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Storms and Waves

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EXECUTIVE SUMMARY

There is a history of strong variability in UK wave climate. Inter-annual variability in the modern wave climate is strongest in the winter and can be related to atmospheric modes of variability, most notably the North Atlantic Oscillation. Rather dramatic increases in wave height occurred between 1960 and 1990, but these are now seen as just one feature within a longer history of variability. There is no clear pattern in results since 1990. Natural variability in wave climate is strong and the role of anthropogenic forcing is uncertain. Previous projections of a strengthening storm track (for example featured in the latest IPCC assessment report) have been contradicted by the projections from UKCP09. These latest projections are for a southward displacement of the storm track, resulting in lower wave heights to the north of the UK and slightly greater wave heights in some southern regions. There is however no consensus on the future storm and wave climate, stemming from diverse projections of future storm track behaviour.

FULL REVIEW

1. What is already happening?

Introduction

Waves and storm-force winds are a significant feature of UK waters and at the coast, particularly in autumn and winter. Waves are forced by the wind, but there is not a simple relationship between local wind speed and wave height. Waves grow and propagate over time, so that waves require sufficient "duration" of the forcing wind and sufficient sea room for the wind to act on the sea surface and the waves to propagate, called "fetch", to grow to a maximum height. In cases where one of these is insufficient, waves are duration-limited or fetch-limited to a smaller height and period. Thus, the largest waves in UK waters are found on the Atlantic boundaries where waves can propagate over large fetches from the ocean, and in autumn and especially winter when strong winds are more intense and persistent. Many factors affect the height of waves in UK waters, but for the Atlantic margin the persistence and strength of westerly winds are particularly important (Wolf and Woolf, 2006). Waves are also refracted by currents and shallow bathymetry and will be affected locally by man-made structures. Waves will decrease in height in shallow water due to bottom friction and wave breaking; the reduction at a particular site will diminish if sea level rises.

Waves and storms are a significant feature of global climate and have been included in many assessments of climate including the latest assessment (AR4) of IPCC (Solomon *et al.*, 2007). Here we focus on UK waters but within the context of global dynamics and regional phenomena.

The Record of the Last 60 years

We review first the data since approximately 1950. This period is chosen since reanalysis products generally extend about this far back and marine data greatly improved then due to the advent of Ocean Weather Stations (OWS) and other reliable sources. The measurement network has evolved in the last sixty years with the gradual demise of the OWS, the advent of the satellite age and new wave measurement networks. The present UK wave monitoring network is described by UKDMOS (www.ukdmos.org). Data are available from satellite altimetry, Marine Automatic Weather Stations (MAWS) on moored buoys and lightships, WaveNet offshore locations, and many nearshore sites especially around the south of England. At the same time modelling of weather systems, air-sea interaction, and particularly for wave prediction and hindcasting, has greatly advanced. There are difficulties in fabricating a homogenous data set when the measurement network has changed. There are also some remaining difficulties in hindcasting wave climate from modelling; notably where there are strong currents or complex topography (even here modelling can succeed where sufficient data is available). Nevertheless, there is high confidence that “we know what happened” as far back as 1950.

Wave climate in UK waters has had a high profile since reports of dramatic rises in wave heights started to emerge in the late 1980s. Bacon and Carter (1991) inferred an increase in mean wave height of about 2% per year “over the whole of the North Atlantic in recent years, possibly since 1950” from observational data notably from Seven Stones Light Vessel (1962-1986).

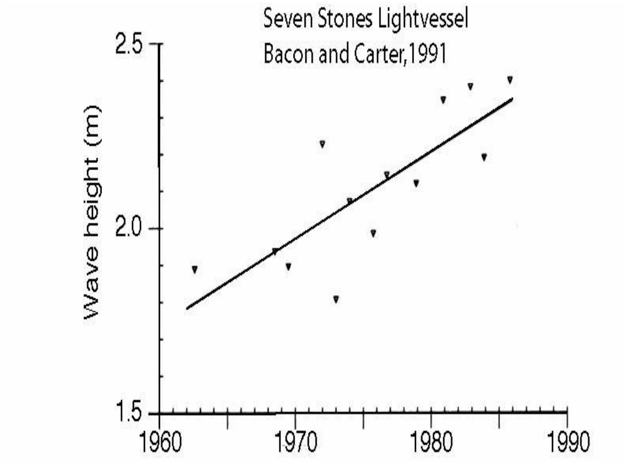


Figure 1*. From Bacon and Carter (1991). The rise in wave heights off the southwest of England (Seven Stones).*

An analysis has also shown there to have been significantly more severe storms over the UK since the 1950s (Alexander *et al.,* 2005).

