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Impacts of climate change on 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. There is as yet no consensus on the future storm and wave climate, stemming from diverse projections of future storm track behaviour, but new projections using the latest generation of climate models, under CMIP5 have yet to be fully assessed.

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), as well as the intensity and frequency of storms ('storminess'). Waves are affected by currents and water depth and locally by coastal geometry and man-made structures. Waves decrease in height in shallow water due to energy dissipation by bottom friction and wave breaking; this reduction at a particular site may diminish if sea level rises, unless the coastal morphology, in areas of mobile sediment, can adapt at a similar rate.

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). Recently, recognition of the central role of waves in atmosphere-ocean interactions has led to an initiative to include wave models more directly into climate model projections (Cavaleri *et al.*, 2012; Hemer *et al.*, 2012). Here we focus on UK waters but recognise that the changes are occurring within the context of global dynamics and regional phenomena.

20th century record

Wave data have only been routinely available since about 1950. Meteorological data collection has a longer history and sea-level pressure (SLP) has been observed since the 19th century, allowing construction of isobaric charts and analysis of winds and storms. Previously (e.g. Woolf and Wolf, 2010), we have reviewed the data over the last 60 years, since reanalysis products generally extended back to that date 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 and particularly in the last 20 years since the advent of satellite wind and wave observations. In this update, we review the same information, but utilize also a longer time series based on sea-level pressure.

All wind and wave time series show a great deal of variability including inter-annual and inter-decadal fluctuations, but in some notable cases a distinct trend is observable within the variability. 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). An analysis has also shown there to have been significantly more severe storms over the UK since the 1950s (Alexander *et al.*, 2005). During this period, 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.

Recently a new reanalysis of the whole 20th century has become available (Compo *et al*., 2011) and Wang *et al*. (2012) have produced a reconstruction of the North Atlantic wave heights from 1871-2010, based on the 56-member ensemble of SLP analyses. The SLP data set in the North Atlantic was found to be homogeneous since 1871. A statistical model of the relationship between SLP and wave height, Hs, was calibrated and validated against the ERA-Interim reanalysis from 1981-2010. The reconstruction has been used to examine trends and their significance over the 140-year period. Trends in the reconstructed annual mean and maximum Hs are found to be consistent with those derived from the ERA40 reanalysis. The Hs trend patterns generally feature increases in the north-east North Atlantic with decreases in the mid-latitudes; but there are seasonal variations. The main features of the patterns of trends over the last half century or so are also seen in the period (1871–2010), but the trend magnitudes are much greater in the last half century than over the whole 140 years.

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 North Atlantic Oscillation (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 NAM specifically in the Atlantic sector (the NAO index is a measure of a mean atmospheric pressure difference, Azores (or Gibraltar) – Iceland, e.g. Jones *et al*. (1997). Inter-annual variability in monthly mean wave heights is large, particularly from December to March, the months primarily associated with the NAO. 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, 2003).

Weisse *et al*. (2005: Figure 8) also show that, according to reanalysis data, the leading pattern of varying storms is highly correlated to a sea-level pressure pattern resembling that associated with the NAO. Observed storm counts over the North Sea (Weisse *et al*., 2005; Figures 2 and 3) exhibit much inter-annual variation and evidence of an upward trend between 1960 and 1990. 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). Thus, many of the changes over the last 50 years can be understood in terms of the behaviour of the NAO. The strong trend in the NAO from the 1960s to early 1990s (towards stormier conditions) is apparently unique in its history, but it is controversial as to whether this is a response to greenhouse gas forcing (Osborn, 2004).

There are likely to be many factors affecting the atmospheric circulation in general and more specifically the North Atlantic storm track and the phase of the NAO. (See for example, Seierstad and Bader, 2009, for one of many discussions). It is almost impossible to "unpick" these many influences from the historical record. Two influences that have come to the fore in recent years are worth mentioning, nonetheless: Arctic sea ice (e.g. Budikova, 2009; Seierstad and Bader, 2009) and stratospheric forcing (e.g. Scaife *et al*., 2005; Kunz *et al*., 2009). The warming of the Arctic may be related to a reduction in the latitudinal gradient of sea-level pressure (typically leading to lower, or negative, NAO Index) and thus weaker storm systems. Thus, it is plausible that the retreat of Arctic sea ice in the last two decades is a significant factor in halting the upward trend in storminess and the more frequent occurrence of NAO-negative winters.

