Quantifying uncertainty in tide, surge and wave modelling during extreme storms

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Abstract

Interactions between meteorological and hydrodynamic processes are poorly understood, and may result in large uncertainties when assessing the performance of sea defences in extreme conditions. This study integrates numerical weather prediction models with models of wave generation and propagation, and surge and tide propagation. By using an ensemble methodology, the uncertainty at each stage of the model cascade may be quantified. Subsequently, this information either as a proxy or appropriately transformed into predictive uncertainty (Krzysztofowicz, 1999) will be valuable in calculating the likelihood of hydraulic and structural failure in extreme storms. This paper describes results for a domain centred on one of the locations for the proposed Severn Barrage. This barrage will be the focus for the world's largest marine renewable energy scheme and will potentially have a significant impact on the coastal flooding response of this part of the Severn Estuary.

Dynamically downscaled, high resolution wind and pressure fields of historic extreme storms are generated using the Weather Research and Forecasting (WRF) modelling system. The state of the art tide and surge model, POLCOMS, in conjunction with a third generation wave model (ProWAM) utilises the meteorological data, producing hydrodynamic parameters such as surge and wave heights at a proposed location of the Severn Barrage. European Centre for Medium range Forecasting (ECMWF) Ensemble Prediction System data are used for boundary conditions in WRF, producing a 50-member ensemble. The variation in storm track and intensity between members allows the uncertainty in model system to be quantified in terms of wave and surge heights. This work is part of the NERC funded EPIRUS consortium research but is closely allied to the interests of the EPSRC FRMRC project and the HEPEX international network focused on ensemble prediction in the context of hydrological prediction systems.

Introduction

The environmental impacts of traditional energy supplies from non-renewable sources, such as coal, oil and natural gas, are well documented, and together with their limited resources, have precipitated investment into research of alternative energy sources. Renewable energy sources, such as wind, solar, and hydropower, are seen as key to an economically, as well as environmentally, sustainable future. Technological and engineering advances have led to improvements in photovoltaic cells and wind turbines, making both solar and wind power generation more cost efficient. However, there is increasing investment in marine energy (wave and tidal power). In the UK it is estimated that tidal power could provide up to 30% of the electricity demand (Burrows *et al.*, 2009). The heavy Atlantic swell and strong tidal currents off northern Scotland, have already led to it being dubbed the "Saudi Arabia of marine energy". Indeed, this year has seen the world's first commercial wave and tidal lease agreements signed for waters around the Orkney Islands and the Pentland Firth (Crown Estates, 2010), with developers proposing an installed capacity of 1.2GW by 2020 capable of powering 750,000 homes.

Unlike wind and solar power generation, energy extracted via tidal barrages built across estuaries is wholly predictable. The world's first and largest tidal barrage was constructed in the 1960s in the La Rance Estuary in northern France. Thanks to the 2.4m tidal height, the 750m barrage has a peak capacity of 240MW (Pelc and Fujita, 2002). The Severn Estuary's tidal range of 24m, the second highest in the world, means it has the potential to provide a significant contribution to the UK's energy demand. One of the larger of the proposed options, the Cardiff-Weston scheme, has the potential to generate in excess of 8GW (equivalent to 4.4% of the UK electricity demand) (Sustainable Development Commission, 2007). The construction of a barrage across the Severn Estuary has long been debated. Along with energy generation, a barrage may offer flood protection, transport links via roads and/or rail, new commercial opportunities (e.g. tourism) as well as increased recreational activities. These benefits must be balanced against any environmental impacts, such as environmental degradation and habitat loss (Mettam, 1978; Wolf *et al.*, 2009).

In addition to the potential electricity generated from a tidal barrage installation across the Severn Estuary, the structure would offer some level of flood protection to locations upstream. An increase in population and wealth along UK coastlines in recent years mean over £130bn of assets are now at risk from coastal flooding, with around 4 million properties in England and Wales under threat (Office of Science and Technology, 2004). Projections of sea level rise (IPCC, 2007) and changes in the intensity and frequency of severe storms (Ulbrich *et al.*, 2008) in the future mean coastal flooding will continue to be a significant threat to human life and property.