Trends in wind speed around the UK were much weaker than for wave heights, and therefore most of the increase in wave heights is attributed to “Atlantic swell” (waves generated far outside of UK waters but propagating here from the ocean) rather than locally-generated “wind sea”. This may be enhanced by an increase in ‘persistence’ of westerly winds.

Changes in winds and waves can be better understood by considering their relationship to atmospheric pressure gradients (Bacon and Carter, 1993) and particularly to large-scale atmospheric variability such as the North Atlantic Oscillation (NAO). Historical changes in the atmosphere have been reviewed as part of the IPCC process (Trenberth *et al.*, 2007). For the UK, the behaviour of the northern hemisphere storm track is very significant. Variation in the storm track can be usefully described in terms of atmospheric modes, particularly the Northern Annular Mode (NAM) or the NAO. The NAM describes much of the variation of the northern hemisphere storm track The NAO can be thought of as describing the behaviour of the NAM specifically in the Atlantic sector. Inter-annual variability in monthly mean wave heights is large, particularly from December to March, the months primarily associated with the NAO. The NAO index is a measure of a mean atmospheric pressure difference, Azores (or Gibraltar) – Iceland, e.g. Jones *et al.*(1997). Wave heights in the North East Atlantic and northern North Sea are known (from analysis of *in situ* data, satellite data and model reconstructions) to respond strongly and consistently to the NAO (e.g. Woolf *et al.*, 2002 and 2003).

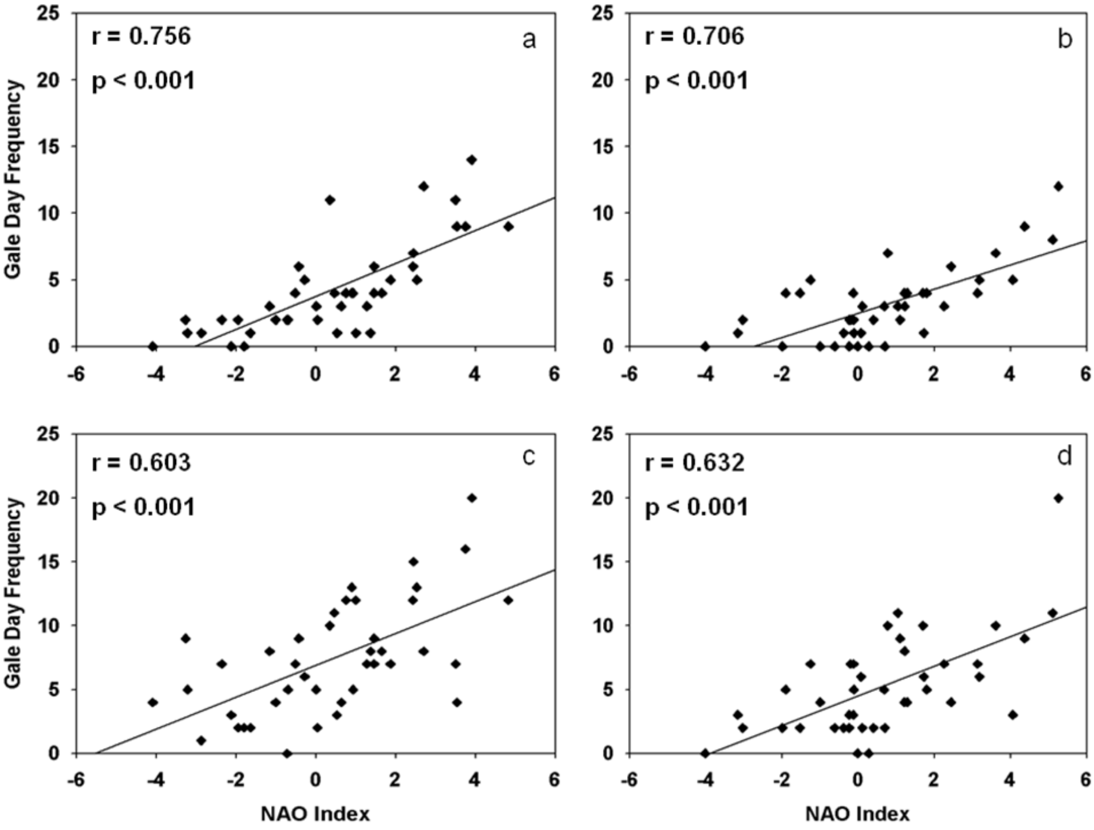


Figure 2. *From Coll (2007). Gale day frequencies versus monthly NAO Index (1960-2000). More positive values for the NAO are significantly associated with a greater frequency of gale days. Datasets are from (a) Stornoway, Isle of Lewis, Outer Hebrides (January); (b) Stornoway, February; (c) Tiree, Coll, Inner Hebrides, January; (d) Tiree, February.*

