THE WAVE AND SURGE CLIMATE OF THE NW EUROPEAN CONTINENTAL SHELF

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1. INTRODUCTION

Coastal areas (less than 100m above sea level) are the most densely populated on earth with, at present, more than 35% of the world's GDP and 40% of population (Lichter et al., 2011). Combinations of economic, geographic and historical conditions attract people and drive coastward migration (Seto, 2011), especially to coastal cities, and this phenomenon (which affects 22 out of 27 EU Members States with maritime boundaries) is expected to continue in the future, as a function of projected socio-economic development pathways. These low-lying, highly valuable, areas are vulnerable to coastal flooding by a combination of mean sea level, storm surge together with wave setup and overtopping. The NW European continental shelf is a large area of relatively shallow water (<200m deep), in which storm winds can generate large surges and waves. The most vulnerable coastlines lie around the southern North Sea, threatening coastal flooding in the United Kingdom, Belgium, the Netherlands, Germany and Denmark. Widescale coastal flooding is identified as one of the main national risks e.g. in the UK National Risk Register. In the future this risk is likely to rise because of global warming, mainly due to the effect of sea level rise, which makes the occurrence of extreme water levels more frequent, even without any change in the forcing.

It is likely that 21st century sea-level rise will be greater than during the 20th century. For global warming above 2ºC by 2100, global sea level rise could reach 1m in the RCP8.5 scenario, due to a combination of thermal expansion and the melting of glaciers and ice sheets. There are large uncertainties in process-based model projections e.g. with the contribution from Greenland. Semi-empirical model projections are for up to 1.6m by 2100 (e.g. Jevrejeva et al, 2010). An upper limit for sea level rise by 2100 has been set at 2m (Pfeffer et al, 2008), which although highly unlikely is not impossible. Modelling uncertainty contributes at least as much to the overall uncertainty as uncertainty about future GHG emissions scenarios.

There is a perception that, if human societies can cut emissions of greenhouse gases, global temperature increase would be stabilized and the most dangerous consequences of climate change could be avoided. However, even if temperatures stabilize, sea level will continue to rise for several centuries (Schaeffer et al., 2012). For all scenarios the rate of sea level rise is positive for the coming centuries, requiring 200-400 years to drop to the 1.8 mm/yr 20th century average (Jevrejeva et al, 2012). This makes adaptation to sea-level rise essential for coastal zones and the vulnerability to coastal flooding due to all the above factors will increase. There is thus a requirement for knowledge of the probability of high waves and extreme surge events for the design of coastal and offshore structures, warnings of coastal flooding and coastal defence against erosion (Wolf, 2009). There are other environmental considerations of and change in wave climate. Waves are important agents of surface mixing and resuspension of bottom sediments, and hence, can impact ecology in terms of the availability of nutrients and benthic habitats. The long-shore drift due to waves is a key determining factor for coastal sediment transport.

Thus there is a need for accurate and reliable forecasts and projections of waves and surges using dynamical models which can provide understanding of processes and increasing confidence in projections.

The main uncertainty in storm surge and wave modelling is in the forecasting of storms in the atmosphere and the future projections of these events. On the NW European continental shelf we are mainly concerned with changes in the location and intensity of the storm tracks of mid-latitude depressions coming from the North Atlantic.

Possible increases in storminess in the North Sea may lead to problematic scenarios of combined surges, waves and regional sea level rise (e.g. Katsman et al, 2011, who carried out a study for the Netherlands), although there is little evidence that storm surges themselves will increase (e.g. Sterl et al., 2009, see below). Over recent years various studies of the wave and surge climate of the NW European continental shelf have been made, using surge and wave models, generally based on operational forecasting systems. These models have been thoroughly validated against coastal tide gauges and wave observations and therefore can be regarded as quite reliable, at least in their normal mode of operation (which may include some data assimilation). Projections for extreme values under the present day climate or future climate forcing must be treated with more caution. The future climate forcing is uncertain, with a large amount of variability in projections of storms. Storms are poorly resolved in global models, due to their relatively small spatial extent, and, in general, this leads to underestimation of extreme winds and waves (Caires and Sterl 2005), which can significantly bias the impact model results. Numerical Weather Prediction (NWP) models are now often run as ensembles to estimate the uncertainty due to initial conditions over a few days of forecasts (e.g. the UK Met Office Global and Regional Ensemble Prediction System - MOGREPS). The same models are now commonly used as climate models, perhaps at a coarser resolution, with regional models being nested within global models. Model uncertainty can be estimated with multi-model ensembles (MME) and perturbed physics ensembles (PPE).