One of the key aspects during the design phase of the proposed Severn Estuary barrage will be calculating the extreme loading from hydrodynamic processes (e.g. currents, tides, and waves) and the hydrostatic pressure the structure will be subject too. An understanding of the sea conditions, particularly in extreme storm events, is not only imperative for designing a structurally sound installation, but also one that is an efficient electricity producer (Jones, 2009). Buoy or vessel observations of current velocities and wave heights are typically used in this design phase. However, these may not be sufficient, particularly when considering extreme events, and it is then appropriate to employ a modelling methodology.

This paper describes the development of an integrated meteorological-hydrodynamic modelling framework, aimed at improving the quantification of uncertainty in modelling surge and wave heights during extreme storm events in the Severn Estuary. A key factor in the barrage project will be the ability to successfully model surge and wave heights, which are largely dependent on the ability to successfully model surface atmospheric pressure and windspeeds. Inherent uncertainties in model structure, including the parameterisation of complex physical interactions, combined with uncertainty in the initial conditions, propagate through the model cascade. In order to have confidence in the modelling system it is important to be able to identify and quantify these uncertainties. Not only can this methodology be employed in the design phase of the tidal barrage, but it is also suited for operational use once the barrage is constructed. An ensemble framework such as this may be utilised by energy companies in real time, in order to estimate short-term electricity generation with a quantified level of certainty.

The first section of this paper outlines the model framework, detailing the atmospheric and hydrodynamic models, and their integration. An ensemble methodology is described, with results presented from a test case of a severe storm event (26^{th}-30^{th} October 2004). This storm caused flooding in many areas of southern England, and while regions surrounding the Bristol Channel were less severely impacted it provides an opportunity to assess the proposed methodology. Modelled surge and wave heights at a location near one of the proposed sites for the Severn Estuary barrage are presented, with the effect of a barrage quantified. The ensemble methodology utilised here, demonstrates how uncertainty in the model cascade may be quantified.

Data and methods

Atmospheric pressure and surface windspeed are two key driving variables in hydrodynamic models of surge and wave generation and propagation, and are required to be input at every timestep at every node. These values may be derived from the spatially and temporally averaged meteorological fields of global reanalysis products. However, these data are usually too coarse to act as an effective input for hydrodynamic models, and therefore a downscaling tool must be used to bridge the scale gap. Simple linear interpolation of the meteorological data has been shown to produce unrealistic results due to the dynamic nature of extratropical cyclone evolution (Winter *et al.*, 2008). Other statistical downscaling methods exist, but despite being more computationally expensive dynamical downscaling has been shown to be preferable, especially for extreme storms (Pryor *et al.*, 2005; Schwierz *et al.*, in press).

In order to generate the high resolution wind and pressure fields required by the hydrodynamic models, European Centre for Medium-range Weather Forecasts (ECMWF) forecast data are dynamically downscaled using the numerical weather prediction product Weather Research and Forecasting model (WRF), described by Skamarock *et al.* (2008). Ensemble Prediction System (EPS) data produced by the ECMWF comprise of one deterministic forecast and 50 perturbed forecasts. Each perturbed forecast is intialised with slightly different conditions, and is generated by a model with slightly different parameterisations of sub-grid scale physical processes (Persson and Grazzini, 2007). The forecasts run for 10-days, at 6-hour timesteps. In addition to the perturbed forecasts from the EPS, ECMWF reanalysis data (ERA Interim) is utilised, and may be considered the "control" dataset. The ARW (Advance Research WRF) dynamical core of WRF version 3.1 is used to downscale both the 50-member ensemble of ECMWF forecasts and control dataset for the periods 26th October 2004 – 3rd November 2004 and 15th October 2004 - 3rd November 2004 respectively.. The model domain extends from 22^{o}W to 12^{o}E and from 47°N to 67°N, with a resolution of 27km, and a 60-second timestep. Four dimensional data assimilation is employed, where WRF is run with extra nudging terms for horizontal winds, temperature and water vapour, with these nudged point by point to a 3D space- and time-interpolated analysis field.

