Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

We have updated the review by Woolf and Wolf (2013) by summarising the results of the IPCC AR5 report for storms and waves and then including more-recent work published since 2013. There are similar conclusions: wave-model results are controlled largely by the quality of the wind data used to drive them, and the forcing climate models have slightly improved in accuracy as well as resolution. In general, trends are obscured by wide natural variability and a low signal-to-noise ratio. Assessment of changes in storminess and waves over the last 200 years are limited by lack of data, while future projections are limited by the accuracy of climate models.

Recent work has led to more insight in some areas. There are now more climate- and wave- model ensembles, more in-depth assessments of the results of CMIP5, and the CMIP6 project and IPCC AR6 assessments have started. There is a move towards higher-resolution models, which give better accuracy for simulation of tropical and extra-tropical storms. Further work is being done with coupled atmosphere-ocean-wave models, which give insight into key dynamic processes.

There is evidence for an increase in North Atlantic storms at the end of the 20th Century. Some projections for North Atlantic storms over the 21st Century show an overall reduced frequency of storms and some indication of a poleward shift in the tracks, in the northern hemisphere (NH) winter, but there is substantial uncertainty in projecting changes in NH storm tracks, especially in the North Atlantic. Projections for waves in the North Atlantic show a reduction in mean wave height, but an increase in the most-severe wave heights. There is a likelihood of larger wave heights to the north of the UK as the Arctic sea ice retreats and leads to increased fetch.

1. INTRODUCTION

Surface wind waves and storm-force winds can cause much damage in UK coastal waters, particularly in autumn and winter. Understanding the

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characteristics of the mean and extreme wave climate, its variability, and historical and projected future change is an important consideration for sustainable development of coastal and offshore infrastructure, and management of coastal resources and ecosystems. The effects of waves are also critical to shipping; storm waves need to be avoided on shipping routes. The reduction in summer sea-ice due to global warming is opening up the Arctic sea routes to ships, but also increasing the fetch of waves in these regions (Aksenov *et al*., 2017).

Except for tsunamis, waves are driven by the wind, with a nonlinear relationship to wind-speed, fetch and duration over which the wind blows. The largest waves in UK waters tend to be found on the Atlantic-facing coasts where waves can be generated over large fetches in the ocean, and during the period October to March (autumn and 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, as well as the intensity and frequency of storms (‘storminess’). In the North Sea, westerlies have a more-limited fetch, but can still generate high waves. Northerly winds can generate high waves particularly in the central and southern North Sea, whereas strong southerly winds can generate high waves in the northern North Sea.

For the UK, the behaviour of the North Atlantic storm track is critical to understanding storms and extreme waves. Decadal variability in terms of storms and waves within the north-east Atlantic Ocean is mainly related to the North Atlantic Oscillation (NAO), and affects the west-facing coasts of the UK, but its effects can also be detected in the North Sea. The NAO index is related to the pressure difference between the Azores and Iceland, which influences the North Atlantic jet stream, storm tracks and blocking and thereby affects winter wave climate over the North Atlantic (IPCC, 2013). A positive NAO is usually accompanied by increased mean wave heights and storminess in the Atlantic Margin and North Sea, whereas a negative NAO tends to have the opposite effect (N.B. the NAO can also affect summer weather, see Folland *et al*., 2009).

Significant Wave Height (SWH, often referred to using the variable H_S) represents a measure of the energy in the wave field, consisting of both wind–sea and swell, and is approximately equal to the highest one-third of wave heights. Other important parameters are wave period and wave direction, which affect how waves impact the coast. Figure 1 shows an estimate of the 50-year return period SWH from Bricheno *et al*. (2015) to illustrate the differences in wave exposure around the UK. It can be seen that the largest waves are found in the north-west Approaches, north-west Scotland and the Outer Hebrides. Lowest waves are seen in the more sheltered waters of the eastern Irish Sea, southern North Sea and the eastern English Channel, although wave height is not the only cause of danger. Short, steep seas of lower height can be hazardous to small craft in storm conditions, even in relatively short-fetch conditions.

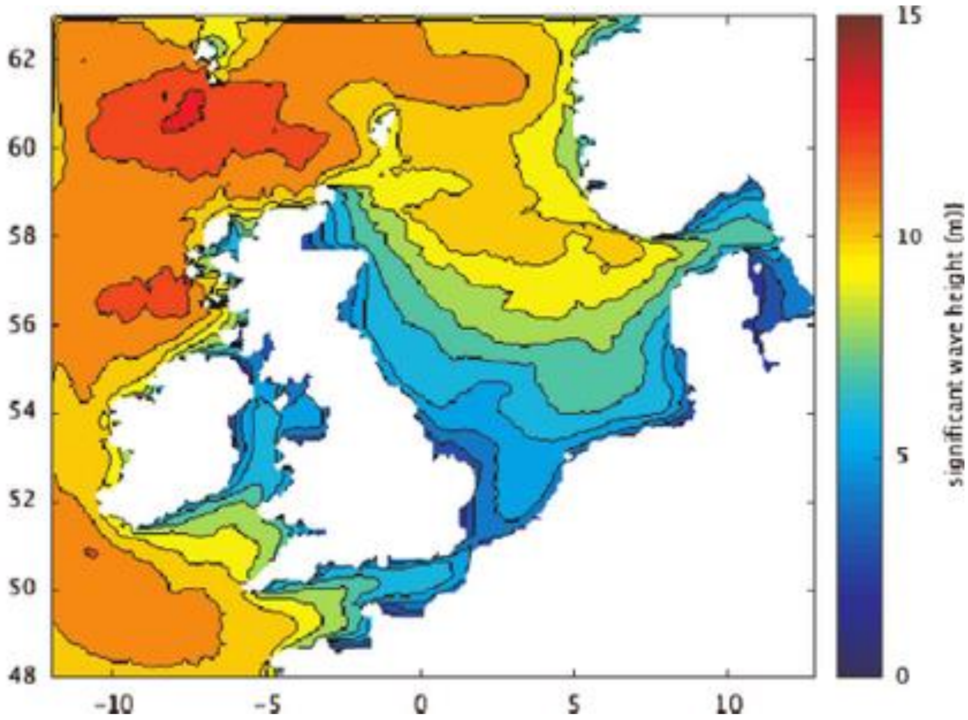


Figure 1: 50-year return-period wave-height around UK from 10-year hind-cast 1999–2008 (from Bricheno et al.*, 2015). This figure is just an example to show the spatial distribution of wave height around the UK but should not be referred to as the best estimate of the 50-year return period as it has been extracted from too short a sample of model data.*

In coastal waters, waves are affected by tidal currents and water depth, and locally by coastal geometry and man-made structures. Coastal defences, such as harbours, breakwaters and seawalls, are designed to dissipate wave energy before it impacts the coast, as well as protecting against extreme water levels caused by sea-level rise, tides and surges. Waves themselves can contribute to raising the water level in a storm by means of wave setup, run-up and overtopping (Prime *et al*., 2016). Waves will have different impacts on sandy beaches, compared with rocky coasts, estuaries or saltmarshes. Some background on coastal wave processes, monitoring and modelling is given in Wolf (2016). Waves decrease in height as they shoal, due to energy dissipation by bottom friction and wave breaking; this reduction in energy 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. An important factor with respect to coastal wave impact is 'coastal squeeze', in which the nearshore depth profile is steepening as coastal defences are hardened on the inland side and offshore water levels increase. Changes in this coastal zone may be exacerbated by offshore aggregate extraction (although this is regulated in the UK) or other man-made changes. In some areas there is now a move towards the introduction of soft defences, such as beach recharge and nature-based solution such as re-introducing saltmarshes ('managed re-alignment').

