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Coastal flooding: impacts of coupled wave–surge–tide models

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Abstract Wind waves and elevated water levels together can cause flooding in low-lying coastal areas, where the water level may be a combination of mean sea level, tides and surges generated by storm events. In areas with a wide continental shelf a travelling external surge may combine with the locally generated surge and waves and there can be significant interaction between the propagation of the tide and surge. Wave height at the coast is controlled largely by water depth. So the effect of tides and surges on waves must also be considered, while waves contribute to the total water level by means of wave setup through radiation stress. These processes are well understood and accurately predicted by models, assuming good bathymetry and wind forcing is available. Other interactions between surges and waves include the processes of surface wind-stress and bottom friction as well as depth and current refraction of waves by surge water levels and currents, and some of the details of these processes are still not well understood. The recent coastal flooding in Myanmar (May 2008) in the Irrawaddy River Delta is an example of the severity of such events, with a surge of over 3 m exacerbated by heavy precipitation. Here, we review the existing capability for combined modelling of tides, surges and waves, their interactions and the development of coupled models.

Keywords Tides · Storm surges · Wind waves · Coastal flooding · Wave–current interaction · Numerical modelling

1 Introduction

Coastal flooding is generally caused by a combination of high water levels, which may be caused by tides and storm surges, together with waves, which can lead to overtopping of coastal defences and inundation of low-lying areas, potentially causing damage to life and property. Waves and storm surges are caused by storm events with high winds blowing over the adjacent sea. In some areas such as deltas and estuaries, precipitation and river

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flow may also contribute to coastal flooding. Tsunamis, caused by undersea earthquakes, landslides, volcanic eruptions and meteorites can also be important in causing coastal flooding in some areas of the world, notably the islands of the Pacific Rim (Abe 1979). Tsunamis are waves of similar wavelength to tides and can be predicted using the shallow water wave equations. NW Europe is much less susceptible to tsunamis although Horsburgh et al. (2008) examined the potential for an earthquake similar to that in Lisbon in 1755 to generate a tsunami and there are some similarities in modelling the propagation of a tsunami to modelling other waves and tides; however, tsunamis will not be considered further here.

The storm surge is the meteorologically driven component of water level driven by synoptic variations of atmospheric pressure and wind. If the storm surge is combined with tide, the combined water level may be known as the 'storm tide' or sometimes the 'still water level' since changes occur over periods of hours to days, compared to typical wave periods of 1–20 s. Wave overtopping occurs when individual wave crests exceed the available 'freeboard' (height above still water level) of the coastal defences causing further flooding beyond that due to the surge. See Pullen et al. (2007) for the coastal engineering approach to overtopping. The impact of waves at the coast also includes breaking and run-up on beaches and foreshores which can cause coastal erosion depending on the configuration of the coast and the supply of mobile sediment.

There is an increased risk of devastation due to socio-economic factors as the flood-risk areas (coastal and flood plains) with fertile soil and access to communications are generally densely populated; many cities develop at the coast and coastal property may be very valuable (Hinton et al. 2007). Driven by projected increases of sea levels, more intense rainfall, and stronger wind speeds, flood risks are anticipated to increase in the future (Hall et al. 2007). Coastal flood defences have been built in some areas to protect housing, businesses or infrastructure and emphasis is increasingly being focussed on their sustainability in the light of future sea level rise (SLR), e.g. Pye and Blott (2006). In the Netherlands, where two-thirds of the country is below storm surge level, large rural areas may presently be defended to a return period of 1:10,000 years, with less densely populated areas protected to 1:4,000 years. In the United Kingdom, where low-lying areas are much smaller, e.g. the Norfolk coast of the southern North Sea or the Thames Estuary, new residential developments are required to be defended to the 1:200 year return period of flood level. Waves combined with higher water levels may overtop or possibly breach hard or soft coastal defences (seawalls, revetments or dunes) which can cause persistent flooding by trapping the water, potentially damaging or destroying defences, coastal structures and property and causing coastal erosion.

The basic theory of the generation of storm surges and waves by wind is understood in principle (Gill 1982), although some details still need elucidation. For example, the wind-stress is modelled empirically very successfully although the actual process of transfer of momentum and energy from the atmosphere to the sea via wind waves is very complex and not fully understood (Janssen 2004). There are also several interactions between the mean circulation and wind-waves (Peregrine and Jonsson 1983). The propagation of waves in shallow water is dependent on water depth and this means that the total water depth, which includes tide and surge, will affect wave propagation. In fact, the tidal propagation is also modified in the presence of a surge, leading to tide-surge interaction (Wolf 1981; Horsburgh and Wilson 2007). Waves are modified by the presence of currents generated by tide and surge. They contribute to water level and mean circulation through wave setup and longshore currents, due to radiation stresses in shallow water (Longuet-Higgins and Stewart 1962).

This article presents a review of some recent work on coastal flooding due to storm surges and waves with the focus especially on coupled wave–tide–surge modelling. Coastal impacts are discussed with examples from various parts of the world. The development of tide–surge and wave models is briefly mentioned, followed by a discussion of the interaction processes. The state of the art in operational oceanography is illustrated, mainly with reference to the UK. Wave and tide–surge models have been running in different national centres for many years but it is only recently that fully coupled models are becoming available. This is partly due to the fact that tide–surge models, especially in 2D, are quite cheap and quick to run, whereas the state-of-the art 3rd-generation spectral wave models require more computer resources. Finally, we examine some likely future developments and gaps in the knowledge.

2 Impacts of coastal flooding

The costs of coastal flooding can run to many lives and very large losses of property. In the southern North Sea, the 1953 storm surge cost over 2000 lives (Gerritsen 2005) and prompted much research, leading to the development of the Storm Tide Forecasting Service (STFS) and the building of the Thames Barrier in the UK (Wolf and Flather 2005). The tide-surge model is now run operationally at the UK Met Office and many other countries around the North Sea now have national storm surge forecasting as reviewed by Flather (2000). The regular depressions passing over the NW European continental shelf in winter from the Atlantic cause storm surges and waves in the shallow sea areas. Wind-stress is particularly effective in piling up water against the coast in the shallow water of the continental shelf as the effect is inversely proportional to water depth. Depths in the southern North Sea and the eastern Irish Sea are only about 40 m on average. The UK, in common with many other countries, has assets worth billions of pounds at risk from coastal floods, river floods and coastal erosion (Wolf 2008).