Sterl et al. (2009) assessed extreme surge heights at the Dutch coast for two 51-year periods (1950–2000 and 2050–2100), using the wind fields from a 17-member ensemble climate change simulation (Sterl et al 2008a) in combination with an operationally-used surge model for the North Sea area. Wind speeds in the southern North Sea are projected to increase due to an increase in south-westerly winds (Sterl et al, 2008b). However, the highest surges along the Dutch coast are caused by north-westerly winds, because of their long fetch and the geometry of the coastline. As a result, local extreme surge heights are largely unaffected by the increase in wind speed (Sterl et al. 2009), as was found in earlier climate model studies (e.g. Lowe and Gregory, 2005).

There has been much recent research aimed at understanding past and future changes in storminess over NW Europe, due to the changes in mid-latitude storms over the NE Atlantic. Trends in severe wind storms around the UK are difficult to identify, due to low numbers of such storms, their decadal variability, and the unreliability of direct wind speed observations (Wang et al., 2009). Their analysis shows that storminess conditions in this region have undergone profound decadal or longer time-scale fluctuations, with considerable seasonal and regional differences. The most notable differences are seen between winter and summer, and between the North Sea area and other parts of the region. Over the last century the number of winter storms has decreased then increased again. The observational evidence indicates that the strength of mid-latitude sea level pressure (SLP) gradients and associated westerly circulation has increased in the northern hemisphere, especially during winter, since at least the late 1970s. Behaviour of the North Atlantic storm tracks seems to be a key to understanding present and future changes in storminess. Future climate model projections have a particularly large spread between models and a low signal to noise ratio over Europe compared to other mid-latitude regions (Hawkins and Sutton 2009). Woollings (2010) identifies future European climate as particularly uncertain because (i) the spread between the predictions of current climate models is still considerable and (ii) Europe is particularly strongly affected by several processes which are known to be poorly represented in current models such as the small scale structure of storms. The last IPCC-report (IPCC, 2007) examined projected wind changes over Europe. Some models were found to predict an increase in storminess over middle and northern Europe, while others predicted a decrease.

Some of this variability seems to be related to the large-scale atmospheric patterns such as the North Atlantic Oscillation (NAO), which is related to the SLP difference between Iceland and the Azores. Low-frequency SLP variability, and with it the variability of the NAO, is essentially caused by the distribution of the synoptic systems.

In this paper we examine some results from recent hindcasts of surges and waves on the NW European continental shelf using the POLCOMS-WAM circulation and wave model system, driven by the Met Office/Hadley Centre NWP, in order to understand the patterns of response to the present day forcing conditions and describe the wave and surge 'climate'. Projections of waves and surges have also been made using the Met Office/Hadley Centre climate model PPE ensemble, which has been run for up to 140 years (1960-2100) for the SRES A1B scenario and some results of these are shown. Some issues of model downscaling, especially for coastal waves, are discussed.

2. WAVES AND SURGES ON THE NW EUROPEAN CONTINENTAL SHELF

Storm surges in the southern North Sea have been of concern over many years. The United Kingdom and the Netherlands coastal flood warning systems were both established following the disastrous North Sea storm surge of 1953. During the night of 31 January, coastal flooding caused the deaths of 1,795 people in the Netherlands and 307 in the United Kingdom (McRobie et al., 2005). The maximum surge exceeded 2m over most of the southern North Sea and reached 3.90m at Harlingen on the Dutch coast, while waves in the southern North Sea reached 8m (Wolf and Flather, 2005).

The amplitude of the main lunar semi-diurnal tide in the North Sea is typically of the order of 1 to 3 metres, with a large spring-neap variation and important non-linear effects in the shallow coastal zone generating higher harmonics. On top of this, in the winter extra-tropical (mid-latitude) depressions can cause surges that are comparable in amplitude to the tides. Mid-latitude winter storms, originating in the North Atlantic, typically track across the UK from SW to NE (Brown et al., 2010). Studies of storm surges over many years (e.g. Heaps, 1983) have shown how surges on the east coast and west coast of the UK are related to somewhat different types of storm events, their track, translation speed and intensity. Brown et al. (2010) found that, on average, one to two storms per year could generate a storm surge>1.5m at Liverpool, corresponding to wind speeds of Beaufort force 8 (gale force) or larger. Similarly there are likely to be a few storms per year where there is a significant storm surge in the North Sea.

For the west coast of the UK, there can also be significant storm surges, causing coastal flooding. Major surges at Avonmouth have been associated with secondary depressions which pass north-eastwards over Ireland at a critical speed approaching 40 knots (Heaps, 1983, Lennon, 1963).

Wind is the dominant driving force of storm surges, with atmospheric pressure gradients contributing approximately 20–30 per cent of the total (Pugh, 1987). Storm surge forecasts are issued by either the National Meteorological Services (United Kingdom, the Netherlands, Denmark, Norway) or the National Maritime Services (Belgium, the Netherlands, Germany) of the countries bordering the North Sea.

