Predicted Wave Climate for the UK: towards an Integrated Model of Coastal Impacts of Climate Change

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Abstract

The effect of global climate change on the wave climate of the coastal regions of the UK is investigated. A state of the art third generation wave model is used to predict changes in wave climate in the North East Atlantic and UK coastal waters. The driving meteorological data is provided by global and regional climate models, driven by different future greenhouse gas emissions scenarios. Present day wave climates are validated against a previous hindcast, which has been calibrated with wave observations, and good agreement is found in regions of interest. These studies downscale the affect of global climate changes on wave climate to a previously unresolved scale. Ouput of these wave climate predictions are to be used in a regional *Coastal Simulator* manged by the Tyndall Centre for Climate Change Research. The Coastal Simulator is a framework of integrated hydrodynamic, morphological and socio-economic models that provides predictions of the increased risks of coastal flooding and cliff erosion on the East Anglia coastline. The drivers of increased risks are sea-level rise and increased storm surges and waves in possible future climate scenarios. On a large scale, for the range of future climate scenarios, strong positive changes in significant wave height are predicted in the North East Atlantic and South West of the UK. On the regional scale of the Southern North Sea the spatial pattern of changes in wave height varies considerably with possible future scenario, but positive changes in the mean and high percentiles of wave height are predicted off-shore from the particular region of interest on the East Anglia coastline.

1 Introduction

Climate change potentially poses a serious threat to coastal regions. The combined effect of sea-level rise, changes in extreme events such as storm surges, and changes in wave climate can cause increased risk of coastal flooding and erosion, as well as changes to biodiversity and ecosystems. Recent reports show that current shoreline management plans (SMP's) are unsustainable [DEFRA 2006]. To develop improved SMP's and improve wider coastal management requires a better knowledge of the combined risks associated with climate change and requires the integrated analysis of the change in the off-shore sea environment, sandbank morphology, cliff structure, and human response.

An example of the approach needed is being set by the Tyndall Centre for Climate Change Research's *Coastal Simulator*. For a detailed plan of the project see [Nicholls et al. 2007] and [Nicholls et al. 2007b]. This project is focused on East Anglia, where coastal erosion and flooding are longstanding problems and hence there are already extensive coastal defence systems in place. In order to model the morphological evolution of this region requires the off-shore wave and surge climate in the North Sea (as well as global-mean sea-level rise). This requires downscaling of climate scenarios from the global scale to the regional level of the North Sea and UK waters, and down further still to the scale of the simulator domain, which in the demonstration project is sub-cell 3b (Sheringham to Lowestoft), shown in figure 1. The modeling framework of the Coastal Simulator is shown in figure 2, which shows the interaction of the different modeling components of the project.

Waves play an important role in the effect of climate change on coastal areas. Along with sea-level rise and currents, off shore wave action affects coastal erosion and flooding [Jacoub et al. 2007]. The future wave climate in the North sea and off-shore from any regions susceptible to erosion and flooding needs to be predicted to allow the morphodynamics of the domain to be modeled. Increases in extreme climate events may cause an increase in extreme wave events as well as an increase in average wave energy reaching the coast. Changes in average wave direction on the coastline will also affect morphololgy.

The future global climate will be very sensitive to future human activity, in particular greenhouse gas (GHG) emissions. The International Panel on Climate Change (IPCC) produced a *Special Report on Emissions Scenarios* (SRES) [Nakicenovic et al. 2000], which lists a range of future socio-economic scenarios which reflect a variety of possible future emissions. Using these scenarios, global and regional climate models can be run to predict the future climate down to mesoscale phenomena. By using these models to drive state of the art wave models, on a previously unresolved resolution, the predicted changes can be downscaled to regional coastal scales, and used in positive SMP's for the future.

The structure of the remainder of this paper is as follows. Section 2 describes the models used in this study, from global climate models down to regional wave models. Section 3 presents some results from the wave modeling, focusing on predicted changes in wave climate under different future climate scenarios. The final section discusses the initial results and intended future work.

2 Modeling Framework

2.1 Climate Modeling and Future Climate Scenarios

The Hadley Centre for Climate Prediction and Research uses climate models to predict the climate up to the year 2100 under certain GHG emission scenarios and social responses. Coupled ocean-atmosphere models are unable to simulate synoptic scale events such as storm surges as the atmospheric and ocean resolution is too coarse. Regional climate models have a higher spatial resolution (50km or finer) and thus can resolve these events better, but are not coupled to the ocean.