Tropical cyclones (hurricanes and typhoons) are smaller and more intense than mid-latitude depressions and more difficult to predict in atmospheric models since higher resolution is required (Emanuel et al. 2008). Their impact at the coast can be even more devastating, especially if they make landfall in areas of high population density. Winds, coastal surge and waves (including wave setup) can all contribute to their destructive power. In one of the most recent global catastrophes the low-lying delta of the Irrawaddy was flooded by a storm surge caused by Cyclone Nargis in May 2008 (see Fig. 1). This area had a high population of people with few resources and little ability to evacuate. The total number of people dead or missing exceeds 130,000 as of June 2008. In this case, the destructive power of waves could only exacerbate the huge losses of property due to inundation. The death toll includes those further inland, due to wind and rainfall as well as those affected by coastal flooding. The following paragraphs describe some studies of tropical cyclones in recent years. Numerical models have often been used in diagnostic hindcast studies; in a later section we discuss the potential for forecasting of the impacts in operational modelling systems.

In the United States of America, the city of New Orleans is still recovering from Hurricane Katrina in 2005. Hurricane Katrina was the most costly and one of the five deadliest hurricanes in the history of the United States. It was the sixth-strongest Atlantic hurricane ever recorded and the third-strongest on record to make landfall in the United States. The most severe loss of life and damage to property occurred in New Orleans, Louisiana, which was flooded as the levee system catastrophically failed, in many cases

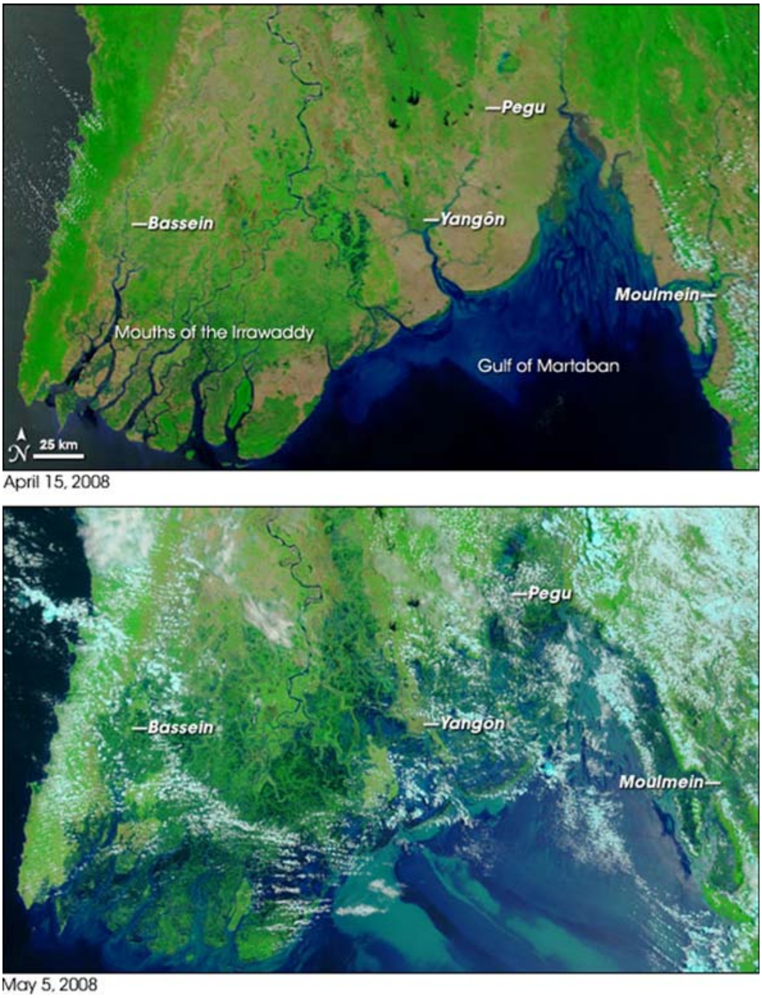

Fig. 1 Before Cyclone Nargis: 15 April 2008 (*top*) After Cyclone Nargis: 5 May 2008 (*bottom*). Image courtesy of MODIS Rapid Response Project at NASA/GSFC

hours after the storm had moved inland. Post-Katrina many lessons may still have to be learned about coastal development and protection (United States Congress 2006).

In a study by Wang et al. (2006), Ivan, a strong Category 4 hurricane (downgraded to a Category 3 at landfall), caused widespread erosion and overtopping along the northwestern Florida barrier-island beaches, within 100 km from the storm centre at landfall. Significant beach and dune erosion was measured as far as 300 km east of the storm centre. The highest elevation of beach erosion extended considerably above the measured storm–surge level, indicating that storm–wave setup and swash run-up played significant roles in controlling the elevation of beach erosion. In another study, Zhang et al. (2005) studied beach erosion due to Hurricane Floyd in 1999 using LIDAR surveys to estimate the areas of erosion, showing how new technology can vastly improve our ability to quantify impacts. Chen et al. (2007) studied the impact on coastal highways which are important for evacuation in severe weather. There are more than 60,000 miles (96,500 km) of coastal roadways in the 100-year floodplain in the United States vulnerable to the attacks of water surges and storm waves generated by hurricanes. The advanced storm surge and circulation model ADCIRC (ADvanced CIRCulation; Luettich et al. 1992; Westerink et al. 1994a, b) was used for surge modelling either forced directly by wind or using water levels from coastal tide gauges. The waves were modelled with the open-source, third-generation spectral wave prediction model SWAN (Simulation of waves in Nearshore areas; Booij et al. 1999; Ris et al. 1999). At the time of writing, the 2008 Atlantic hurricane season is an ongoing event in the annual cycle of tropical cyclone formation. The season officially started on June 1 and will run through till November 30. These dates conventionally delimit the period of each year when most tropical cyclones form in the Atlantic basin. This year the season began slightly early when Tropical Storm Arthur formed off the coast of Belize on May 30. The season has been far more active than normal and has been particularly devastating for Haiti, where hundreds of people were killed by four consecutive tropical cyclones (Fay, Gustav, Hanna and Ike) in August and September. The season has also been very destructive, with over US$50 billion in damage so far, mostly in the U.S. Hurricane Ike has been the most destructive storm this year so far, making landfall near Galveston, Texas, at category 2 intensity and causing a particularly devastating storm surge due to its large size.