Other parameters - such as cyclone activity (Gulev *et al*., 2001) and the number of “gale days” at coastal sites in Scotland - show a weaker, but still significant response to NAO. Gale day frequency over the last few decades at west Scotland sites is significantly correlated to NAO, with greater frequency in NAO positive winters associated with an increased frequency of easterly tracking depressions across the region (Coll *et al.*, 2005; Coll, 2007). Similarly, an analysis of wind direction and strength together, indicates that the occurrence of strong south-westerly winds at sites around the Scottish coast are closely linked to the behaviour of the NAO (Corbel *et al*., 2007).

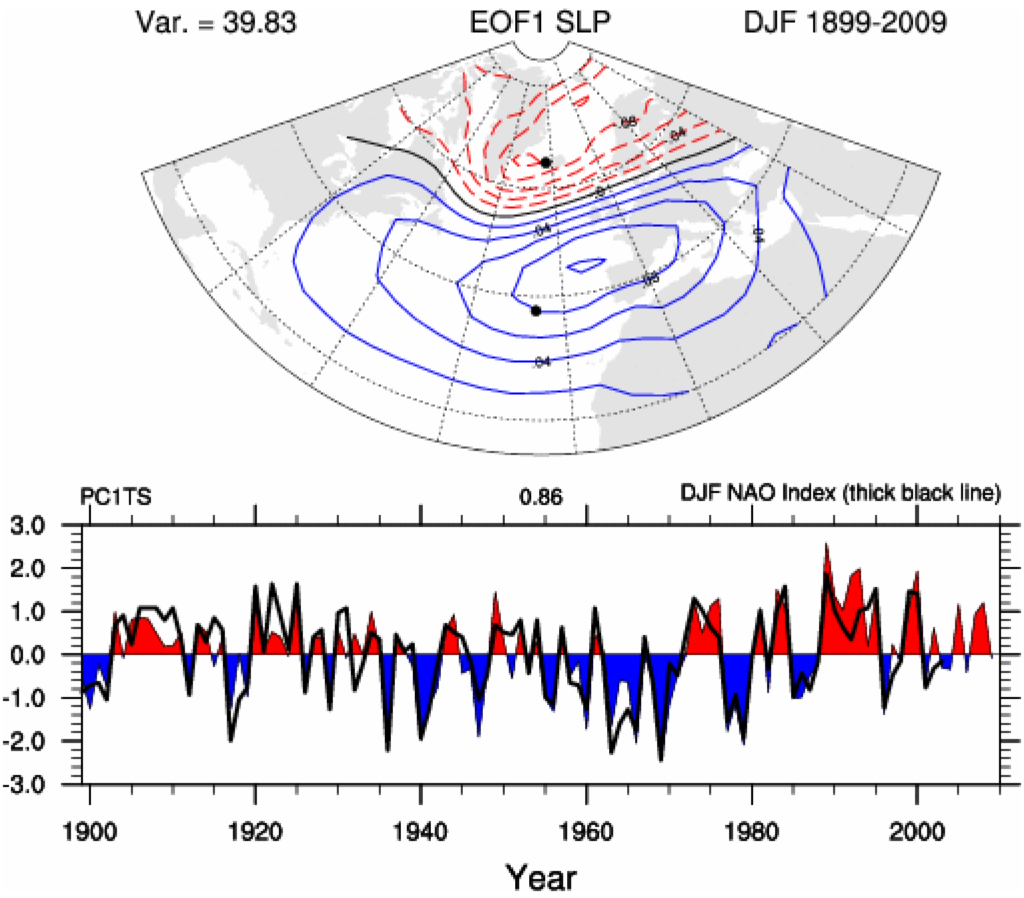


Figure 3. *A Principal Component based analysis of the North Atlantic Oscillation. The thick black line in the time series is a station-based analysis (station locations marked on map). Taken from* *http://www.cgd.ucar.edu/cas/jhurrell/indices.info.html#naopcdjfm*

Thus, many of the changes over the last 50 years can be understood in terms of the behaviour of the NAO. The recent strong trend in the NAO (towards stormier conditions) is apparently unique in its history, but it is controversial whether this is a response to greenhouse gas forcing (Osborn, 2004). More general changes in westerlies in the North Atlantic region are implicated in changes in wave heights and storminess around the UK and the behaviour of the NAO is not the only relevant factor. Modelling reveals that many different factors can affect wave heights (Wolf and Woolf, 2006). The NAO is only one facet, or mode of variability, of changes over the North Atlantic. Another pattern of atmospheric pressure anomalies, the East Atlantic Pattern (EAP) appears to explain another large part of the inter-annual variability in winter wave climate (Woolf *et al.*, 2002 and 2003; Sykes, 2005). Together, NAO and EAP can describe much of the variability to the west of the UK, but they are not exhaustive and may not be optimal to describe the changes over the last 50 years. Neither NAO nor EAP are significant to wave climate on the east coast of the UK.

