Climate Change Impacts on Storms and Waves Relevant to the UK and Ireland

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KEY FACTS

What is already happening

- There has been a poleward shift in the storm track since the 1990s and an increase in the annual mean number of storms.
- Mean significant wave height has reduced over the last 30 years in northern UK waters and increased in the south.
- Observed trends in storms and waves cannot be directly attributed to climate change because of the high variability and limited understanding of associated mechanisms.
- Winter storm track position and intensity is a sensitive and important control on wave climate.

What could happen in the future

- Climate change could affect storms and waves in the North Atlantic, but natural variability will continue to dominate over the next few decades.
- The most severe waves could increase in height by 2100 under a high-emissions scenario, but there could be an overall reduction in mean significant wave height in the North Atlantic.
- Wave heights are expected to decrease in the mean but experience increased frequency and intensity of extreme events.
- Projections imply that more very severe winter storms will cross over the UK. The chance of severe storms reaching the UK during autumn may increase if tropical cyclones (such as hurricanes) become more intense, and their region of origin expands northwards.

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SUPPORTING EVIDENCE

Introduction

Storm-force winds and wind-driven sea waves can cause much damage in UK coastal waters, particularly in autumn and winter. Understanding the characteristics and variability of wave climate, 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. Waves contribute directly to coastal flooding, and wave conditions are critical to safe operations in shipping and offshore industries. Storm waves need to be avoided on shipping routes, which are evolving in the context of reduced Arctic Sea-ice (Aksenov *et al*., 2017, 2022). Waves are 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. Bonaduce *et al*., 2022). Storm surges (raised water levels driven by low pressure weather systems) can also impact the coast, as high winds act on the sea surface. Additional water level from storm surges can interact with tides, and waves, to cause coastal flooding.

Wind-driven waves are created by the momentum input at the sea surface under local winds. Wave energy propagates away from storm regions as swell, leading to storm effects being felt at a great distance from the area in which the waves were first generated. The largest waves in UK waters tend to be found on the Atlantic- coasts, which receive waves generated over large fetches in the ocean. Due to seasonal variation, waves around the UK are highest during the period October to March when strong winds are more intense and persistent. Lobeto et al (2024) classify Northwest Europe as having the most exposed coast to storms in the world. The UK also experiences storm clustering, with typically less than two weeks between successive storms along much of the coastline. This pattern is associated with a strong and persistent jet stream (e.g., Pinto et al., 2014). Short-term clustering of exceedances is common, with the North Atlantic and Bristol Channel showing the highest clustering for storm surges (Jenkins et al., 2022).

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 as fetch increases away from western coasts. 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 and Europe, we are mainly concerned with extra-tropical cyclones (ETCs), also known as ‘mid-latitude storms’. While extratropical storms are routinely forecast, there are uncertainties in the strength and destructiveness of these storms. Most commonly in the autumn, ETCs can have transitioned from tropical cyclones (Baker *et al*., 2021). The highest winds are sometimes associated with ‘sting jets’ (narrow, intense regions within some cyclones Clark and Gray, 2018). However, large waves are more likely to be affected by length of fetch and rate of progression of the storm, while impacts of sting jets might be quite localised. Post-tropical cyclones (PTCs) extend many hazards associated with tropical cyclones to the midlatitudes. Sainsbury et al. (2023) find a disproportionately large fraction of high-impact windstorms impacting Europe are caused by post-tropical cyclones.

Significant Wave Height (SWH, often referred to using the variable Hs) represents a measure of the energy in the wave field, consisting of both wind sea and swell, and is approximately equal to the average of the highest one-third of wave heights. Other important parameters are wave period and wave direction, which affect how waves impact the coast. In coastal waters, waves are affected by tidal currents and water depth, and locally by coastal geometry and man-made structures. Waves will have different impacts on sandy beaches, compared with rocky coasts, estuaries or saltmarshes. Wave changes in shallow water are a balance of shoaling (an increase in wave height due to waves slowing down in the shallows), bottom friction (a decrease), depth-limited wave breaking (a decrease) and refraction (an increase or decrease dependent on how the wave energy is focused or defocused over shoals and canyons). Future climate impacts on waves will come from the changing storminess, but also interaction with sea-level rise (SLR) and changes in morphology associated with coastal erosion.