In this work a coarse coupled ocean-atmosphere global climate model (OAGCM) is used to provide ocean boundary conditions for a global climate model (GCM) which is then used to provide boundary conditions for a regional climate model (RCM) on the North West European continental shelf. The OAGCM (called HadCM3) has an atmospheric resolution of $2.5° \times 3.75°$, 19 atmosphere vertical levels, an oceanic resolution of $1.25° \times 1.25°$, and 20 ocean vertical levels. The GCM (HadAM3H) has an atmospheric resolution of $1.25° \times 1.88°$ and is driven on its oceanic boundary by sea surface temperatures from the OAGCM. The RCM (called HadRM3H) has an atmospheric resolution of $0.44° \times 0.44°$ and the ocean boundary is driven by coarser sea surface temperatures form the GCM. For information on the OAGCM, GCM and RCM see [Johns et al. 1997] and [Jones et al. 2001]. The OAGCM is also used to predict global sea-level rise.

The OAGCM was integrated from pre-industrial times to 2100. Before 1990 historical GHG concentrations are used. After 1990 the GHG concentrations are taken from the IPCC's SRES. The two scenarios used in this study are *A2* and *B2* [Nakicenovic et al. 2000]. These scenarios are taken from a set of combinations of demographic change, social and economic development, and broad technological developments. The A2 scenario represents a world where environmental concern is low, and has a population of 15b by 2100, and a global average per capita income of $7200. The B2 scenario is a world where environmental concern is high, and has a population of 10b by 2100, and a global average per capita income of $12000. The resulting average global temperature rise is $3.5°C$ in the A2 scenario and $2.5°C$ in the B2 scenario. The GCM and RCM are run for two different time slices, 1960-1990 and 2070-2100, so that changes in future climate can be predicted. These choices are used to coincide with previous work on this subject.

2.2 Wave Model

To estimate the wave climate in UK waters and to provide boundary conditions for the modeling of the morphodynamics of sandbanks, Hadley Centre GCM and RCM winds are used to provide driving wind information for Atlantic and regional wave models. The wave model being used is the PROWAM model [Monbaliu et al. 2000], which is a modified version of the WAM cycle 4 3rd generation wave model [Komen et al. 1994]. This wave model includes wave generation by wind, non-linear wave-wave interactions and dissipation processes including white-capping and bottom friction. The wave model is run on two regions. The first is a $1° \times 1°$ degree deep water model of the Atlantic, forced by GCM winds. This is used to provide boundary conditions for a higher resolution, regional, shallow water wave model on the North West European continental shelf, run on a $1/6°$ longitude by $1/9°$ latitude grid, and driven by RCM winds.

The two model domains are shown in figure 3. The inclusion of the Southern Atlantic in the courser resolution model allows occasional swell events to propagate into the regional wave model domain. Although swell events from the Atlantic may not have much effect on the wave climate in the North Sea, they could be important for applications in the South West of England, for example. Figure 4 shows the wave energy in the swell component of the sea spectrum, demonstrating the propagation of swell from the Southern Atlantic towards the boundary of the regional wave model. Figure 4 also shows the difference in wave energy between a coarse model run which includes the Southern Atlantic and one which does not, averaged over the regional wave model boundary. The differences are sporadic in nature, with larger differences occurring in the Northern-hemisphere summer, corresponding to large swell from events in the Southern Atlantic at this time of the year. Averaged over the year this difference in wave energy is small, 5%, but individual events may be important and the use of the Southern Atlantic in the Atlantic wave model is justified, particularly as the computational expense is very low (1.2 times slower).

The regional wave model supplies spectral wave information to the region surrounding the Tyndall Centre Coastal Simulator domain, as well as providing integrated wind sea and swell information for the entire North Sea and UK waters. The wave model is run for the same time-slices as the RCM, a hindcast period (1960-1990) and two future periods (2070-2100) corresponding to the two climate scenarios A2 and B2.

3 Future Changes in Wave Climate

As surface gravity waves are driven by the surface winds, changes in the global and regional climate, paricularly storms, will significantly affect the global and regional wave climate. Local significant wave heights (SWH) have been shown to be well correlated to global indices such as the North Atlantic Oscillation (NAO). If the phases of the NAO are forced to change in the future this could impact on the local wave climate, as positive phases in the NAO generally produce stronger Westerly winds. By comparing the predicted wave climate from these models for the future time slices (2070-2100 driven by A2 and B2) and for the hindcast period (1960-1990), we can obtain estimates of the change in wave climate due to different climate forcing situations.