Wind also drives wind-waves which increase with wind-speed, fetch and duration, with the largest waves experienced on the west-facing coasts of the UK, France and Ireland, exposed to the long fetch of the Atlantic. Largest waves on the NW European shelf are experienced to the NW of Scotland. Wolf and Woolf (2006) discussed the effect of storm frequency, track, speed and intensity as well as the strength of the prevailing westerly winds on waves in this region. Mean monthly wave heights were most sensitive to the relative strength of the westerlies. The maximum wave height is fairly sensitive to all variables except for the frequency of storms. The largest waves are associated with a strong background wind field and intense storms translating slowly on a relatively northerly track. Typically the waves grow most in the SE quadrant of the storm where the wind speed is in the same direction as the storm is moving.

3. DATA AND MODELS

Some of the main tide gauges providing an international network around the North Sea are shown in Fig. 1, part of the North Sea Observing System (NOOS). These gauges provide a long record of high frequency water elevation data, including tides, surges and mean sea level changes. Tide gauges show that global mean sea level rose at a rate of around 1.7 mm/year over the 20th century, but there have been significant decadal variations around this value. For example, using a non-linear trend analysis on the long record from Cuxhaven, Mudersbach et al. (2013) found that prior to the mid-1950s and from about1990 onwards, changes in high sea levels were not different from mean sea level changes. However, from the mid-1950s to 1990 changes were significantly different from those observed in mean sea level. Possible reasons for this appear to be due to changes in the amplitudes of several main tidal constituents, which are apparent since the mid- 1950s as well as decadal variability in the storm activity (with strong westerly winds in the North Atlantic region from 1960 to the1990s, which is also the period of large positive values of the NAO). Satellite measurements show a rate of global mean sea-level rise of around 3 mm/year over the last 2 decades.

Coastal impacts also depend on the vertical movement of the land, which can either add to or subtract from climate-induced sea-level change, depending on the particular location. The relative sea-level rise, which is observed at a given location, depends partly on the local vertical land movement (Bradley et al. 2011). In order to interpret the cause of sea-level rise, corrections to sea level observations must be made for these movements, which may be due to, for example, glacial isostatic adjustment (GIA), tectonics (e.g. earthquakes), or subsidence of land due to ground-water extraction. Geodynamic models exist at present only for GIA. Contributions to vertical land movement, of whatever origin, are now being measured at many sites using advanced geodetic techniques (e.g. Ostanciaux et al., 2011). Around the North Sea relative sea level rise is generally larger in the south and smaller in the north due to GIA.

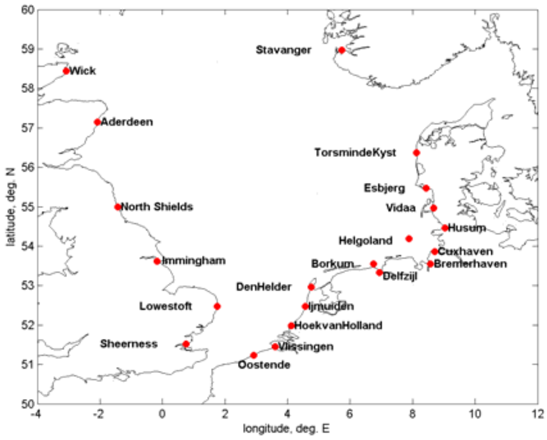

Figure 1: Tide gauges around the North Sea

The tide gauge records have allowed surges to be observed over many years, identifying the tidal residual by subtracting the tidal prediction for each location. Table 1 shows some events identified over 20 years from 1991-2011 and catalogued on the eSurge website (http://www.storm-surge.info/sears-sev-list?aoi=/sears/AOI/AOI_010). It may be seen that there is not necessarily a significant event every year although some years have several.

Storm surge warning systems have been set up for the countries around the North Sea. The United Kingdom operational warning system is now called United Kingdom Coastal Monitoring and Forecasting (UKCMF). Meteorological forcing is taken from regional atmospheric models that have resolutions of O(10km). The United Kingdom Met Office and Germany have their own models, Belgium uses the results from the United Kingdom model and the other countries are members of the HIRLAM (High Resolution Limited Area Model) consortium of European meteorological institutes and run their own version of the HIRLAM model.

The storm surge models which are used may be 2D (depth-averaged) or 3D and have a variety of resolutions, covering either the whole of the north-west European continental shelf, or being nested within larger, coarser models for local detail. The current United Kingdom operational 2D tide-surge model covers the entire north-west European continental shelf at ~12-km horizontal resolution (Flather, 2000) forced by the North Atlantic and European (NAE) mesoscale atmospheric model.