Changing water depth will affect where waves feel the seabed. However, there is an insufficient evidence base to understand changes to bathymetry and, therefore, in detail wave impacts along UK coastlines under SLR. Future trends in mean water levels, and coastal flooding for the UK are detailed in companion report cards (Horsburgh, 2020; Haigh *et al*., 2024).

What is already happening?

Atmospheric circulation and storminess

Long-term changes in storminess and waves will be strongly affected by to changes in atmospheric circulation. Variability in atmospheric circulation can be either natural variability or a response to climate change. The most significant long-term trends of extreme waves can be explained by intensification of teleconnection patterns such as the North Atlantic Oscillation (NAO, Hurrell et al, 2003) and West Europe Pressure Anomaly (WEPA, Castelle et al. 2017). On a global scale and informed by a dynamical understanding, greater heating at higher latitudes implies 'global stilling' of winds, but a general decline of global wind speeds over several decades has been followed quite recently by a recovery (Wohland *et al*., 2021).

Woollings *et al*. (2015) assess the decadal and longer timescale variability in the winter NAO. This has considerable impact on regional climate, yet it remains unclear what fraction of this variability is potentially predictable. On the shorter (interannual-decadal) timescale the NAO is dominated by variations in the latitude of the North Atlantic jet and storm track, whereas on the longer (multidecadal) timescale it represents changes in their strength instead. 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. Predictions at seasonal or longer timescales may depend on relationships to the North Atlantic Oscillation or Arctic Oscillation (Feng et al., 2023). A simultaneous winter teleconnection between the El Niño–Southern Oscillation (ENSO, McPhaden et al 2006) and the North Atlantic is well established, but recently Scaife et al. (2024) demonstrated an opposing lagged (1 year later) response of NAO to ENSO, suggesting a positive NAO one year later is more likely to follow an El Nino.

On UK Atlantic coasts, change in wave climate are related to the number, intensity and propagation speed of cyclones (Wolf and Woolf, 2006), the storm track and the North Atlantic Oscillation. Coasts exposed to waves from the north or north-east are affected by increased fetch from that sector resulting from ice loss in the Arctic. The frequency of winds from that sector is important on those coasts.

There are also at least two lines of evidence that suggest that the atmospheric dynamics pertinent to the UK experience may differ from the global situation. First, the local mid-latitude storm track is likely to be sensitive to the latitudinal gradient of atmospheric temperature over the North Atlantic, which will be affected by the Atlantic Meridional Overturning Circulation. Second, some of the more intense storms originated in tropical cyclones (Sainsbury *et al*., 2020), which have a distinct dynamical response to global heating. Priestly *et al.* (2020) report an increase in the annual mean number of cyclones of all origins over Western Europe in the two most recent decades. Additionally, Seneviratne *et al*. (2021) express a medium confidence in a poleward shift since the 1990s of where extreme storms are experienced, which will also be relevant to local trends in wave height.

North Atlantic waves and surge

Historic trends can be investigated with wave hindcast models, driven by atmospheric re-analysis which includes some observed signal of climate change. Several hindcasts, 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 such as satellite data from ERA5 (Hersbach *et al*., 2020). Several global datasets of historical wind waves and surges have recently become available, e.g. Liu *et al*. (2021), Alday (2021), Ribal and Young (2019), ECMWF (2019), Mentaschi et al., 2023, and Agulles et al. (2024). These can be more accurate than the global wave component of ERA5, particularly in regions of strong current and large SWH and some offer finer spatial and spectral resolutions and updated global bathymetry. In addition to long term records of SWH from satellite altimetry, which have recently been revised and updated (Young *et al*., 2019, Dodet *et al*., 2020, Li *et al*., 2020), recent observations of sea state (2015 to 2020) from SAR imagers on board satellites have been released as part of the ESA Sea State Climate Change Initiative. These novel products provide parameters beyond

SWH, including swell wave height and estimates of wave period (Pleskachevsky *et al*., 2022). However, a conclusion from these datasets is that inconsistencies exist between models, buoy and satellite data, yielding some differences in SWH trends (Figure 1).

