied to shallow water. For this study period, coastal tide gauge data is available for the stations Hilbre, Liverpool and Heysham from the UK Tidal Network (http://www.bodc.ac.uk/data/online_delivery/ntslf/). Wave data is available from the offshore (23.0 – 30.4 m deep) Cefas WaveNet bouy (http://www.cefas.co.uk/data/wavenet.aspx) and the Coastal Observatory nearshore (<18 m deep) Triaxys buoy (http://cobs.pol.ac.uk/cobs/fixed/#WaveBuoy). We present results for the two wave buoys and the Hilbre tide gauge (<5 m deep), all located in Fig. 1. This allows validation of the performance of ProWAM close to the coast, which is the main aim of this manuscript, and allows assessment of the influence of wave-setup on the surge in shallow water. Model results from SWAN are used in addition to observation to determine where improvements in the ProWAM model are required. The model efficiencies are also examined to determine if ProWAM could be used operationally in a coastal application.

2. Modelling method

A high (180 m) resolution Liverpool Bay model has been used to developed a tide–surge–wave model for storm conditions in shallow water. For the hindcast storm event (18th January 2007) hourly wind and pressure data were provided by the UK Met Office North West European Continental Shelf (mesoscale) model (Fig. 2), with a resolution of 0.11° (∼12 km). This was used to force all of the models implemented. A 3 day simulation was performed from 17th January 2007 00:00, the first day was used to spin up the models so it is not presented in the results. The waves and surge in Liverpool Bay are affected by the conditions propagating from the Irish Sea, thus a nested model approach is needed. Since the opposite is not true, a 1-way nesting into the study area suffices (Fig. 2).

The surge generated externally to the eastern Irish Sea due to meteorological forcing is as equally as important in Liverpool Bay as the local surge (Jones and Davies, 1998). The wave field consists of local wind sea generated in the eastern Irish Sea. To include the external surge and any background swell the 180 m Liverpool Bay model was nested within the 1.8 km POLCOMS–ProWAM Irish Sea model, which in turn was nested into the 1/9° by 1/6° (∼12 km) operational Continental Shelf surge model (run at the National Oceanography Centre, Liverpool). The surge generated within the

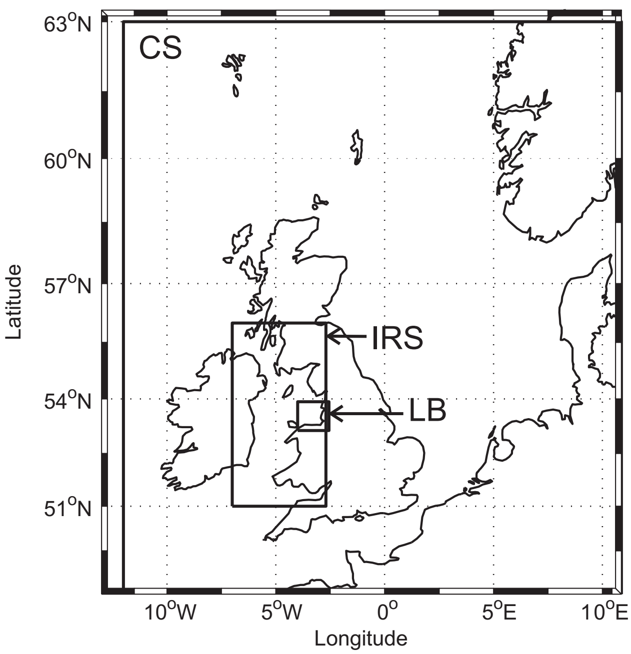

Fig. 2. The mesoscale model domain with the nested models embedded within it, where CS = the operational Continental Shelf model, IRS = the Irish Sea Model and LB = the Liverpool Bay model.

operational model (described in Flather (1994)) is the result of meteorological conditions and tide–surge interaction. In the Irish Sea model, waves influence the surge through 2-way coupling between POLCOMS and ProWAM via the bottom and surface roughness lengths (see Section 2.3). The influence of waves is extended here by including wave-setup within the Liverpool Bay model. The operational surge model provided total (tide plus surge) hourly elevation and velocity boundary forcing, while the Irish Sea model provided half hourly hydrodynamic boundary forcing and hourly wave forcing.

At the highest resolution all models are setup on the same numerical grid as POLCOMS to enable efficient model coupling. The grid consists of a regular rectilinear grid with 180 m spacing in both directions. When uncoupled the mean (still) water depth from POLCOMS was used in the wave model (see Fig. 1) and no current velocities were included. POLCOMS–ProWAM and POLCOMS–SWAN were coupled in a 1-way manner so that the hydrodynamics could influence the waves. The results have been used to improve the ProWAM simulation close to the coast. Comparable model settings to those in ProWAM have been activated in SWAN to facility model-model assessment. For the POLCOMS–ProWAM system 2-way coupling is also included so that the hydrodynamics can influence the waves which in turn influence the hydrodynamics. An assessment of the contribution of wave-setup can then be achieved in addition to the increase in water level due to the meteorological forced surge interacting with the tide.

To assess the models performance the model output, m, is compared with observation, o, over a time series of data points, i, output at 30 min intervals for surge and hourly intervals for waves. Three error metrics are applied as follows: the root mean square error (*RMS error*):

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

the mean percentage error (*MP error*):

$$MP = \frac{100\sum_{i=1}^{n}\frac{m_i - o_i}{o_i}}{n} \tag{2}$$

and the percentage bias of the peak (maximum value) in the wave or surge event, denoted by ^, (*PB*):

$$PB = 100\frac{(\hat{m} - \hat{o})}{\hat{o}}. \tag{3}$$

The error metrics are calculated over 1 day for the surge event (18th 00:00–19th 00:00 January) and over two days (18th 00:00–20th 00:00 January) for the wave event. The longer period for waves allows tidal modulation effects to be included.

2.1. POLCOMS

Here, the Liverpool Bay POLCOMS model provides current and elevation information to both wave models through 1-way coupling. The model is also coupled in a 2-way system to ProWAM to allow wave-setup to be included in addition to the surge resulting from meteorological forcing. The 3D POLCOMS model (Holt and James, 2001) is used to simulate the tides and surge within Liverpool Bay. The model is formulated in spherical polar coordinates on a B-grid with a terrain following (sigma) coordinate system in the vertical. The computational grid is staggered, scalars are calculated at the corners of each grid box (grid points) while vector quantities (fluxes) are computed centrally within each grid box. The horizontal grid resolution applied to Liverpool Bay was 180 m, in the vertical 12 levels were implemented and a 3 s time step was used. POLCOMS can simulate both the barotropic and baroclinic processes, which arise from the tides, meteorological and riverine forcing. Density effects have not been included here. The turbulence closure scheme used is that of Mellor and Yamada (1982) and has been modified to account for surface wave breaking (Craig and Banner, 1994). POLCOMS includes a 'wetting and drying' scheme so drying areas are excluded from the model computation; this feature has been implemented here in the coupled ProWAM for use on Liverpool Bay. The minimum depth considered to be 'wet' was set to 0.02 m in POLCOMS to provide elevation information to both wave models.

In both the Irish Sea and Liverpool Bay model 2-way coupling between POLCOMS–ProWAM (Osuna and Wolf, 2005) incorporates tide–surge–wave interaction at different levels. For the Irish Sea model the wave-interaction is through bottom friction and surface roughness (Wolf et al., 2002). This has been developed further to include radiation stress and apply it in this model application for Liverpool Bay.

In POLCOMS the method of Charnock (1955) is used in the surge simulation to represent the surface roughness with a constant value tuned for optimum results. A constant value of 0.0185 is used here for the eastern Irish Sea (see Brown and Wolf, 2009). When coupled to ProWAM waves influence the surface roughness through a wave related Charnock parameter (Janssen, 2004). The presence of waves increases the surface wind stress, which is important for accurate surge generation. Wave–current bottom friction is calculated in ProWAM using Madsen's (1994) method, the bottom roughness is then imposed within POLCOMS. Waves enhance the bottom roughness increasing the frictional influence on the current field. Without wave influence a constant bottom roughness length, with a default value of 0.003 m in Liverpool Bay, is used. Recently, 3D radiation stress and stokes drift have been added within the coupled model (Bolaños et al., 2008). The radiation stress has been included in this investigation to allow the effects of wave-setup to be studied. This stress results from gradients in the excess momentum flux due to the presence of waves and it locally generates wave-induced currents modifying the tide–surge current field. In deep water radiation stress is negligible compared with the wind stress, but in shallow locations radiation stress becomes important and cannot be neglected as it may contribute significantly to the total water level during a storm surge (e.g. Mastenbroek et al., 1993).

The 2-way coupling between POLCOMS–ProWAM has been included so that the performance of POLCOMS can be verified when wave generated stresses are included. In addition, this enables the importance of wave-setup during a storm event to be investigated within Liverpool Bay. The 2-way coupling between POLCOMS–SWAN is not investigated since the focus is on improving the performance of POLCOMS–ProWAM in coastal waters.