NAME	DATE
Storm Ulli	3 Jan 2012
Unnamed Storm	27 Nov 2011
Cyclone Berit	24 Nov 2011
Northeast Storm	14 Jul 2011
North sea storm surge	4 Feb 2011
North sea surge	11 Oct 2010
Winter storm Emma	2 Mar 2008
Major North Sea storm surge	8 Nov 2007
Complex triple storm event	18 Jan 2007
Winter Storm Britta	1 Nov 2006
Atlantic depression over Scotland	13 Jan 2005
Winter storm Gudrun (Erwin)	9 Jan 2005
Westerly storm over Denmark	20 Mar 2004
Northerly storm over Denmark	6 Dec 2003
Rapid displacing storm low	27 Oct 2002
Easterly storm over Denmark	21 Feb 2002
Westerly storm in North Sea	28 Jan 2002
"Kanaalrat" event	28 May 2000
Cyclone Anatol	3 Dec 1999
Rapid changing winter flow	19 Feb 1996
Rapidly moving low-pressure system	28 Jan 1994
Wave event in southern North sea	14 Nov 1993
Winter Storm Undine	6 Jan 1991

Table 1: recent surge events in the North Sea (from eSurge database, see project web site: http://www.storm-surge.info/sears-sev-list?aoi=/sears/AOI/AOI_010)

The operational surge forecasting models are non-linear and include the astronomical tide as well as the meteorological effect on the water level, thus include tide-surge interaction (Wolf, 1978; 1981). However, tidal heights for coastal forecasts are derived from tide tables generated using harmonic analysis, since even at the finest resolution numerical models do not give comparable accuracy (see, for example, Jones and Davies, 1996). In practice, the astronomical tide from the model is replaced by the results of a more accurate harmonic analysis to provide a time series of water level upon which wave effects (wave setup) may then be added.

The performance of the storm surge models has been monitored over many years, and is found to be seasonally dependent (Horsburgh et al., 2011). In the summer season, with generally little surge, the errors are of the order of the observational error, but in winter the errors increase with forecast lead time. Errors in individual forecasts for more extreme surges can be significantly larger but, as these occur less frequently, a standard deviation for such errors is less meaningful. Validation of the United Kingdom models is performed monthly by comparison with observed sea-level data from the National Tide Gauge Network (see: http://www.pol.ac.uk/ntslf/surgemonthlyplots/).

Typical monthly mean RMSEs are of the order of 0.1m, but maximum instantaneous errors can be as large as 0.5m. Recent developments include an ensemble surge model system, based on MOGREPS (Flowerdew et al., 2010), which provides an estimate of the uncertainty related to the atmospheric model forecast from different initial conditions.

The operational wave observing system for UK waters, WaveNet (see Fig. 2), was set up in 2002 and now includes over 10 years of real-time monitoring data with nearly 90 active observing stations plus archives of older data.

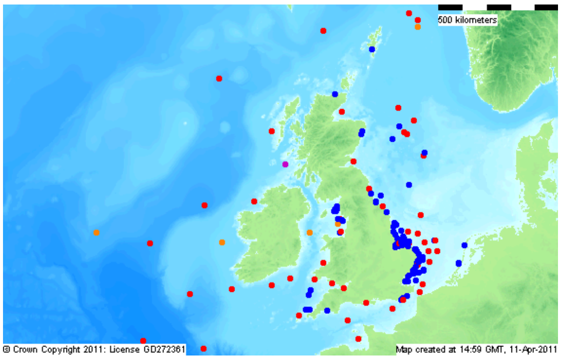

Figure 2: WaveNet wave observing system operated by CEFAS (UK)

These wave data are used to validate the UK Met Office wave model, which is run four times daily. The WAVEWATCH III model (http://polar.ncep.noaa.gov/waves/) was introduced as the Met Office's operational model in October 2008.

The model system which is used in the present work is the POLCOMS-WAM coupled model system developed at NOC (Liverpool, formerly the Proudman Oceanographic Laboratory, POL). This combines the 3D baroclinic POLCOMS model (Holt and James, 2001) with a wave model which is based on the well-tested 3rd-generation spectral model WAM. A modified version of the third-generation spectral WAMC4 model (named ProWAM, Monbaliu et al., 2000) has been used. The model system has been implemented on two grids: a coarse 1° grid for the Atlantic to provide boundary conditions (sometimes just the NE Atlantic), and a 12km model of the NW European continental shelf, which is the same grid as the operational surge model, CS3 (Fig. 3), with surges calculated in the POLCOMS model on the latter grid. It is not necessary to provide oceanic boundary conditions for the surge model since the inverted barometer effect at the shelf edge represents the pressure effect and wind stress is only effective in driving storm surges over the shelf sea area (<200m depth). To improve the performance of POLCOMS as a surge model the Charnock parameterisation of wind-stress (Charnock, 1955) has been implemented in place of the original Smith and Banke (1975) formulation. This also allows a wave-related drag coefficient to be used in the wave-coupling (Brown and Wolf, 2009). The optimum value for the Charnock parameter appears to vary with model area and resolution and there can be some sensitivity to the wind model resolution (Bricheno et al., 2013).