Waves and storms are a significant feature of the global climate and have been included in many assessments of climate including the latest assessment (the Fifth Assessment Report) of the Intergovernmental Panel on Climate Change (IPCC, 2013, hereafter referred to as 'AR5'), which was published since our last review, and consolidates the state of knowledge up to 2013. We summarise the results of AR5 and discuss work carried out since then.

Here we focus on UK waters, but recognise that local changes in waves depend on changes at much larger scales, since waves integrate wind energy across ocean basins. In turn, large-scale patterns in winds are related to global teleconnections that may manifest as inter-annual and decadal variability over a regional scale, such as the North Atlantic Ocean. For the UK and Europe, we are mainly concerned with extra-tropical cyclones (ETCs), also known as 'mid-latitude storms'). However, we include a discussion of potential changes in Tropical Cyclones (TCs) – termed 'hurricanes' in the North Atlantic, because some TCs undergo 'extratropical transition' and can then track across the North Atlantic to Europe and the UK. Note also that hurricane-force winds (Beaufort scale Force 12 and above) are those with wind-speeds >32.6 m s^{-1}, which may also occur in events which are not actually hurricanes.

In general, we include only references published since the previous review in 2013, and not including those given in AR5, except where a topic was not previously included. New topics include the use of coupled atmosphere-ocean-wave models in the climate system and the emerging issue of attribution of extreme events to climate change. We also extend the discussion of storm and wave impacts at the coast and coastal adaptation to climate change.

In Section 2 we mainly rely upon historical data, model hind-casts and climate model reanalyses to understand what is already happening. In Section 3, looking to the future, we rely on model projections. Confidence in historical trends in storms and waves is generally low due to limited observations of extreme events, and changes in observing methods. Future projections also are subject to low confidence due to the dominance of natural variability in the storm and wave climate.

2. WHAT IS ALREADY HAPPENING?

To understand past changes and trends in wave climate we need a long time–series of observations, and where these are not available we may use proxies, such as sediment deposits in peat bogs, to identify the occurrence of past storms over palaeo timescales, e.g. Orme *et al.* (2017). Where there are limited data available, as in the relatively recent past (since ~1800), we can use model hind-casts e.g. WASA-Group (1998), STOWASUS-Group (2001), NESS, NEXT and NEXTRA (Williams, 2005; 2008) and, increasingly over the last decade, re-analyses combining models and observations. Re-analyses use data assimilation in a dynamical model of the atmosphere and ocean, which ideally maximises the benefit of the limited data, especially in the earlier time periods, as well as providing dynamically consistent wind and wave fields, allowing the calculation of wind and wave statistics in areas where there are no data. New re-analyses have been released following improvements in the models and/or data assimilation schemes from operational Numerical Weather Prediction (NWP) centres. The re-analyses differ in terms of the models and data assimilation methods used to produce them, so they produce different results. However, some issues have been found with inhomogeneities in long reanalyses, usually related to step changes where new data assimilation is introduced, e.g. wave data from altimeters in 1991 in ERA-Interim (Aarnes *et al*., 2015). The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into re-analysis output.

Since AR5 there have been many further studies, which are mentioned in more detail where relevant in the following sections. The next IPCC Assessment Report (AR6) has commenced. Waves are increasingly being recognised as having an important role in air–sea fluxes and mixing processes in the ocean as well as contributing to changes in mean water level (e.g. Staneva *et al*., 2017). The use of coupled wave–atmosphere–ocean models is increasing, although wave models have not yet been included in the Coupled Model Intercomparison Project (CMIP), now in its 6th phase (CMIP6, Eyring *et al*., 2016). The physics of atmospheric models is being improved continually, with clouds, aerosols, atmospheric chemistry, biogeochemical cycles and interactions with the ocean and cryosphere receiving attention, some of which may have implications for storm initiation and evolution. For example, Tamarin-Brodsky and Kaspi (2017) show that increased latitudinal propagation in a warmer climate is due to stronger upper-level winds and increased atmospheric water vapour. Stopa *et al*. (2016) discuss the importance of waves in the marginal ice zone (MIZ) and Ardhuin *et al*. (2018) examine the physics of interactions between waves and sea ice.

Some excerpts of AR5 are summarised in the next paragraphs for TCs, ETCs and waves in the North Atlantic (details of spatial variation around the UK are discussed elsewhere and note that IPCC definitions of likelihood and confidence are adopted):

- Some high-resolution atmospheric models have realistically simulated tracks and counts of TCs and models generally are able to capture the general characteristics of storm tracks and ETCs with evidence of improvement since the AR4.

- Storm track biases in the North Atlantic have improved slightly, but models still produce a storm track that is too zonal and underestimate cyclone intensity (Zappa *et al*., 2013a, b).
- There is *low confidence* in long-term (centennial) historical changes in TC activity, after accounting for past changes in observing capabilities, but over the satellite era (since the late 1980s), increases in the frequency and intensity of the strongest storms in the North Atlantic are robust (*very high confidence*). The cause of this increase is debated and there is *low confidence* in attribution of changes in TC activity to human influence. This is due to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and TC activity and the low level of agreement between studies about the relative importance of internal variability, and anthropogenic and natural forcings (see AR5 sections 2.6.3, 10.6.1, 14.6.1).
- Over periods of a century or more, evidence suggests a slight decrease in the frequency of TCs making landfall in the North Atlantic (in North America, not Europe), once uncertainties in observing methods have been considered. For ETCs, a poleward shift is evident in both hemispheres over the past 50 years, with further, limited, evidence of a decrease in wind storm frequency at mid-latitudes. Several studies suggest an increase in intensity, but data sampling issues hamper these assessments.
- Global and regional time series of wind-wave characteristics are available from buoy data, Voluntary Observing Ship (VOS) reports, satellite measurements and model wave hind-casts. There is very strong evidence that storm activity has increased in the North Atlantic since the 1970s.
- Positive regional trends in extreme wave heights have been reported at several buoy locations since the late 1970s. Satellite altimeter observations provide a further data source for wave height variability since the mid-1980s. Model hind-casts based on 20CRv2 (spanning 1871–2010) and ERA40 (spanning 1958–2001) show increases in annual and winter mean SWH in the North-East Atlantic, although the trend magnitudes depend on the re-analysis products used (e.g. Stopa and Cheung, 2014). Analysis of VOS observations for 1958–2002 reveals increases in winter mean SWH over much of the North Atlantic, north of 45°N, with typical trends of up to 20 cm per decade.

19th–21st Century record – observations

Wave data have only been routinely collected by calibrated instruments, such as wave buoys, 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 from these data. Voluntary Observing Ships (VOS) have provided some useful data on wind and waves since 1856 (Gulev *et al*., 2003; Gulev and Grigorieva, 2004). Centennial time series of visually observed wave height were derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) along the major ship routes worldwide. In the North Atlantic, and other basins, significant upward changes (up to 14 cm/decade) are observed, but only for the last 50 years and not for centennial records. Long-term changes in wind wave height are closely associated with the North Atlantic Oscillation (NAO) in the Atlantic. The reliability of such data has been examined by Gulev *et al*. (2003).