Dynamically downscaled wind and pressure fields generated by WRF drive the surge and wave models. A third generation spectral wave model, WAM, is used to solve the wave action balance equation without any pre-defined shape of the energy spectrum (Günther *et al.*, 1992). A modified version of WAM, ProWAM, developed by Monbaliu *et al.* (2000) also includes the current effects on wave modelling. Meanwhile, to simulate tide and surge generation and propagation, POLCOMS, a baroclinic three-dimensional current model with coverage of both the deep ocean and the continental shelf (Holt and James, 2002) is used. Forcing at the open boundaries of POLCOMS is provided by CS3, a two-dimensional tide and surge model which generates harmonic tidal conditions (both water levels and currents) using 26 harmonic coefficients over a smaller, higher resolution domain (Flather, 2000). The integrated meteorological and hydrodynamic model system was set at two downscaling domains, with the coarse domain covering the North-East Atlantic Ocean (20°W-10°E and 45°N-65°N) at a resolution of 0.1° latitude and longitude, and fine domain covering the English & Bristol Channels (8.0°W-4.5°E and 48.0°N-52.5°N) at a resolution of 0.05°. The WAM model is initially run at the coarse domain to provide wave boundary conditions/forcing to the nested fine domain. The coupled POLCOMS & WAM models then run at the fine domain to calculate tides, surge and waves in the English and Bristol Channels, with additional tidal boundary conditions provided by CS3 model.

The impact of the proposed Severn Estuary barrage on surge and wave heights during the storm is assessed by driving the hydrodynamic models with the downscaled control data, with and without an idealised, impermeable barrage in the domain (whose location is shown in Figure 1). Simulated surge and wave heights driven by the downscaled EPS forecasts are further analysed at a point near the proposed location of the barrage (shown as a star in Figure 1) to demonstrate how this integrated model framework allows the uncertainty in the hydrodynamic response to severe storms to be quantified. The divergence between different ensemble members provides a proxy measure of the uncertainty in the system.

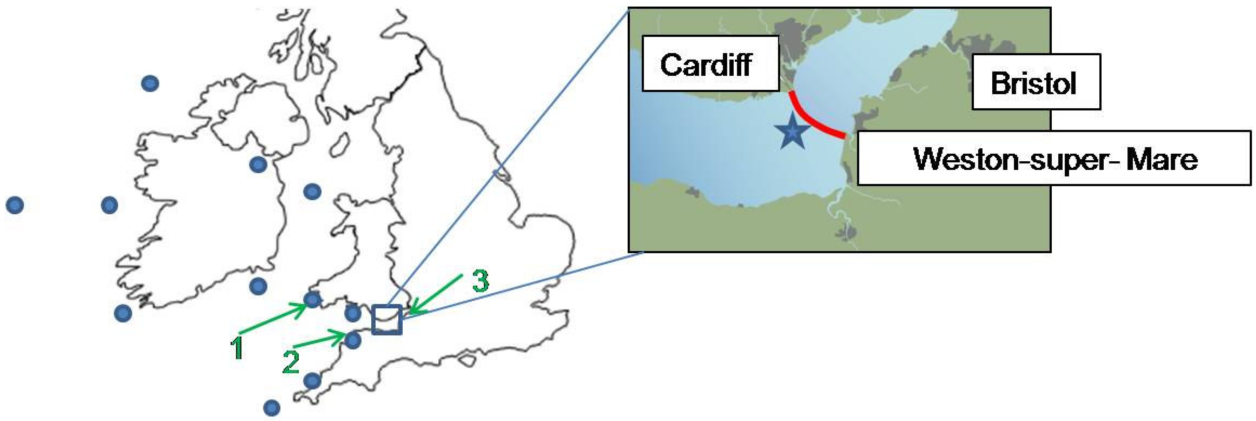

Figure 1 - Map of wind observation locations (dots) used in the verification of the downscaling process. Three tidal gauge locations (arrows) provide data to verify the surge model. A proposed location for a Severn Estuary tidal barrage is between Cardiff and Weston-super-Mare (inset).