For the hindcast studies referred to here, the wave model was not run in a 2-way coupled mode with the tide and surge model (although this has been done for other applications e.g. Osuna and Wolf, 2005; Bolaños et al., 2011; Brown et al., 2011a; 2013). Even when these processes are important in the short-term (order of days, during stormy periods), their effect on the wave statistics in the long-term is not clear.

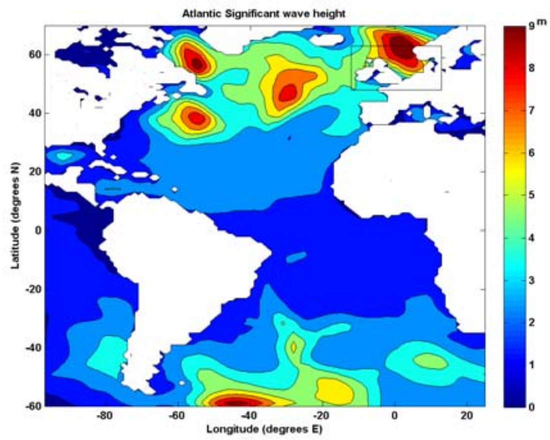

Figure 3: Nested NW European shelf model (CS3) within Atlantic wave model

The model is forced by Met Office mesoscale (~12km) NAE atmospheric model winds over the CS3 grid. The Atlantic (1° by 1° resolution) region has been forced by ECMWF winds. It is worth mentioning that, even when the CS3 implementation is forced by the open boundary conditions generated by a previous coarser grid, the first 4 or 5 days of simulation on the continental shelf must be considered as a 'spin-up' period.

ProWAM computes the evolution of the 2D-spectra, from which we estimate various integrated parameters (significant wave height, mean wave direction, zero-crossing wave period, etc.) at every point of the computational domain. In order to evaluate the temporal and spatial distribution of the wave conditions around the UK continental shelf, a number of output stations have been chosen (see Table 2 and Figure 4). A subset of all the available wave data points has been selected to find a point representative of a given sea area (with some duplicates). This allows an assessment of whether the surge and wave models are consistently over- or under-predicting in certain parts of the continental shelf.

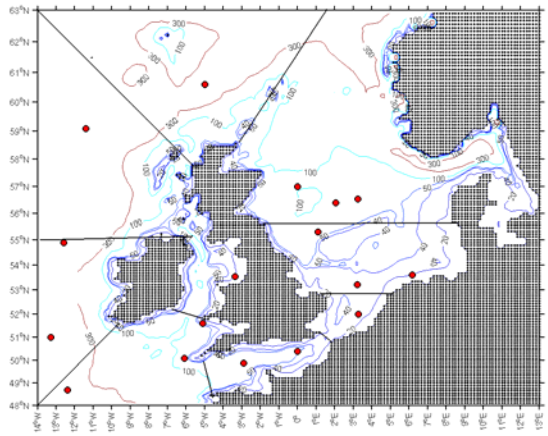

Figure 4: Selected wave validation points

Station	Lat	Lon	Sea area
K1	48.70	-12.40	Atlantic
K2	51.00	-13.30	Atlantic
K4	54.54	-12.36	Atlantic
K5	59.10	-11.40	Atlantic
K7	60.70	-4.50	Atlantic
K16	57.0295	-0.1100	N North Sea
AUK	56.4183	2.0505	Central North Sea
K17	55.3570	1.0840	Central North Sea
Greenwich LV	50.4363	-0.1098	English Channel
Channel LV	49.9538	-2.8956	English Channel
Seven Stones LV	50.1468	-6.1933	SW Approaches
Liv Bay WN	53.6525	-3.3506	Irish Sea
Ekofisk	56.5500	3.2500	Central North Sea
K13	53.2169	3.2200	S North Sea
EUR	51.9986	3.2763	S North Sea
VTN_SON	53.5955	6.1666	German Bight

Table 2: selected wave model validation stations

4. HINDCASTS

Results from several multi-year hindcasts are discussed here. In general we should define wave climate over a period of about 30 years, although many earlier studies, based on observations, had to rely on much shorter periods. The 'design wave' is an important concept for coastal engineering and management, based on the expected lifetime of a structure, and requires the projections of future wave events to return periods of 50 or 100 years or even longer. It is of interest to examine shorter periods for a 'snapshot' of the wave climate but much longer decadal hindcasts are required to examine climate variability. What we can learn from these hindcasts is the patterns of response of waves and surges in different sea areas

(i) A 5 years' run of the PROWAM CS3 wave model output (2000-2004) was used to validate the wave model and derive various results about the spatial and temporal variability of the wave climate on the NW European continental shelf.

