EPIRUS: AN INTEGRATED "CLOUDS-TO-COAST" ENSEMBLE MODELLING FRAMEWORK OF COASTAL FLOOD RISK

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1. INTRODUCTION

In the UK coastal flood defences are usually designed to withstand extreme events with a return period of between 50 to 200 years, taking account of sea level rise. Currently, there is a lack of a robust and integrated 'cloud-to-coast' framework for assessing coastal flood risk. The interactions between the atmosphere, oceans and coasts are poorly understood. There are large uncertainties in the performance of sea defences and predictions of coastal flood risk in extreme conditions. The project: "Ensemble Prediction of Inundation Risk and Uncertainty arising from Scour (EPIRUS)" funded by NERC brings together a team of hydro-meteorologists, oceanographers and coastal engineers to address this issue (Zou et al. 2008, 2009).

A key aim of the project is to integrate meteorological modeling, regional scale wave, tide and surge modeling and surf zone hydrodynamic and morphological modeling to construct an ensemble prediction framework of coastal flood risk. This type of ensemble prediction approach allows us to estimate the probabilities of different outcomes and so improve our understanding of the reliability of results. This approach also provides a measure of the uncertainty associated with predictions and how the uncertainty propagate from meteorological forecasts to overtopping and toe scour and coastal flood risk predictions.

2. METHODOLOGY

This integrated ensemble modelling framework consists of three strands: (I) meteorological modeling to down-scale global model forecasts; (II) regional scale wave, tide and surge modeling and (III) surf zone hydrodynamic and morphological modeling.

(I) METEOROLOGY MODEL

Meteorological models routinely run over the UK domain in national weather centres, have such a coarse spatial resolution that coastal models have difficulty utilising their output as an effective input. Therefore, a downscaling procedure is required to bridge the scale gap between the large-scale meteorological modelling domains and coastal modelling domains.

This study utilises the WRF modelling system to resolve the dynamics over high resolution grids. The Weather Research and Forecasting (WRF) model is a next-generation mesoscale numerical weather prediction and data assimilation system (described in detail in Skamarock et al. 2008). For this study WRF version 3.1 is run, with the ARW (Advance Research WRF) dynamical core used to dynamically downscale coarse meteorological data, generating high resolution wind and pressure fields of extreme extratropical cyclones. These fields are subsequently used as input in hydrodynamical models described later. An initial test case of the severe storm of 16th October 1987 has been identified (Fig. 1).

The ECMWF (European Centre for Medium-range Weather Forecasts) reanalysis dataset ERA40 (Uppala et al. 2005) is used to initialise the model and define the lateral boundary conditions. In order to accurately simulate surface wind speeds, the model must be run at a sufficiently high temporal and spatial resolution to capture the transfer of energy to the lower atmospheric levels, primarily by gravity waves. However, this is computationally expensive, so a 3-domain nested configuration of the model is set up, with domain 2 nested in the coarsest domain

(domain 1), and domain 3 nested within domain 2. The model is run for the period 1st -31st October 1987, with a 0.2 degree spatial temporal resolution in the smallest domain (domain 3), and a temporal resolution of 30 seconds.