The earlier trend in wave height did not continue in the 1990s. So far, a clear trend has not emerged for the more recent period, though there has been much variability and the occasional intense storm.

In summary, evidence for a substantial change in the incidence of high winds is generally weak. Evidence for recent substantial changes in wave climate is more compelling and can be summarised as follows:

Wave heights in winter (when they are largest) increased through the 1970s and 1980s, as shown by data: in the northeast Atlantic (significant increase between the 1960s and early 1990s); in the North Sea (increase from 1973 to the mid 1990s); at Seven Stones off Land's End (increase of about 0.02 m/yr over 25 years to 1988). However, recent trends are not clear and may depend on region; some series appear to show a decrease. Year-to-year variability is such that there is no clear longer-term trend.

Winter wave heights correlate significantly with the NAO Index and other measures of the strength of westerly winds at UK latitudes, in the west and the Irish Sea; the correlation is particularly strong in the north west.

In very shallow waters (e.g. near coasts) trends are reduced; wave heights are limited by water depth (as waves break); however, if sea levels (raised by climate change) increase depths, then larger waves may approach the shore.

Indicators on a Longer Time Scale

In general, it is far more difficult to recreate weather patterns including storminess and wave heights further back than the last 60 years. It is worth noting what the limited evidence indicates, since this context sets the better known records (including increasing wave heights between 1960 and 1990) in a different light.

Estimates of wave climate variation prior to 1950 are limited to fragmentary records, mainly relating to visual observations in ships' log books. There is a reasonable record for the North East Atlantic and these more extensive data sets confirm a significant upward trend in wave heights in the North Atlantic, but only for the last 50 years and embedded within a pattern of multi-decadal variability over more than a century (Gulev and Hasse, 1999; Gulev and Grigorieva, 2004).

Allan *et al.*.(2009) (as Alexander *et al.*, 2005) used rapid falls in atmospheric pressure as an indicator of severe storms and were able to extend their study to the period 1920-2004. The general picture is one of large-scale natural climate variability modulating the intensity and frequency of storms over the UK. Winter (Jan-Mar) storms are significantly correlated to NAO, but the correlation fluctuates with time. Autumn (Oct-Dec) storms indicate separate and more complicated drivers than winter storms, with high latitudes, the tropical Atlantic and even the tropical Pacific (and El Nino) appearing to modulate storminess.

An alternative measure of storminess, “gale day frequency” also shows a complex history with no clear trend but much decadal variability through the twentieth century. Some coastal weather stations, e.g. from the west coast of Scotland (Dawson *et al.*2007), date back a century or more and give a record of wind speeds and storminess. They concluded that a period of increased storminess in the late nineteenth century was not related to the NAO but speculated that this difference may reflect the influence of an expanded sea-ice cover in the Greenland Sea that caused a considerable southward displacement of the North Atlantic storm track.

There has also been a growing interest in “palaeo proxies” of storminess, notably either sea-salt Na^+ (Dawson *et al.*, 2002) or non-sea-salt Ca^{2+} (Mayewski and Maasch, 2006) from Greenland ice cores as a proxy of northern hemisphere westerlies. Both the Stornoway and Greenland records suggest that the storminess of the last decades is unexceptional and that there were previous stormier periods, notably in the late nineteenth century. While in the southern hemisphere an upward trend in westerlies (from non-sea-salt Ca^{2+} in Antarctic ice cores) over the last few decades is exceptional (Turner et., 2009) and anthropogenic origins are implicated, there is a much weaker case for proposing an anthropogenic effect for northern hemisphere westerlies in general and the storminess and wave climate of UK waters in particular.

Two primary insights follow from the longer time scale data. Firstly, the case for the late twentieth century trends in UK waters being anthropogenic in origin is significantly weakened by this evidence. Secondly, since the ice core records suggest some strong and abrupt natural changes in Northern Hemisphere westerlies within the Holocene period (most recently and dramatically c1400 AD), there should be a preparedness for dramatic changes in the future, with or without strong anthropogenic forcing.