(ii) Surges and waves in the Irish Sea on a 1.8km grid have been investigated in an 11-year hindcast by Brown et al. (2009, 2010**).**

(iii) A 10-year run of the POLCOMS-WAM model on the CS3 grid: 1999-2008

As discussed above, the results can be sensitive to the sea area, wind model resolution and form of the wind-stress parameterisation. For example Fig 5 shows results for 2 formulations of wind-stress for a surge event in the eastern Irish Sea. The Smith and Banke (1975) formulation for the drag coefficient underestimates the surge height at Liverpool and Heysham. A detailed study of Liverpool Bay has been made using wave buoys and acoustic instruments as well as an HF radar system (measuring currents and waves), supplemented by an 11-year wave model hindcast (Wolf et al., 2011). The variation of wave climate over various time-scales from seasonal and inter-annual to inter-decadal is examined, using various statistics, including extreme value methods. Projections of 50-year return period wave heights differ between different instruments and model datasets.

A cluster analysis was carried out, using the wave model response to a typical storm event (January 2005). Seven sea areas were characterised by maps of correlation between (i) wave height and wind speed (ii) wave height and mean wave period (iii) wave height and peak wave period and (iv) wave height and mean wave direction (Fig. 6). This shows a rather similar partitioning of the NW

European shelf to that which would be done by a geographical sub-division.

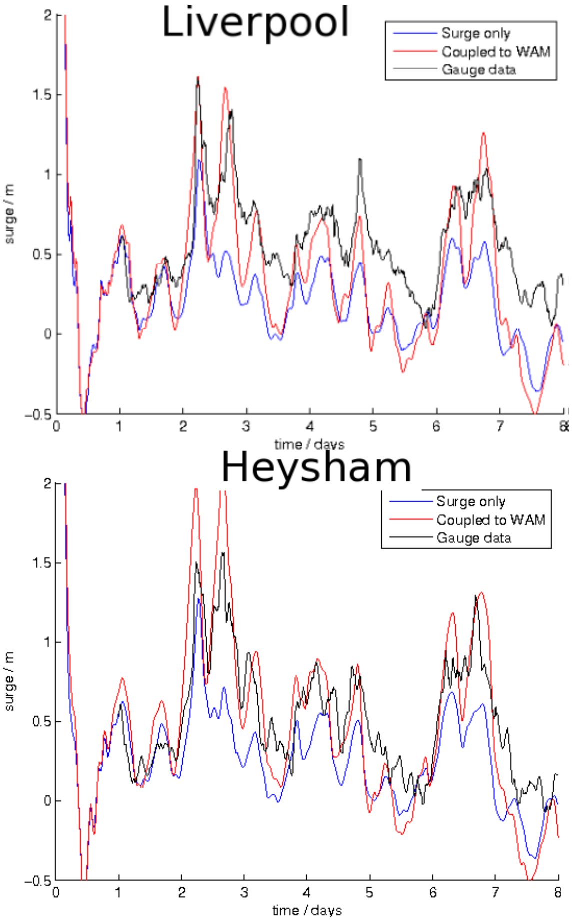

Figure 5: comparison of a surge event in the Irish Sea modelled with the coupled and uncoupled model. Here the blue line is the surge computed with Smith and Banke (1975).

Different responses can be identified for the Atlantic (medium blue), the outer shelf (dark blue), the North Sea, northern North Sea, Irish Sea, English Channel and the Norwegian coast. These can be identified with different exposure to wind-sea and swell. The confined areas of the Irish Sea and English Channel show a mixed response, some areas being more exposed to swell (brown) and other fetch-limited (green). There are similarities between the eastern Irish Sea/Liverpool Bay and the North Sea, being mainly dominated by wind-sea with little exposure to swell. This analysis allows us to limit the validation points to a few representative of the typical response of each sea area.

From the 5-year run, different return periods have been calculated for each point in the model grid and these are shown in Figure 7. The 50-year return period in the NW Scotland is over 16m, which is in reasonable agreement with wave atlases.

Different accuracy of results for different sea areas may depend on the (i) physics/dynamics of the response to wind (ii) geometry (iii) resolution (iv) coastal vulnerability. For the latter there are more sensitive areas e.g. Thames/London, East Anglia, Somerset Levels, NW England and Sefton Coast and some of the south coast of UK. Further analysis of hindcast surge and wave model output is needed to understand these effects in detail. There are examples in Wolf et al. (2011), Brown et al., (2009, 2010), Bricheno et al., 2013).