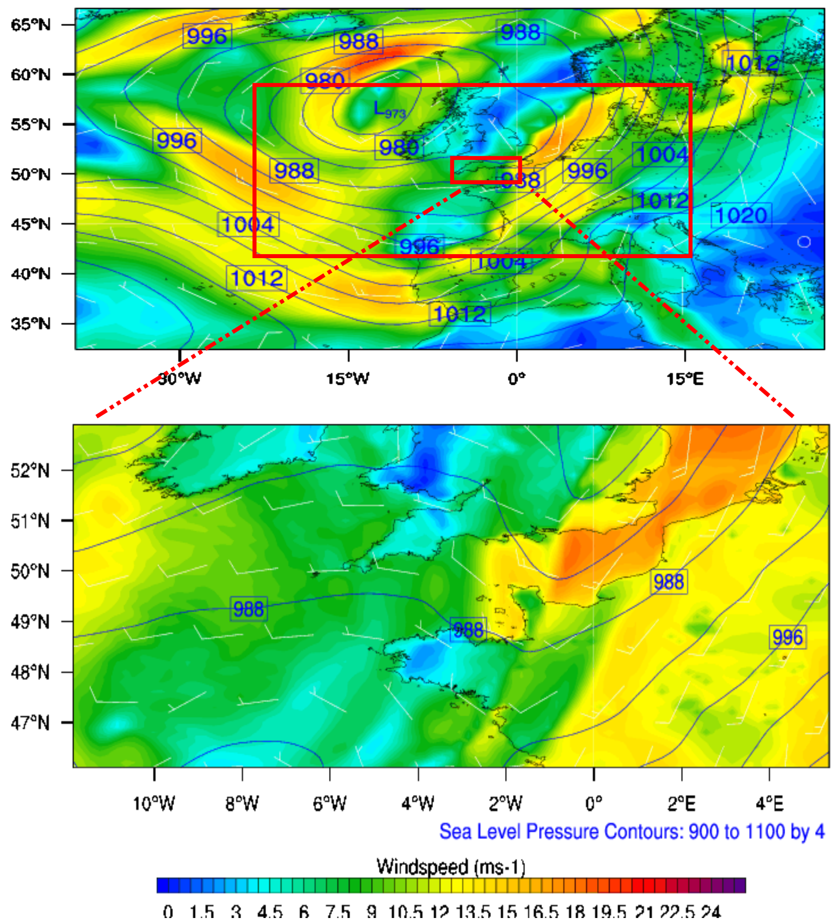


Figure 1 WRF simulation of wind and pressure fields at 03:00 UTC on 16th October 1987, in domains 1 (upper) and 3 (lower), dynamically downscaled from ECMWF ERA40 data.

(II) WAVE, TIDE AND SURGE MODEL

The aim of wave, tide and surge model in this study is to transform the global meteorological information to the oceanic and coastal hydrodynamic conditions, and these conditions are subsequently used to drive the wave and current model in the surf zone to study the impact of storm events on coastal flooding and erosion. To achieve this, a nested modelling system was setup, which includes a third generation spectral wave model (WAM), a 3D baroclinic tide and surge model (POLCOMS) for detailed tides, waves and storm surge to be predicted, see Wolf et al. (2002), Osuna et al. (2004), Pan et al. (2009) for details.

The model system consists of two cascading domains: the large/coarse one covering the North-East Atlantic Ocean (20°W-10°E & 45°N-65°N), and the downscaled fine one covering the English & Bristol Channels (8.0°W-4.5°E & 48.0°N-52.5°N) as shown in Fig. 2. The resolutions for these domains are 1/10° x 1/10° and 1/20° x 1/20° respectively.

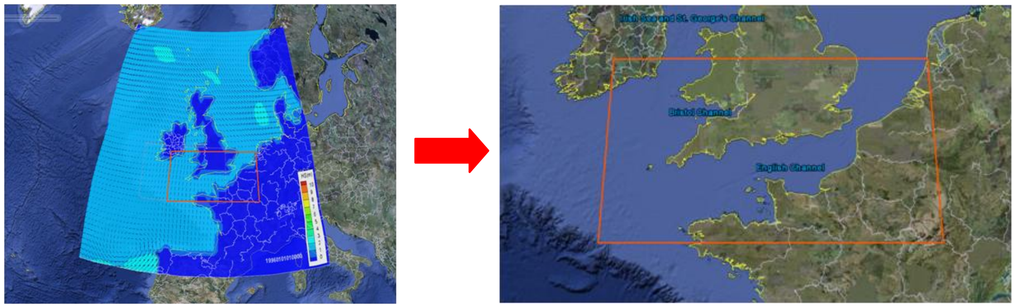
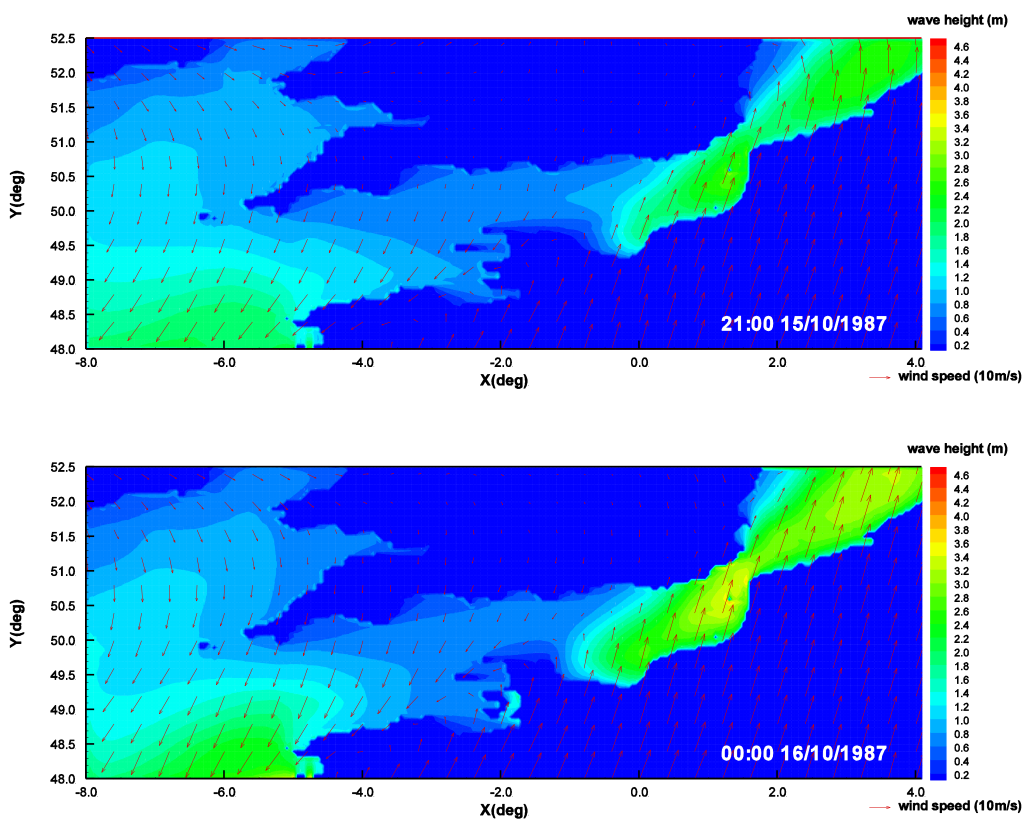