2.2. SWAN

SWAN is a state-of-the-art shallow water model (Booij et al., 1999) developed for accurate wave simulation in high resolution coastal regions, e.g. spatial scales <30 km and depths <30 m, but can also be applied for large scale deep water applications. An unstructured grid option (Zijlema, 2010) allows high coastal resolution to be embedded within a large domain for efficient computations, without the need for model nesting. SWAN's numerical efficiency in shallow water, in addition to the low 0.05 m minimum depth limit, makes this model very suitable in this and other coastal applications. In SWAN the minimum water depth is applied to (de)activate a grid point, i.e. to make it wet and dry. Here, SWAN is used in non-stationary mode to produce a reference set of results. These results are used to assess and improve the performance of ProWAM in the presence of time varying elevations, currents and winds in shallow water. We therefore use the same nested Liverpool Bay model grid, bathymetry, wind forcing and boundary conditions as applied in POLCOMS and ProWAM.

This 3rd generation wave model has been set up using the present default settings (unless otherwise stated below) to include wind generation, whitecapping, quadruplet wave–wave interaction, bottom friction and depth-induced breaking. The exponential wind growth was simulated by Komen et al. (1984) and not Janssen (1991) as in ProWAM. The Janssen (1991) method in SWAN 40.72 was found to never converge, unlike SWAN 40.51 when applied to Liverpool Bay in non-stationary mode. It was assumed that version 40.72 should be better than 40.52 so the newer version was used. Following the 40.72 user manual, in the results presented, the Komen setting is applied consisting of the Komen et al. (1984) whitecapping formulation and a modified Snyder et al. (1981) wind input term. Depth-induced breaking is simulated by the Battjes and Janssen (1978) method using a constant breaker parameter (the maximum individual wave height to depth ratio). Battjes and Stive (1985) re-analysed laboratory and field data for a range of bathymetries to find an average breaker parameter of 0.73 was an appropriate constant value, this is the default value in SWAN, which is used here. SWAN solves the spectral balance of action density and accounts also for refractive propagation due to bathymetry and currents. When run as part of the POLCOMS–SWAN coupled system the time varying depths and depth-averaged currents are provided every 30 min. The bottom friction is implemented as a choice of wave-alone formulations, even when currents are included. This was motivated by the unsystematic results found by Tolman (1992) for the influence of currents on wave-induced bottom friction. Here the default JONSWAP model (Hasselmann et al., 1973) was used as it gives good results in very shallow water (Booij et al., 1999) and is also available in ProWAM. The constant bottom friction coefficient applied takes a default wind sea value (0.067 $m^2\ s^{-3}$) in SWAN, but a lower swell wave value (0.038 $m^2\ s^{-3}$) in ProWAM. The efficient computation of SWAN allowed quick comparison of both settings, demonstrating the swell wave setting to yield more accurate wave heights in the Dee Estuary under storm conditions. The swell wave setting was therefore imposed in both models. This is discussed further in Section 4.1. SWAN also includes the following shallow water effects: depth-induced breaking, triad wave–wave interaction and wave-setup. Apart from triad wave–wave interaction, which is unavailable in ProWAM, these shallow water terms have been activated. Initial model tests in Liverpool Bay found triad interaction had little effect on the wave simulation at the Triaxys location as found by Wornom et al. (2001).

SWAN is very similar to ProWAM, but is much more efficient in shallow water through the use of an implicit scheme, which is solved iteratively. SWAN was set up over the same Liverpool Bay model grid and bathymetry as used in POLCOMS–ProWAM (see Section 2). The model was driven by boundary conditions provided by the coupled Irish Sea ProWAM model, as was the Liverpool Bay ProWAM model, and local winds, again we use the mesoscale wind forcing (Fig. 2). The POLCOMS Liverpool Bay model was used in a 1-way coupled approach, to provide the time varying depth and current fields every half hour to SWAN. To allow time varying winds and hydrodynamics the model was run in non-stationary mode with a 15 min time step following an initial stationary simulation to spin up the initial conditions. The default gradient convergence criterion was applied. The default number of maximum iterations per time step (1) and limiter constant (0.1), determining the maximum change in energy spectra per iteration, where applied. This is a similar setup to the reference run in the sensitivity study of SWAN performed by Claessens et al. (2002). Although they found the default numeric's with 20 min time step caused SWAN to respond too slowly to the passage of a frontal system, in this study with slightly reduced time step SWAN performs well offshore and within the estuary region. The default limiter setting applied in SWAN to prevent numerical instability (Booij et al., 1999), did not hamper tidal modulation on the modelled significant wave heights within the Dee, and so was left unchanged.

Although SWAN can be implemented in parallel it was used in serial over Cartesian coordinates for the best approximation of wave-setup, this had no affect on the significant wave height simulation when the boundary conditions were provided in spherical coordinates from ProWAM. Calculation of wave-setup is only a 2D approximation and does not account for all effects of current velocity. This approximation is for the open coast where the setup continues to increase towards the shore and is therefore inaccurate within the estuary interior.

2.3. ProWAM

WAM, a state-of-the-art 3rd generation spectral model (Komen et al., 1994), modified for shallow water applications (ProWAM, Monbaliu et al., 2000) has been applied to the Irish Sea and Liverpool Bay. The shallow water modifications include time varying current and depth fields, which refract the waves, depth-induced breaking (Battjes and Janssen, 1978) and the introduction of a wave–current bottom friction (e.g. Madsen, 1994). Changes to the model numeric's were also introduced allowing high resolution applications. For the Liverpool Bay application ProWAM simulates the 2D wave spectral evolution considering energy input by wind, energy dissipation by whitecapping, bottom friction and depth-induced breaking, and non-linear quadruplet wave–wave interactions. The inclusion of the wetting and drying scheme within the Liverpool Bay POLCOMS model is required for accurate simulation within its estuaries and along its coast. To correctly simulate the nearshore wave field in this study the wetting and drying scheme was also implemented in the coupled ProWAM model.

For this shallow water application a 3 s propagation and 1 s source term time step were implemented for stable computation in the shallow areas over the 180 m grid (described in Section 2). The Battjes and Janssen (1978) depth-induced breaking procedures in ProWAM apply a constant breaker parameter of 0.8 based on Miche's criterion. This was reduced in this study to match the chosen value in SWAN, of 0.73. When coupled to POLCOMS, ProWAM uses (spatially and temporally interpolated) wind forcing in addition to current and depth fields provided via the surge model (see Osuna and Wolf, 2005). For this study the exchange of information between POLCOMS and ProWAM occurs every 30s. In the uncoupled model the wind forcing and mean water level is imposed directly into ProWAM. In this application the coupled setup uses the method of Madsen (1994) and the bottom current velocity from POLCOMS to account for wave–current effects on bottom friction; otherwise the method of Madsen et al. (1988) is used for uncoupled (wave-alone) ProWAM simulations. This enhances the bottom roughness increasing the frictional influence on the current field and the wave field. The Doppler velocity modifies the wave dispersion due to variable current fields in the coupled setup only. The depth-averaged current field is provided by POLCOMS to include the Doppler effect (see Ozer et al., 2000). Wave refraction in the coupled model is simulated due to the time varying current and depth fields (Wolf et al., 2002). For the uncoupled case the mean water depth is used to determine refraction due to the topography alone. ProWAM was modified to use a 3D current field and also to provide the radiation stress at each vertical model level to POLCOMS (for details see Mellor, 2003). The 3D current allowed the Doppler shift and the current dependent wave refraction to be computed using the current profile, vertically-integrated over a depth depending on the wave's frequency, instead of using the depth-average current (Mellor, 2003). Implementing the 3D current in ProWAM (Bolaños et al., 2008) has removed the problem of which current level (e.g. surface) to use to refract the waves or whether the depth-average current should be used. Before the implementation of the 3D code in ProWAM for this study the depth-average current was used in both SWAN and ProWAM.

Modifications to ProWAM were required in this study for accurate simulation within the shallow (<18 m) estuaries in Liverpool Bay. Although the model was stable and ran using a 3 s propagation time step and 1 s source term time step, when coupled to POLCOMS the tidal modulation of the significant wave height within the Dee was lost. To ensure numerical stability ProWAM applies a limiter to the high frequency end of the growth spectrum (Hersbach and Janssen, 1999; Monbaliu et al., 2000). Offshore ProWAM produced a good simulation of the significant wave height, with an *RMS error* of 0.44 m, when coupled to POLCOMS (Fig. 3a). Nearshore the default limiter restricted the rate of change of the wave spectrum, preventing tidal modulation of the waves (Fig. 3b). ProWAM allows the limiter to only be applied to the highest frequencies, a suggested level of application is to frequencies >0.25 Hz (Monbaliu et al., 2000). For a small enough time step a limiter is not required (Hargreaves and Annan, 2001; Monbaliu et al., 2000). Since ProWAM runs in near real time for this high resolution application reducing the time step was not economical. A proper frequency level to determine when the limiter would be applied for dynamic coastal situations was therefore sought after. For this application applying the limiter to frequencies >0.3 Hz was found to maintain numerical stability and greatly improved the tidal modulation of the modelled significant wave height nearshore with small effect, 2.34% increase in percentage error of the peak value, offshore (Fig. 3). The relaxed limiter allowed a faster change in the spectral density. When applied to this study the initial increase in significant wave height occurs later, but much more rapidly. This is seen in Fig. 3 as the steeper line gradient when the relaxed limiter is included (filled dots) compared with when it is not (open squares). In the nearshore tidally varying depths cause rapid modulation of the significant wave height. The effect of the limiter is mainly visible nearshore with falling tides (e.g. Fig. 3b between days 18.6 and 18.8 and between days 19.1 and 19.3). Without the relaxed limiter the variations (line gradients in Fig. 3b) are similar to those offshore, where the tidal elevations have less influence on the total depth.