There have been several new global datasets analysing historic (global) wave climate, which improve our understanding of historic trends, and internal climate variability (Casas-Prat et al. 2022; Morim et al. 2022; Patra et al. 2023; Fanti et al 2023; Hochet et al. 2023). A meta-analysis of trends in global ocean wave hindcasts across a 35-year period between 1980 and 2014 was published by Erikson *et al*. (2022). They find spatially coherent patterns of change including downward trend in both winter and summer SWH across the North Atlantic (NA). However, the annual number of rough days (when daily maximum SWH exceeds 2.5 m) and high-wave days (exceeding 6.0 m) is seen to increase around the UK at a rate of around 0.5 days per year. Full attribution is difficult but effects at a coast will relate to the strength, direction and persistence of winds forcing the waves to which that coast is exposed. A trend in the timing of storm surge season has been observed between 1950-2000. The season begins later, in the North Sea a shift of around 4 days/decade is observed, related to the phase of the NAO (Roustan et al, 2022). Tadesse et al. (2022) also identify, long term positive trends in the magnitude of extreme surges (4.5 mm/year) in the North Sea (since 1930-1950) but possibly diminishing in more recent years since 1980.

Drivers of variability and wave trends in the North Atlantic

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 over various time periods. In particular, wave trends are highly sensitive to seasonality and affected by the substantial short-term variability. Meucci *et al*. (2020) identified the North Atlantic (NA) as an area of disagreement in trends between studies. The NA is well known to exhibit high interannual and decadal variability in sea state (Hochet *et al*., 2021). The NAO is the main driver of the NA inter-annual winter sea state variability. A positive NAO is associated with a positive SWH anomaly at latitudes higher than 45°N (Hochet *et al*., 2021). Variability in winter-mean wave height north of ~52°N is primarily related to NAO, while the West Europe Pressure Anomaly (WEPA) is dominant farther south as explained in Castelle *et al*. (2017).

Kümmerer et al. (2024) reinforce the importance of choosing a time period over which to investigate the trends. For example, there is a positive upwards trend if you take a period from the 1960 to the early 1990s. However, a negative trend is evident in the period 1992–2017. These trends are consistent with a 'swing' in the NAO over those decades. 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 waves. Wave heights may have been enhanced by an increase in persistence of westerly winds (Wolf and Woolf, 2006). Looking at a different period, Figure 1 presents the decreasing trend in mean SWH during January/February/March around the UK during the period 1992–2017. These data are from ERA5, Ribal and Young (2019), (RY2019) and ESA Climate Change Initiative for Sea State level 4 version 1.1 gridded altimetry product (CCI2019), and ECMWF WAM hindcast *without* wave assimilation (CY46R1). Yet another different period is analysed by Castelle *et al*. (2018). They use a 69-year (1948–2017) numerical weather and wave hind-cast to investigate the interannual variability and trend of winter wave height along the west coast of Europe. The Castelle *et al*. study was not a wave-assimilating reanalysis and they observe an upward trend in winter-mean wave height. However, this is mainly related to the NAO, while a periodicity at 6–8 years in recent decades is related to WEPA.

The strong influence of regional processes, on interannual and decadal sea state variability, complicates predictability and evaluation of trends over multidecadal timescales. Within the sea state community, research effort is currently directed at better understanding these issues.