Summary of New Evidence

Little new data on recent historical change or its direct interpretation has been found since a previous review (Woolf and Coll, 2007). We have however now incorporated evidence from a longer time scale. It is difficult to know how much weight to give to older records, particularly palaeo records relying on proxies (Wolff, 2006), but taking them on face value, the likelihood of the increase in wave heights since 1960 being a facet of anthropogenic change appears lower on review. There remains a view, primarily through atmospheric modelling (see next section), that greenhouse gases or aerosols may have modified “Centres of Action” in atmospheric pressure and thus altered storminess and waves. However there is a different and wholly reasonable point of view (as espoused by for example Dawson *et al.* (2007)), that considers the longer historical context, to conclude that the last few decades are unexceptional and should not be “blamed” on anthropogenic climate change. It is certainly clear that there has been strong natural climate variability in storminess and waves over the decades and centuries.

2. What could happen in the future?

Global Climate Models (GCMs) and Regional Climate Models (RCMs)

An ability of climate models to project changes in waves and storminess around the UK depends on their ability to project changes in the storm track for instance as shifts in indices of NAM or NAO. The simulation of the historical storm track, cyclone activity and the modes of variability by climate models has been reviewed within the IPCC process by Randall *et al.*(2007). Most models reproduce a reasonably satisfactory storm track but there are discrepancies in position and intensity. HadCM3 is relatively successful in reproducing the correct position of the storm track near the UK (Murphy *et al.*, 2009). Modes of variability like the NAO do occur spontaneously in climate models but the recent strongly positive phase of NAO is not generally reproduced. Multi-decadal variations are generally weak in simulations and the recent strong trend is not reproduced by the models solely under external forcing. There are conflicting theories about the causes of this recent trend - it may be related to variations in sea-surface temperatures in the N. Atlantic or remote ocean basins (Rodwell *et al*. 1999; Hoerling *et al*. 2001; Sutton and Hodson 2007), or be related to trends and variability in stratospheric winds (Scaife *et al*. 2005) or both. Scaife *et al.* (2005) report that the trend is reproduced when the lower stratospheric circulation is prescribed in the model. Variation might possibly be a result of chance year-to-year fluctuations which are in no way predictable.

The projection of the behaviour of NAM, NAO and other modes climate models has been reviewed within the IPCC process by Meehl *et al.*(2007). Many GCMs suggest a general trend towards a positive NAO in the 21st century (e.g. Terray *et al.*, 2004; Kuzmina *et al*., 2005) with anthropogenic forcing. If so, and if the link with storminess is maintained, worsening wind and wave conditions in the wintertime in western and northern UK waters are inevitable (Wang *et al.*, 2004; Tsimplis *et al.*, 2005; Wolf and Woolf, 2006). However, alternative analyses primarily based on RCMs suggest different and mostly weaker changes in winds and storminess (e.g. Hulme *et al*., 2002; Hanson *et al*., 2004; Lozano *et al.*, 2004; Barnett *et al*., 2006; Leckebusch *et al.*, 2006).

In an analysis of outputs from fifteen coupled GCMs forced by enhanced greenhouse warming experiments there is a simulated reduction in the total number of storm events and an increase in the number of intense events (Lambert and Fyfe, 2006). With no apparent change in the geographical positions of the storm tracks seen on hemispheric charts, the authors conclude that there is no obvious shift in storm tracks associated with global warming (Lambert and Fyfe, 2006). In terms of the behaviour of the NAO/NAM when forced with increasing concentrations of greenhouse gases and sulphate aerosols, Miller *et al.*(2006) detect decreasing sea level pressure (SLP) over the pole and a compensating increase in mid-latitudes across a multi-model average, although individual model trends vary widely. These findings suggest that an associated poleward shift of the storm track and a strengthening of the upper level westerlies are likely with global warming. However the results from the UK Met Office HadCM3 model are somewhat different (see next section).

UKCP09

DEFRA recently published new climate projections for the UK, known as UKCP09. These include both terrestrial and marine projections. The overall climate projections are described in Murphy *et al.*(2009). A primary basis of UKCP09 projections is a single GCM, HadCM3 AOGCM (Atmosphere Ocean Global Climate Model), with 3.75° by 2.5° horizontal spatial resolution). Alternative variants of model parameters were selected to create a “perturbed physics ensemble” (PPE) and the results were also compared to results from a set of independent climate models (referred to as a multi-model ensemble (MME)) to provide insight into uncertainties. Any climate model “will inevitably contain some structural errors in its physical representation of the real climate system (Murphy *et al.*2009)”,but there is some evidence that HadCM3 is an adequate physical representation, particularly with respect to the behaviour of the North Atlantic storm track and other basic drivers of waves and storminess. Modes of variability like the NAO do occur spontaneously in HadCM3, but unlike some preceding models, none of the ensemble members of HadCM3 show significant NAO trends. Greeves *et al.*(2007) have shown that HadCM3 models the position of the NE Atlantic storm track relatively accurately (compared to other AOGCMs) but uncertainty in the projection of the storm track is still high (Murphy *et al.*, 2009). UKCP09 projections show a southerly movement in storm tracks, with a slight reduction in intensity. Projected changes in surface winds may thus be related to changing storm tracks which in turn are a result of global warming caused by increased amounts of atmospheric greenhouse gases e.g. carbon dioxide.