Finally the bottom friction formulation was assessed. A method accounting for wave–current interaction (Madsen, 1994) and a wave-alone method (Hasselmann et al., 1973), as activated in

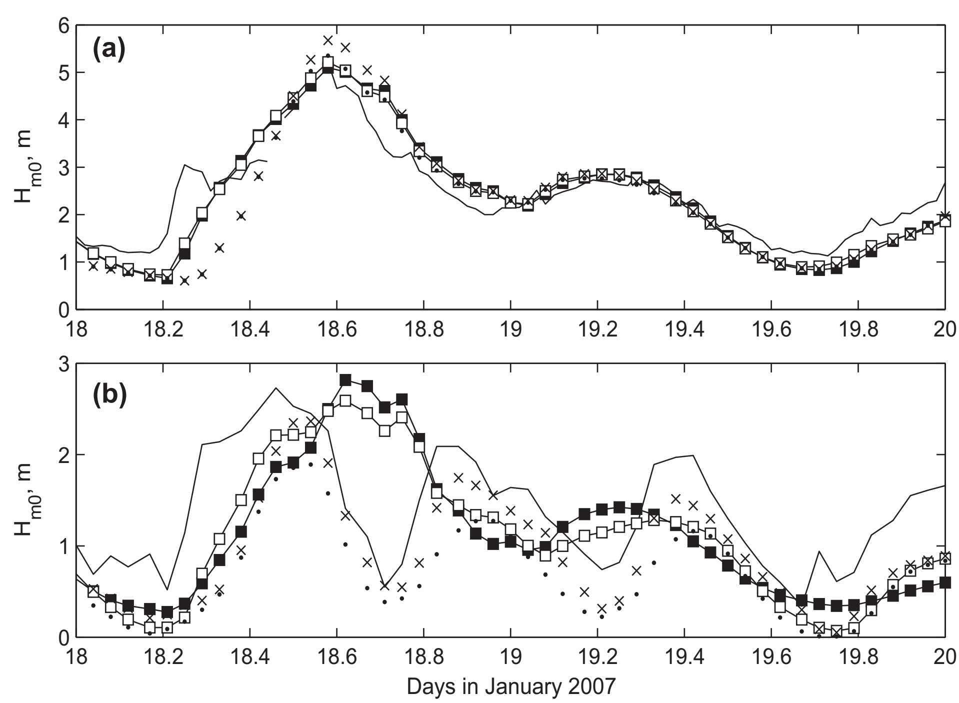

Fig. 3. The offshore (a) and nearshore (b) significant wave height observations (solid line) compared with the uncoupled ProWAM hindcast with reduced JONSWAP bottom friction (line with filled square symbols), the 1-way coupled POLCOMS–ProWAM hindcast with wave–current bottom friction (line with unfilled square symbols), the 1-way coupled POLCOMS–ProWAM hindcast with relaxed limiter (filled dots) and also with reduced JONSWAP bottom friction (crosses). The measured offshore data is unavailable just before the peak in significant wave height, shown by the break in the line.

SWAN, have been implemented. The constant bottom friction coefficient applied in the wave-alone formulation is set, as recommended by Hasselmann et al. (1973), for swell wave conditions ($0.038\ m^2\ s^{-3}$) in ProWAM. In the nearshore the bottom stress can be significantly enhanced by wave–current interaction. Rosales et al. (2008) have shown the Christoffersen and Jonsson (1985) wave–current method can result in double the bottom stress predicted by the Hasselmann et al. (1973) wave-alone formula. Therefore a wave-alone and a wave–current method have been used in ProWAM when coupled to POLCOMS to determine which procedure is most appropriate in the nearshore and offshore. The Madsen (1994) method is chosen over the Christoffersen and Jonsson (1985) method since it is not related to a single wave period (Monbaliu et al., 2000).

3. Local wind forcing

Observation from the meteorological station located on Hilbre Island enables validation of the mesoscale wind forcing interpolated within POLCOMS to the nearest grid point to the Triaxys buoy location. Locally in Liverpool Bay the wind is important in surge and wave generation. The external surge will however, also be affected by the atmospheric pressure forcing. For the Liverpool Bay model the wind speed has an *RMS error* of 2.38m/s and the direction has an *RMS error* of 15.05°. Compared with the variability in the data (Fig. 4) these errors are significant, an error in the wave prediction is therefore expected. Smoothing of the variability in speed due to the time resolution also occurs, e.g. the spike in the data at ~18.3 days is lost (Fig. 4a). The magnitude is over predicted by on average 29% (Fig. 4a), especially for the period after the peak in surge (day 18.6–19.6), which causes the duration of the surge to be overestimated. Sensitivity tests using SWAN found that a 10% increase in wind speed caused an average increase of 9.47% in the significant wave height offshore. This increase is greatest during the peak of the storm (day 18.5–19.5). Nearshore an average increase in the significant wave height of 5.59% occurs. This increase mainly occurs during the peaks in the tidal modulation of the wave height.

Any error in the wind direction could have significant impact on the wave heights within the Dee, due to the angle of the wind acting on short fetches between shallow banks and Hilbre Island. The modelled wind initially has a stronger southerly component (day 18.0–18.2, Fig. 4b) than that observed. The modelled wind direction therefore has shorter fetch across the estuary, which has a southeast alignment, than the observed wind causing the model to under predict the estuary generated waves at the onset of the storm (day 18.0–18.2, Fig. 3b). This initial under prediction in significant wave heights could prevent the initial peak in significant wave height being modelled at the correct time. An increased spatial discretisation within the Dee may also be required to resolve the channel–bank system.

4. Results

4.1. Sensitivity to the modified limiter and bottom friction

The performance of the ProWAM simulation with different model settings is presented in Table 1. Nearshore the 1-way coupled ProWAM results were slightly modified by the tidal signal but not significantly until the limiter was modified as described in Section 2.3 (Fig. 3). In the nearshore ProWAM with modified limiter under predicted the peak in significant wave heights compared with standard ProWAM (Fig. 3b). When the bottom friction was based on the wave-alone JONSWAP relation, with swell coefficient, rather than a wave–current method the peaks in the modulated significant wave heights improved (Table 1, giving the result presented in Fig. 3b). Offshore, this modification led to the over prediction of the peak significant wave heights (Fig. 3a). In this hindcast event the lower JONSWAP friction coefficient of $0.038\ m^2\ s^{-3}$, which is recommended for swell conditions (Hasselmann et al., 1973), performs better within an estuary than the recommended coefficient of $0.067\ m^2\ s^{-3}$ for wind sea conditions

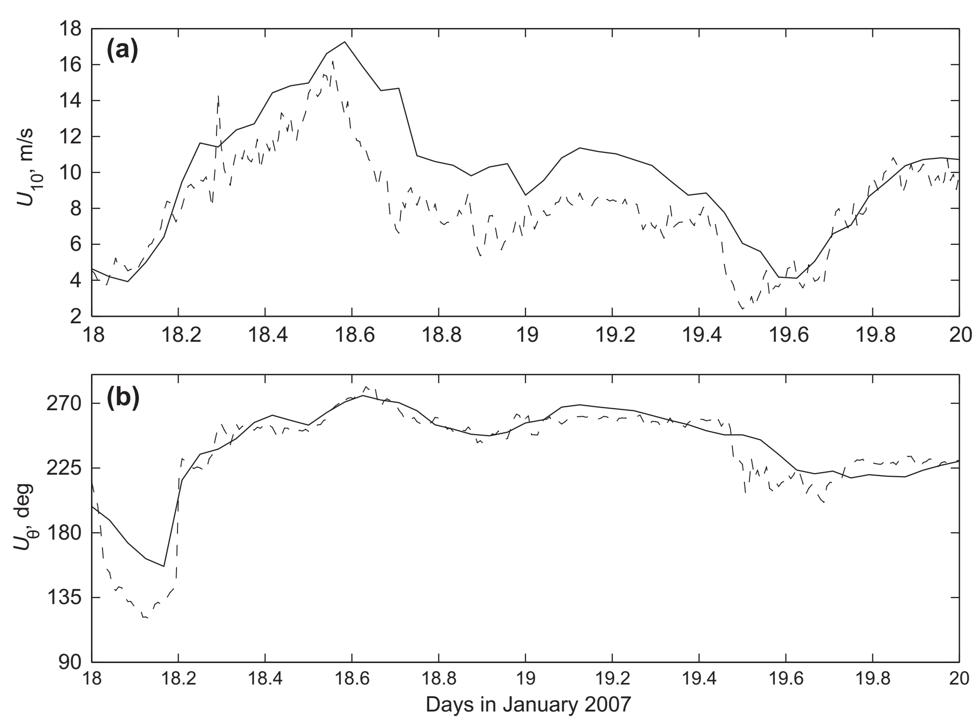

Fig. 4. (a) The wind speed at 10 m and (b) the wind direction (nautical conversion) observed at Hilbre Island (dashed line) and interpolated to the Triaxys buoy location from the Mesoscale model by POLCOMS (solid line).

Table 1
Quantification of the model error for the significant wave height, H_{m0}, compared with observation at the two wave buoy locations for the 18th 00:00–20th 00:00 January 2007. POLCOMS (*P*) is coupled in 1-way to both ProWAM (*W*) and SWAN (*S*). A Madsen wave–current or Madsen wave-alone bottom friction is used in ProWAM and the reduced JONSWAP bottom friction in SWAN. For ProWAM the relaxed limiter (+*L*) and reduced JONSWAP bottom friction (+*F*) have also been included in additional simulations.