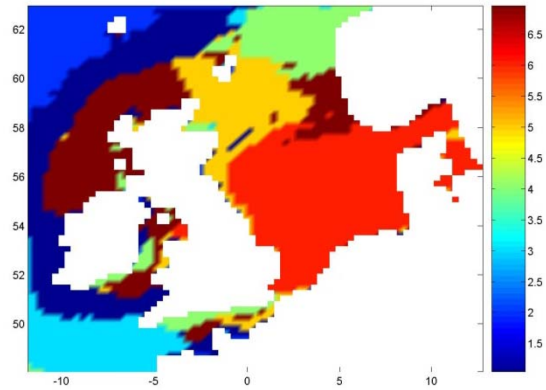

Figure 6: Partition of NW European shelf based on wave characteristics

5. FUTURE PROJECTIONS OF SURGE AND WAVE CLIMATE

A recent assessment of the projections of waves and surges for the 21st century was carried out in UKCP09 (Lowe et al., 2009). The tide-surge model was based on the 2D operational flood forecasting model as discussed above.

In order to forecast changes in the storm surge climate Howard et al. (2010) consider the changes in the statistics of the extremes of the distribution of high water levels, which in turn depend on changes in local MSL and changes in the atmospheric storminess. Several authors (e.g. Lowe et al. 2001; Howard et al. 2010) agree that these two effects can be added linearly to first order for coastal locations around the North Sea and so typically an experimental design for forecasting century-scale changes in the North Sea surge climate will include an assessment of regional relative MSL change and an independent assessment of the impact of changes in storminess.

The atmospheric winds and pressures from the HadRM3 regional climate model (RCM) perturbed parameter ensemble (PPE) were used to drive the surge model. This approach gives a distribution of simulated extreme water levels which are much more nearly comparable with observations than

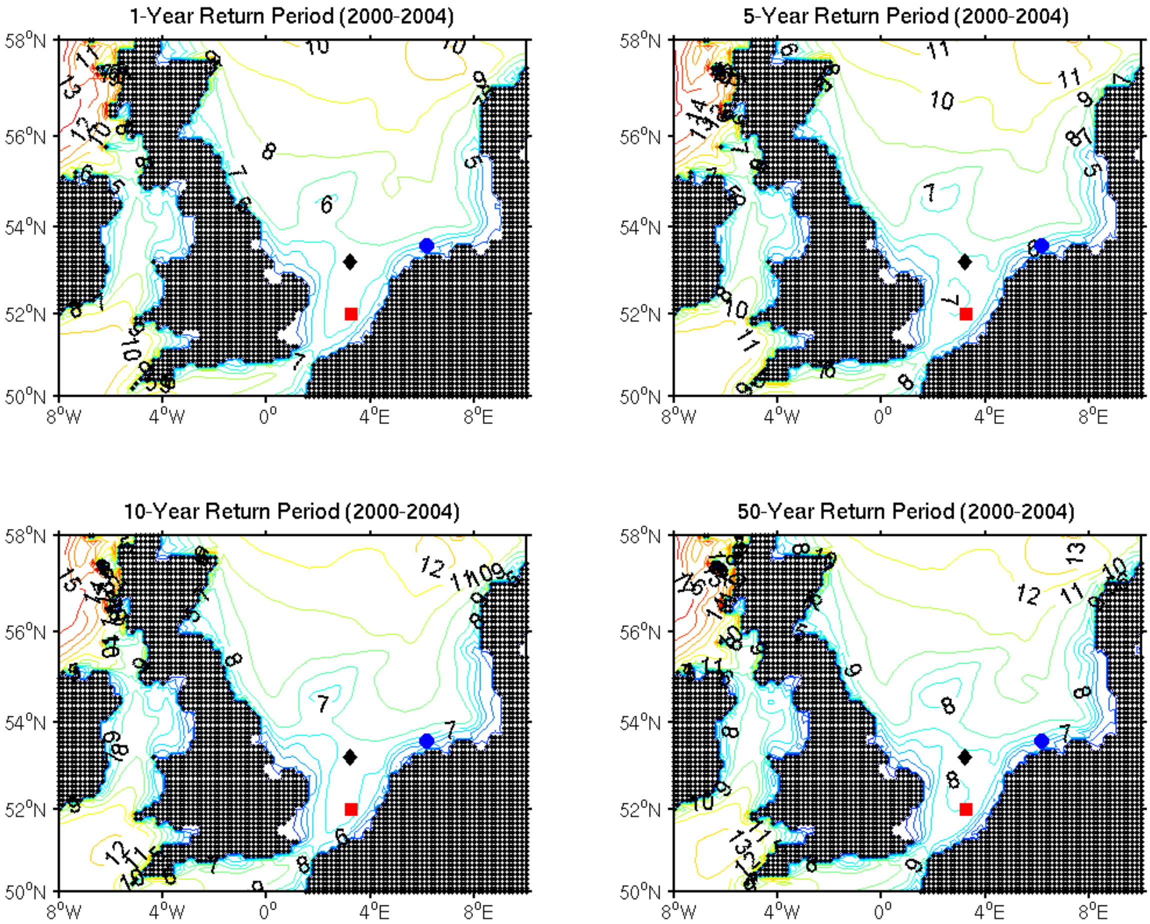

Figure 7: Return period wave heights for NW European shelf

those produced by driving the surge model directly with the HadCM3 global climate model (GCM) wind and pressure fields. Owing to the computational expense only a single emission scenario (the A1B scenario) was considered for the PPE.