In Woolf and Wolf (2010), we reviewed the observational data over the last 60 years, since reanalysis products at that time generally extended over that era, and marine data greatly improved at that time, due to the advent of Ocean Weather Stations (OWS) and other reliable sources of wind and waves data. The measurement network has evolved in the last 70 years and particularly in the last 30 years, since the advent of satellite wind and wave observations. In the last update (Woolf and Wolf, 2013), we reviewed the original information, plus longer time–series based on sea-level pressure. Here we add the information gathered from VOS and more-recent, high-resolution, long re-analysis datasets, which can maximise the benefits of earlier data, as well as identifying biases introduced by changes in the methodology.

Existing wind and wave data sources around the UK can be found via the MEDIN (Marine Environmental Data & Information Network) wave metadata tool https://portal.medin.org.uk/portal/start.php, among others, which allows discovery of wave and other marine data. The data sources include wave buoys of the Wavenet monitoring network https://www.cefas.co.uk/cefas-data-hub/wavenet/, operated by Cefas, the Irish Marine Institute, the Met Office and the Channel Coastal Observatory (CCO), originally focussed in the southern UK, but which also provides links to other regions, namely the north-east, north-west, Anglia and the East Riding of Yorkshire. In recent years, projects such as the EU-funded COASTALT project (2009–2011), http://www.coastalt.eu/ has aimed to recover more altimeter data in the nearshore zone, including waves.

A large amount of metocean data (including that for wind and waves) are collected *in situ*, by, or for, major oil and gas companies, at considerable cost. These companies have many offshore oil and gas fields scattered worldwide in seas and on continental shelves, often in remote areas. Metocean analyses provide them with essential information needed to complement their working practices, such as in the design and engineering of offshore installations and for the forecasting of meteorological events. The System of Industry Metocean data for the Offshore and Research Communities (SIMORC) is one source of long-term data (https://www.bodc.ac.uk/projects/data_management/european/simorc/).

Another source of proxy data about the historical storm climate is available using sand dune data, e.g. Bateman *et al*. (2018), which can record the effect of extreme events.

Re-analyses

Since the last review, there are many more and longer wind and wave model re-analysis datasets available, e.g. ERA-Interim (ERA-I), JRA-25, JRA-55, NCEP-CFSR, MERRA and MERRA-2 (Hodges *et al*., 2017). The production of a new ECMWF climate reanalysis, called ERA-5, to replace ERA-Interim re-analysis has started, with a higher spatial and temporal resolution (down to ~31 km and hourly) also with an ensemble to provide estimates of uncertainty at reduced resolution. The ERA5 re-analysis will be completed by mid 2020 (http://climate.copernicus.eu/products/climate-reanalysis), by which time the full re-analysis will be available extending from 1950-present. Wang *et al.* (2016) present an inter-comparison of extra-tropical cyclone activity in nine re-analysis datasets: the ERA-20C Re-analysis (ERA20C), the Twentieth Century Re-analysis, version 2c (20CRv2), the Japanese 55-year Re-analysis (JRA55), the Modern Era Retrospective-analysis for Research and Applications (MERRA), the NCEP Climate Forecast System Re-analysis (CFSR), ERA-I, the ERA40 Re-analysis, the NCEP–NCAR Re-analysis (NCEP1), and the NCEP-DOE Re-analysis (NCEP2). The inter-comparison is based on cyclones identified using an objective cyclone tracking algorithm. Re-analyses with higher horizontal resolutions show higher cyclone counts.

Storms in re-analyses

To use climate models for future projections, we need to understand their limitations and, to some extent, this is being done in CMIP. Analysis of CMIP5 models by Zappa *et al*. (2013a; b) shows that too many cyclones are found in the eastern Atlantic, which would lead to an over-prediction of strong winds in this area. When compared with the ERA-I, all but one of the CMIP5 models were biased low when comparing the mean SWH. However, many members of the model ensemble were also seen to over-estimate the annual maximum SWH. These biases arise primarily from deficiencies in the CMIP5 models' ability to simulate the position of the storm track, and the intensity of local wind fields. Those CMIP5 models performing the best at capturing the position of the storm track (with respect to ERA-Interim cyclone track position at 0 degrees E) are HadGEM2-ES, EC-Earth, and GFDL CM3. The storm track is too far south in BCC, CNRM and MRI-CGCM3. ACCESS is not assessed in Zappa *et al*. (2013a; b). It is important to note that the biases in the seven models evaluated are not spatially correlated with the change signals observed in those models, i.e. we can separate out the relative changes from the model biases. This is the case for both the patterns of mean and annual maximum SWH change. Hodges *et al.* (2017) examined the ability of climate re-analyses to represent TCs and concluded that although the re-analyses generally represented the storms, TC intensities are significantly under-represented in the reanalyses compared to the observations. Further statistical analysis of the CMIP5 global model outputs for waves and the climate change signal plus uncertainty is given in Wang *et al*. (2014; 2015). In the IMILAST project (Intercomparison of MId

LAtitude Storm diagnosTics), different objective tracking methods were compared for ETCs (Neu *et al*., 2013). These are an important tool for analysing large model outputs and looking at changes. Different methods were found to agree for the most intense storms, but there could be significant differences for more-shallow systems, with a different number of cyclones identified.

Observed trends

All wind and wave time–series data show a great deal of variability including inter-annual and inter-decadal fluctuations, but in some cases a distinct persistent trend is observable within the variability, over various time periods. In the late 20th century there was a period of increasing wave heights over the North-East Atlantic, while trends in wind speed around the UK were much weaker, 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. Wave heights may have been enhanced by an increase in persistence of westerly winds. Earl *et al*. (2013) discuss variability in the UK wind climate (1980–2010). Long re-analyses include 20CRv2 (Compo *et al*., 2011; Cram *et al*., 2015), and ERA-20C (Poli *et al*., 2016). Bertin *et al*. (2013) showed an increase in SWH over the whole North Atlantic, superimposed on the inter-annual variability, reaching 0.01 m per year north of 50°N, based on 20CR.

Woollings *et al*. (2015) assess the decadal and longer timescale variability in the winter North Atlantic Oscillation (NAO). This has considerable impact on regional climate, yet it remains unclear what fraction of this variability is potentially predictable. On the shorter timescale the NAO is dominated by variations in the latitude of the North Atlantic jet and storm track, whereas on the longer timescale it represents changes in their strength instead. Castelle *et al*. (2017) derive a new climate index controlling winter wave activity along the Atlantic coast of Europe. The Western Europe Pressure Anomaly (WEPA) is based on the sea level pressure-gradient between the stations Valentia (Ireland) and Santa Cruz de Tenerife (Canary Islands). The WEPA positive phase reflects an intensified and southward shifted SLP difference between the Icelandic low and the Azores high, driving severe storms that funnel high-energy waves toward western Europe southward of 52°N. WEPA is similar to the NAO, but outscores by 25–150% the other leading atmospheric modes in explaining winter-averaged SWH and by an even larger amount the winter-averaged extreme wave heights. WEPA is also the only index capturing the 2013/2014 extreme winter that caused widespread coastal erosion and flooding in western Europe. Castelle *et al*. (2018) use a 69-year (1948–2017) numerical weather and wave hind-cast (forced by 6-hourly SLP and 10-m wind fields from the NCEP/NCAR reanalysis project) to investigate the interannual variability and trend of winter wave height along the west coast of Europe. Variability in winter-mean wave height north of ~52°N is primarily related to NAO, while WEPA is dominant further south. An upward trend in winter-mean wave height is mainly related to NAO, while a periodicity at 6–8 years in recent decades is related to WEPA.