To put any trust in these predictions first requires some validation of the hindcast timeslice. We choose to compare the model results from the regional wave model to the ERA-40 project. This project was run by the European Centre for Medium-Range Weather Forecasts (ECMWF). It consists of climate and wave model hindcasts for the period 1960-2000. The data is then reanalysed using a compilation of observations of parameters such as wind speed and wave height. Although not as ideal as real observations this dataset provides excellent coverage of the wave climate and is useful for comparisons of this type. The details of the wave climate produced by the ERA-40 project can be found in [Sterl and Caires] and [Caires et al.]

The climate models used to drive the wave models in this study are run on a 360-day calender, rather than real dates. This makes event-by-event comparison of data impractical. As we are interested in changes in extremes and means, it seems reasonable instead to look at seasonal statistics in the wave climate as a validation tool. Figures 5 and 6 show comparisons of the seasonal means of SWH for the regional wave model output to those of the ERA40 hindcast. Figure 5 shows the statistics at the point 0W 57 N, in the North Sea, slightly North of the domain of the Tyndall Centre Coastal Simulator. Figure 6 shows the same statistics at the point 6W 51N in the Irish Sea. The cumulative distribution plots for the four seasons (Winter: JFM, Spring: AMJ, Summer: JAS, Autumn: OND) are shown, and a reasonable match can be seen between the model data and the ERA-40 hindcast.

Before looking at the predicted change in regional wave climate it is worth looking first at the North East Atlantic. Figure 7 shows the change in the winter mean value of SWH for the Atlantic wave model results. This value is obtained by taking the mean of hourly SWH data in the months Jan-Mar (JFM) for the 31-year time-slice and subtracting the hindcast (1960-1990) values from the future values (2070-2100). The significance of changes is found using a simple t-test on the distributions of SWH and any insignificant changes are set to zero. For both the A2 and B2 scenario, a strong positive difference in winter mean SWH (> 14cm) can be seen in the North East Atlantic and the the South West of the UK. Figure 8 shows the change in winter maximums. The winter maximum value is obtained by taking the mean of the maximum values of each of the 31 winters in the time-slices. Again, a strong positive difference is seen in the North East Atlantic. The A2 scenario shows a change of up to 130cm while the B2 scenario shows a weaker change of up to 100cm in the winter max of SWH.

[Wang et al. 2003] used an observed relationship between sea level pressure

(SLP) and SWH to predict future wave climate scenarios, using the two future climate scenarios A2 and B2. Their work did not use a wave model to estimate the wave climate, and focused on the North Atlantic. The changes in this work are in agreement with these previous studies, [Wang et al. 2003] and [Kass et al.]. Their works show a typical increase of 5-35cm in mean winter SWH in the North East Atlantic, whereas this work shows a typical value of $>$ 14cm. The increases in the NE Atlantic are accompanied by decreases in the mid-latitudes of the North-Atlantic, which can be seen in figures 7 and 8, and also in the work of [Wang et al. 2003].

The increases in SWH in the North East Atlantic are directly related to changes in the climate. The difference in SLP over the North Atlantic increases in both the A2 and B2 scenarios, and this creates stronger westerlies and thus increases wave heights in this region. This agrees with the results of [Wang et al. 2003] which suggest that climate change causes the NAO to be in the positive phase more often, thus creating stronger westerlies, and larger SWH in the North East Atlantic.

In the results of [Wang et al. 2003] and the results from the coarse grid wave model here, predicted changes in the Southern North Sea, near the domain of the Tyndall Centre Coastal Simulator, are small if not insignificant. The GCM used to drive this wave model is not able to resolve small-scale features well, and cannot be expected to pick up regional climate variation. The Atlantic wave model is also a deep-water model, and is not able to model waves particularly well in the shallow shelf region around the UK. However, we can use the results of the regional wave model to look at the effects of climate change on the wave climate at the required smaller scales of the Tyndall Centre Coastal Simulator.