The emergent range of North Atlantic storm track responses of the HadCM3 PPE does not span the full range of the corresponding responses of the many different valid atmosphere-ocean coupled models considered in AR4. At least one of these models predicts a significant strengthening of the North Atlantic storm track, a response which is not seen in the HadCM3 ensemble. So, in addition to the HadCM3 ensemble results, a surge model simulation was produced based on the IPCC AR4 model with the largest increase in North Atlantic storminess (Howard et al., 2010). Since RCM data for this model is not available, a crude scaling of wind and pressure fields from one of the regional atmospheric ensemble members was developed, based on the band-passed filtered SLP variability (which is a well-used large-scale measure of storminess) to give a representative simulation of a potential future storm surge climate under a strengthened storm track.

A similar exercise was carried out using 3 members of the PPE (control, high and low climate sensitivity) to force the ProWAM wave model

Comparing the period 1960-1990 with 2070-2100 the seasonal mean and extreme waves are generally expected to increase to the SW of UK, reduce to the north of the UK and experience little change in the southern North Sea and the Irish Sea (Lowe et al., 2009). This is consistent with a southward movement of the storm tracks. There are large uncertainties especially with the projected extreme values, which are dominated by decadal variability. On the other hand, there is little change in storm surges, beyond that anticipated due to sea level rise, which will reduce the return period for a given storm surge event.

For the coast of East Anglia there was projected to be little change in the significant wave height, but the more subtle changes in wave directions can affect coastal sediment transport, which may change the coastal impacts (Chini et al., 2010). The future wave climate of Liverpool Bay is not expected to change significantly from the present day (Brown et al, 2011b), but there is evidence for variability on decadal time-scales, with some correlation with the NAO, thus future extreme wave events will be closely related to future North Atlantic storm tracks.

6. DISCUSSION

The process of model downscaling, in a climate modelling sense, is generally taken to refer to the generation of locally relevant data from the output of Global Circulation Models of the atmosphere and ocean. The aim is to connect global scale projections and regional dynamics to generate regionally specific projections relevant to coastal management decision making. Dynamical downscaling from a GCM (coupled atmosphere-ocean), using an RCM, has been used to provide more realistic and detailed simulations of wind and pressure over the NW European continental shelf. These were then used to drive storm surge and wave models. Downscaling can be done in several ways (i) using process models (ii) using empirical/statistical relationships and (iii) hybrid methods e.g. using pattern recognition. The first method has been used above but is most computationally expensive and checks must still be made to ensure the resulting atmospheric circulation is compatible and dynamically consistent with the larger scale forcing. In general the surge and wave models, especially near-shore, are much more dissipative and less affected by initial conditions. Thus the downscaling for these models mainly consists of a nesting procedure whereby the high resolution model is driven by boundary conditions from a coarser model, with local forcing at high resolution.

In the NERC FREE project EPIRUS (Ensemble Prediction of Inundation Risk and Uncertainty arising from Scour) examined the effects of an ensemble system consisting of the POLCOMS-WAM model forced by a perturbed-parameter WRF atmospheric model. The results showed that the ensemble mean is largely in agreement with the control deterministic model run (with optimum parameter settings). The upper and lower bounds of the forecast ensemble provide a proxy measure of the uncertainty in the wave and surge height predictions.

6. CONCLUSIONS

Multi-year hindcasts of waves and surges are very useful for understanding the patterns of response of shelf seas to storms and can give insight into the important processes. This allows some confidence in future projections if we can assess whether the underlying assumptions remain valid.

Wave models are important in diagnosing shifts in storm tracks, as they have a more sensitive response to changes in storms than surges, which are more constrained by coastal geometry.

The RISES_AM project, which is about to start (funded by EU-FP7) will explore the need for adaptation to climate change as well as mitigation, since we already know that there will be more potential coastal floods. The project will deal with high end climatic scenarios and will identify novel coastal interventions according to climatic mitigation based on local, well-documented vulnerability hotspots). We need to continue to refine our understanding of the likelihood of future extreme events. The uncertainty about the magnitude of sea level and the possibility of some change in the storm climate cannot be used as an excuse for inaction. Novel ways of protecting and developing our coasts are required.

Acknowledgements

Thanks to Jacob Woge Nielsen of DMI for providing a map of tide gauges in the North Sea Observing System area.

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