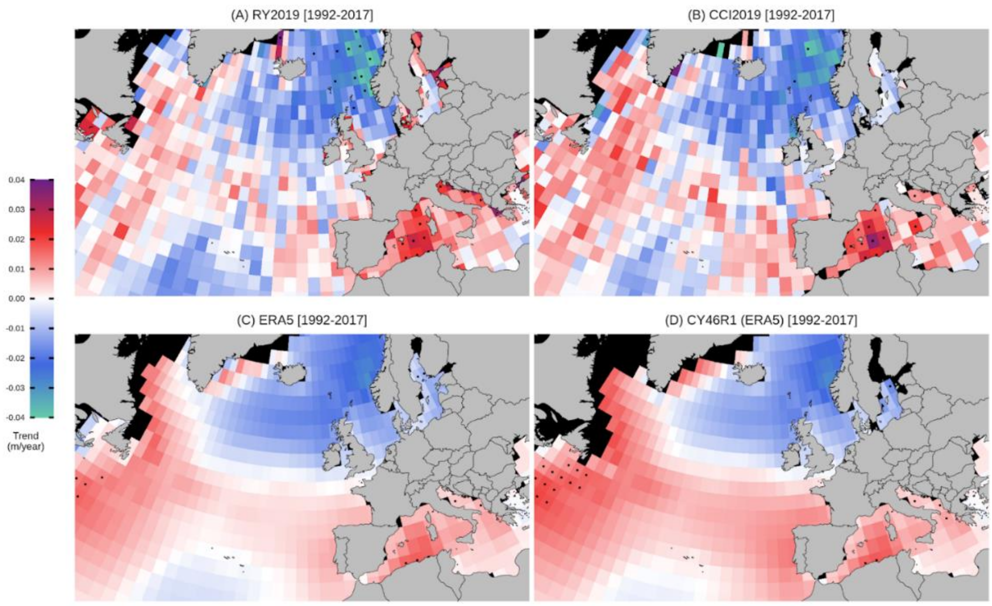


Figure 1: *Distribution of January-March SWH trend estimates on a 2°×2° grid over 1992–2017 for a selection of satellite and model reanalysis datasets. (a) RY2019 (model), (b) CCI2019 (model), (c) ERA5 (satellite), and (d) CY46R1 (satellite). Dots indicate grid cells where the trend coefficient is significant at the 1% level (replotted from global data in Timmermans, 2020).* The lack of robust trends (and sparsity of dots), is linked to high sea state variability on interannual and decadal timescales during that period.

Combined changes in wave height and period will affect tidal wave power. Reguerro et al. 2019) found a historic decrease in wave power in the North Atlantic between 1999–2008, but increased in the previous decades. As well as changes in SWH there is some research around changes in wave period and direction. This is of particular importance at the coast, for example when considering logistics around harbours, as well as sediment transport and coastal erosion. In the meta-analysis of 35-year hindcasts, Erikson (2022) finds no change in mean wave period around the UK. They do identify a shift in mean waves to come from an increasingly clockwise direction (in both summer and winter). A clockwise rotation of waves is consistent with a poleward shift in the storm track reported by e.g. Seneviratne et al. (2021). The trend is of the order 0.5 degrees per year to the west of the UK, rising to 1 degree per year to the north of the UK and in the North Sea. However, these trends are not statistically significant. In the summer months, there is also an indication of a shift in the anti-clockwise direction to the south-west of the UK. This trend is statistically significant. However, it is small, measuring less than 0.5 degrees per year.

Recent studies highlight the predictive power of climate indices (and associated wave patterns) in coastal response (Scott et al., 2021). Wiggins et al. (2019,2020) consider the impact of bi-directional waves on coastal erosion, demonstrating how atmospheric drivers such as WEPA and NAO alter coastal exposure through changing wave power and coastal rotation. More recent studies (e.g. Masselink et al., 2023) state that winter wave conditions that are associated with NAO and WEPA (explaining 50-80% variability), are directly linked to winter shoreline variability.

Climate change impacts

Detection and attribution of the human influence on climatic changes in surges and waves remains a challenge (Ceres *et al*., 2017). The close relationship between local extreme sea-levels and long-term mean sea-level rise implies that observed changes in these extremes can be attributed, at least in part, to human-caused climate change (Fox-Kemper *et al*., 2021). A few studies have attempted to quantify the role of anthropogenic climate change in extreme sea-level events around the UK (e.g. Turki *et al*., 2020). 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. Waves have also been reviewed in the latest IPCC report (AR6) Fox-Kemper *et al.* (2021). Their most robust conclusion regarding wave trends around the UK, is the effect of sea ice loss in the Arctic leading to increased wave heights over the period 1992–2014, which is also reported with medium confidence in the previous IPCC report (Collins *et al*., 2019).