Attribution

In many cases, people will ask whether a particularly large storm or a sequence of storm events, such as occurred over the UK and Europe during the winter of 2013/14, is a result of climate change. Previously the standard response was that individual events could not be attributed to global warming, but such questions are increasingly being addressed in the scientific literature, e.g. by the National Academy of Sciences, Engineering and Medicine (NASEM, 2016).

From Figure 2, it may be seen that TCs and ETCs have low understanding and low confidence in attribution, although there is better understanding of the likely effects of climate change on TCs. This means it is not easy at present to predict long-term changes.

An assessment of the attribution of extreme events to climate change (NASEM, 2016) concludes:

- TCs: Most climate models have inadequate resolution for attribution studies, though specialised higher-resolution models are better and improving quickly. Few attribution studies of individual storms have yet been performed. Some aspects of the underlying physics are understood; for example tropical cyclone intensity and precipitation are confidently expected to increase with warming. Detection of trends in observations is challenging due to low frequency variability as well as inhomogeneity and shortness of records.
- ETCs: Climate models can simulate these events to some extent, though the resolution and physics may still be limiting in many models, particularly in their ability to resolve the most-extreme local manifestations of the storms such as strong winds and heavy precipitation. Detection of trends in observations, robustness of projections, and physical understanding of climate change influences are all weak. Few attribution studies have been performed, making long-term prediction of climate change effects difficult.

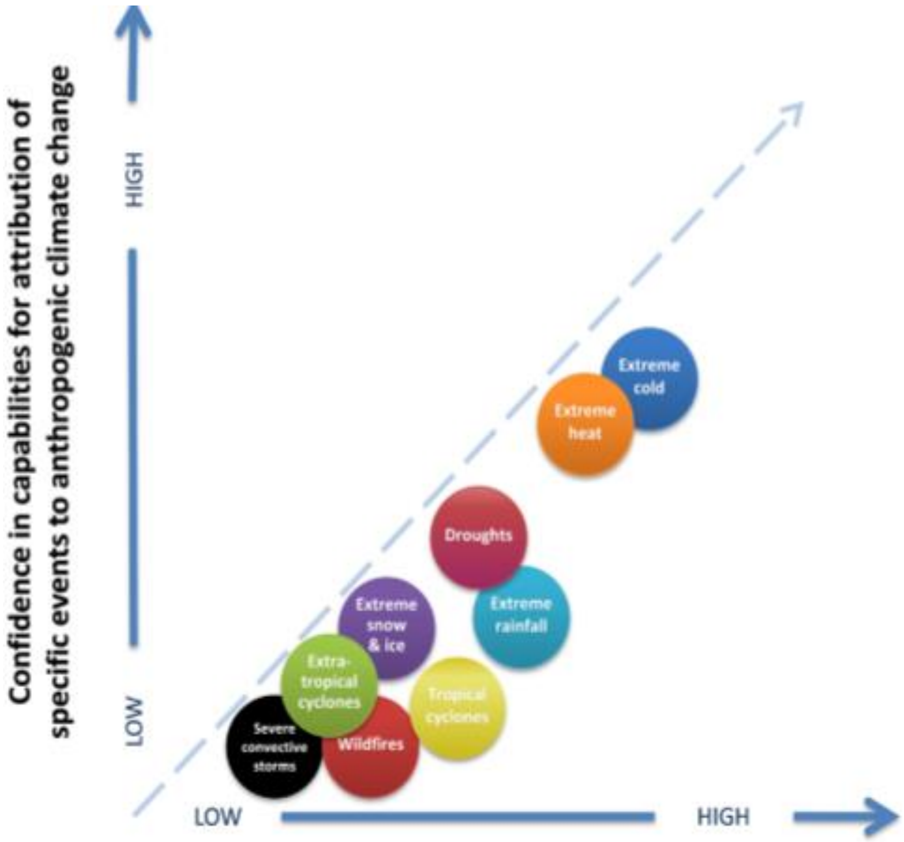


Figure 2 (figure S.4 in NASEM, 2016): Schematic depiction of this report's assessment of the state of attribution science for different event types. The horizontal position of each event type reflects an assessment of the level of understanding of the effect of climate change on the event type. The vertical position of each event type indicates an assessment of scientific confidence in current capabilities for attribution of specific events to anthropogenic climate change for that event type. A position below the 1:1 line indicates an assessment that there is potential for improvement in attribution capability through technical progress alone (such as improved modelling, or the recovery of additional historical data), which would move the symbol upward. A position above the 1:1 line is not possible because this would indicate confident attribution in the absence of adequate understanding. In all cases, there is the potential to increase event attribution confidence by overcoming remaining challenges that limit the current level of understanding.

Summary of new evidence

- Over periods of a century or more, evidence suggests slight decreases in the frequency of TCs making landfall in the North Atlantic (in North America not Europe), once uncertainties in observing methods have been considered.
- For ETCs, a poleward shift is evident in both hemispheres over the past 50 years, with further but limited evidence of a decrease in wind storm frequency at mid-latitudes. Several studies suggest an increase in intensity, but data-sampling issues hamper these assessments.
- The latest assessments show that, due to problems with past observing capabilities, it is difficult to make conclusive statements about long-term

trends. There is very strong evidence, however, that storm activity has increased in the North Atlantic since the 1970s, at least into the 1990s.

- Climate models have continued to be improved since the AR5, particularly in terms of resolution. There are still errors in the reproduction of storm tracks from CMIP3 to CMIP5 (although CMIP5 showed some improvement) and CMIP6 is in production.
- There has been evidence that the air–sea drag coefficient should be limited in extreme winds (Moon *et al*., 2007; 2008), and more-accurate modelling of this, among other things, has led to improvements in coupled models (Breivik *et al*., 2015).
- Some new information from hind-cast and re-analysis studies has been obtained since the last review (Woolf and Wolf, 2013). There are new long re-analyses, e.g. ERA-20C. We have now incorporated evidence from a longer timescale, including VOS data.
- 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.

3. WHAT COULD HAPPEN IN THE FUTURE?

For AR5 and beyond, the scientific community has defined four new scenarios, known as the Representative Concentration Pathway (RCP) scenarios. The four RCPs (RCP2.6, RCP4.5, RCP6.0, RCP8.5) are a consistent set of projections of the components of radiative forcing named according to their 2100 radiative-forcing level, estimated from the greenhouse gas (GHG) concentrations and other forcing agents (Moss *et al*., 2010). In RCP2.6 the GHG concentrations are reduced substantially over time. RCP4.5 (medium-low) and RCP 6.0 (medium-high) are stabilisation scenarios, where the radiative forcing is stabilised before and after 2100 respectively by assuming the use of a range of technologies and strategies to reduce GHG emissions. RCP8.5 is characterised by radiative forcing that increases more rapidly than the other RCPs (assuming normal condtions, with no GHG reduction up to 2100) and continues to increase until 2200. As a result, we see global warming in all these scenarios, with only RCP2.6 projected to have a global average temperature less than 2˚C above the pre-industrial era. The RCP scenarios have been produced by integrated assessment models to 2100, and are then extended beyond that using simple algorithms intended for use as pathways to drive long-term earth-system simulation experiments. While the RCPs span a wide range of total forcing values, they do not span the full range of plausible emissions in the literature, particularly for aerosols. However, they have been used in global climate model projections, such as in the CMIP5.