Results

Model verification

Meteorological model (WRF)

Before considering the results from the hydrodynamic models, it is important to verify the atmospheric component of the model framework is capable of producing reliable downscaled meteorological variables, and thereby adding value to the raw ECMWF data. Hourly surface mean windspeed observations from the UK Met Office (UK Met Office, 2010) and Irish Marine Institute (Irish Marine Institute, 2010) are compared to control data (linearly interpolated to provide hourly values) and dynamically downscaled control data at the locations indicated in Figure 1, for the period 15th October to 3rd November, 2004. The downscaled data are shown to be more reliable at capturing the variance of observed windspeeds than the raw reanalysis data (correlation coefficients of 0.92 and 0.9 respectively). In addition, a positive bias exhibited by the reanalysis data of 0.51 ms^{-1} is higher than that shown by the downscaled data (0.40 ms^{-1}). A full analysis of WRF as an effective downscaling tool is beyond the scope of this paper. However, the brief windspeed analysis described above, coupled with further analyses of the low pressure centre intensity and track (not shown), indicate that WRF is fit for purpose.

Surge and wave models

Tide gauges located at Milford Haven (1), Ilfracombe (2) and Avonmouth (3), shown in Figure 1, are used to verify the simulated surge heights during the storm event. The dynamically downscaled control data are used to drive the hydrodynamic models. Figure 2 shows the simulated and observed surge heights values for Milford Haven, demonstrating a good agreement between the two. Similar results are found for Ilfracombe, while Avonmouth shows some discrepancy, likely due to the nonlinear effects of the astronomic tide in the shallow waters of the estuary. Unfortunately wave height data is not available for this period in the Bristol Channel, but verification work on other locations in the English Channel reveals a good agreement between simulated wave heights and those observed during the same storm.

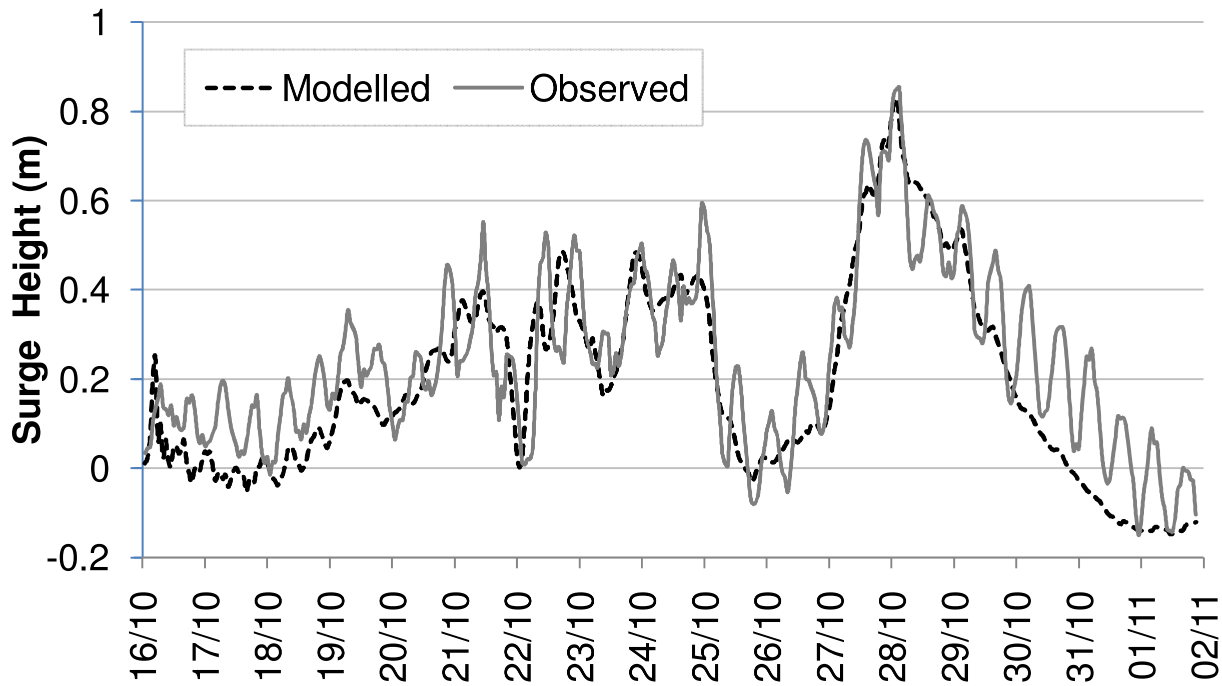

Figure 2 - Modelled (dotted) and observed (solid) surge height at Milford Haven between 16th October and 2nd November, 2004.