Simulation	*RMS error* (m)		*MP error* (%)		*PB* (%)	
	WaveNet	Triaxys	WaveNet	Triaxys	WaveNet	Triaxys
P–W	0.48	0.59	−17.65	−53.54	−0.13	−5.11
P–W + L	0.66	0.79	−22.20	−55.80	2.47	−30.73
P–W + L + F	0.71	0.60	−23.76	−36.62	8.67	−13.37
P–S	0.46	0.50	−13.66	−30.49	−5.11	−13.49
W	0.52	0.81	−18.76	−56.81	−2.35	3.16
S	0.46	0.63	−13.44	−40.62	−9.16	−45.03

Table 3
Quantification of the model error for the peak wave period, T_p, compared with observation at the two wave buoy locations for the 18th 00:00–20th 00:00 January 2007. POLCOMS (*P*) is coupled in 1-way to both ProWAM (*W*) and SWAN (*S*). A Madsen wave–current or Madsen wave-alone bottom friction is used in ProWAM and the reduced JONSWAP bottom friction in SWAN. For ProWAM the relaxed limiter (+*L*) and JONSWAP bottom friction (+*F*) have also been included in additional simulations. The *PB* value is to be treated with caution since there are no distinct peaks in the observation due to the poor quality of the data.

Simulation	*RMS error* (s)		*MP error* (%)		*PB* (%)	
	WaveNet	Triaxys	WaveNet	Triaxys	WaveNet	Triaxys
P–W	2.47	1.49	−33.70	−38.27	−34.94	−18.84
P–W + L	2.45	2.05	−32.39	−39.30	−29.98	−42.94
P–W + L + F	2.33	1.62	−31.10	−33.29	−26.77	−23.21
P–S	1.04	0.84	−12.80	−16.91	−20.82	−11.14
W	2.51	1.62	−33.31	−34.33	−40.66	−23.48
S	1.01	1.54	−11.89	−31.30	−20.82	−2.19

(Bouws and Komen, 1983). A possible reason (related to the wind errors) has been suggested in Section 3. Table 2 shows the SWAN performance, using Eqs. (1)–(3), with different bottom friction coefficients. Offshore the lower value improves the peak in the hindcast but the general over prediction of the significant wave height is increased. In the nearshore the lower value performs better for all three error metrics. At this location the troughs in time variation of the significant wave height are similar with both friction coefficients. This is likely to be a consequence of the lower tidal levels at this time causing depth-induced breaking to dominate. However, the lower value noticeably improved the peak values (during high tidal levels) and therefore the range in significant wave height in response to tidal modulation. This gives a more accurate hindcast of the overall period and the peak values.

4.2. Uncoupled versus coupled models

The model performance, assessed using Eqs. (1)–(3), is given for different model set ups in Table 1 and 3. In the uncoupled wave model simulations ProWAM outperforms SWAN offshore and nearshore at predicting the peak in significant wave height (Fig. 5). However SWAN has a smaller error when considering the full time period. Offshore there is less noticeable tidal modulation in the significant wave heights (Fig. 5a) and the uncoupled models perform well compared with the coupled systems. In the nearshore a strong tidal signal is present in the observed significant wave height (Fig. 5b). Without coupling neither model has any tidal modulation in the nearshore, ProWAM seems to capture the peak significant wave height, whereas SWAN significantly under predicts the significant wave heights. For both the uncoupled ProWAM and SWAN models the nearshore significant wave heights are a scaled down version of the offshore conditions.

When coupled in 1-way to POLCOMS the nearshore wave simulations improved (Table 1, Fig. 5a). The SWAN significant wave heights are enhanced and tidally modulated. Simulations with and without currents concluded that the modulation was mainly a result of tidal elevation. Offshore (Fig. 5a), the coupling of the hydrodynamic and wave models had little effect on the results. The use of a vertically-integrated 3D current field allowing the inclusion of the Doppler shift effect on each wave frequency slightly improved the offshore wave hindcast, while slightly reducing the accuracy of the nearshore hindcast.

The over predictions in the offshore significant wave height for uncoupled and coupled models (Fig. 5a) may be accounted for by the overestimation in the wind speed (Fig. 4a). However in the nearshore the significant wave height is under predicted. This implies that the balance between energy input and loss in the activated model source terms becomes less accurate in shallow water. The need to reduce the energy loss may explain the need for a reduced bottom friction coefficient in shallow water.

The modelled offshore and nearshore peak wave period, T_p, (Fig. 6) were less accurate (Table 3) than the modelled significant wave height (Table 1). T_{m02} is sensitive to wind speed and the high frequency cut-off of discrete spectra, so it is not a robust parameter for model validation. Due to discrepancies in integration ranges to compute the mean absolute wave period, T_{m02}, between the model and observation the peak wave period, T_p, has been used here for validation. T_p can be an unstable parameter to use because the peak can irregularly change frequency for multi-modal spectra (Krogstad et al., 1999). However, this parameter is used here due to limited wave period data (T_{m02} or T_p) at these locations. Unfortunately, in the nearshore the observations are of poor quality limiting validation. When coupled in 1-way to POLCOMS, SWAN quite accurately predicts the peak wave period, while ProWAM consistently under predicts it (Fig. 6). The effect of the relaxed limiter and reduced JONSWAP friction is greater in the nearshore. Relaxing the limiter leads to a worse hindcast nearshore and better hindcast offshore (Table 3). The wave-alone (reduced JONSWAP) bottom friction improves the modified limiter ProWAM hindcast (crossed line in Fig. 6) both offshore and nearshore (Table 3). SWAN is found to produce a better hindcast of this wave parameter than ProWAM.

The errors in the meteorologically forced surge hindcast by POLCOMS and the combined meteorological surge and wave-setup hindcast by the 2-way coupled models are quantified in Table 4. The measured surge is the additional water level on top of the astronomical tide due to meteorological and wave forcing with any tide–surge–wave interaction included. The surge elevation at the Hilbre tide gauge is approximately the same for the POLCOMS alone and POLCOMS–ProWAM model (Fig. 7). This is a conse-

Table 2
Quantification of the SWAN model error for the significant wave height, H_{m0}, compared with observation at the two wave buoy locations for the 18th 00:00–20th 00:00 January 2007. The JONSWAP bottom friction coefficient is set to suggested values for wind sea (0.067 $m^2\,s^{-3}$) and swell waves (0.038 $m^2\,s^{-3}$).

Friction coefficient ($m^2\,s^{-3}$)	*RMS error* (m)		*MP error* (%)		*PB* (%)	
	WaveNet	Triaxys	WaveNet	Triaxys	WaveNet	Triaxys
0.038	0.46	0.50	−13.66	−30.49	−5.11	−13.49
0.067	0.45	0.55	−13.23	−35.17	−6.69	−16.68

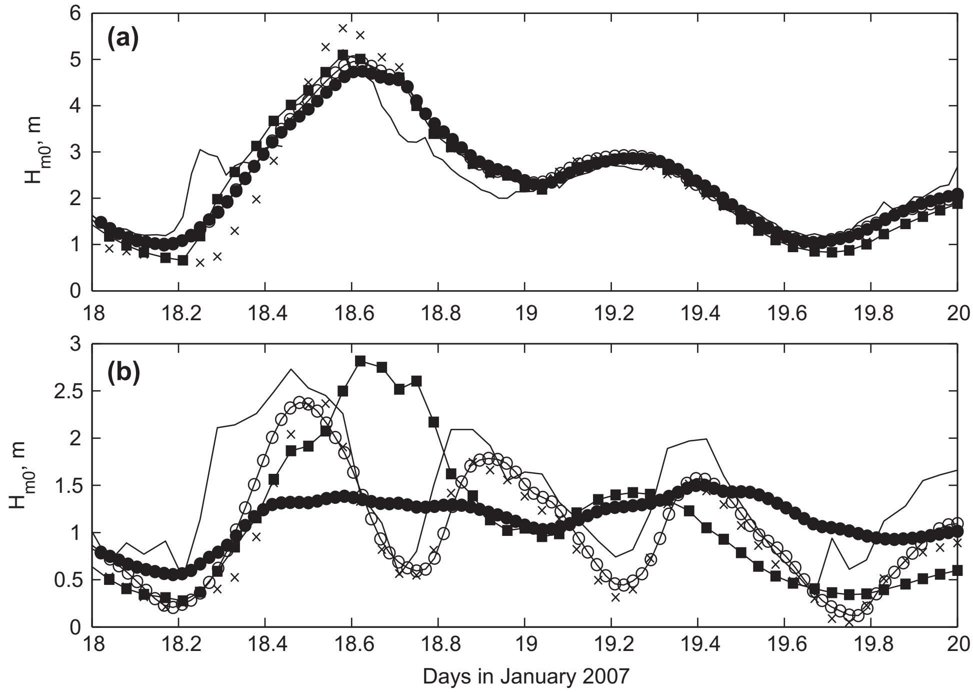

Fig. 5. The offshore (a) and nearshore (b) significant wave height, H_{m0}, observations (solid line) compared with the 1-way coupled POLCOMS–ProWAM with relaxed limiter hindcast and reduced JONSWAP bottom friction (crosses), the 1-way coupled POLCOMS–SWAN hindcast with reduced JONSWAP bottom friction (line with unfilled circle symbols), the uncoupled ProWAM hindcast with Madsen wave-alone bottom friction (line with filled square symbols) and the uncoupled SWAN hindcast with reduced JONSWAP bottom friction (line with filled circle symbols).