Figure 2 Schematic diagram of modelling domains

The modelling system was tested with the WRF meteorological data for October 1987, with a particular interest in the Great Storm occurred on 15-16 October 1987.

Fig. 3 shows the computed wave significant heights during the storm period superimposed with the wind speed vectors. It can be seen that the modelled waves respond well to the surface wind forcing and boundary wave forcing. Due to the fact that winds are predominately from the south-west direction related to the storm centre, the waves gradually increase towards the north-east, which generally agrees with the GEOSAT track measurements during the storm (Wu et al, 1994). Further validation of model by quantitative comparison of wave characteristics at some fixed wave gauges with higher resolution meteorological inputs will be carried out in the future study. The model tests presented here form a part of model calibration for the full scale ensemble predictions to be carried out.



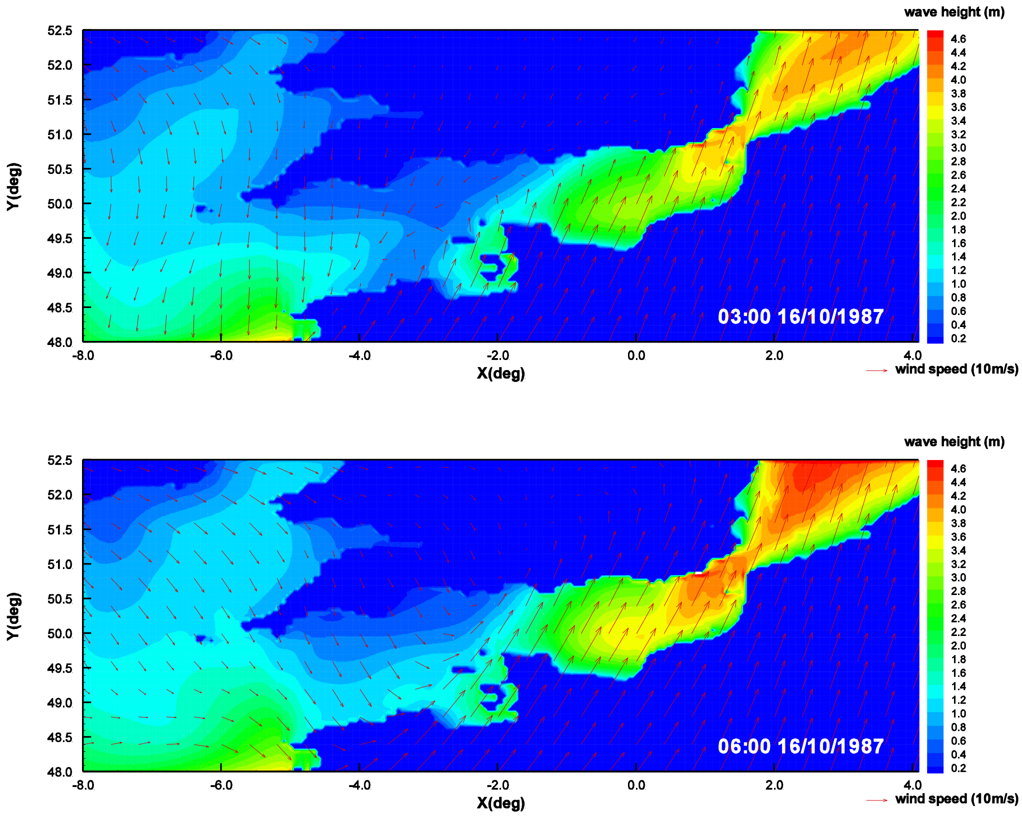


Figure 3 Computed significant wave heights in the English & Bristol Channels

(III) SURF ZONE MODEL

The objective of this study is to determine wave overtopping, breaking, turbulence and streaming in the surf zone and thus analyze the performance of sea defences and predict coastal flood risk in extreme conditions. Both 2D RANS-VOF and 3D LES-VOF-LES models are employed in this study (Lin, et al. 1998; Lv et al., 2008). The RANS-VOF model solve the Reynolds-Averaged Navier-Stokes equation for the mean flow using a non-linear k–ε model to resolve turbulent flow and a Volume of Fluid (VOF) method to capture free surface.

The overtopping prediction using the RANS_VOF is carried out for the field conditions at Portmellon reported in Magar et al. (2009). The schematic diagram of computational domain is shown in Fig. 4. The numerical setup includes a vertical seawall located between x=340 m to x=341 m and a dissipative beach with 1/30 slope made of quarry rock. The spongy layer with a length of 78 m (approximately one wave length) was added to the right of the inlet boundary. An open boundary condition was applied at the inlet boundary. The free-slip condition was applied at the rest solid boundaries. On the free surface, the zero gradient boundary