In the past there has been little evidence for long-term systematic changes in storminess emerging above natural variability (Marcos *et al*., 2015). However, recent work (Calafat *et al*., 2022) identifies trends of storm-surge extremes, separating attribution from natural and anthropogenic variability. Natural changes display a north–south dipole, with increasing surge north of 52°N and a decrease to the south, while anthropogenic forcing leads to an increase in surge extremes all around the UK coast. An experiment by

Howard et al (2024) projects an increase in mean and annual maximum storm surge, due to an AMOC collapse. This was predicted to strengthen the north Atlantic storm track and the winter westerlies due to an increase in the north-south sea surface temperature contrast in the north Atlantic. While a total AMOC collapse is an extreme and low likelihood future, a weakening of the AMOC has been observed in multiple studies. E.g. Zhu et al., (2023); Rahmstorf (2024). Experiments by Scussolini et al. (2023) find a naturally forced warmer climate leads to increased sea level extremes (surges) for coastlines along the North Sea. Storm surges and their coastal impacts are covered in more detail in Haigh *et al*. (2024).

What could happen in the future?

Atmospheric circulation and storminess

Climate change may affect storminess, storm tracks and hence winds and wave heights. Future projections in UK waters are very sensitive to climate models designed to represent the North Atlantic storm track, which remains an area of considerable uncertainty. Models can generally represent the storm track effectively, but over the last decades have underestimated an increasing trend in jet strength and multi-decadal variability (Blackport and Fyfe, 2022; Bracegirdle, 2022), raising concerns about their use in projection. Over the next few decades, the natural variability of mid-latitude storm systems is likely to more strongly control storminess around the UK than changes attributable to anthropogenic forcing (Horsburgh *et al.*, 2021). Seneviratne *et al*. (2021) project little change in the number and intensity of extra-tropical cyclones globally. Wohland *et al*. (2021) confirm the conceptual model that reductions in latitudinal temperature gradients lead to global stilling, but expect internal climate variability to dominate in this century. However, recent modelling studies (e.g. CMIP6 and CESM) are generally consistent in predictions relating to the NA storm track that contradict global trends. Notably, an increase in large and intense wintertime storms (Dai and Nie, 2022; Ginesta et al., 2024; Larsén et al., 2024), a greater clustering of successive storms (Karwat et al., 2024) and compound events (Lopez-Marti et al., 2024). Overall, there might be a decrease in cyclones (Priestly and Catto, 2022) and a weakening of storm tracks during summer (Chemke and Coumou, 2024) but the increasing wintertime frequency and characteristics local to the UK and Ireland are concerning. Projections carry caveats on future climate change; for example, projections differ under AMOC collapse (Orbe et al., 2023). Some models can now capture local intensification within parts of a cyclone (Gentile and Gray, 2023; Manning et al., 2023) and suggest increasing hazard. Whilst from a global (and IPCC) perspective, storminess may not increase, there is a likelihood that the UK will experience increasing storminess and an intensified wintertime storm track.

Though progress in models is encouraging there are specific deficits that continue to limit certainty in results, including biases in storm track (Priestly et al., 2023) and under-representation of some events (Liu et al., 2022). Oudar *et al*. (2020) evaluated the wintertime midlatitude atmospheric circulation in CMIP6 models and identified a tripole structure in the North Atlantic, where the zonal wind strengthens over Western Europe and decreases north and south. The zonal wind is observed to shift poleward in the Pacific while it is squeezed and strengthened over Northern Europe. It was concluded that the present-day zonal wind biases have been reduced between CMIP5 and CMIP6. The latest models (CMIP6 and C-ESM) are generally found to give a better representation of storm tracks and zonal winds but with room for further improvement (e.g. Priestly et al., 2020 and 2023; Crawford et al., 2023). Note that any errors in the storm track and zonal winds will feed into errors in projected wave climate through strong physical links (Wolf and Woolf, 2006).

Future wave projections

A leap forward in future wave climate projection comes from the work of Morim *et al*. (2019): a model intercomparison analysis of a suite of global wave climate models 'COWCLIP', with datasets published in Morim *et al*. (2020). The Coordinated Ocean Wave Climate Project (COWCLIP) is a multi-method ensemble of 155 global wave climate simulations derived using both dynamical and statistical downscaling method from 10 separate studies. This ensemble approach helps overcome issues related to standardisation of wave-climate datasets and limited sampling of uncertainty space inherent to individual studies. Analysed in detail by Morim *et al*. (2021), there are some robust findings for the North Atlantic, generally showing it to become calmer over time: reduction in number of rough days by around 10% increased frequency of low days and reduced frequency of high days, and reduction in wave-storm-spell duration (10%). These signals are consistent for end-of-century projections between, and become stronger and more robust when moving from RCP4.5 to RCP8.5.