In Taiwan, typhoon Doug almost completely destroyed the breakwaters and docking facilities in the Lungtung harbour at the northeast tip of Taiwan in 1994 (Wang et al. 2005). The estimated maximum sea level rise was about 3 m. Their model results indicate that sea levels reached a maximum of about 2 m at the peak of the storm. The largest surge, however, does not occur at the location where the most severe damage was located, which suggests that the wave run-up could be an important contribution to the storm surge.

Recently, Kumar et al. (2008) carried out a simulation of storm surge for the Andaman Islands in the Indian Ocean using a two-dimensional hydrodynamic model MIKE 21 from the Danish Hydraulic Institute (DHI 2002). Madsen and Jakobsen (2004) discussed the merits of MIKE 21 model in reproducing the sea-level heights associated with the 1991 Bangladesh storm surge, which caused the deaths of about 140,000 people.

Severe storms and cyclones contribute 29% of the total damage cost from natural hazards in Australia. In 1999 prices, this amounted to $40 billion during the period 1967–1999 (including the cost of deaths and injuries: Nott 2006). Tropical cyclones also cause substantial erosion of the coast, e.g. coast of Northern Australia. The combination of surge, tide, wave set-up, waves and wave run-up can overtop aeolian coastal dunes or ridges where they are unconsolidated, causing them to be eroded vertically and removed. At times, this can result in the deposition of sand sheets that extend inland for several hundreds of metres and taper in thickness landward.

Returning to mid-latitude storms, a cyclone (known as Gudrun in the Nordic countries) developed over the North Atlantic and travelled over the British Isles, Scandinavia and Finland on 7–9 January 2005, as reported by Tönisson et al. (2008). This cyclone generated strong SW–W winds which created a record high storm surge (275 cm) in Pärnu, Estonia, as well as in many other locations along the west Estonian coast. The January storm caused changes in the development of shores and the dynamics of beach sediments over almost all of Estonia. The largest changes occurred in areas most exposed to the storm winds and waves. This storm caused significantly larger changes to the depositional shores in west Estonia than the cumulative effects of ordinary storms over the preceding 10–15-year-period due to the absence of protecting ice cover in the sea and relatively high sea level for a long period before the storm.

On 11–12 January 2005, a severe storm hit the Outer Hebrides off NW Scotland with winds exceeding 20 ms^{-1} and there was flooding on the islands of South Uist and Barra, caused by storm surge and waves. Five lives were lost in one family as they attempted to cross the causeway linking North and South Uist in two cars. The surge reached over 1 m at the nearby port of Stornoway, where regular storm tide forecasts are available. A suite of nested wave models was used to run a hindcast of this event. The local wave setup was calculated using the SWAN model and was very high locally to South Uist (over 0.48 m) due to the very high waves entering the rapidly shoaling water near-shore (Wolf 2007). From Fig. 2 it may be seen that the wave heights reached 14.3 m close inshore. The wave setup for the Sea of the Hebrides is shown in Fig. 3. Thus, this is a case where the waves may have contributed substantially to the total water level as well as their direct impact and overtopping of the causeway.

3 Tide–surge modelling

Tides, caused by the gravitational effect of sun and moon, are periodic and very predictable. They are large on the NW European shelf but small in the Mediterranean. The world's maximum tidal range can reach 16 m in the Bay of Fundy in Canada, where there is near-resonance with the dominant lunar semi-diurnal tidal period. The 2nd largest tides (>14 m) are found on the NW European Shelf in the Severn Estuary, which is also close to resonance. Surges, on the other hand, are quasi-periodic and caused by meteorological forcing. The most important mechanism for surge generation is wind-stress acting over shallow water. Surges at the coast are produced by Ekman dynamics, behaving as forced Kelvin waves (Gill 1982). The size of the surge is proportional to the wind-stress divided by the water depth. The wind-stress is usually taken to be proportional to the square of the wind-speed with a drag coefficient which increases with wind speed (accounting for some effect of surface roughness due to waves (Brown and Wolf 2008)). Due to transient effects

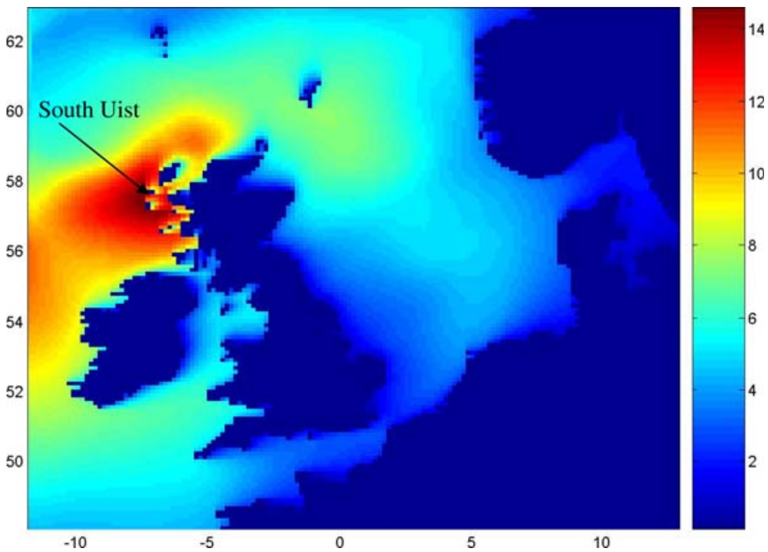

Fig. 2 CS3 model wave height at time of maximum modelled waves at South Uist, 23:00 11 January 2005