Impact of a Severn Estuary barrage

The impact of the proposed Severn Estuary barrage on waves and surge at the storm peak (early hours of 28th October, 2004) is considered using the downscaled control data to drive the hydrodynamic models. For the sake of brevity the results presented here are kept to a minimum, and are aimed at merely demonstrating how the model framework may be applied in further investigations into the impact of any barrage.

Wave heights

Wave heights in the Bristol Channel simulated with and without the barrage show little difference at the storm peak, except at a region very close to the structure, where increases in excess of 10% are seen with a barrage. This is likely due to the barrage blocking the tidal current, thereby reducing the Doppler effect on waves and permitting greater wave heights. Also, there may be some element of wave reflection off the barrage increasing wave height in that vicinity.

Surge heights

Compared to simulations without the barrage, peak surge heights computed with a barrage in the domain are up to 5% lower near the structure, simultaneously increasing by a similar magnitude approximately 50km downstream. Since surges have a long wavelength, the increase in amplitude downstream is likely compensating for the reduced amplitude upstream caused by the barrage. It must be noted that the crude model used in this study assumes that the barrage is a solid barrier, thereby somewhat limiting any inferences that may be drawn from these preliminary results.

Ensemble prediction

The use of dynamically downscaled meteorological data to drive hydrodynamic models has been demonstrated above, along with a brief description of the impact of a proposed barrage on surge and wave heights in the Bristol Channel. This section now presents results generated using the integrated modelling system in an ensemble framework.

Predicted wave (Figure 3) and surge (Figure 4) heights using the downscaled EPS forecast data and control dataset are presented for the storm event. Unfortunately, no observations are available for the proposed site of the barrage for verification. However, wave and surge heights simulated using the downscaled control dataset have been shown to be reliable at other locations, so may be considered as a proxy for observations at this location.

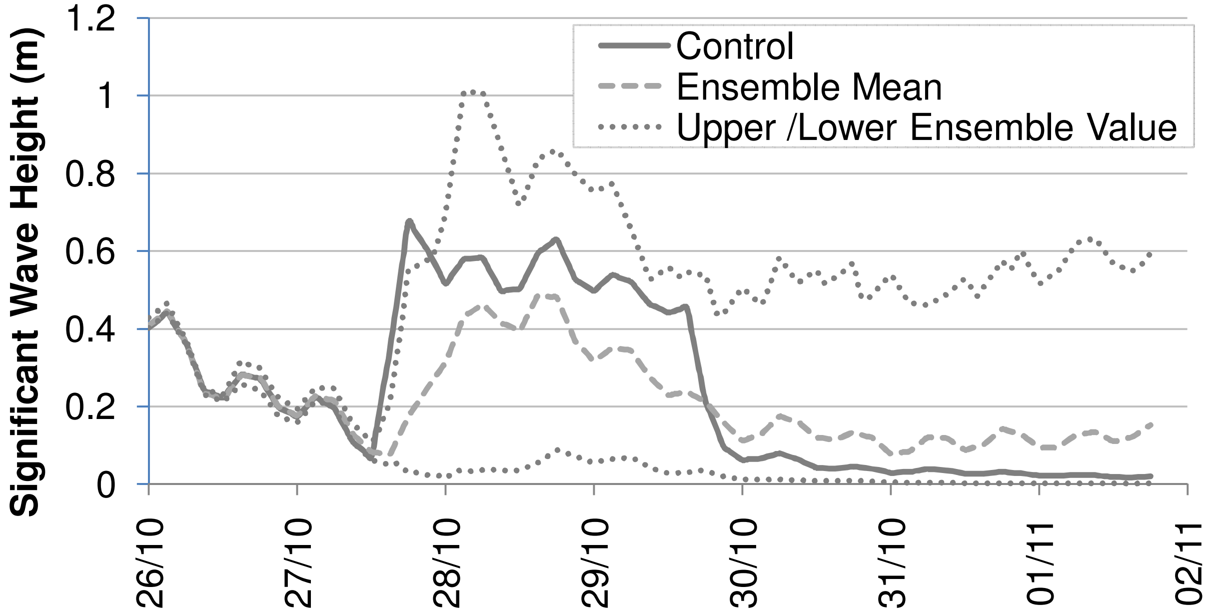

Figure 3 - Significant wave height at the proposed barrage site for 26th October - 2nd November 2004, predicted using the control data (solid line). Mean (dashed), upper and lower (dotted) values of the wave height simulated using the downscaled EPS forecasts are also shown.