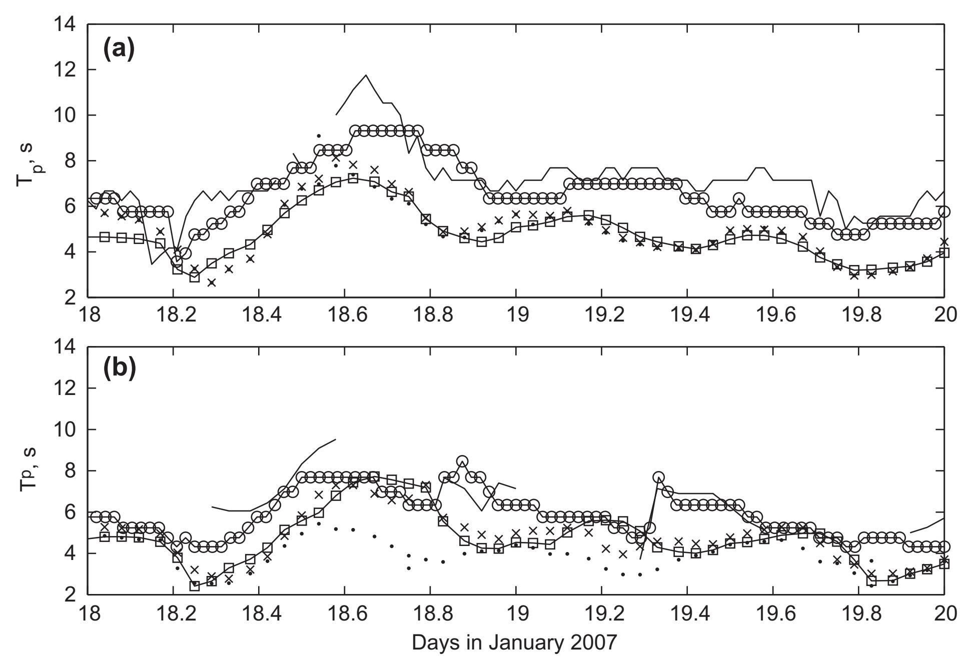

Fig. 6. The offshore (a) and nearshore (b) peak wave period, T_p, (solid line) compared with the 1-way coupled POLCOMS–ProWAM hindcast with wave–current bottom friction (line with square symbols) the 1-way coupled POLCOMS–SWAN hindcast with reduced JONSWAP bottom friction (line with circle symbols), the 1-way coupled POLCOMS–ProWAM hindcast with relaxed limiter (filled dots) and also the reduced JONSWAP bottom friction (crosses).

quence of local surge generation within Liverpool Bay having little impact in addition to the external surge from the eastern Irish Sea, i.e. the boundary conditions dominate the surge hindcast. However when radiation stress is included, to account for the additional effect of wave-setup, the peak surge is significantly enhanced (by 12% ∼26 cm) to a value similar to that observed, although its occurrence is too early (Fig. 7). This time shift is caused by the inclusion of 3D radiation stress. Spatial gradients in the wave field generate this stress, the time shift is therefore likely to be due to errors in the growth of the initial peak in the modelled significant wave height compared with observation (day 18.2–18.5, Fig. 5b). The relaxed limiter condition and wave-alone reduced JONSWAP bottom fiction have little influence on the surge prediction, although the smallest bias in the peak surge magnitude is obtained

Table 4
Quantification of the model error for the surge elevation compared with observation at Hilbre for the 18th 00:00–19th 00:00 January 2007. POLCOMS (*P*) is coupled in 2-way to ProWAM (*W*), while the SWAN (*S*) wave-setup is linearly added to the POLCOMS hindcast. A Madsen wave–current bottom friction is used in ProWAM and the reduced JONSWAP bottom friction in SWAN. For ProWAM the relaxed limiter (+*L*) and JONSWAP bottom friction (+*F*) have also been included in additional simulations. In the POLCOMS only simulation and the initial POLCOMS–ProWAM model radiation stress (−RS) was not included in POLCOMS.

Simulation	*RMS error* (m)	*MP error* (%)	*PB* (%)
P alone	0.24	−92.33	−13.30
P–*W* − RS	0.24	−93.40	−12.10
P–*W*	0.24	−93.14	−0.64
P–*W* + *L*	0.25	−93.73	1.00
P–*W* + *L* + *F*	0.25	−95.05	−0.07
P–*S*	0.25	−96.25	−8.72

with this set up (crosses, Fig. 7). Thus, this model approach gives a good nearshore tide–surge–wave hindcast (Fig. 7). The SWAN wave-setup hindcast was linearly added to the POLCOMS surge prediction (Fig. 8). The SWAN approximation for wave-setup performs well compared with observation (Table 4) and the 2-way coupled POLCOMS–ProWAM model in the mouth of the Dee Estuary. The timing in the surge peak is better than that simulated by ProWAM, most likely in consequence to the different 2D radiation stress approximation and the fact wave-setup is being linearly added to the surge and not interacting with the tide and surge as it does in the 2-way coupled 3D POLCOMS–ProWAM model. POLCOMS–SWAN also, more accurately predicted the timing and initial growth of the peak in significant wave height. Overall, the POLCOMS–ProWAM model however, gives a slightly better hindcast of the magnitude of the peak surge elevation and the duration (width) of the surge event than POLCOMS–SWAN (Table 4).

The overestimated local wind speed (Fig. 4a), did not lead to an over prediction of the surge elevation. This is most likely due to surges in the Irish Sea being principally caused by external surges propagating into the Irish Sea. In the eastern Irish Sea the inverse barometer effect also contributes more to the surge level than the wind effect. Additionally, in the eastern Irish Sea the local wind only contributes to 36% of the total wind driven surge component (Olbert and Hartnett, 2010).

4.3. Spatial wave and surge POLCOMS–ProWAM model results

ProWAM has been used to investigate wave-setup during the storm event across the region (Fig. 9). A large wave-setup (0.2–1.0 m) was hindcast across the coastal region at high water (Fig. 9a). The wave-setup was largest in the Ribble Estuary area due to greater wave activity in this region (Fig. 9b). Without regional observations the modelled wave-setup in this area cannot be validated. Such observations would be valuable in this area for future research, as it noticeably contributes to the water levels. The wave-setup was less (<0.3 m) during low water (Fig. 9c), a result of reduced wave activity within the lower estuaries (Fig. 9d). At low water the wave-setup was confined to the wet channels within the estuaries (see the Mersey, Fig. 8c) due to the wetting and drying scheme. At all stages of the tide the wave-setup decreased with distance into the estuary. This is in response to attenuated wave activity in the upper estuary.

The 2-way coupling between POLCOMS–ProWAM prevents numerical instability occurring over drying banks as depths tend towards zero and also allows wave-setup to be accurately hindcast within an estuary environment, since the POLCOMS model can simulate flow in response to the wave-induced stresses. SWAN cannot accurately simulate setup within the estuary interior as the approximations are only valid for the open coast.

The maximum value of flood risk parameters (wave-setup, surge, surge plus setup, total high water elevation, skew surge and significant wave height) at each grid point over the 2 day storm event are shown in Fig. 10. An important parameter in flood risk is the skew surge, which is the additional water level experi-

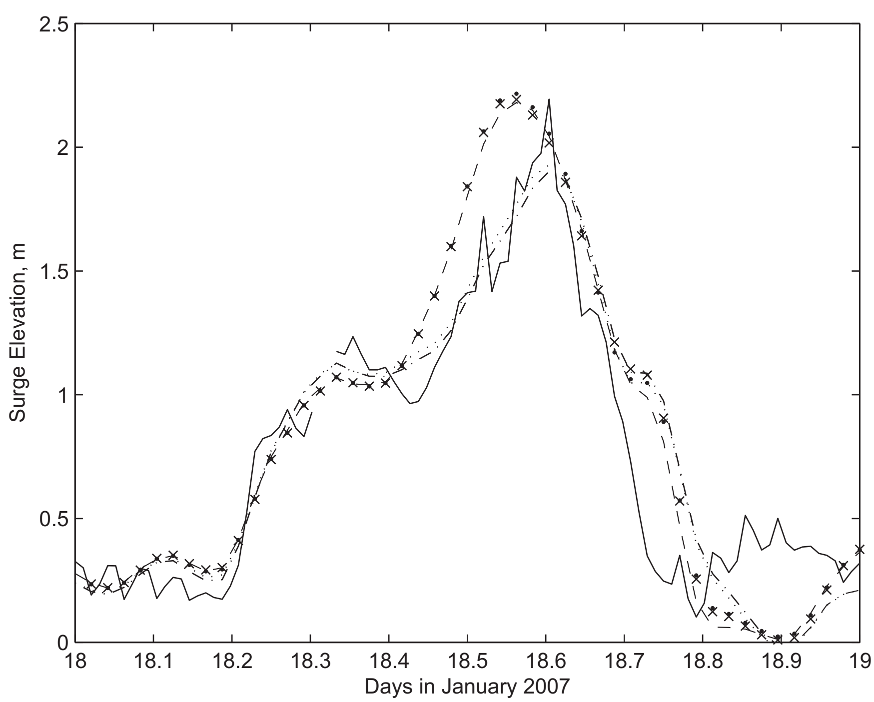

Fig. 7. The observed surge at Hilbre (solid line) and the modelled hindcasts for the following model set ups: POLCOMS with current-alone bottom friction (dash dot line), 2-way coupled POLCOMS–ProWAM with wave–current bottom friction (dotted line), 2-way coupled POLCOMS–ProWAM with radiation stress and wave–current bottom friction (dashed line), 2-way coupled POLCOMS–ProWAM with radiation stress, relaxed limiter and wave–current bottom friction (dots) and 2-way coupled POLCOMS–ProWAM with radiation stress, a relaxed limiter and reduced JONSWAP bottom friction (crosses).