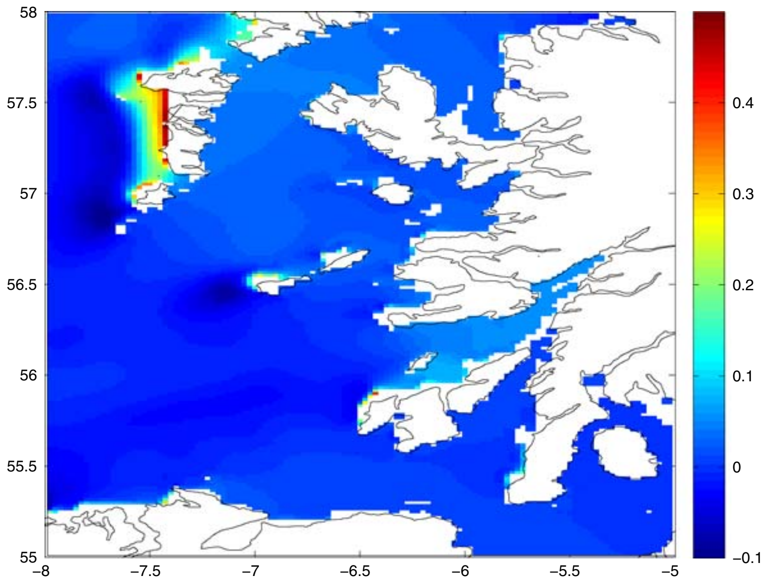

Fig. 3 Wave set-up at peak of storm: 23:00 11 January 2005

there is also an increase in surge height with wind duration. Surges are, therefore, largest where storms impact on large areas of shallow continental shelves. In deep water, surge elevations are approximately hydrostatic with a 1 hPa decrease in atmospheric pressure giving about 1 cm increase in surge elevation (Flather 2000). Surges in the Mediterranean as a whole are likely to be much lower due to the much deeper water. However, they are important in local areas of shallow water, e.g. the Northern Adriatic, where Venice is susceptible to flooding. Some modification is caused by seiching, when winds trigger oscillations at the natural periods of enclosed sea areas, e.g. in the Adriatic the wind tends to trigger the 22-h seiche (Gill 1982) and its harmonics (11 and 7-h oscillations).

Barotropic tides and surges are generally modelled using the 'shallow-water equations' since they have very long wavelengths (hundreds of kilometers) compared to the water depth (Gill 1982). Heaps (1983), Flather (1981) and Pugh (1987) reviewed earlier work on numerical modelling of storm surges. Limited area models are subject to errors in boundary conditions and tidal models may omit some tidal frequencies, local effects of the tide-generating forces and load tide response of the solid Earth. Shum et al. (1997) reviewed ocean tidal models, concluding that all the models agree within 2–3 cm in the deep ocean. However, tidal models are still inferior to harmonic analysis and prediction for shallow water tides at locations where coastal tide gauge data are available. The tide–surge model predictions reflect this in using the model surge together with harmonic predictions for tides to provide the total water level (Flather and Williams 2004).

It has long been recognized that in shallow water areas with a large tidal range, the nonlinear effects of tide–surge interaction are important. The peak of the surge in the southern North Sea tends to 'avoid' predicted tidal high water, due to the speeding up of the tidal wave propagation in the presence of the deeper water caused by the surge level and other subtle changes are caused by bottom friction. Prandle and Wolf (1978), Wolf (1981), Davies and Lawrence (1994), Jones and Davies (1998) and Horsburgh and Wilson (2007) have described work on the effects of tide–surge interaction. Figure 4 illustrates the

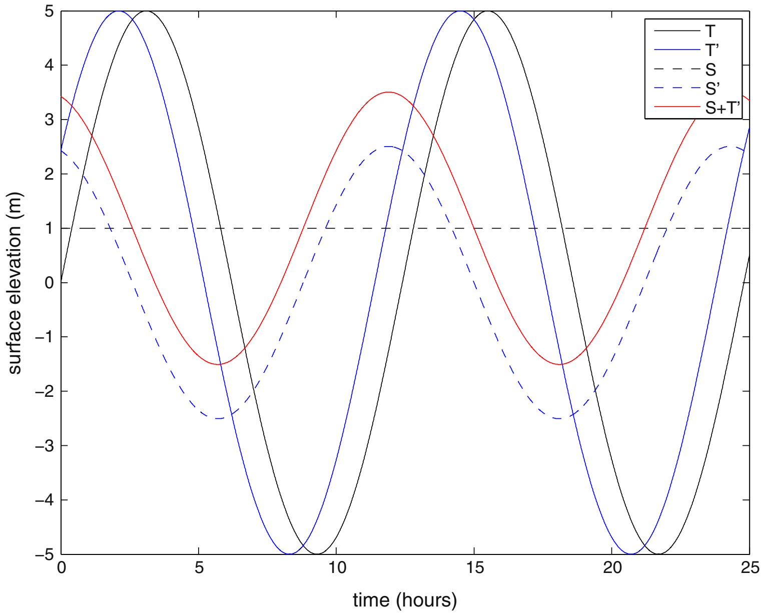

Fig. 4 Illustration of tide–surge interaction. Undisturbed tide (predicted tide, T) is *solid black line*, phase advanced tide (T′) is *solid blue line*, meteorological surge (S) is *dashed black line*, tide–surge interaction (S′) is *dashed blue line*, net residual is *solid red line*

mechanism by which tide-surge interaction leads to a surge peak on the rising tide. The tidal phase is advanced due to the deeper water caused by the presence of a positive surge level. The difference between the phase-shifted (T′) and undisturbed tide (T) is added to the surge to give the net tidal residual (red line), which has a peak 3 h before predicted high water.