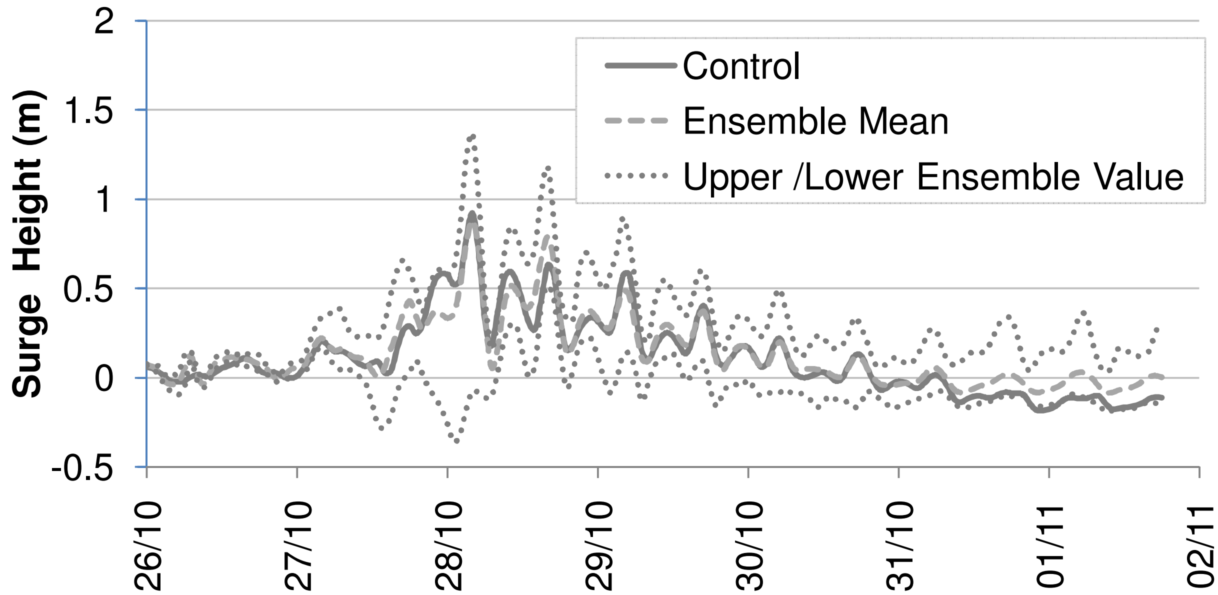

Figure 4 - Surge height at the proposed barrage site for 26th October - 2nd November 2004, predicted using the control data (solid line). Mean (dashed), upper and lower (dotted) values of the surge height simulated using the downscaled EPS forecasts are also shown.

Generally the modelled wave and surge heights produced by downscaled EPS data envelope the control values. The ensemble mean is largely in agreement with the control, demonstrating in part the benefit to an ensemble prediction system over a deterministic forecast. The degree to which the upper and lower bounds of the forecast ensemble diverge provides a proxy measure of the uncertainty in the wave and surge height predictions.

Information of this nature would likely be useful when considering the operation of an electricity producing tidal barrage, such as the one proposed for the Severn Estuary. Depending on the type of installation, certain adverse sea conditions may result in periods when electricity production will cease. Having an integrated forecast model, with quantifiable uncertainty, such as the one outlined in this paper, would provide vital information to decision makers responsible for the barrage operation. In addition, the framework developed here may also be applied for storm hindcasting, allow an analysis of previous sea conditions which would be useful in the design phase of the barrage, in terms of both an energy generation, as well as flood protection, standpoint.