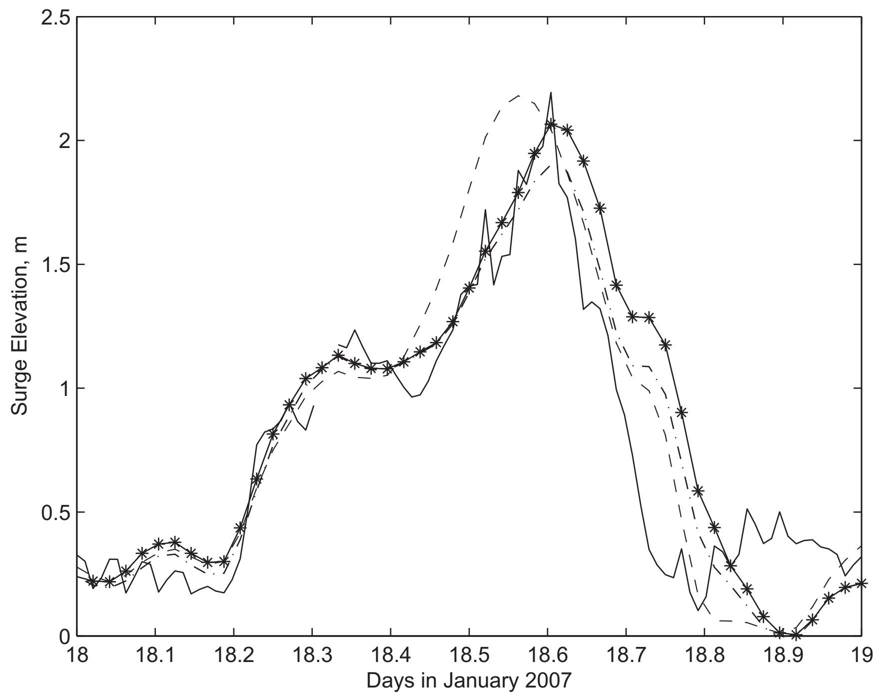

Fig. 8. The observed surge at Hilbre (solid line) and the modelled hindcasts for the following model set ups: POLCOMS with current-alone bottom friction (dash dot line), 2-way coupled POLCOMS–ProWAM with radiation stress and wave–current bottom friction (dashed line) and 1-way coupled POLCOMS–SWAN wave-setup prediction linearly added to the POLCOMS surge prediction with current-alone bottom friction in POLCOMS and reduced JONSWAP bottom friction in SWAN (starred line).

enced at high water due to meteorological and wave-induced surge compared with the predicted astronomical high tidal level. The surge causes high water to occur earlier as a result of the tide–surge interaction; however this time shift is not measured by this parameter. Using the POLCOMS–ProWAM hindcast the peak values and spatial patterns in the flood risk parameters are investigated. For this extreme storm event the wave-setup reached ~0.5 m in the Dee increasing towards the north to ~0.75 m in the Mersey and reaching peak values of ~1.25 m in and around the mouth of the Ribble (Fig. 10a). The largest surge only height occurred along the north Wirral and Sefton coastlines, reaching ~2 m (Fig. 10b). The surge alone height is slightly lower, ~1.75 m, in the Dee. The combined surge-setup elevation therefore results in large additional water levels around the Ribble mouth and along the Sefton coast, north of Formby Point, reaching ~3 m (Fig. 10c). Lower maximum surge and surge-setup values occur over the drying banks within the Ribble than in the deeper channels and at its mouth. This is a consequence of the peak in surge occurring at low water levels when the banks are dry. During higher water levels these banks are wet but the surge is not at its peak magnitude (see Fig. 11). South of Formby Point around the mouth of the Mersey the combined interaction resulted in levels of ~2.5 m and to the west of the Wirral close the mouth of the Dee the elevations were ~2 m (Fig. 10c).

The maximum total water levels (tide plus coincidental meteorological surge and wave-setup including interactions) during the storm were highest to the north of Formby Point, as a result of: (i) an increasing tidal range towards the north of this coastline, and (ii) the large wave-setup and surge contribution to the total water level in this area (Fig. 10d). The peak total water level due to tide–surge–wave interaction achieved levels of ~5.5 m north of Formby Point, ~5 m south of Formby Point and ~4.75 m west of the Wirral (Fig. 10d). Although the maximum surge and wave-setup values occur during the lower water elevations of the falling tide (Fig. 11), the surge and wave-setup at high water are still considerable, increasing the high tidal level across the coastal region. The additional water level at high water due to tide–surge–wave interaction was ~1.6 m north of Formby Point, ~1 m south of Formby Point and ~0.8 m west of the Wirral (Fig. 10e). The attenuation in significant wave height (Fig. 10f) is less as it approaches the Sefton coast and further north compared with the Wirral and Welsh coast. Much larger waves are therefore able to penetrate into the Ribble compared with the Mersey and Dee. The largest gradients in significant wave height occur in the Ribble in response to strong dissipation processes generating large forces due to gradients in the radiation stress. This is the main factor causing wave-setup to be greater locally around the Ribble. The significant wave heights within the Ribble during this storm peak at ~3.5 m, while in the Mersey they peak at ~3 m and in the Dee they peak at ~2.25 m (Fig. 10f).

The worst risk of coastal flooding and erosion from overtopping due to water levels and waves is therefore along the northern section of the Sefton coast. Even if extreme wave conditions were not present, flood-risk due to tide–surge interaction is still greatest from the north of the Wirral to the Ribble.

4.4. Computation efficiency

All three models described can be implemented on parallel computers. For POLCOMS and ProWAM it is beneficial to use the parallel option due to slow computation times, e.g. the ProWAM, and therefore coupled, model runs in near real time using 64 dual processors of speed 2.6 GHz. From an operational view the POLCOMS–SWAN model is much more computationally efficient than POLCOMS–ProWAM. POLCOMS uncoupled completed the 3 day simulation in 20 h, with a 3 s barotropic time step running in parallel on 64 dual processors. When coupled to ProWAM (in 1- or 2-way) with a 3 s propagation and 1 s source time step implemented in ProWAM the run time increased to 62 h, still implementing 64 dual processors. The SWAN simulation with 15 m time step using the already simulated hydrodynamic output took ~13 h on a single dual processor with speed of 2.13 GHz. The overall POLCOMS–SWAN computation time therefore took 33 h, with POLCOMS run in parallel and SWAN run in serial. Tests on the ProWAM source