A surge model intercomparison exercise (de Vries et al. 1995), using common bathymetry and wind forcing, showed only small differences between models, but highlighted the need for accurate wind-stress since there was a tendency for all models to underestimate the surge. Work on the UK tide–surge model by Williams and Flather (2000) has also shown a need for enhanced wind-stress relative to Smith and Banke (1975) and recently Brown and Wolf (2008) have shown this may be related to wave effects and also nearshore bathymetric resolution.

Observations of tides and surges are generally made at coastal tide gauges, although these locations are not always ideal for model validation since they may experience local effects by being in ports or estuaries rather than reflecting open sea conditions. The importance of good wind forcing and detailed coastal bathymetry for producing good surge forecasts has often been identified. Coastal winds may be modified by local effects such as orography, land-sea breezes and the coastal boundary layer. Better resolution is now available in mesoscale wind forecasts and the use of unstructured grids allows better resolution of the coastline and near-shore bathymetry (Jones and Davies 2005, 2008).

Extreme water levels at UK Class A tide gauges were investigated by Dixon and Tawn (1995) using various joint probability methods, viz. Joint Probability Method (JPM), Revised Joint Probability Method (RJPM) and Spatial Revised Joint Probability Method (SRJPM). These take some account of tide–surge interaction in a local sense.

4 Wave modelling

The state of the art of wave modelling was presented by Komen et al. (1994) at the end of the development period of the WAM (Wave Model) 3rd generation (3G) spectral wave model, which incorporated the nonlinear interaction terms for the first time explicitly. Models based on WAM physics have become standard for global to regional wave model applications. Since then further development of shallow water physics has been carried out and reviewed recently (The WISE group 2007). Initially wave observations were quite limited, with only few wave buoys and often only short-term deployments being available, but now satellite altimeters can routinely provide wave height as well as water level. These wave height data are routinely assimilated in global wave models, running at national centres. Further networks of wave buoys have been installed, e.g. Wavenet in UK (http://www.cefas.co.uk/data/wavenet.aspx) and the situation is therefore improving. The United States National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) network gives the global coverage of wave data (http://www.ndbc.noaa.gov/). There is also a more comprehensive list (although not complete) of wave observation networks on the JCOMM services web site http://www.jcomm-services.org/Wave-and-storm-surge-data.html.

5 Combined wave and storm surge modelling

The principles of wave and surge generation by wind are universal, although the impacts vary in different geographical locations. For both it is necessary to have a good wind forecast model of as high resolution as possible and this can be used to run separate wave and surge forecasts which, although not coupled, can be combined to give estimates of coastal flooding. A combined surge and wave prediction model is described by Bargagli et al. (2002) who show that prediction of surges in the Adriatic is improved by modelling the whole Mediterranean due to better representation of the principal modes and the pressure effect. They use a combined system comprising a limited area (LAM) atmospheric circulation model, a wave model and a shallow water model. The regional atmospheric circulation model provides a high-resolution forcing for the wave model (surface wind) and for the shallow water model (pressure field and surface wind). In the Irish Sea, using the UK Met Office mesoscale winds is definitely an improvement for the wave model (Osuna et al. 2007). Of course the LAM model predictive quality is to a certain extent controlled by the quality of its boundary conditions, which are determined by how good the coarser global atmospheric model is.

Wolf and Flather (2005) carried out a hindcast of the 1953 storm event using wave and surge models driven by the same wind forcing although the models were not coupled. This allowed a better understanding of the event to be obtained, showing that wave heights reached 10 m in the southern North Sea at the height of the storm. The maximum surge coincided closely in time with tidal high water, producing very high water levels along the coasts of the southern North Sea. Maximum surges exceeded 2.25 m over most of the Southern Bight of the North Sea, with values of 3 m and more on parts of the Dutch coast. Both surge and wave components were estimated to be approximately 1 in 50 year events. The maximum water level also occurred when the offshore waves were close to their maximum. Deriving an estimate of return period for the total water level is more problematic and is dependent on location.

The question remains as to how far we can go with uncoupled models although it has proved difficult to demonstrate an improvement in forecast accuracy using coupled models. In the following sections, we review the physical interaction processes and the state of the art of coupled wave–tide–surge models.

6 Wave–tide–surge interaction

There are several mechanisms by which waves and the currents and water level associated with tide and surge interact, each component of the combined motion affecting the others (Wolf et al. 1988). These may be summarized as (a) the effects of water levels and currents on waves and (b) the effect of waves on tides and surges (Peregrine and Jonsson 1983).

First, we consider the effect of water levels on nearshore wave transformation. As waves enter shallow water, when the depth is less than half the wavelength, the processes of shoaling and refraction change the wavelength and phase speed but the wave period remains constant (in the absence of currents). As energy propagates at the group velocity, by energy conservation the wave height first decreases then increases (this is because of the group velocity property that it increases first with intermediate depth, only to decrease when the depth becomes shallower see, e.g. Wiegel 1964). Finally, the energy dissipation processes of breaking and bottom friction start to limit the wave height. If the water depth is modified, by mean sea level changes or tide and/or surge, this will have corresponding effects on wave height. At the coast an increase in water depth will increase the wave height and also the distance to which waves can penetrate inland. Tide and surge currents can affect wave generation, propagation and dissipation. The effect on surface stress is to change the apparent wind and effective fetch. There may also be an enhancement of the wave friction in the bottom stress (e.g. Grant and Madsen 1979) although Soulsby and Clarke (2005) state this is negligible. Current gradients in the horizontal also cause wave refraction and currents produce a Doppler shift of frequency. In the presence of currents it is the wave action which is conserved rather than wave energy. All these processes are described in more detail in Wolf et al. (1988), Osuna and Wolf (2005) and Ozer et al. (2000).

Waves can affect the mean flow and water level in the nearshore zone through radiation stress causing longshore drift and wave setup (Longuet-Higgins and Stewart 1962). In the surface layer there is a net transport due to waves (Stokes' drift). Waves may affect the generation of surges by affecting surface roughness. As stated earlier, air–sea interaction, by which momentum is transferred from the wind to the waves and the mean flow is a complex process. Janssen (1989, 1991) introduced the concept of wave stress in which wave age affects the surface roughness and implemented it in the WAM model. Further investigation of this has been carried out recently by Brown and Wolf (2008). Waves may enhance the bottom friction experienced by currents in shallow water as discussed, e.g. in Grant and Madsen (1979).