conditions for turbulence generation were applied which is based on the assumption of no turbulence exchange between the water and air. A log-law distribution of the mean tangential velocity in the turbulent boundary layer is applied near the solid boundary. The initial condition consists of a still water situation with no current and wave motion. An internal wave maker was placed between x=80.5 m to 81 m. The surface elevation time series and spectrum were given in Fig. 5.

The predicted time evolution of discharge and overtopping volume per wave cycle were shown in Fig. 6 and 7 respectively. As can be seen from Fig. 6, the average overtopping discharge q_d=0.0135m^2/s. The numerical results are in good agreement with the following empirical formula recommended by EurOtop Manual (EurOtop, 2007).

The formulae to probability design and prediction proposed by TAW (2002) for breaking and non-breaking waves ($\xi_{m-1,0} < 5$):

$$\frac{q}{\sqrt{g * H_{m0}^3}} = \frac{0.067}{\sqrt{\tan\alpha}} * \gamma_b * \xi_{m-1,0} * \exp(-4.75 * \frac{R_c}{\xi_{m-1,0} * H_{m0} * \gamma_b * \gamma_f * \gamma_\beta * \gamma_v}), \tag{1}$$

with a maximum of:

$$\frac{q}{\sqrt{g * H_{m0}^3}} = 0.2 * \exp(-2.6 * \frac{R_c}{H_{m0} * \gamma_f * \gamma_\beta}). \tag{2}$$

Where α is the slope of the front face of the structure, R_c is the structural freeboard, H_{m0} is the energy spectrum based significant wave height at the toe of the slope and the Irribarren number is defined as:

$$\xi_{m-1,0} = \frac{\tan\alpha}{\sqrt{H_{m0} / L_{m-1,0}}},. \tag{3}$$

Where $L_{m-1,0}=gT^2_{m-1,0}/(2\pi)$ and $T_{m-1,0}$ being the mean energy wave period,. The coefficients γ_b, γ_f, γ_β, and γ_v in Eq. (1) and (2) are introduced to take into account the influences of the berm, the permeability and roughness on wave overtopping, the oblique wave attack and the vertical wall on the slope respectively. All these coefficients are set to 1.0 in this particular problem. The empirical overtopping discharge q is found to be 0.013 which is very close to our predicted value. (cf. figure 6). 3D simulation and its comparisons with the above 2-D model will be carried out to assess 3-D effects on the overtopping predictions.

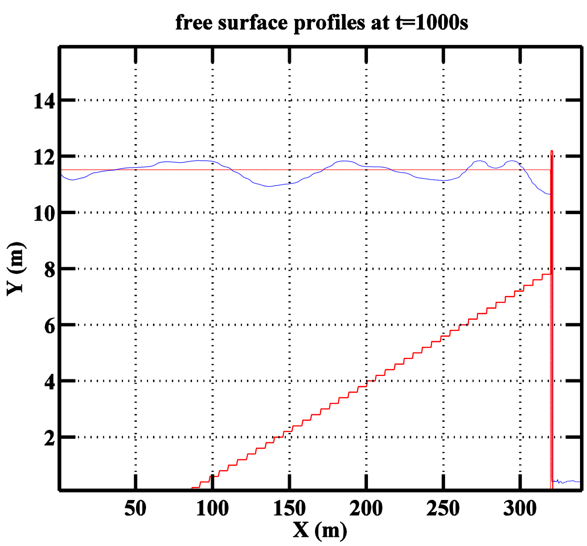


Figure 4 Schematic diagram of computational domain.