Both near-term and long-term projections are included in AR5 and the results are summarised here:

Near-term projections (for period 2016–2035 relative to the reference period 1986–2005, from AR5):

- There is *medium confidence* in near-term projections of a northward shift of Northern Hemisphere storm tracks and westerlies, (see AR5, section 11.3.2).
- There is *low confidence* in basin-scale projections of changes in the intensity and frequency of tropical cyclones (TCs) in all basins to the mid-21st century. This low confidence reflects the small number of studies exploring near-term TC activity, the differences across published projections of TC activity, and the large role for natural variability and non-GHG forcing of TC activity up to the mid-21st century.
- There is *low confidence* in near-term projections for increased TC intensity in the North Atlantic, which is in part due to projected reductions in North Atlantic aerosols loading, (see AR5, section 11.3.2.5.3).

Long-term projections (to 2100 and beyond, from AR5):

- Poleward shifts in the mid-latitude jets of about 1 to 2 degrees latitude are likely at the end of the 21st century under RCP8.5 in both hemispheres (medium confidence), with weaker shifts in the Northern Hemisphere (NH).
- Substantial uncertainty and thus low confidence remains in projecting changes in NH storm tracks, especially for the North Atlantic basin.
- In the NH winter, the CMIP5 multi-model ensemble shows an overall reduced frequency of storms and less indication of a poleward shift in the tracks than previous assessments.
- It is very likely that wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea-ice extent.
- There is low confidence in region-specific projections due to the low confidence in tropical and extratropical storm projections, and to the challenge of downscaling future wind fields from coarse-resolution climate models.

Figure 3 shows projected changes in winter ETC storm track density, taken from AR5. The upper two panels are for the NH under RCP 4.5 and RCP 8.5 respectively. In addition to an overall decrease in storms over the NH, there is a tri-pole pattern with areas of decrease over Iceland and the Mediterranean and an increase over the UK (Zappa *et al*., 2013b). Figure 4 shows projected changes in wind-waves from global wave models in the Coordinated Ocean Wave Climate Projection (COWCLIP) Project (Hemer *et al*., 2013).

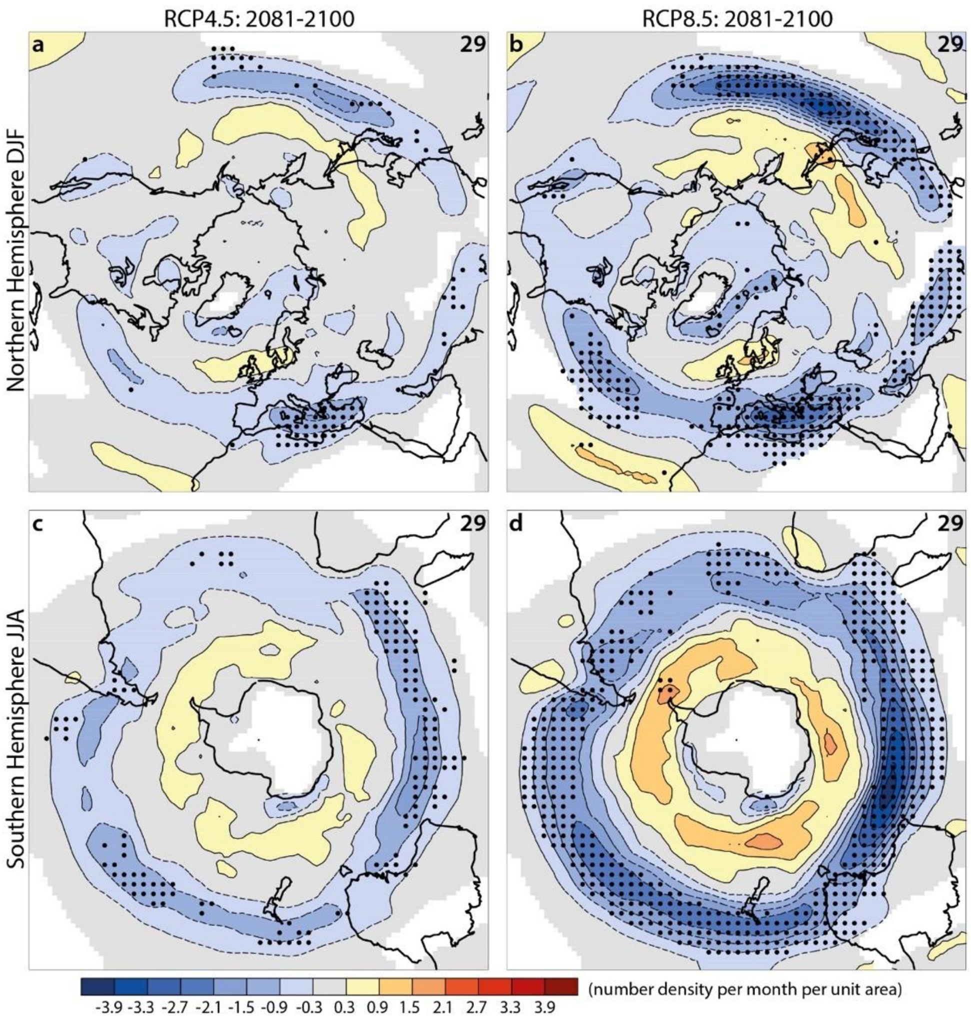


Figure 3 (from IPCC, 2013, figure 12.20): Change in winter, extratropical storm track density (2081–2100) – (1986–2005) in CMIP5 multi-model ensembles: (a) RCP4.5 Northern Hemisphere December, January and February (DJF); (b) RCP8.5 Northern Hemisphere DJF; (c) RCP4.5 Southern Hemisphere June, July and August (JJA); and (d) RCP8.5 Southern Hemisphere JJA. The number of models used appears in the upper right of each panel. DJF panels include data for December 1985 and 2080 and exclude December 2005 and December 2100 for in-season continuity. Stippling marks locations where at least 90% of the models agree on the sign of the change. Densities have units (number density per month per unit area), where the unit area is equivalent to a 5° spherical cap (~106 km^2). Locations where the scenario or contemporary-climate ensemble average is below 0.5 density units are left white.