Lowe *et al.*(2009) describe how the HadCM3 results are applied to marine and coastal projections, including those for waves. This report includes a section on “simulated changes in European winter storms” since these underpin many marine impacts including surges and waves. Both the PPE from HadCM3 and the MME are reviewed, and in particular the simulated change over a century of the latitude and strength of storms is reported. It is notable that the PPE and MME project quite different results. The PPE typically shows a slight weakening and southward displacement of storm tracks. The MME projects a variety of results straddling weakening/strengthening and southward/northward displacement.

The UKCP09 marine projections for waves up to 2100 (Lowe *et al.*, 2009) were driven by representative members of the HadCM3 PPE with a nested HadAM3 RCM (Regional Climate Model, ~25km resolution) winds. There is discussion about the validity of using RCM winds for forcing of surge and wave models, as they may not have sufficient resolution to properly reproduce extreme events, however this approach may at least allow us to see what trends occur between the 'present-day' (represented by the nominal 1960-1990 in the climate model) and 2070-2100.

The wave model which was used is based on the well-tested 3rd-generation spectral model "WAM", implemented on two grids: a coarse 1° grid for the whole Atlantic to provide boundary conditions, and a 12km model of the NW European continental shelf. The WAM model has been well-validated previously and is statistically in reasonable agreement with the ERA-40 reanalysis (which is a comprehensive global hind-cast of the last 40 years of waves and wind, combining model fields with a wide range of observations) for the NE Atlantic.

The model was run using three sets of atmospheric model wind forcing covering the period 1960-2100. The cases comprised (i) an unperturbed run with medium climate sensitivity for the whole 140 years and (ii) two other members of the PPE (based on the same medium emissions scenario), with 'low' and 'high' sensitivity respectively (the sensitivity is defined as the response of the global temperature to a given increase in atmospheric greenhouse gases). The latter two cases were run for two time-slices only: 1960-1990 and 2070-2100.

The results of the wave projections show that winter mean and extreme waves are generally expected to increase to the SW of the UK, reduce to the north of the UK and experience little change in the southern North Sea or Irish Sea. There are large uncertainties especially with the projected extreme values. Changes in the winter mean wave height are projected to be between -35cm and + 5cm. Changes in the annual maxima are projected to be between -1.5m and +1m. Projections of longer return period waves reflect the same pattern but with larger error bars. The other ensemble members show a similar pattern to different degrees. These differences are consistent with the southerly shift in storm tracks discussed above (see Wolf and Woolf, 2006).

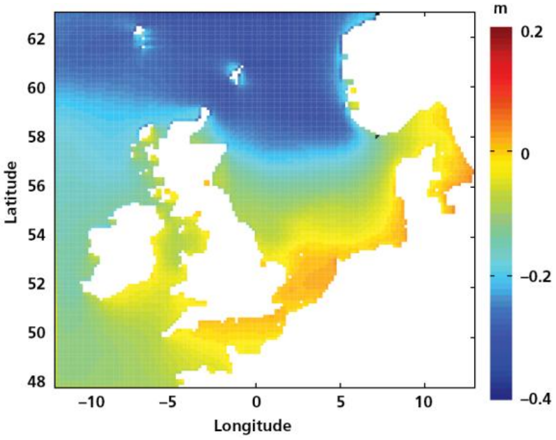


Figure 4. *Change to the mean winter significant wave height for 2070-2099 compared with 1961-1990 values, under a medium emission scenario. Source pages in UKCP Marine Projections report: pp58 (Lowe et al 2009).*