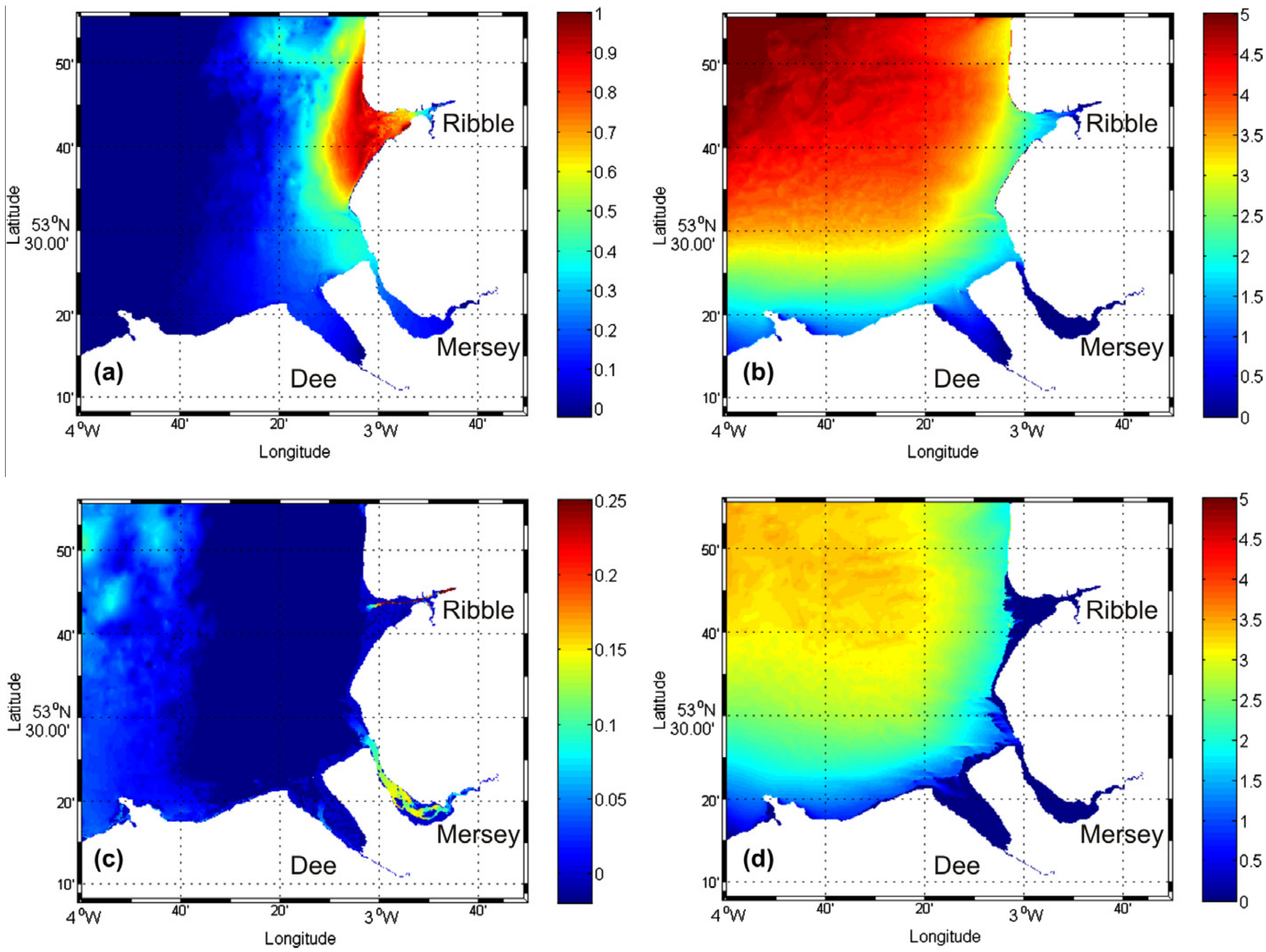

Fig. 9. The high water wave-setup (a) and significant wave height (b) and the low water wave-setup (c) and significant wave height (d) hindcast by ProWAM across Liverpool Bay. The colour bar scale is different in panel a and c to resolve the much larger wave-setup at high water.

term time step found that using a 15 s step reduced the computation time significantly, while maintaining numerical stability. This allowed the source terms to be updated twice in the 30 s time interval between the exchange of information between POLCOMS and WAM. The significantly increased source term time step considerable reduced the computation time of the 3 day simulation to 28.9 h, which is comparable to the computation speed of SWAN when run in serial. The loss in accuracy due to changing this time step is minimal, compared with the reduced computation cost (56% reduction in run time), and actually improves the result in some of the error metrics (e.g. Table 5). For prediction of flood risk and coastal erosion conditions the POLCOMS–ProWAM model with increased source term time step in ProWAM is slightly more efficient than the presented POLCOMS–SWAN set up and gives good wave prediction for both the open coast and internal estuary region when the hydrodynamics are included. However once wave-setup becomes parallelised in SWAN, this will be the more efficient wave model.

5. Discussion

The POLCOMS–ProWAM model for shallow water has been modified to improve the wave hindcast in the nearshore to allow improved prediction within estuaries and along the coastal zone. First the model results are discussed followed by a discussion of the accuracy.

This investigation has allowed the importance of using a 2-way coupled model at the coast to be investigated. For this study site the total water levels and significant wave heights are significantly influenced by the wave-hydrodynamic interactions. However these interactions are only modelled by ProWAM when the limiter is relaxed. At Hilbre the POLCOMS–ProWAM model hindcast a 1.93 m surge maximum combined with 2.37 m significant wave height maximum, which created a maximum wave-setup of 0.48 m. The combined effect at high water was an additional 1.25 m in elevation (Fig. 11). The maximum surge level was enhanced through the coupling of POLCOMS–ProWAM (Fig. 7). Two-way (bottom and surface) coupling increased the surge level by 0.027 m, while the inclusion of radiation stress further increased the surge level by 0.25 m. The influence of modifying the bottom friction formulation, friction coefficient and the ProWAM limiter had little influence (<0.04 m) on the surge component. Offshore the significant wave heights were improved by an increase of 0.12 m due to the coupling, but nearshore the significant wave heights decreased by 0.23 m (Fig. 3). For waves the coupling was more important nearshore through the modulation of the significant wave height when the ProWAM limiter was relaxed. Relaxing the limiter increased the significant wave height by 0.17 m at high water and reduced it by 1.88 m at low water. This model applica-

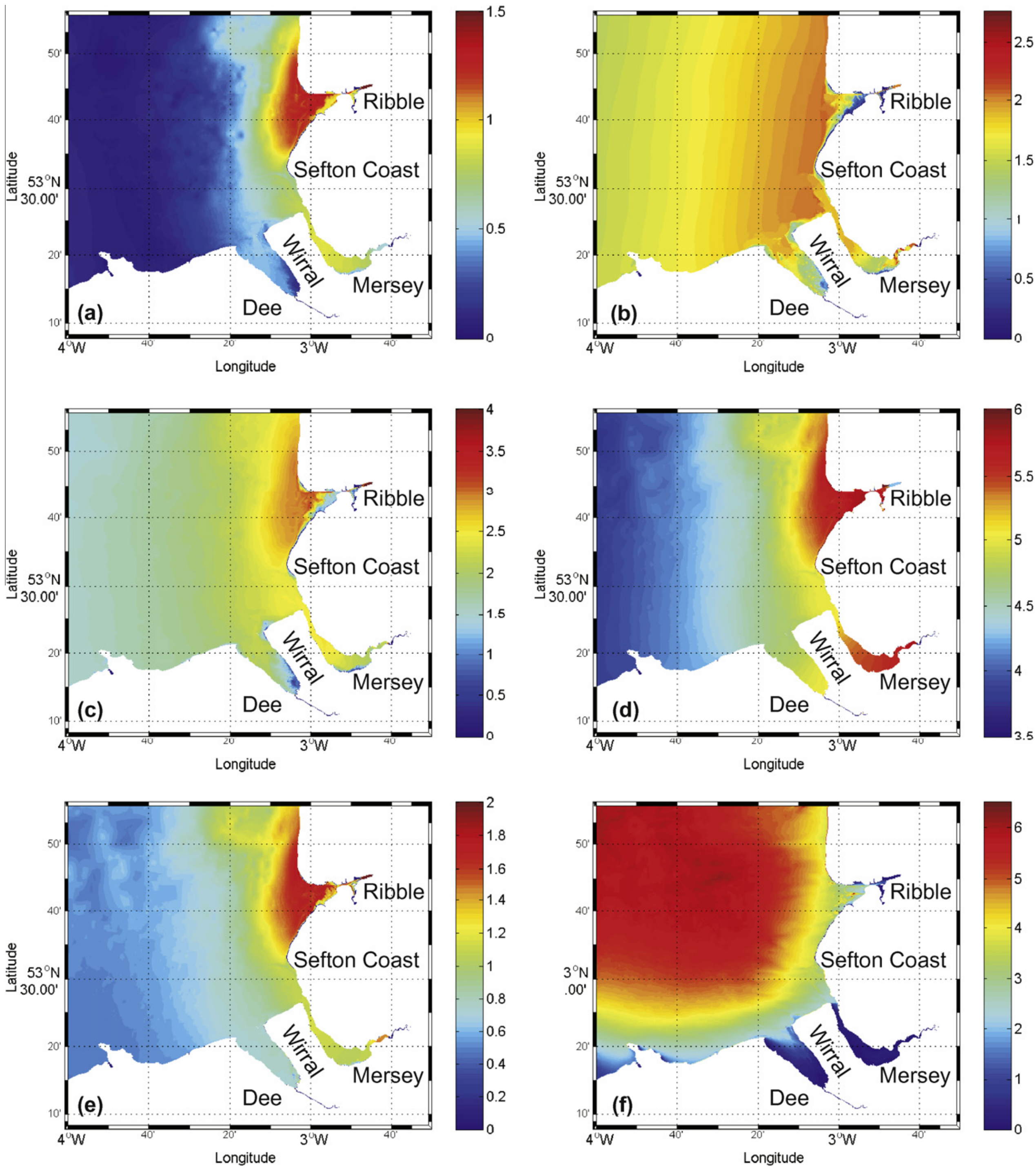

Fig. 10. The POLCOMS–ProWAM hindcast maximum value in (a) wave-setup, (b) surge, (c) surge plus setup, (d) total high water elevation, (e) skew surge and (f) significant wave height at each model grid point.

tion shows model limiters should be applied with care so they do not affect the model solution, while ensuring numerical stability. When a small time step cannot be implemented to remove the need for a limiter, good modelling practise requires an optimal time step to be found such that acceptable simulation times are achieved while ensuring model accuracy and stability.