7 Coupled model development

Heaps (1983) identified the need for a wave model to improve the specification of wind-stress in surge models. Various interaction mechanisms including the modification of surface drag by waves were identified as potentially important by Wolf et al. (1988). Hubbert and Wolf (1991) implemented current refraction in the WAM model and investigated the modulation of waves over an idealized Gulf Stream ring. Some results from early attempts at coupling are given in Wu and Flather (1992) and Wu et al. (1994). Tolman (1990) concluded from his investigation into the effects of tides and storm surges on wind waves that 'both the instationarity and the inhomogeneity of depth and current play a significant role in wave–tide interaction' and recommended further investigations into the effects of wave–tide interactions on wave heights. Mastenbroek et al. (1993) show the influence of a wave-dependent surface drag coefficient on surge elevations. Even if these surge elevations can be reproduced with an appropriate 'tuning' of this parameter in conventional wind-stress formulations, e.g. the dimensionless constant in the Charnock relation (Charnock 1955), they argue that 'a wave-dependent drag is to be preferred for storm surge modelling'. The dissipation of tide and surge energy may be affected by waves modifying the bottom friction coefficient for currents. Wolf and Prandle (1999) noted a change in tidal current amplitude related to wave height. Rosales et al. (2008) made a detailed study of the effect of wave–current interaction in the bottom friction. Davies and Lawrence (1994) noticed a significant change of the tidal amplitude and phase in shallow near-coastal regions due to enhanced frictional effects associated with wind-driven flow and wind wave turbulence.

A summary of the contributions to coupling, up to the end of the WAM project, is given by Burgers et al. (1994) and Cavaleri et al. (1994). This has led to the development of coupled models for waves, tides and surges and for waves, ocean and atmosphere, e.g. in ECAWOM (MAST II Project MAS2-CT940091) based on more complete physics. Although some interaction processes have been shown to produce a significant effect, a clear demonstration that coupled models give consistently better results than tuned separate models is required to persuade operational agencies to adopt them (Ozer et al. 2000). In the EU PROMISE project, Monbaliu et al. (1999, 2000) developed a version of WAM (here termed ProWAM) more suited to shallow water and high resolution. Ozer et al. (2000) presented a coupling module. In recent years, the improvement in computer capability has allowed high-resolution three-dimensional models of tides and surges to be developed (Jones and Davies 1998) and increasingly coupled with wind-wave models (Davies and Lawrence 1994; Osuna and Wolf 2005). Wolf (2004), Osuna and Monbaliu (2004) and Osuna and Wolf (2005) have presented applications of two-way coupled models (i.e. including effects of wave on currents and vice versa). Zhang and Li (1996) implemented a coupled model for the South China Sea. Choi et al. (2003) implemented a coupled wave–tide–surge model to investigate the effect of tides, storm surges and waves in the Yellow Sea.

In our implementation, ProWAM works as a module of POLCOMS, the Proudman Oceanographic Laboratory (POL) 3D baroclinic circulation model (Holt and James 2001), so the wave model uses the same bathymetry and wind information as supplied to the hydrodynamic model. The model has been implemented on a parallel computer. The wave–current interaction module allows the synchronous exchange of information between POLCOMS which computes the three-dimensional baroclinic current field) and WAM. Figures 5 and 6 show some results of two-way coupling for the Irish Sea on a one nautical mile grid. In order to incorporate swell coming from the Atlantic, a coarser resolution wave model, which includes part of the northeast Atlantic Ocean (NEA), was used. The open boundary conditions for the hydrodynamic model were generated by an implementation of POLCOMS for the northwest European continental shelf on 12 km resolution. Results indicate that the effect of currents on the waves (e.g. modulations of wave height and mean period) can be significant in the Irish Sea area (see Fig. 5). Larger effects are observed around headlands and shoals, where the magnitude and shear of currents are large. The effect of waves on currents is also evident around headlands and shoals (Fig. 6). During

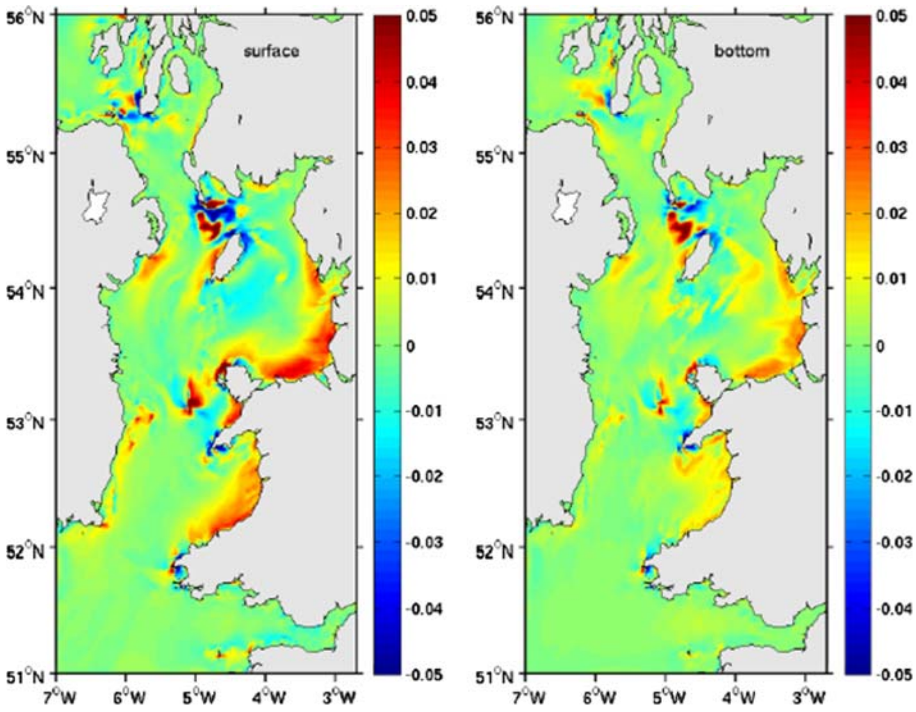

Fig. 5 Daily mean differences (coupled minus uncoupled) of wave height (in m) and mean wave period (in s) corresponding to the 11/02/1997

stormy periods, differences in the daily mean current speed are mainly caused by the wave-dependent surface stress. The effect of the combined wave–current bottom shear stress is confined to coastal areas.