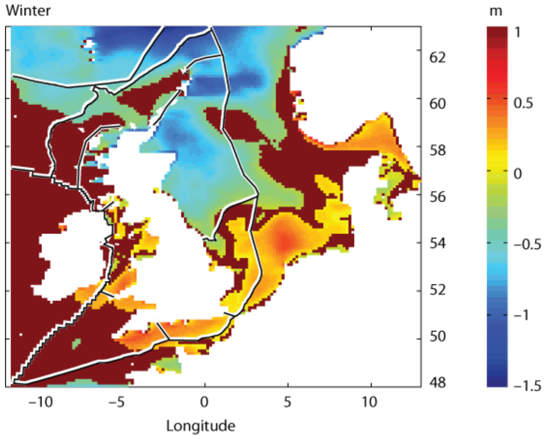


Figure 5. *Change to the mean winter maximum significant wave height for 2070-2099 compared with 1961-1990 values, under a medium emission scenario. The darkest red shading indicates areas where the change in mean SWH is not statitstically significant compared to 1961-1990 levels. Source pages in UKCP Marine Projections report: pp60 (Lowe et al 2009).*

The implications of coastal impacts of climate change for various parts of the UK coast can be examined. The SW is expected to see slightly higher wave heights, with lower waves to the north of Scotland. For the UK coasts of the southern North Sea little change is anticipated.

Summary on future projections

Climate change may affect storminess, storm tracks and hence winds and wave heights. Future projections in UK waters are very sensitive to climate model projections for the North Atlantic storm track, which remains an area of considerable uncertainty. Some older results, including those featured in IPCC AR4 (Solomon *et al.*, 2007; Meehl *et al.*, 2007) are contradicted by UKCP09 and specifically by HadCM3. Most members of the HadCM3 ensemble project a slight weakening and southward displacement of the storm track over the UK and projected changes in storminess and waves follow from this large-scale change.

The basic dynamics of shifts in the strength and path of the mid-latitude storm track are uncertain, so that it is unclear which, if any, climate model is capable of satisfactory projections. Murphy *et al.*(2009) present some reasons for optimism that HadCM3 (and thus UKCP09) can make useful projections of the behaviour of the storm track.

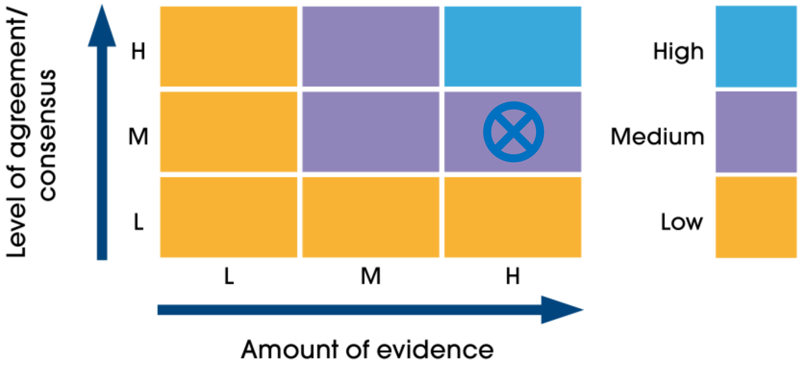
Where a global climate model produces a useful large-scale projection, some uncertainty remains as to the most appropriate methods for downscaling that information to wave heights at a more useful local scale. UKCP09 has used an RCM and this is the generally favoured method. However, there is also a case for statistical downscaling based on predicted general structural changes in the atmosphere (e.g. intensity and position of storm track).

A preference for UKCP09 is justified by HadCM3's relatively convincing simulation of the storm track near the UK and by the use of a strong downscaling method. Note however that the main innovation from UKCP02 to UKCP09 is in providing some probability and uncertainty information, by running an ensemble of climate model projections. Up to present the limitations of computational effort have precluded the running of a full ensemble of wave projections.

UKCP09 projects small decreases in mean annual wave height to the north of the UK and some slight increases in wave height in most southerly regions. Similar results for the annual or winter maximum wave height are found but with larger confidence limits, which mean only the reduction in wave height to the north is significant.

3. Confidence in the science

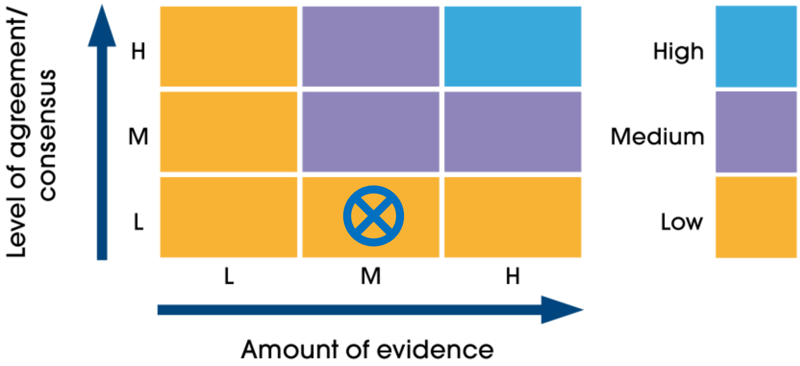
What is already happening: Medium



There is a large amount of data at least for the historical period and we know of no substantial contradictions in that data. Model hindcasts (forced by reanalysis data) are in close agreement to direct observations of waves. In these respects, the confidence is high, but dynamic models are unable to reproduce the past behaviour of the storm track. Modes of variability occur spontaneously in climate models mimicking the general behaviour of observed modes, but the specific time history of observed modes has not been explained (but may simply be random). It is questionable whether the full dynamics of the storm track is adequately represented in current models.