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.

A hindcast study for storms, surges and waves in the Irish Sea (1996-2007) by Brown *et al*. (2010a, b, c) has shown that the largest surges at Liverpool are generally driven by winds from the south to the west while the largest waves are forced by winds from the west to the north-west. The worst storm conditions in Liverpool Bay result under south-westerly wind conditions that veer to the west. The number of low level surge events increased in the study area over this decade, although it is too short to determine any long-term trends in the wave and surge levels.

Further analysis and comparison of observed and model waves for Liverpool Bay (Wolf *et al*., 2011) showed more evidence for interdecadal variability of the wave climate and a weak correlation with the NAO.

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 North-East 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 and inter-decadal variability is such that there is no clear longer-term trend.

• Winter wave heights correlate significantly with the North Atlantic Oscillation 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.

• A new reanalysis from 1871-2010 shows a positive trend in wave heights in the North-East Atlantic but less than that which occurred from 1960-1995.

• 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.

Summary of new evidence

Some new information from hindcast and reanalysis studies has been obtained since the last review (Woolf and Wolf, 2010). We have now incorporated evidence from a longer time scale. There is evidence for an increase in wave height for the NE Atlantic over the whole 20th century although a stronger increase occurred over the period 1958-2001.

2. WHAT COULD HAPPEN?

GCMs and RCMs

The 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 AR4 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. Future climate change has been projected by GCMs using SRES scenarios (a set of emission scenarios for 21st century climate produced and documented in the Special Report on Emission Scenarios; Nakićenović and Swart, 2000) with different global climate models (GCMs) in the World Climate Research Programme (WCRP) Climate Model Intercomparison Project (CMIP). The version used for IPCC AR4 was CMIP3.

The projection of the behaviour of NAM, NAO and other modes in 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 winter-time 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 Regional Climate Models (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).

New work is being done for the next IPCC report, AR5, using somewhat updated GCMs, e.g. including a better representation of the stratosphere (Gerber *et al*., 2012) and choosing a different approach to greenhouse gas (GHG) forcing called Representative Concentration Pathways (RCPs), in CMIP5. There are four RCPs, each defined in terms of its radiative forcing in the year 2100 and direction of change (van Vuuren *et al*., 2011). There are not yet any regional climate model runs with the new RCPs, however, some early assessment of changes in global wave climate due to new GCM results are shown, e.g. using RCP8.5 and RCP4.5 (representing 8.5 and 4.5 W m^{-2} respectively – high and intermediate levels) in the EC-Earth model and modelling resulting waves by Dobrynin *et al.* (2012). Both scenarios indicate a future increase of wind speed and wave height in the Arctic and Southern Ocean and a decrease in the Pacific Ocean. In the North Atlantic there is a change of sign from currently positive to negative trends in the 21st century. However, these are very preliminary results with a single model.

The representation of changing North Atlantic sea surface temperatures and Arctic sea ice (Deser *et al*., 2007) may also be important to the prognostic ability of climate models. There is a dynamical argument that Arctic warming and weakening of latitudinal temperature gradients may lead to a weakening of the storm track and its displacement southward. On the other hand, the retreat of sea ice necessarily increases the fetch of waves from the Arctic sector. Thus, the north and west of Scotland might suffer greater exposure to some storms.

Downscaling from global to regional climate change projections is vital for the study of meaningful local impacts (Wolf *et al*., 2012). 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 (GCMs). The aim is to use global scale projections, using accepted greenhouse gas emissions scenarios to generate regionally specific and useful forecasts, with increased spatial and temporal resolution, and including processes that are not resolved in a coarser model, if possible. 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. Nesting a regional climate model (RCM) into an existing GCM is an example of the first method, termed dynamical downscaling. An RCM is a dynamic model, like a GCM, but it can give higher resolution results. At the large scale it is essentially driven by the GCM, but it uses its own physics-based equations to resolve local effects. Downscaling can also be done using statistical regression, at various levels of complexity. This aims to capture the essential relationships between the global model and local variables.