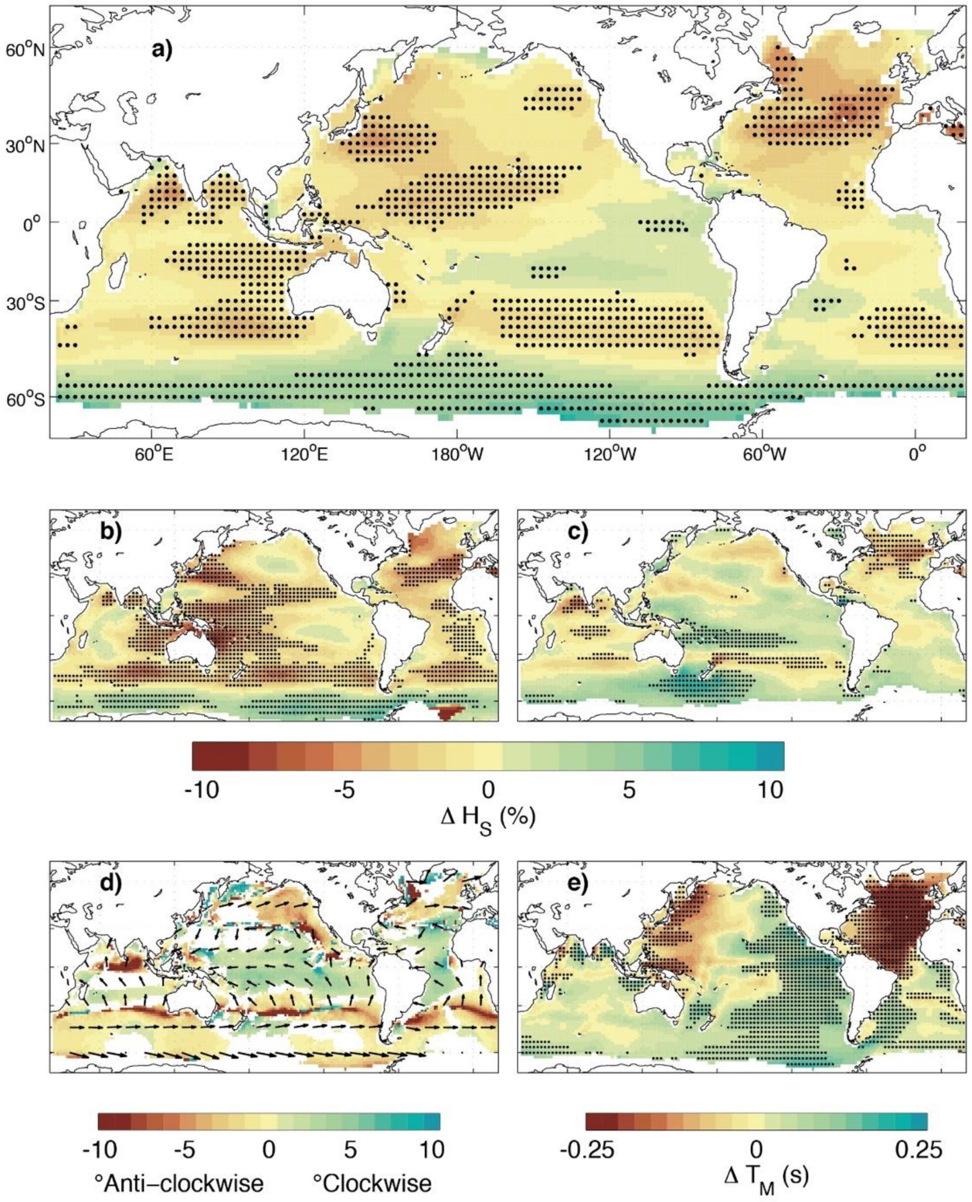


Figure 4 (from IPCC, 2013, figure 13.26): Projected changes in wind–wave conditions (~2075–2100 compared with ~1980–2009) derived from the Coordinated Ocean Wave Climate Projection (COWCLIP) Project (Hemer et al.*, 2013). (a) Percentage difference in annual mean SWH. (b) Percentage difference in means of January to March SWH. (c) Percentage difference in means of July to September SWH. Hashed regions indicate projected change is greater than the 5-member ensemble standard deviation. (d) As for (a), but displaying absolute changes in mean wave direction, with positive values representing projected clockwise rotation relative to displayed vectors, and colours shown only where ensemble members agree on sign of change. (e) As for (a), but displaying absolute changes in mean wave period. The symbol ~ is used to indicate that the reference periods differ slightly for the various model studies considered.*

Work on storms, blocks and jets since AR5

Since AR5 there have been various new projections and work on understanding the behaviour of the CMIP5 atmospheric models. Haarsma *et al*. (2013) use a very high resolution global climate model (~25 km grid size) with prescribed sea-surface temperatures to show that greenhouse gas induced warming enhances the occurrence of hurricane-force (> 32.6 ms^{-1}) storms over western Europe during early autumn (August–October), the majority of which originate as a TC. The rise in Atlantic tropical sea surface temperatures extends eastward the breeding ground of TCs, yielding more frequent and intense hurricanes following pathways directed toward Europe. En route they transform into ETCs and re-intensify after merging with the mid-latitude baroclinic unstable flow, showing that future tropical cyclones are more prone to hit western Europe, and do so earlier in the season, thereby increasing the frequency and impact of hurricane force winds.

Harvey *et al*. (2014) find that there is a large spread in the storm track projections of the CMIP5 climate models, examining the relationship between the climate change responses of the storm tracks, as measured by the 2–6 day mean sea-level pressure variance, and the equator-to-pole temperature differences at upper- and lower-tropospheric levels. In the NH the responses of the two temperature differences are not significantly correlated and their associations with the storm track responses are complicated. In winter, the responses of the upper- and lower-temperature differences both play a role. There is potential to reduce the spread in storm-track responses by constraining the relative magnitudes of the warming in the tropical and polar regions. Harvey *et al*. (2015) show that the large spread of projections for the extratropical storm track present in the northern North Atlantic in particular is mostly associated with changes in the lower-tropospheric equator-to-pole temperature difference. Zappa *et al*. (2015) suggested that a climate-related signal emerges sooner from the natural variability if seasonal averages rather than an annual mean are used to examine the climate response. This suggests that by considering extreme winter waves, we may be able to see emergent signals more easily than by looking at the annual means.

Other recent studies on future projections of storms in climate models include Masato *et al*. (2014) who studied changes in the blocking of storms by stationary high-pressure systems. These features can be a challenge to climate models to predict correctly. They find there is a mean twenty-first-century winter poleward shift of high-latitude blocking with a decrease in European blocking frequency in the twenty-first-century model runs. The poleward shift of the storm track into the region of frequent high-latitude blocking may mean that the incidence of storms being obstructed by blocks may actually increase. Molter *et al*. (2016) review projections of future storminess over the North Atlantic European region, showing regional differences. There is broad consensus that the frequency and intensity of storms, cyclones, and high-impact wind speed will increase over Central and Western Europe, and these changes will probably have the potential to produce more damage. In contrast, future extratropical storminess over Southern Europe is very likely to decrease. For Northern and Eastern Europe the results are inconclusive; there are competing factors affecting future storminess. They found indications of a likely north- and eastward- shift in storm track in most studies. Results from three studies suggest a north-eastward shift of the North Atlantic Oscillation. Li *et al*. (2018) compare results for 1.5°C and 2°C warming, showing that under an additional 0.5°C of warming there is a poleward shift of the North Atlantic jet exit and an eastward extension of the North Atlantic storm track. Michaelis *et al*. (2018) use the WRF model at high resolution (20 km) with the RCP8.5 scenario to try to reconcile different projections for storms in the North Atlantic. They find enhanced ETC activity in the North-East North Atlantic, but there is a change in the storm populations, with a reduction in the number of strong storms and a change in storm dynamics. Stryhal and Huth (2018) examine trends in CMIP5 circulation patterns, based on sea level pressure, finding that over the British Isles the models that better simulate the latitude of zonal flow over the historical period indicate a slight equatorward shift of westerlies in their projections, while the poleward expansion of circulation—expected in future at global scale—is apparent in those models that have large errors. A similar weather typing approach is used by Santos *et al*. (2016) to understand projections for precipitation. Baatsen *et al*. (2015) use a very high resolution (~25 km) global climate model to explore the mechanisms of extra-tropical transition. Results show that that more-severe Autumn storms will impact Europe in a warmer future climate, mainly due to storms with a tropical origin, especially in the later part of the 21st century. As their genesis region expands, tropical cyclones become more intense and their chances of reaching Europe increase.