Figure 9 and 10 shows the change in winter mean SWH and winter max SWH, respectively, for the regional wave model results. The spatial patterns of predicted changes differ for the two scenarios, A2 and B2. Two partiular differences are worth noting. The first concerns the region near the Tyndall Centre Coastal Simulator domain. For both the winter mean and winter maximum SWH, the A2 scenario shows positive changes in the Southern North Sea (10cm for the mean and 20cm for the maximum). The B2 scenario, however, shows negative changes (-4cm and -19 cm). The second change between the two scenarios concerns the predicted changes along the West coast of the UK. The positive pattern observed in the North East Atlantic extends all the way up the West Coast of the UK in the B2 scenario, but not so in the A2 scenario, where the negative changes in the higher latitudes extend further down.

Predicted changes in annual maximums show similar spatial patterns to those of winter maximums, as can be seen in figure 11. The Southern North Sea shows positive changes in A2 but negative in B2 (typical values being 20cm and -56cm). Thus positive changes in annual maximum are mainly driven by changes in winter, but negative changes are driven by changes in the other seasons.

The increases in mean and maximum SWH in the South of the UK for the A2 scenario make sense in terms of the future climate scenarios. [McDonald 2002] suggests that the number of low-pressure storm systems crossing the UK in winter will increase from typically 5 in present day to 8 in 2080. This increase is accompanied by increases in winterly winds in the South of the UK (6%) but slight reduction in the far North. This explains the negative differences in the seas in the North of the UK for the A2 scenario,, as can be seen in figure 9. In general, the A2 scenario, which should exhibit more storms does have positive changes in SWH in the Southern North Sea. However, the differences in the wave climates in the Southern North Sea for the two scenarios clearly needs more detailed analysis, especially in terms of its relation to the future local climate.

4 Discussion

The effect of climate change on the wave climate of the North East Atlantic and UK waters has been investigated in the hope of developing an integrated approach to coastal management under changing future climates

Two wave models were integrated for this study. The first model domain covered the Atlantic and was driven by surface winds from a global climate model. This was used to provide wave boundary conditions to a higher resolution, regional scale wave model, which was driven by surface winds from a regional climate model, itself driven at the boundaries by the global climate model..

Two possible future climate scenarios were used to drive the future global and regional climate models, both taken from the International Panel on Climate Change's Special Report on Emissions Scenarios. The first, A2, represents a 'medium high' emissions future and has a global average temperature rise of $3.5°C$. The second, B2, represents a 'medium low' emissions future and has a global average temperature rise of $2.5°C$.

The two wave models were run for two different time-slices. A hindcast run (1960-1990), driven by a simulated present day baseline climate, was used as a reference for future change. Some simple statistical validation was applied to verify the distribution of significant wave height at certain locations. Two time-slices were run for (2070-2100) and were driven by the A2 and B2 climate scenarios. Future changes in wave climate were predicted by comparing the future time-slices to the hindcast time-slice.

On the Atlantic scale, increases in both mean and maximums of winter significant wave height were predicted for both future scenarios. T he positive change in the North East Atlantic was accompanied by a negative change in the mid-latitudes of the North Atlantic. This spatial pattern is in agreement with previous studies [Wang et al. 2003]. The changes in significant wave height in this region are a result of increased storminess in the North Atlantic, caused by increased Westerlies resulting from a stronger sea-level pressure difference across the region. The A2 scenario showed stronger changes due to its larger increase in winter storminess than the B2 scenario [Lowe and Gregory 2005].

This work has been able to extend the effects of climate change on wave climate to a previously unresolved scale. On the regional scale, in the Southern North Sea at the boundary to the Tyndall Centre Coastal Simulator domain, significant increases in mean and maximum winter wave height, and annual maximum wave height, were predicted for the A2 scenario, due to increased stoms in the A2 scenario. However negative changes were observed in the B2 scenario, and this results requires further investigation in terms of its relation to changes in future climate.

Future work will include the use of these wave model results, along with predictions of changes in storm surges and sea-level rise, to drive a morphological model on the East Anglia coastline. This will allow coastline projects, such as the Tyndall Centre Coastal Simulator to develop future plans to combat changes in the risk of coastal flooding and erosion.

Future work will also involve a more detailed study of the variablity of the wave climate. This will be in terms of both natural variability, by studying hindcasts of wave climate, and also in terms of model variability, by using ensembles of climate models to investigate the range of variability caused by the methodology of climate modeling.