From the nearshore investigations, unless time varying depth and current conditions are provided to the wave models, a poor shallow water simulation occurs. Once coupled in a 1-way fashion to a hydrodynamic model SWAN out performs the standard 1-way couple ProWAM model, giving a good hindcast result. By relaxing the default limiter on the spectral wave evolution per time step, as applied here to frequencies higher than 0.3 Hz, ProWAM is capable of simulating nearshore waves as accurately as SWAN. If the reduced JONSWAP bottom friction is activated, as in SWAN, instead of the wave–current bottom friction the nearshore result is further improved. An advantage to using POLCOMS–ProWAM is the 2-way coupling facility which is already implemented in the code. This facilitates 3D simulation of the radiation stress and therefore an improved physical basis to include wave-setup in the hydrody-

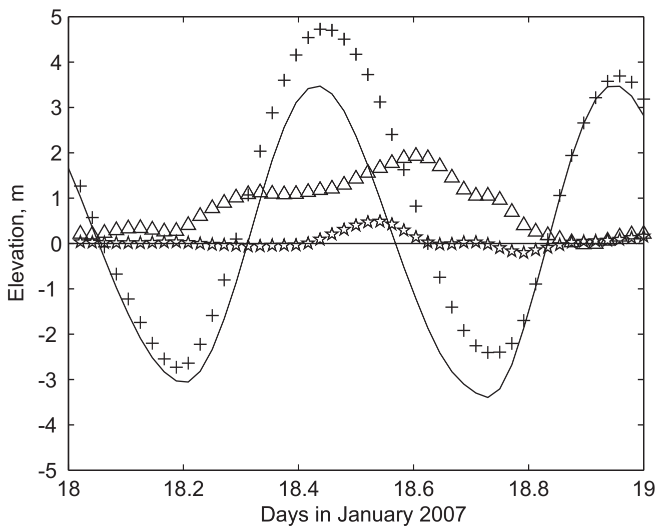

Fig. 11. The POLCOMS modelled tide (solid line) with the meteorologically forced surge (triangles) and wave-setup (stars) leading to the total water elevation (crosses) at Hilbre tide gauge. The elevation is related to mean tidal level (MTL).

namic model. Here, SWAN has been applied using Cartesian coordinates for the "best" approximation of wave-setup. This 2D approximation has shown to be good within the Dee Estuary mouth, compared with the POLCOMS–ProWAM hindcast and surge observation, however it is not valid with distance into the estuary. The wave-setup predicted by SWAN is not included in the flow model (POLCOMS) limiting its use as a 1-way coupled modelling system. The 1-way coupling procedure allows wetting and drying to be included within the ProWAM and SWAN simulation. Dry banks become (de)activated in the computation. This leads to a more realistic wave hindcast within the estuaries. The 2-way coupling to the flow model however, prevents the continual growth of the wave-setup as the depth decreases within an estuary and the waves decay to zero. By calculating the wave-setup in the hydrodynamic model allows wave induced changes in the depth and current fields to modify the tide–surge propagation, representing the tide–surge–wave interaction. Offshore in Liverpool Bay the waves are relatively unaffected by the hydrodynamics. At this deeper location both ProWAM and SWAN perform well, predicting the peak significant wave height in time and magnitude. SWAN is slightly better than ProWAM at the two observation sites. By modifying ProWAM to include the tidal modulation effect on the wave simulation at the Triaxys location actually made the error worse, since the unmodified result fell between the extremes of the modulated observation causing the errors to cancel out over time. The unmodified ProWAM performed better offshore while on average (mean percentage error, Eq. (2)) the modified version performed better nearshore. In general, it has been shown that ProWAM has similar accuracy, for the considered case, to the state-of-the-art shallow water model SWAN.

The distance between adjacent banks along different fetches depending on the wind direction and any unresolved banks in the model could also lead to different significant wave heights between the observed and modelled data. For such short fetches the wave hindcast is sensitive to both the wind speed and direction as well as the geographic resolution. Although the main channel–sandbank system is resolved within the Dee and locally around its mouth, a higher geographic resolution may be required to improve the local wave hindcast. Offshore the wave–current bottom friction performs well at this resolution. This raises the question as to which friction formulas and coefficient settings are most suitable for use in very shallow water. The need for a reduced bottom friction locally at the mouth of the Dee could be a result of errors in the local wave field, or missing physics in the bottom roughness. For example, the presence of ripples and sand waves will modify the bottom roughness as well as the presence of fine sediments in the estuary. Alternatively the recommended wind sea coefficient (0.067 $m^2\ s^{-3}$, Bouws and Komen, 1983) could be too high for this case study. It is unlikely that a constant bottom friction coefficient will be sufficient in varying depths and different stages of wave growth (Weber, 1988). However, it is most likely the reduced bottom friction is required for a proper balance of the model source terms in very shallow water (see The WISE group, 2007).

To properly account for the impact of wave-setup during a storm event a 2-way coupled model is required, in which the tide–surge model calculates the wave-setup as a result of wave-induced stresses modifying the current field. By using a 2-way coupled model the impact of wave-setup is fed back into the hydrodynamic simulation. The wetting and drying scheme allows more accurate depths to be used within the wave model, i.e. dry points (<0.02 m for ProWAM) are removed. This allowed POLCOMS–ProWAM to produce a realistic regional wave-setup map at different water levels within the estuaries. The channel–sandbank systems were reflected in the hindcast as a result (Fig. 9). This also produced a realistic upper estuary simulation. The 2-way coupled model allowed for a more robust wave-setup simulation within the estuary regions compared with the 1-way coupled SWAN approximation for open coast, which used a minimum water depth (of 0.05 m) to deactivate drying banks.

The POLCOMS–ProWAM model has shown to give good hindcast of an extreme surge event on the 18th January 2007. Using the POLCOMS–ProWAM hindcast the worst flood risk from wave-setup alone during this event was in the shallowest locations of Liverpool Bay, which are in the vicinity of the Ribble Estuary mouth. Flood risk by wave overtopping is greatest along the northern section of the Sefton coast, while flood-risk due to tide–surge interaction is greatest along a larger section of coast from the north of the Wirral to the Ribble.

6. Conclusion

Liverpool Bay with its shallow estuaries and extensive sandy beaches has been used as a representative shallow coastal location where significant tide–surge–wave interaction occurs. The POLCOMS–ProWAM model has been modified: (i) to include wetting and drying of intertidal zones and (ii) to allow more freedom in the evolution of wave spectra (modified limiter). Although computationally expensive this model set up performs well providing a good

Table 5
Quantification of the model error for the significant wave height, H_{m0}, compared with observation at the two wave buoy locations for the 18th 00:00–20th 00:00 January 2007. POLCOMS is coupled in 1-way to ProWAM with the relaxed limiter (P–W + L) and Madsen wave–current bottom friction, with different source term time steps applied in ProWAM.

Time step (s)	Run time (h)	*RMS error* (m)		*MP error* (%)		*PB* (%)	
		WaveNet	Triaxys	WaveNet	Triaxys	WaveNet	Triaxys
1	66.29	0.66	0.79	−22.20	−55.80	2.47	−30.73
15	28.90	0.66	0.79	−22.19	−55.54	2.18	−30.85

wave–water level hindcast for the mouth of the Dee Estuary and offshore. Nearshore the model has a similar performance in H_{m0} as POLCOMS–SWAN. However, both models underestimate the observed H_{m0} and T_p. The tidal modulation of significant wave height and the enhanced surge peak due to wave-setup were simulated in good agreement with observations and the state-of-the-art shallow water wave model SWAN. Using a current independent bottom friction formulation in the wave model was found to be more appropriate in shallow (estuarine) water, while a wave–current bottom friction was more appropriate offshore (at 25 m depth). The estuarine prediction was improved further by reducing the recommended friction coefficient for wind seas (0.067 m^2 s^{-3}, Bouws and Komen, 1983) to the recommended friction coefficient for swell dominated wave systems (0.038 m^2 s^{-3}, Hasselmann et al., 1973) in the wave-alone JONSWAP formula. It has been shown tide–surge–wave interaction is necessary for correct nearshore simulation of both the significant wave height and storm tide elevation. The modifications to ProWAM presented here are required to create a robust and valid coupled tide–surge–wave shallow water model, which can be used for flood risk assessment. However, it is likely 2D radiation stress would also perform as well as 3D radiation stress within a 2-way coupled model to simulate the total water level. By increasing the source term time step the computation cost is dramatically reduced without significant loss of accuracy.

Using the model hindcast for Liverpool Bay, it has been found that during extreme south-westerly storms, which track northeast, the coast north of Formby Point seems most susceptible to large surge conditions combined with large wave-setup and significant wave heights. On top of the large tidal ranges in this area flood risk and coastal erosion is the consequence of significantly elevated water levels (up to 1.6 m in this case) combined with coincidentally large significant wave heights (up to 3 m in this case).

POLCOMS–SWAN produced a good approximation of wave-setup and significant wave height compared with the observation in the open mouth of the Dee Estuary. However the 2D approximations in SWAN are not designed to hindcast wave-setup internally within an estuary. A 2-way coupled model is thus more suited to simulating wave-setup than a 1-way coupled model in an enclosed region. For this application the coupled POLCOMS–ProWAM model was capable of including wave-setup over shoaling beaches and within estuaries.

Operationally the POLCOMS–ProWAM (multi processor) modelling system coupled in 2-way is as efficient as POLCOMS–SWAN (multi processors–single processor) modelling system coupled in 1-way, and gives good results along the open coast and offshore within Liverpool Bay. Both wave models gave acceptable results when implemented in a 1-way coupled approach. For accurate wave simulations at the coast the influence of tide–surge interaction must be taken into consideration. In contrast, an adequate surge simulation (with similar error as the coupled system) can be achieved without the influence of waves, given the correct surge boundary conditions and local wind forcing. However, the inclusion of radiation stress improves the peak elevation in the surge prediction. For operational flood and erosion management in Liverpool Bay both coupled models provide acceptable wave–water level forecasts in feasible computations times for the open coast. Observations within the estuaries, particularly for wave-setup, would further validate the presented modelling systems in the very nearshore. This would also enable further investigation and validation of the benefit to using 3D radiation stress compared with 2D radiation stress.

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