Mellor (2003, 2005) and Ardhuin et al. (2008) have used a derivation of the generalized Langrangian mean equations of motion to provide consistent equations for general wave–turbulence–mean flow interactions in three-dimensions, facilitating the computation of the Stokes' drift, radiation stress and other wave–current interaction processes in numerical models. Bolaños et al. (2007) made some calculations using the POLCOMS-WAM coupled model using Mellor's formulation to include effects of vertical variation of currents.

8 Operational forecast systems

Separate tide–surge and wave models have long been in operation at many centres with global and regional wave models and national surge and tide models for limited areas. Usually 2D models are sufficient for tide and surge forecasting although 3D models may be used to give other variables as well.

The EU PROMISE (Pre-Operational Modelling In Seas of Europe) project advanced the capability of pre-operational modelling (Prandle 2000). Flather (2000) reviewed the existing operational forecast systems for NW Europe, which were already quite mature. There have been some updates since then and operational modelling is rapidly growing elsewhere in the world, usually associated with meteorological forecasting.

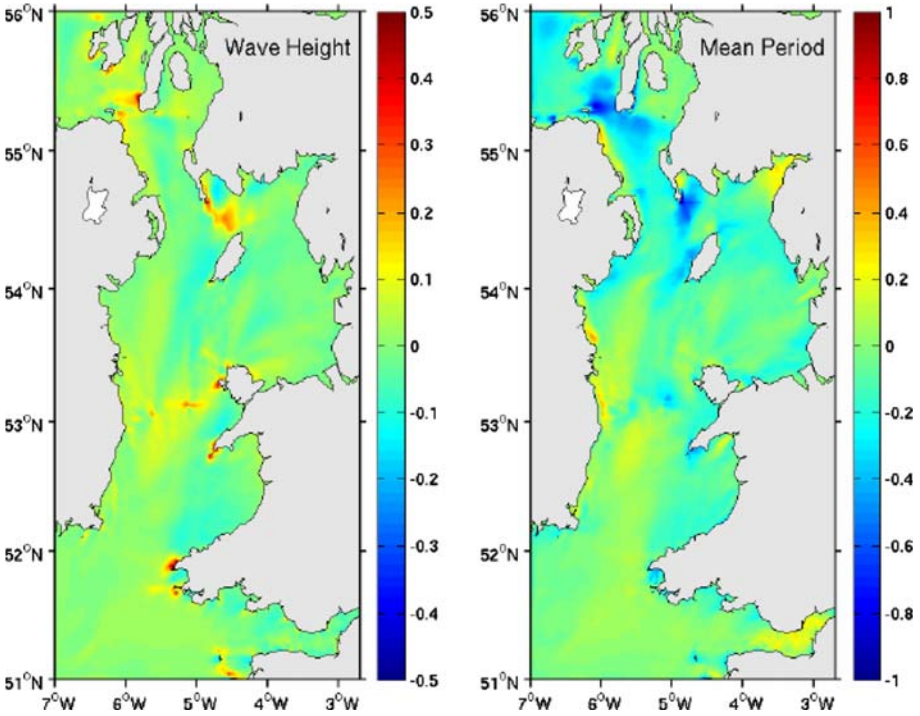

Fig. 6 Daily mean differences (coupled minus uncoupled) of currents at the surface (*left panel*) and the bottom (*right panel*) (m/s) for the 11/02/1997

The UK Met Office has run the 2D coupled tide–surge model, developed at POL, operationally since 1978. The present model, CS3, was introduced in 1991 with resolution 1/6° by 1/9°, forced by Met Office NWP mesoscale winds on a similar resolution (~12 km). It has open boundary input of 15 tidal harmonics and an external surge component, assumed hydrostatic. Tide-generating forces and the drying and flooding of intertidal areas are accounted for. The 2nd generation (2G) wave model is based on Golding (1983) and updated by Holt (1994). There is a global version of the wave model within which is nested a European wave model, and then a UK waters model. The latter includes time-varying currents from the tide–surge model, with interactions due to bottom friction and refraction in depths less than 200 m i.e. one-way coupling. The performance of the 2G model compared favourably with 3G until recently, but this is no longer the case when compared with buoy data (Bidlot et al. 2007). A routine inter-comparison of operational wave forecasting is carried out by JCOMM with monthly reports available on the JCOMM web site (https://www.jcomm-services.org/documents.htm?parent=190). The surge–tide model is used to predict the storm surge component, accounting for interaction with the tides, by subtracting the model predicted tide from the tide with surge solution. This is then added to the harmonically predicted tide based on tide gauge observations to estimate total water level. Results are used by the UK Storm Tide Forecasting Service and the Environment Agency (EA) as the basis for flood warnings on the coasts of England and Wales. The UK National Tide Gauge Network consists of gauges at about 35 sites, from which data are retrieved in near real-time to check forecast accuracy and for assimilation.

The model forecast accuracy achieved varies for different parts of the coast is typically 10 cm RMS.

A new combined wave and water level flood warning system has recently been launched as part of the UK National Flood Forecasting System, initially for the NE of England from Berwick-on-Tweed to the Humber Estuary (Lane et al. 2008). It uses transformation of offshore wave forecasts with a wave overtopping model (Hedges and Reis 1998) combined with the tide and surge forecasts already available and produces flood warnings which consider land use and flood risk. It went online just in time to warn of floods at Whitley Bay, Scarborough and Roker and Sunderland caused by a large surge in November 2007 (3 m in Thames region).

Other methods of combined surge and wave forecasting include joint probability methods for waves and water levels which takes account of wave–tide–surge interactions (Hawkes et al. 2000).