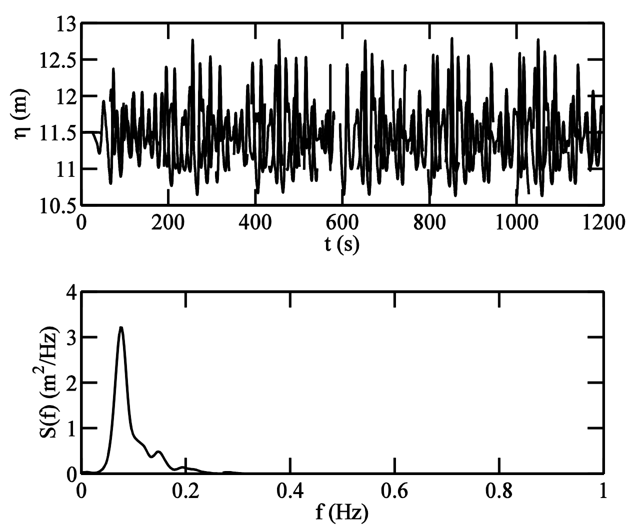


Figure 5 Surface elevation, η, and frequency spectrum density, $S(f)$, at x=320m (overtopping point). $H_{1/3}$=1.6063 m; T_{mean}=10.1978s; T_{peak}=12.8s; H_{m0}=1.5173m; T_{m0}=9.8044s.

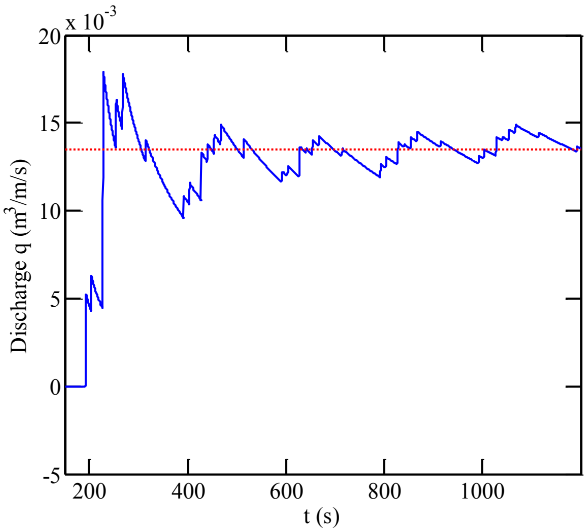


Figure 6 Time series of overtopping discharge q. Average discharge q_d=0.0135 m^2/s was obtained. (Results after 12 waves when discharge prediction becomes stable are shown here.)

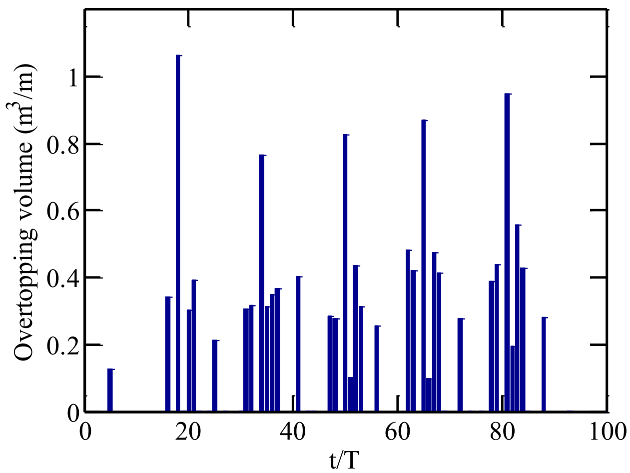


Figure 7 Overtopping volume in per wave cycle calculated from the volume flux on the crest of the seawall, T is peak wave period.

3. MODEL INTEGRATION

For each member of an ensemble of past/future storms events, the predicted wind and pressure fields by the meteorology model is used to drive the wave/tide/surge models. These give forecasts of wave and mean water level at the offshore boundary of surf zone, which in turn are used to drive the surf zone model to predict the beach and structure response and to establish an ensemble predictions of coastal flood risk arising from overtopping and scour.

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