Some recent impact studies for the UK, based on CMIP3 outputs from the HadCM3 model projections, using the UKCP09 offshore waves (Lowe *et al*., 2009) have been carried out for the eastern Irish Sea (Brown *et al*., 2011) and north Norfolk (Chini *et al*., 2010a, b). In both cases these areas were projected to have small/not significant changes in offshore wave height but in the latter case changes in wave directions may be important in terms of changes in coastal morphology. There is some suggestion of a change in frequency and intensity of storms. For example in the case of the Irish Sea, although there is a slight increase in the severity of the most extreme events, the frequency of extreme wind and wave events is slightly reduced. For the Norfolk coast it is shown, that wave statistics are sensitive to the trend in sea-level rise, and that the climate change scenario leads to a significant increase of extreme wave heights in the northern part of the domain. For nearshore points, the increase of the mean sea level alters not only extreme wave heights but also the frequency of occurrence of extreme wave conditions. Increasingly, impact studies in shallow coastal areas are being done with coupled models of waves with water levels and currents (Brown *et al*., 2010b, 2011; Bolaños *et al*., 2011).

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 (Meehl *et al*., 2007; Solomon *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.

New results from the CMIP5 have yet to be fully assessed especially in terms of downscaling through RCMs.

3. KNOWLEDGE GAPS

a. The basic dynamics of shifts in the strength and path of the mid-latitude storm track are still 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.

b. 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. Both RCM and and statistical downscaling based on projected general structural changes in the atmosphere (e.g. intensity and position of storm track) are being used. Further assessment of this work is continuing.

c. 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 continue to remain uncertain.

4. 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. Wave exposure has been identified as a major determining factor of some marine habitats (e.g. Burrows, 2012).

"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 storm in January 2005 caused loss of life, extensive inundation and damage, due to inundation. There residents, the local council (CnES), Scottish Natural Heritage and other bodies are considering the appropriate response. One of the authors is peripherally evolved 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*., 2008).

(2) Offshore Industry: As evidenced by the 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 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.

5. CONFIDENCE ASSESSMENTS

What is already happening?

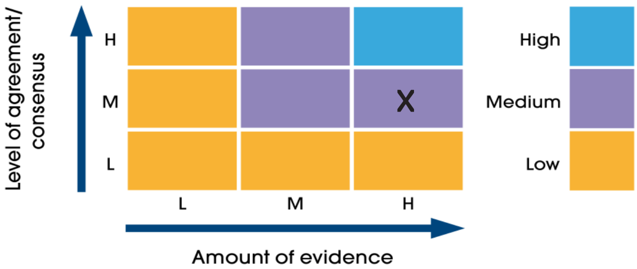
There are many data at least for the historical period and we know of no substantial contradictions in those data. Model hindcasts (forced by reanalysis data) are in close agreement to direct observations of waves. In these respects, the confidence is high, but dynamic models are unable to reproduce 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 some new evidence since 2010, especially due to a new 20th century reanalysis. This has not contradicted the original evidence, but it does re-emphasise the conclusions that multi-decadal variability is important.

What could happen?

Further evidence is accumulating from more and better modelling and projections. The new version of the climate model intercomparison project (CMIP5) has yet to be fully assessed and fed through to RCMs and regional wave models and impacts studies.

CITATION



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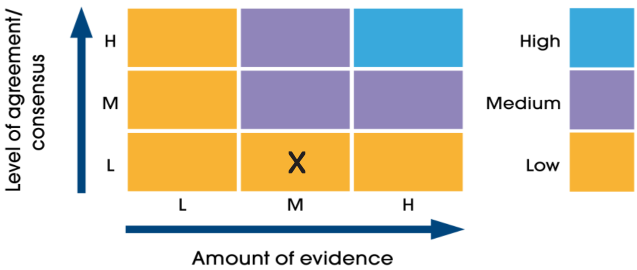

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