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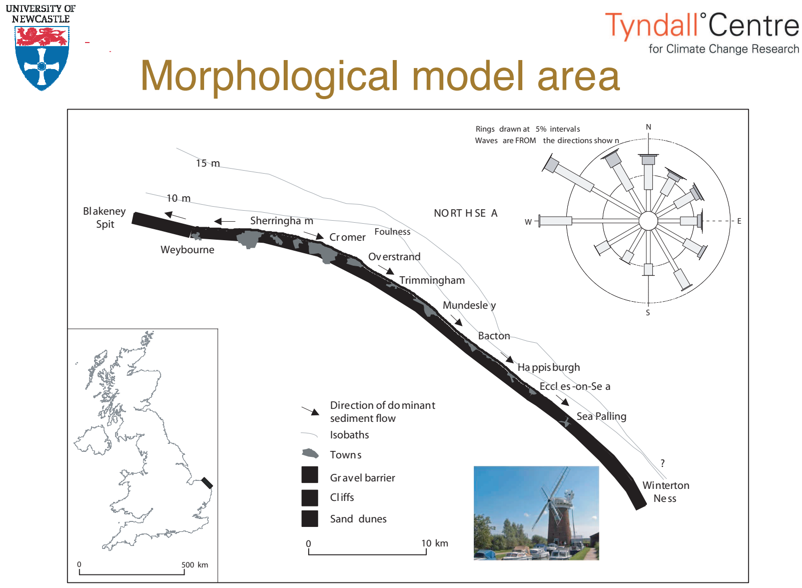

Figure 1: The shoreline morphological model domain. Courtesy Mike Walkden, University of Newcastle and Tyndall Centre for Climate Change Research. The wave rose in the top right shows the average direction of wave propagation. The Inset shows the simulator location on the East Anglia coastline.

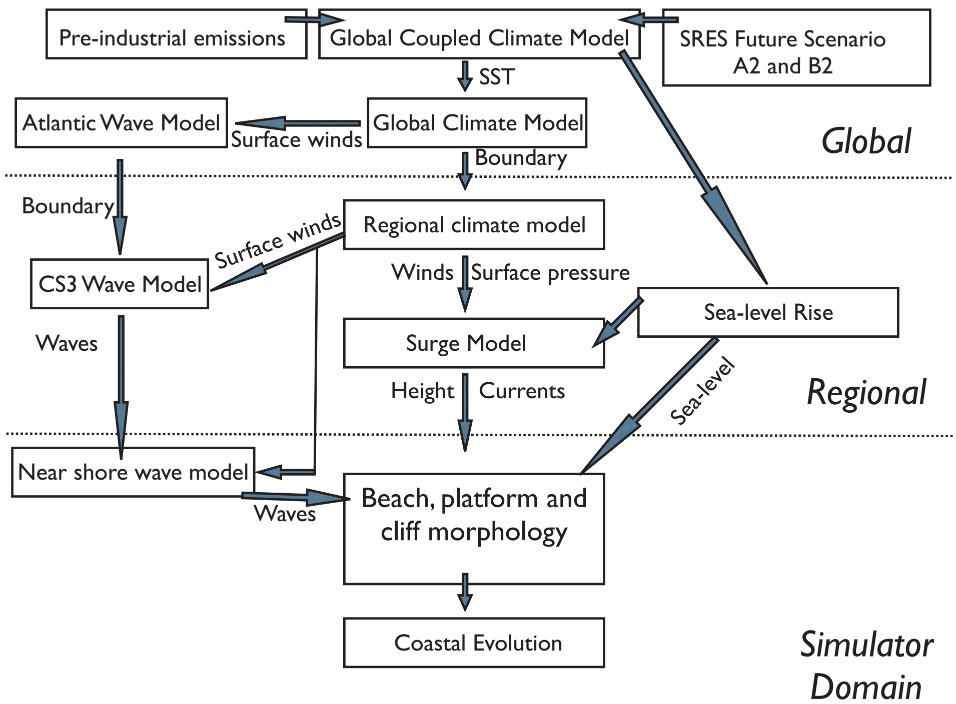

Figure 2: The transfer of physical information from the global scale to the simulator domain in the Tyndall Centre Coastal Simulator.