Aside from but in agreement with COWCLIP, Amores and Marcos (2020) project a decrease in ocean swell peak period and wave energy for European coastlines at the end of the century under emissions pathway RCP8.5, Mentaschi *et al*. (2017) identified a negative trend in extreme Wave Energy Flux along Northern Hemisphere coastlines for the 21st century under RCP8.5. Meucci *et al*. (2020) uses a GCM ensemble to force wave model simulations and pool the outputs to conduct a reduced uncertainty extreme value analysis of wind-wave events. The results show no statistically significant changes in 1 in 100-year extreme significant wave height events in the North Atlantic and along UK coastlines under RCP8.5 by the end of the century, but statistically significant increases are projected for the Eastern North Sea. A meta-analysis of seven global wave models driven using winds from the CMIP5 global climate models was analysed for future waves around the UK coast (Lowe *et al*., 2018). These simulations suggest an overall decrease in mean SWH around most of the UK coastline of 10-20% over the 21st Century under RCP8.5. The model projections show changes in annual maximum SWH also of up to 10-20%, but the sign of change differs among models and coastal location. D'Agostini (2022) use a Lagrangian approach to further investigate future wave conditions in the North Atlantic. They predict fewer, but more intense mid-latitude storms by the end of 21st century under RCP8.5. They also project a significant increase in the number of storm tracks in latitudes above 65°N for the same period. Since the release of CMIP6, there have been global wave model datasets released and analyses performed, e.g. Meucci et al (2024). Preliminary analysis of these data, e.g. Grossmann-Matheson (2024) show no clear trend in N Atlantic tropical cyclones in ssp585 mid-century. An analysis of CMIP6 global projections of storm surge is performed by Muis et al (2022), predicting an increase in the 1 in 10-year storm surge levels in the North Sea.

Wave properties other than SWH are also projected to change in the future. Mean wave period is projected to decrease around the UK in the order 2-3% by the end of the century (Morim *et al*. 2019). These trends are statistically significant, and stronger in RCP8.5 than RCP4.5. Mean wave direction is also projected to change, i.e. to come from an increasingly clockwise direction around the UK. Changes are of the order 3-5 degrees by the end of the century, however these projections are not statistically significant.

Consistent with previous reports (Morim, 2019), recent studies appear to further confirm the expectation that average annual and seasonal wave conditions around the U.K. will decrease towards the end of the century. This may be as much as 0.3 m (Chaigneau, 2023). However, sea state variability, driven by wind and storms in the North Atlantic is sufficiently high to mask the long-term negative trend in, with a “time of emergence” of the long-term trend exceeding 50 years in many regions (Hochet et al., 2023).

The latest high-resolution wave projections for the UK (Figure 2) were made under UKCP18 (Palmer *et al*. 2018; Bricheno and Wolf 2018) forced by the EC-Earth climate model. Projections of average wave height suggested changes of the order of 10 to 20% and a general tendency towards lower wave-heights. Changes in extreme waves are also of the order of 10 to 20%, but there is no agreement in the sign of the change among the model projections. Increases in the annual maximum and 99th percentile wave height as large as 0.5–1 m are predicted. For exposed coasts, the changes in waves are dominated by the global response to climate change, while for sheltered coastal regions, the changes in waves are dominated by the local weather variability. An increase in waves to the north of Scotland results from continuing ice loss in the Arctic and the resulting increase in fetch from that sector. Widening of the probability density function is observed, suggesting an increased intensity of rare high-wave events in the future (Bricheno and Wolf 2018).