The UK Climate Projections (UKCP09) project has been one of the leading sources of climate information for the UK and its regions. UKCP09 provides climate projections for the UK for three different future greenhouse gas emissions scenarios. The UKCP09 marine and coastal projections report (Lowe *et al*., 2009) includes future projections for sea-level rise, storm surge, sea temperature, salinity, current and waves.

The UKCP18 project is currently updating the UKCP09 projections, giving greater regional detail, and providing more information on potential extremes and impacts of climate change. The next set of UK climate projections will use new scenarios from the most recent Intergovernmental Panel on Climate Change (IPCC) report. These are an update to the existing emissions scenarios used in UKCP09, which did not consider specific climate change mitigation strategies to limit emissions.

Waves

The COWCLIP community (Coordinated Ocean Wave Climate Projections; www.jcomm.info/cowclip) aims to generate and share wave climate projections. An ensemble of global wave projections has been made publically available, as described by Hemer *et al*. (2013). This dataset consists of climate-model-driven global wave model simulations, which can be used to explore the influence of climate variability and change on the global wave field. The wave models were driven by climate projections from CMIP5.

The models have been analysed for the 'historical' period (1980–2005), 'mid-century' (2026–2045) and 'end-century' (2080–2099). Two future scenarios were compared: RCP4.5 and RCP8.5. For consistency with the UKCP18 project, a subset of the CMIP5 models was used: ACCESS1.0 (sister model of ACCESS 1-3), BCC-CSM1.1, CNRM-CM5, GFDL-CM3, HadGEM2-ES, INMCM4, MRI-CGCM3, and MIROC5. These global wave models have a grid resolution of the order 1 degree and are driven directly by global climate model winds and ice-cover, with no intermediate downscaling step.

Downscaling from global to regional climate change projections is vital for the study of meaningful local impacts (Wolf *et al*., 2015), until much higher resolution global models are computationally possible. Downscaling uses global scale projections, using accepted greenhouse gas emissions scenarios to generate regional forecasts, with increased spatial and temporal resolution. Processes not resolved in the coarser model may be included. Downscaling can be done by (i) using process models, (ii) using empirical/statistical relationships, and (iii) using hybrid methods e.g. weather typing/pattern recognition (Camus *et al*., 2017). 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. Usually it is an atmosphere-only model, not including coupling with the ocean. At the large scale, it is essentially driven by the GCM, but it uses its own physics-based equations to resolve local effects. The advantages of the RCM can be better resolution of the land-sea interface, inclusion of islands and better resolution of atmospheric synoptic scale features.

A dynamic downscaling approach can also be applied to the wave model configuration, thereby improving the representation of bathymetry and coastal geometry, while the downscaled RCM improves the spatial resolution of the winds. Following this methodology, Bricheno and Wolf (2018) have made new surface-wave projections for North-West Europe driven by the EC-Earth CMIP5 climate model. They use a global and a nested regional model, which have been validated against ERA-Interim for the re-analysis period. Downscaling improves the period and direction but not SWH for the waves. Mean SWH is projected to decrease in future, but the mean annual maximum

SWH can increase by up to 0.5 m. Extreme SWH increases in the North (most likely due to sea-ice retreat) and around Atlantic-facing coasts. There is increased variability of high-end waves in future projections.

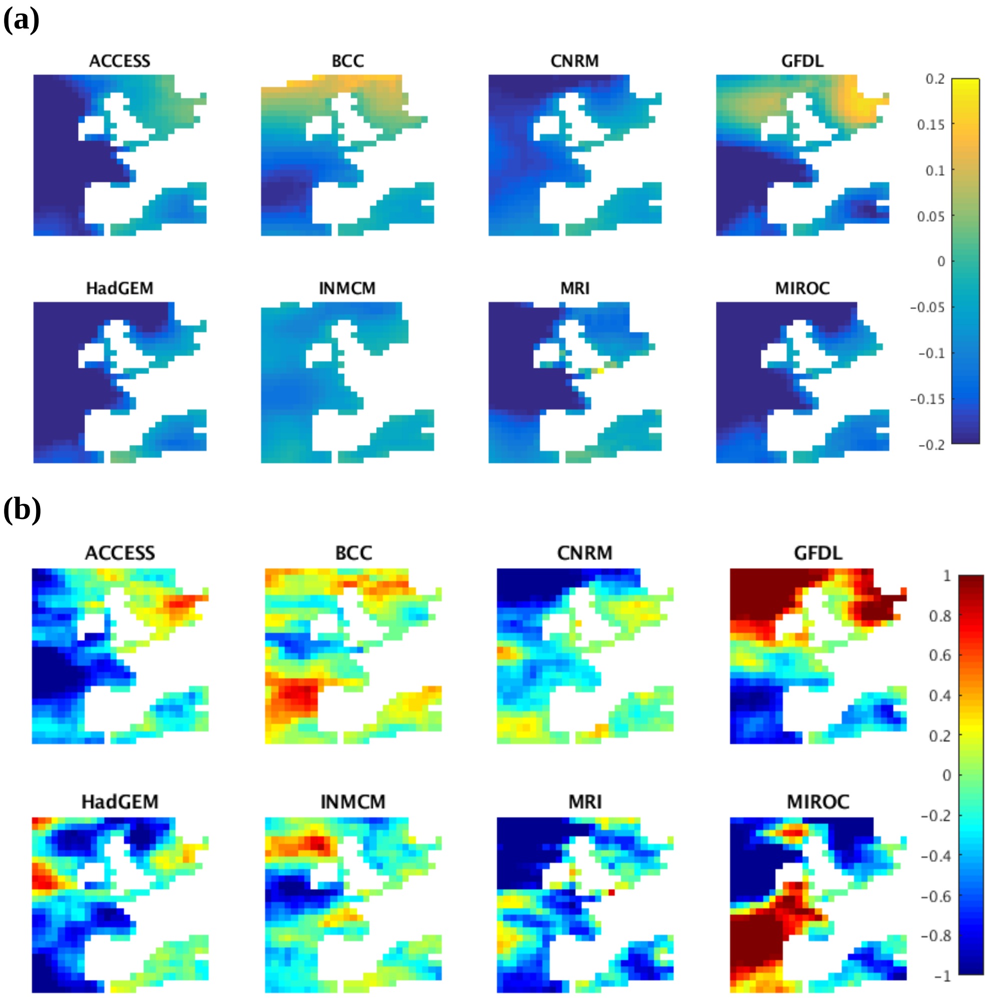


Figure 5: Changes in SWH around NW Europe from eight models in the COWCLIP ensemble. The absolute difference between RCP8.5 (2070-2099) and historical (1970-1999) information is shown: (a) mean SWH, (b) mean annual maximum SWH. See text for explanation of model abbreviations.