It should be noted here, that the storm event under consideration did not produce exceptionally large wave or surge heights in the Bristol Channel, and should be considered as a demonstrative test case only. However, certain ensemble members did produce reasonably high wave and surge heights, and it is worth considering the storm track and intensity in these members. Figure 5 shows the storm track and intensity of the two ensemble members which produced the highest wave and surge heights (members 32 and 16), and the two which produced the lowest wave and surge heights (46 and 08). Windspeed, though not shown here, is related to the pressure gradient between the storm centre and that outside the system. The central pressure is indicated in Figure 5, and in these cases may be considered a proxy for windspeeds.

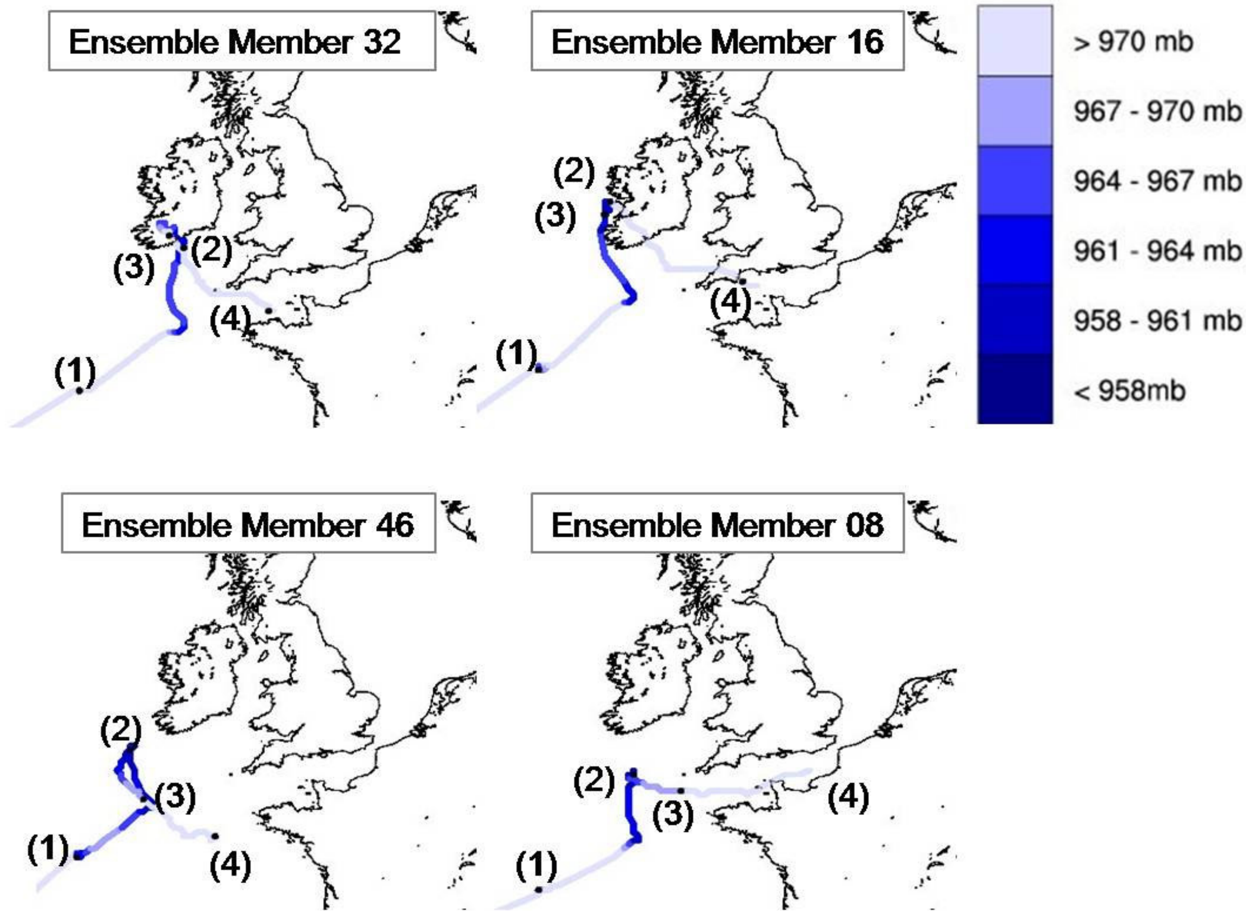

Figure 5 - Storm tracks of the two ensemble members producing the highest wave and surge heights (members 32 and 16, top) and the two producing the lowest wave and surge heights (members 08 and 16, bottom). Numbers (1) to (4) represent the location of the centre of low pressure system at 00:00 on 27th, 28th, 29th and 30th October respectively. The mean sea level pressure of the centre of the low is indicated by the shade of the line.