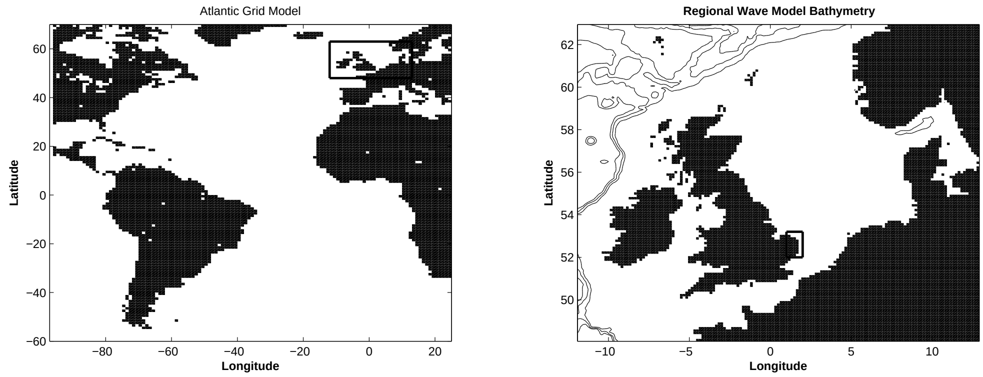

Figure 3: Left Panel: The Atlantic wave model domain, with the box showing the boundary points used to drive the regional wave model. Right Panel: The regional wave model domain, showing the boundary points used to drive the morphological model of the Tyndall Centre Coastal SImulator.

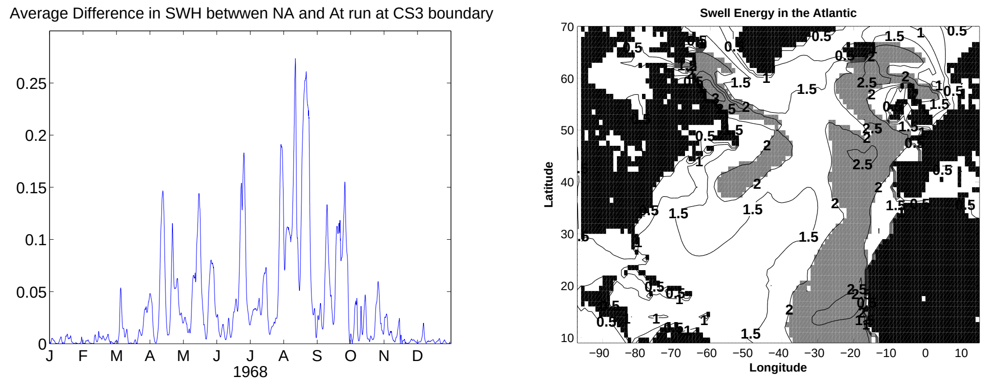

Figure 4: Left Panel: Difference in significant wave height, in m, between an Atlantic wave model run with the Southern Atlantic and one run without, averaged over the regional wave model boundary. Right Panel: A snapshot showing the SWH, in m, of the swell part of the spectrum over the North Atlantic region. The grey area shows values over 2m.

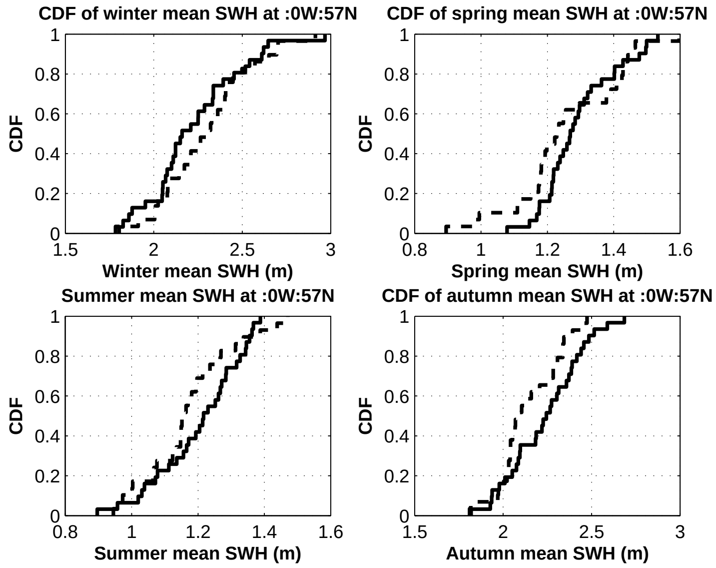

Figure 5: Cumulative distribution function of seasonal means of significant wave height at the point 0W 57N for two datasets. The dashed line is the regional wave model output and the solid line is taken from the ERA40 database.