We have accumulated new evidence since 2007/8. This has not contradicted the original evidence, but it does set that evidence in a different light, thus the tone of the Summary has changed.

What could happen: Low



There is now accumulating evidence from more and better modelling and projection. There is some reason to prefer the recent UKCP09/HadCM3 projections, but the fact that these projections are contradictory to both a multi-model ensemble considered by UKCP09 and the similar multi-model “average” featured by IPCC AR4 forces us to assign a low level of agreement/consensus. The evidence base has improved significantly since 2007/8, but we cannot be sure what evidence to trust.

4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. The basic dynamics of shifts in the strength and path of the mid-latitude storm track are uncertain, so that it is unclear which if any climate model is capable of satisfactory projections. There is most uncertainty about the storm tracks in the NE Atlantic.

2. While there is a reasonable knowledge of storminess and wave statistics over the last sixty years, a more complete synthesis would be most welcome. Ideally this synthesis should be pushed further back in time, so that the important context offered by both early observations and by palaeo-reconstruction is integrated into our understanding. Combining this with 1, we will have greater confidence in climate models if they can be demonstrated to successfully hindcast this record of the past.

3. Predictions are only useful to coastal managers where they can be localized at least to the scale of the "Charting Progress" regions. A global climate model produces a useful large-scale projection, but some uncertainty remains as to the most appropriate methods for downscaling those projections to a useful scale. UKCP09 has used a RCM and this is the generally favoured method. However, there is also a case for statistical downscaling based on projected general structural changes in the atmosphere (e.g. intensity and position of storm track).

4. Waves at the coast can have a large impact. Calculation of this impact depends on good resolution of near-shore bathymetry and may be quite sensitive to small changes in offshore wave conditions, especially wave direction and period, which may not be well-resolved in the regional scale model, thus the details of future wave impacts at the coast remain uncertain.

5. Socio-economic impacts

Waves affect:

- Marine Operations (e.g. transport, fishing, offshore industry). The highest waves are a danger to both fixed platforms (e.g. oil rigs) and shipping and their estimation is essential to safe design.
- Coastal Communities. Waves on their own or (more often) in combination with strong winds, high tides and/or sea surges can cause coastal erosion and damage to infrastructure. Breaches of defences can lead to major flooding incidents.
- Marine Renewable Energy. Waves are of direct interest as a potential source of sustainable energy, but also large winds and high winds are a significant risk factor in the development of offshore wind and tidal energy.
- Marine Ecology. Waves influence stratification and thus the distribution of nutrients, plankton and pelagic ecology. Long waves can affect the sea bed even in shelf water of 200m, inducing currents and stirring up sediment, thus influencing near-shore and benthic habitats.

"Concerned groups" include:

(1) Those interested in coastal protection, particularly regarding the combined effect of sea level rise and changes in storm surges and waves on the threat of inundation. An example would be the Western Isles of Scotland where a January 2005 storm

caused loss of life, extensive inundation and damage. There, residents, the local council (CnES), Scottish Natural Heritage and other bodies are considering the appropriate response. One of the authors is peripherally involved through "Coast Adapt", http://www.hebridesnews.co.uk/coast_adapt_cnes_sept09.html. The east coast of UK, notably the "soft cliffs" of East Anglia and Yorkshire is considered to be particularly vulnerable. The coastline of East Anglia has been relatively well studied (Leake *et al.*, 2009).

(2) Offshore Industry: As evidenced by a recent OGP/JCOMM/WCRP Workshop on "Climate Change and the Offshore Industry", 27-29 May 2008.WMO Headquarters, Geneva, Switzerland. Useful projections for the North Sea would be valued.

(3) Marine Renewable Industry. A recent PhD project at University of Edinburgh (student: Lucy Cradden; Supervisor: Gareth Harrison) has looked at projections with respect to onshore wind and there are clearly implications also for marine renewables.

(4) There is an awareness among intertidal and benthic ecologists that changing wave exposure is a factor in changing species distributions, but in practice it may be very difficult to disentangle this influence from the effects of changing temperature and sea level.

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