Ensemble members 32 and 16 produce high surge heights due to the location of the centre of the storm on the 27th and 28th October. Despite not being as intense as the low pressure systems in other members (e.g. member 46), the storm track in members 32 and 16 are more northerly than most, positioning the centre of the low pressure directly west of the Bristol Channel. The high wave heights in the Bristol Channel produced by ensemble members 32 and 16 are also related to the location of the low pressure centre. Windspeeds are generally higher to the south of the centre of the low pressure, and blow from the south-west, meaning the more northerly storm track of ensemble members 32 and 16 result in winds blowing straight up the Bristol Channel, producing higher wave heights than other ensemble members.

This brief analysis demonstrates the benefit of using an integrated model framework in an ensemble methodology. Individual ensemble members can be identified and further analysed separately, with each storm track and intensity having a different impact on wave and surge heights. It should be noted that individual ensemble members merely represent possible tracks that depict the variability in the evolution and dissipation of an extratropical cyclone (a non-linear chaotic system), each having a very small likelihood of occurrence. The nature of the EPS forecast dictates that each member is theoretically equally likely to occur, thereby creating an opportunity to use the methodology proposed here to generate a large catalogue of sea conditions in severe storms events (each historic storm considered would produce a further 50 sets of sea conditions). Wave and surge heights driven by these theoretical storms will provide important insight into the nature of the model cascade response to different forcings. Such information could be valuable if utilised in the design phase of the barrage, as well as in flood risk management in other areas of the Bristol Channel.

Conclusion

The Severn Estuary is the proposed site for the construction of a tidal barrage, which could provide a significant contribution to the UK electricity demand, as well offer flood protection to locations upstream. This paper describes an integrated model framework of numerical weather prediction and hydrodynamic models of wave and surge generation and propagation. Dynamical downscaling of reanalysis data with the WRF model produces higher resolution wind and pressure fields, suitable for driving the hydrodynamic models. The impact of the proposed barrage on surge and wave heights in the Bristol Channel during a test case storm is quantified. Results demonstrate that an ensemble methodology is a suitable technique in this instance to allow uncertainty in the model cascade to be quantified. The divergence between ensemble members in the simulated wave and surge heights at a particular location and time is a measure of the uncertainty in the system. The benefit of an ensemble methodology for fluvial flood prediction (He *et al.*, 2009) and ocean wave height prediction (Cao *et al.*, 2007) has been shown, with results presented here suggesting further utilisation of EPS in an operational environment (forecasting downtime for a tidal energy plant).

It is crucial to have an understanding of sea conditions in extreme events, in order that any proposed barrage be designed to withstand large loads. Extreme events, by their nature, are rare and therefore few observations are available for such events. Dynamically downscaled wind and pressure fields may be generated by WRF for any extreme storm event in the ECMWF archive (reanalysis data is available from 1959 onwards), and may be used to drive the surge and wave models. The ensemble methodology suggested here enables extreme events from the recent past to be "re-visited" and modelled in such a manner as to produce a large catalogue of wave and surge heights associated with extreme storms.

Future work in this area involves a introducing a higher-performance coastal model, COAST2D, into the model framework. This will be applied to simulate the waves, tides and surge conditions, and will likely provide more accurate predictions in specific coastal areas. While this paper describes the application of the model framework to an historic storm, it is equally suited to analyse the potential impacts of climate change on future storms. Meteorological variables extracted from regional climate model projections of future climate may be downscaled by WRF, and used to drive the hydrodynamic models. The IPCC (2007) have stated that the intensity and frequency of severe extratropical cyclones over the UK is likely to be affected by climate change, with return periods of high windspeeds over the UK projected to decrease in future (Leckebusch *et al.*, 2006; Ulbrich *et al.*, 2008). Any barrage constructed now must consider future climate change (and subsequently sea states) in its design.

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