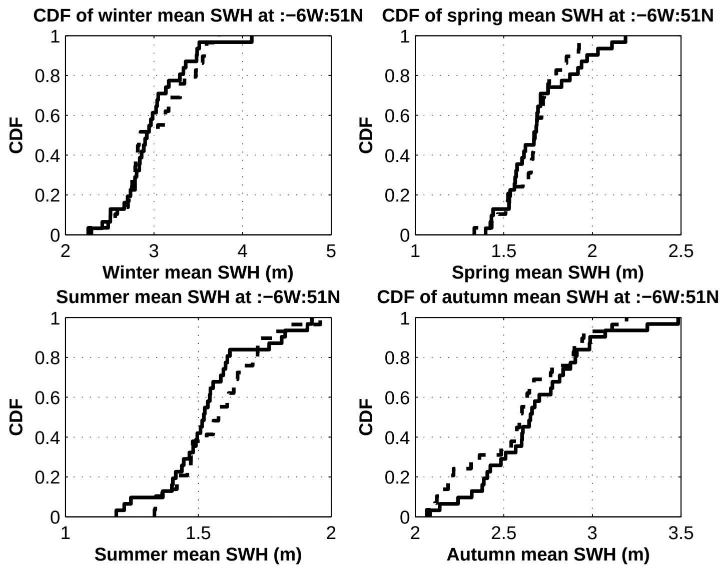

Figure 6: Cumulative distribution function of seasonal means in significant wave height at the point 6W 51N for two datasets. The dashed line is the regional wave model output and the solid line is taken from the ERA40 database.

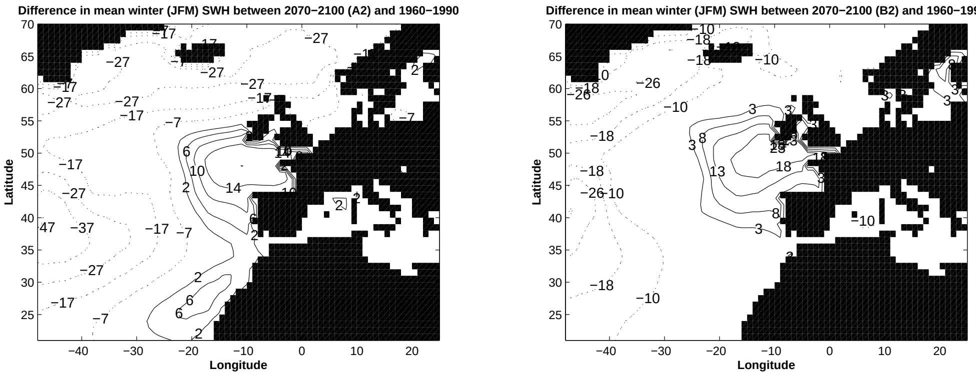

Figure 7: Changes, in cm, in winter (JFM) mean significant wave height from 1960-1990 to 2070-2100 for the A2 (left panel) and B2 (right panel) scenarios. Results are from Atlantic wave model.

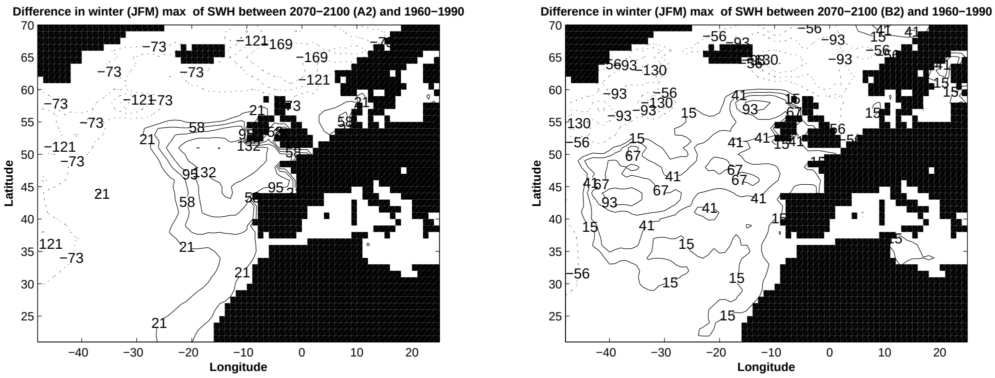

Figure 8: Changes, in cm, in winter (JFM) maximum significant wave height from 1960-1990 to 2070-2100 for the A2 (left panel) and B2 (right panel) scenarios. Results are from Atlantic wave model.