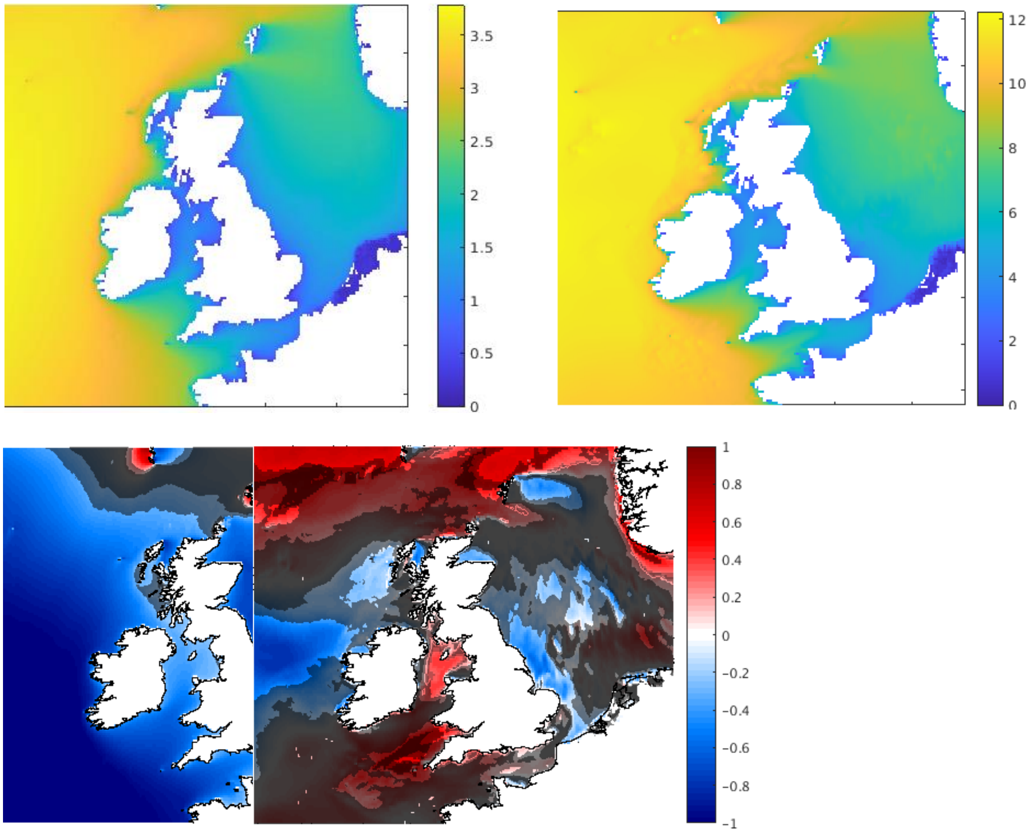


Figure 2: *Historical conditions (top) and projected changes (below) in future mean (left) and AnnMax (right) SWH (m). Areas masked in black have a confidence below 50% and those masked in grey a confidence below 75 % (left) Middle century. (right) End century, Representative Concentration Pathway RCP8.5. (After Bricheno and Wolf, 2018, and Palmer* et al.*, 2018.)*

Coastal impacts

Waves are a primary driver of changes in the coastline and as such changing wave and storm climates will affect shoreline erosion around the UK. Wave parameters are used as inputs to shoreline models, so capturing future changes in these parameters is of importance to understand the morphological response of the UK's coastlines to climate change and the associated risks (see, for example, Masselink *et al*., 2020; Hilton *et al*., 2020; Montaño *et al*., 2021).

Waves and storms are also a contributing factor to extreme water level events, which are caused by a combination of local tides, storm surges and waves superimposed on changing sea levels (Palmer *et al*., 2018; Haigh *et al*., 2025). Although extreme water level events are set to increase due to secular sea-level rise, no significant sign of change in contributions related to atmospheric storminess is detected. However, more work is needed to improve understanding of the contribution of both storm surges and waves to these events (Palmer *et al*., 2018).

Muis *et al*. (2020) presents the Coastal Dataset for the Evaluation of Climate Impact (CoDEC), a global dataset of extreme sea levels which can be used to map the impact of climate change on coastal regions. Although the projected changes in return period are mostly driven by sea level rise, in certain areas the change in water level is amplified by storm surges and tidal interactions.

Storms and waves are a hazard to infrastructure and transport along UK coastlines as well as in offshore waters, and the influence of climate change will directly change the risk posed. Coastal developments as well as marine industries and infrastructure, including shipping, ports, offshore wind farms, oil and gas rigs, pipelines and communications and power cables, are all vulnerable to impacts from changing waves and storms (Izaguirre *et al*., 2021; Jaroszweski *et al*., 2021). Storm waves 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. Some parts of the UK coast (e.g. Slapton Sands and Perranporth) have already changed their state (passed a tipping point) so they may be more vulnerable to future storms and overtopping by waves (Masselink et al.; 2016).