Figure 5 shows the projected change in mean and annual maximum SWH for the end of the 21st century forced by RCP8.5 climate model winds. There is consensus amongst the ensemble, showing a reduction in mean SWH across the majority of NW Europe. The exception in some models is to the north of the domain, where sea-ice reduction can increase SWHs in future. The maps of changing extreme waves (annual maximum, lower eight panels, Figure 5b) have no clear consensus in the direction of change in future. Extreme waves are more sensitive to passing individual storms, and this is shown by the patchiness of change in these future projections. As well as the 2070–2099 time slice, the 2030–2059, and both corresponding RCP4.5 periods were also evaluated. The direction of change in future wave climate is consistent with the mean SWH seen to reduce in both configurations. Stronger changes are seen in the regional model than the global model. Similar patterns are seen in the RCP4.5 projections as the RCP 8.5 projections. Stronger reductions in the mean SWH are observed in 2030–2059 than in 2070–2099. Considering the annual maximum SWH changes in the four future projections, again the spatial patterns are consistent with those shown in Figure 5. However, the largest changes in the annual maximum SWH are seen in 2070–2099. More details can be found in Bricheno and Wolf (2018). A reduction in the mean SWH, with an increase of the extreme SWH can be understood by considering the full probability density function. If the probability density function is widening, and spreading, the tail can move towards higher waves, while the mean conditions remain unchanged, or reduced. The conclusion of a decreased mean SWH, and greater uncertainty associated with extreme wave events, is consistent with the findings of Aarnes *et al*. (2017) who analyse wave change in six CMIP5 models for the North Atlantic/Arctic.

Coastal wave impacts for the UK

Santos *et al*. (2017) derive spatial footprints for extreme wave events from buoy data around the UK, 2002–2016. The winter of 2013/14 appears as an outlier.

Coll *et al*. (2013) and McClatchey *et al.* (2014) discuss the impacts of changes in waves and storminess on remote/peripheral communities including some calculations of specific effects, notably the cost of maintaining ‘lifeline ferry services’. Some services and the social resilience of peripheral communities can be affected by the intensity and frequency of stormy seas. In this respect, some of the projected changes (ensemble members shown in Figure 5) represent a threat to northern peripheral communities.

Brown *et al*. (2016) discuss the evolution of coastal systems in the aftermath of the winter of 2013/2014 when there were a number of severe storms tracking across the UK. Some parts of the coast have changed their state (passed a tipping point) so they may be more vulnerable to future storms and overwash by waves. Masselink *et al*. (2016) show that the 2013/2014 winter wave conditions were the most energetic along most of the Atlantic coast of Europe since at least 1948. Along exposed open-coast sites, extensive beach and dune erosion occurred due to offshore sediment transport. More sheltered sites experienced less erosion and one of the sites even experienced accretion due to beach rotation induced by alongshore sediment transport. Storm-wave conditions such as these have the potential to dramatically change the equilibrium state (beach gradient, coastal alignment, and nearshore bar position) of beaches along the Atlantic coast of Europe.

Gallagher *et al*. (2016) predict an overall decrease in annual and seasonal mean SWH around Ireland for the period 2070–2099 compared to 1980–2009.

Mentaschi *et al*. (2017) identify global trends in extreme Wave Energy Flux (WEF) along coastlines in the 21st century under a high emission pathway (RCP8.5). For the end of the century, results show that in the Northern Hemisphere large coastal areas are characterised by a significant negative trend. The most significant long-term trends of extreme WEF can be explained by intensification of teleconnection patterns such as the ENSO and NAO.

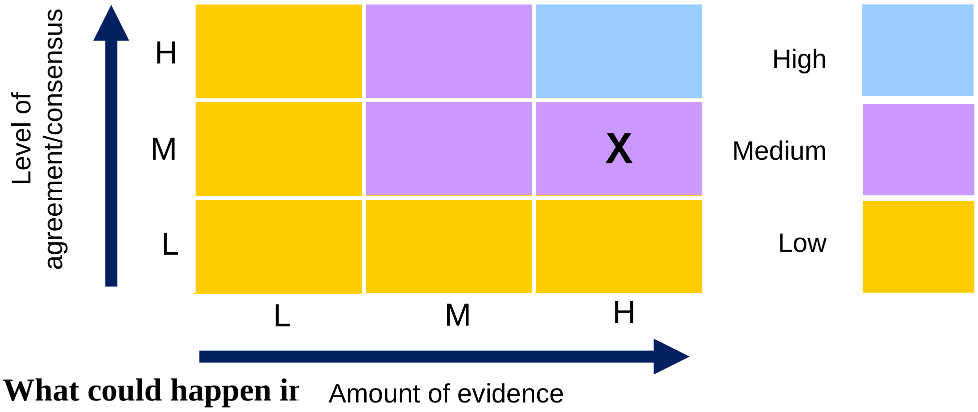
Quante and Colijn (2016) present the North Sea Region Climate Change Assessment (NOSCCA), which is an international climate change assessment for the North Sea, carried out by around 200 climate scientists in different research areas from all countries around the North Sea. It includes chapters on the atmosphere (including winds) and the North Sea (including waves), covering recent changes and future projections. The impacts of recent and future climate change on marine, coastal, lake and terrestrial ecosystems are presented, including climate change impacts on socio-economic sectors such as fisheries, offshore activities related to the energy sector, coastal protection and coastal management and governance. While only covering the North Sea and having limited references for the most recent work, it is very comprehensive.

Summary on future projections

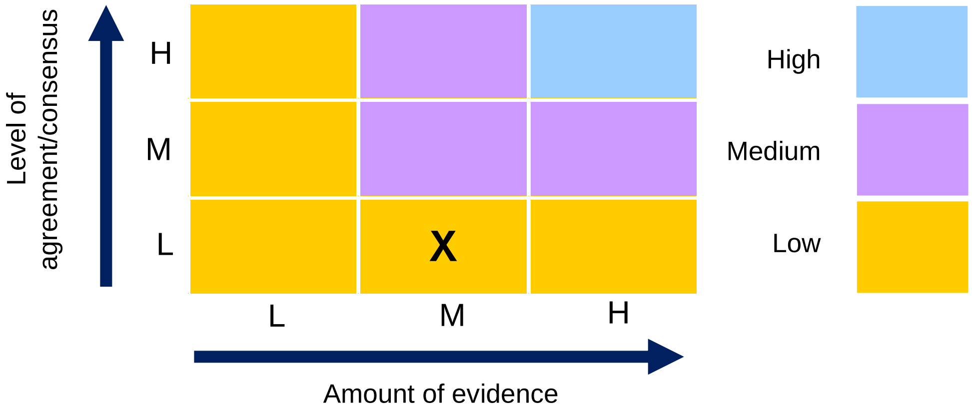
Climate change may affect storminess, storm tracks and hence winds and wave heights. Future projections in UK waters are very sensitive to climate model projections for the North Atlantic storm track, which remains an area of considerable uncertainty. Results from the CMIP5 have been more fully assessed, including downscaling through RCMs. Natural variability still dominates any climate-related trend in storms and waves in the near future. For the larger GHG emission towards the end of the 21st century there seems to be some consensus that the mean SWH is decreasing but the most extreme waves are increasing in height. The reduction in sea ice cover in the Arctic is likely to lead to increasing waves in that area which can enhance waves to the north of the UK

4. CONFIDENCE ASSESSMENT

What is already happening?



What could happen in



The level of confidence is the same as previously – the rationale is that what has already happened is based on existing but necessarily limited data. There is still some room for an increase in the consensus of interpretation of that data and long-term re-analyses are a useful tool for this but still in development. The future changes depend on model projections, which have improved slightly since AR5 but still have some way to go. There are still quite substantial differences between different climate models, but new higher-resolution models promise better representation of storms.

5. KEY CHALLENGES AND EMERGING ISSUES

Collins *et al*. (2018) and Shaw *et al*. (2016) provide support for a consensus on the following key challenges:

1. Improve the simulation of storms by climate models.
2. Improve the understanding of the response to external forcing of North Atlantic storms and blocks.

3. Improve the understanding of climate feedbacks in affecting the rate of retreat of Arctic sea ice and how this affects storms and wave height.

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