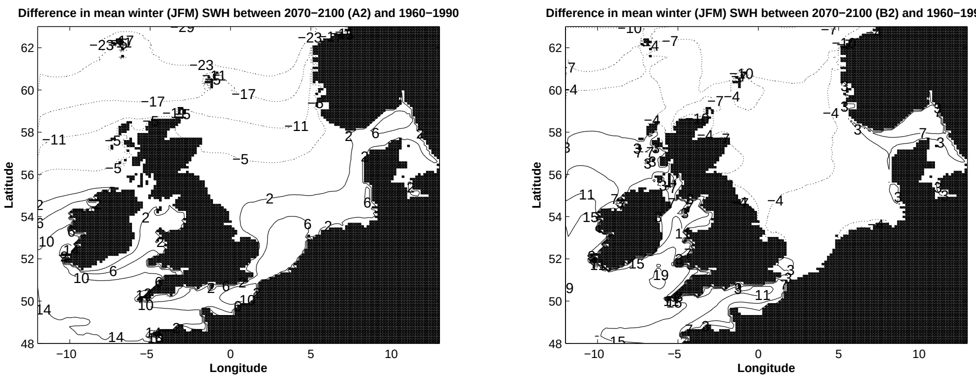

Figure 9: Changes, in cm, in winter (JFM) mean significant wave height from 1960-1990 to 2070-2100 for the A2 (left panel) and B2 (right panel) scenarios. Results are from regional wave model.

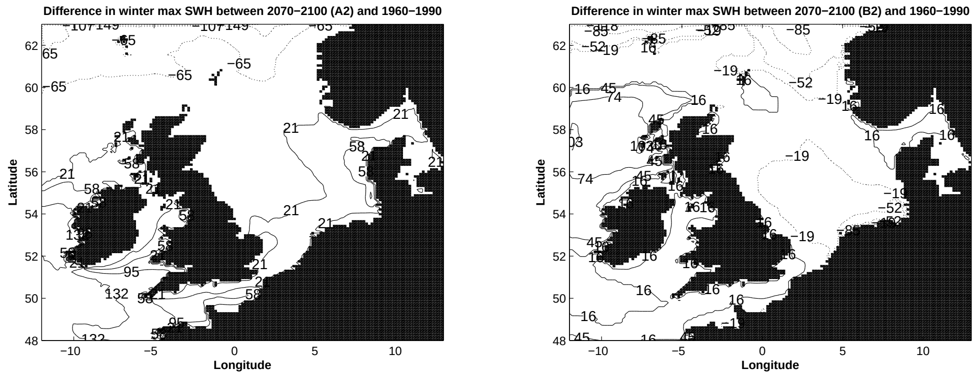

Figure 10: Changes, in cm, in winter (JFM) maximum significant wave height from 1960-1990 to 2070-2100 for the A2 (left panel) and B2 (right panel) scenarios. Results are from regional wave model.

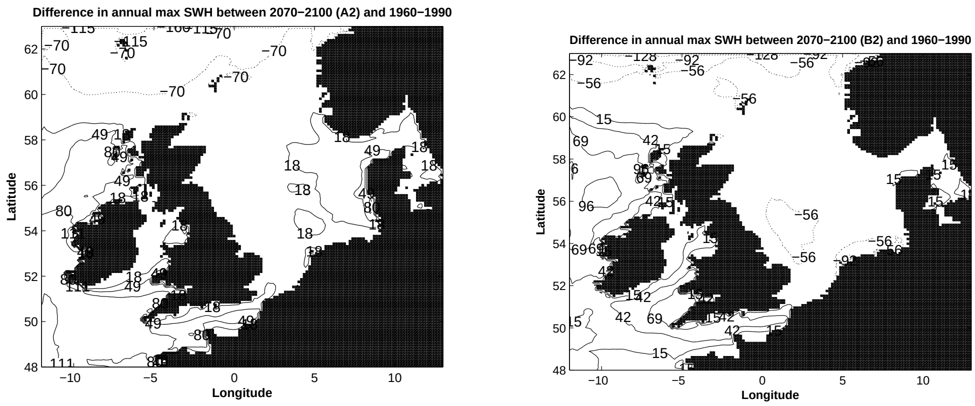

Figure 11: Changes, in cm, in annual maximum significant wave height from 1960-1990 to 2070-2100 for the A2 (left panel) and B2 (right panel) scenarios. Results are from regional wave model.