At the European Centre for Medium Range Weather Forecasting (ECMWF) the wave model (ECWAM) is coupled with the IFS atmospheric model. The effect of wave stress has been shown to improve the coupled model system. Recent statistics are shown by Janssen (2008). The ECMWF system also produces ensemble forecasts, including waves (as also do NCEP and the US Navy). Uncertainties and extreme conditions can be better quantified when ensemble forecasts are used. A recent example is given in de Vries (2008) for storm surges. An ensemble system for the UK storm surge model is being developed (Kevin Horsburgh, personal communication).

NOAA Tides and Currents, managed by the Center for Operational Oceanographic Products and Services (CO-OPS), gives a link to the National Oceanic and Atmospheric Administration's oceanographic and meteorological forecasts (http://www.co-ops.nos.noaa.gov/). The SLOSH model, developed by Jelesnianski et al. (1992), is still the US operational surge forecast model for surges driven by tropical cyclones (Zhang et al. 2008) although many other models are also now available, e.g. the Princeton Ocean model (POM) and its derivatives and ADCIRC.

The operational forecast system for Venice is still based on statistical models since their skill is not yet matched by hydrodynamic models. Problems may arise due to errors in the forecast wind field and seiches (Lionello et al. 1998; Wakelin and Proctor 2002).

9 Climate change effects

A vast amount of effort within many projects has recently been expended to examine the potential future flooding under climate change scenarios. Only a few studies are mentioned here as an illustration. Reanalysis projects over several decades such as ERA40 and NCEP/NCAR have produced consistent analysis of winds and waves, e.g. Caires et al. (2006) which enable trends to be more confidently extracted (Trenberth 2008). Such wind data can then be used to run surge models over these time scales to examine potential trends in coastal flooding. Such an exercise was carried out in the CDV2075 project (Sutherland and Wolf 2001) in which climate model winds produced for present day and twice-CO2 scenarios were used to drive a suite of models from offshore waves, through nearshore wave transformation using SWAN to overtopping, combined with water levels, for five different locations around the UK. Tsimplis et al. (2005) examined local variations in climate impacts on waves and sea level. The Tyndall Coastal Simulator project (Leake et al. 2008) is using Hadley Centre climate model winds with different future climate scenarios to predict changes in wave climate round the UK.

Butler et al. (2007) examine trends in surges from the tide–surge model which shows strong positive trends in the frequency and severity of storm surge events at locations in the north-eastern North Sea, whilst trends at locations in the southern and western North Sea appear to be dominated by decadal variability. Woodworth et al. (2007) conclude that spatial patterns of correlation of extreme high and low waters (extreme still water sea levels) with the NAO index are similar to those of median or mean sea level studied previously. Pirazzoli et al. (2006) examined evidence for recent trends in coastal flooding from several years of data at tide gauges in the English Channel, which showed there was a lot of variability with medium-term coastal flooding risk seems to increase especially at Weymouth, Bournemouth and Portsmouth, and to some extent at Le Havre and Sheerness.

It is generally accepted that in a warming climate the number and intensity of tropical cyclones will increase as their generation is closely linked to sea surface temperature. On the other hand, mid-latitude depressions may not necessarily increase as there are two opposing mechanisms: the Equator-to-pole temperature difference decreases with global warming but there is some evidence that the number of winter storms increases at the downwind end of northern hemisphere storm tracks (Wolf and Woolf 2006). A significant increase in cyclonic activity over the North Atlantic has been observed during the second half of the twentieth century and storminess increased in the NE Atlantic and NW Europe (Alexandersson et al. 1998, 2000). Trends toward higher storm surge levels have recently been reported for various locations of northern Europe (Lowe et al. 2001; Lowe and Gregory 2005; Meier et al. 2004; Woth et al. 2005). However, in a recent paper Matulla et al. (2008) show that the trend of increase in storminess and increased wave height in the North Atlantic from the 1960s to the 1990s has ended with a return to more calm conditions. There appears to be a quasi-decadal cycle which coincided with the strongly positive North Atlantic Oscillation (NAO) over that period but the ability of the NAO to act as a predictor for storminess appears to vary in space and time. Thus, SLR may be predicted with some confidence, although the rate of change is still uncertain, but the future surge and wave climate is more difficult to predict. Nicholls and Lowe (2004) discuss the possibilities for adaptation and mitigation of SLR.

10 Summary and future directions

Waves and surges are both driven by the same atmospheric forcing and already separate wave and tide–surge models are run in parallel. It has been demonstrated that the effects of coupling can be of the order of 10% in significant wave height and 20% in wave period with 10% change in currents. Although it has proved difficult to demonstrate improved accuracy in coastal predictions from coupled models this may be due in part to the limitations of data and model resolution.

Higher resolution modelling is now possible using unstructured grids. There is still a need for good nearshore bathymetry, although this is more readily available with coastal LIDAR surveys filling in the inter-tidal areas. This will allow the full inclusion of effects of wave setup and longshore drift due to radiation stress which is mainly confined to the very nearshore zone. The effects of non-uniform unsteady 3D currents and especially vertical shear need further investigation. The effect of currents on high frequency waves may cause wave blocking producing wave reflection or breaking (e.g. Chawla and Kirby 2002) which may be significant in tidal inlets and areas like the Bristol Channel with tidal currents exceeding 2 ms^{-1}. Further work is needed on surface wind-stress to elucidate the details of the air-sea momentum flux, especially in the coastal boundary layer. Detailed inundation modelling is becoming possible with increased computer power and terrain models. Better observations are becoming available, especially using remote sensing, of wind, waves, water levels, currents and bathymetry, e.g. using HF and X-band radar, LIDAR, nearshore sea-bed pressure sensors for tides, surges and waves, ADCP for combined waves, currents and water levels. Some interesting ideas on the importance of Langmuir circulation and the effects of waves on mixing need to be pursued, e.g. the wave-induced turbulence of Qiao et al. (2004). Further impact studies in the nearshore zone, e.g. the implications of wave groups and the effects on sediment transport and coastal morphology are likely.

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