Future improvements to the evidence base

As shown from the confidence assessment, there is work to be done to improve understanding of long-term trends and decadal variability in wave climate. In particular, work is needed on the drivers of long-term variability, focussing on how wave conditions respond to climate indices such as the NAO, and how these indicies will change in future. Improvements of wave model physics (including coupling to atmosphere and hydrodynamics) will help with our model hindcasts, and thus give confidence in any future projections which are made with the same dynamical models. Better representation of the atmosphere in the latest generation of climate models (CMIP6) will be used to make future wave climate projections of an improved quality. Bias correction methods also have scope for improvement. There is still work to done with regard to understanding and simulating extreme waves. This can be addressed through novel statistical approaches which explore plausible events. The length of the observational record will also improve this issue, as longer datasets will represent more of the natural variability, and have scope to capture a fuller range of extreme events. Relatively short datasets will be improved over time through sustained in-situ observations and the launch of new satellite missions (e.g. SWOT launched in December 2022, Morrow *et al*., 2019).

Dynamical understanding

Climate indices, in particular the NAO and WEPA, are recognised to have strong correlations with wave climates around the UK, with atmospheric conditions determining wind strength and direction over the region, and hence driving the generation and propagation of waves (Masselink *et al*., 2014; Castelle *et al*., 2017, 2018; Patra *et al*., 2020; Wiggins *et al*., 2020; Scott *et al*., 2021; Muis et al., 2022). The link between these wave climates and atmospheric indices, which are inherently more predictable than local wind fields, has the potential to be exploited for seasonal predictions of wave climates and related coastal impacts, as well as informing future trends over the 21st century (Mentaschi, 2017; Hilton *et al*., 2020; Wiggins *et al*., 2020; Montaño *et al*., 2021; Lockwood et al. (2022); Masselink et al., 2023).

High present-era wave variability is also found in recent modelling studies (Casa-Prat, 2023). However, at sites around the U.K. wave climate is related to a limited number of distinct weather regimes themselves linked to modes of atmospheric variability such as the NAO and AO (Scott et al. 2022; Freitas, 2022). This gives rise to distinct bimodality at many locations (Scott et al. 2022). Some changes in atmospheric variability, such as zonal winds, are expected towards the end of the century with commensurate but limited impact on wave climate (Freitas, 2022). Increases in extreme wave heights are projected, driven in particular by certain types of synoptic scale weather patterns (Perks et al., 2023).

Natural variability remains dominant over climate change, and future 'grey swan' events (plausible events within the range of natural variability but outside of the present observational record) will likely contribute more to the extreme tail of the storm surge and wave record than effects of climate change (e.g. Horsburgh et al. 2021).

Multi-hazards

By 2100, sea levels could rise significantly, amplifying compound hazards from flooding, driven by storm surges, waves, and heavy precipitation. Recent literature has increasingly focused on multi-hazard scenarios (e.g., Bulgin et al., 2023) and the potential impacts of the co-occurrence of changing storm patterns and rising extreme sea levels (e.g., Perks et al., 2023) on coastal flood risk. Under the RCP8.5 scenario, certain weather patterns associated with UK coastal extremes—such as storm surges, waves, strong winds, and heavy rainfall—are projected to intensify (Perks et al., 2023; Bloomfield et al., 2024; Green et al., 2024). Haigh et al. (2025) highlights current trends in compound coastal flooding, emphasizing that the risk of flooding has been underestimated to date. Their findings, and similar studies indicate that extreme water levels, resulting from the combined effects of mean sea level rise, storm surges, and wave action, are expected to increase significantly (Jevrejeva et al., 2023; Hermans et al., 2024, Casas-Prat et al., 2024). Furthermore, evidence suggests that extreme sea levels could be further exacerbated by rainfall events and river discharge (Lyddon et al., 2023), adding additional complexity to future coastal flood risk. However Li et al (2024) explain that the increase in projection of compound events are mainly driven by precipitation extremes. Extreme events of rainfall, river discharge and sea level tend to coincide and cause compound flooding events. These compound events can be quite common, as each associated with the same weather pattern of storms crossing the North Atlantic (Camus et al., 2022). Lyddon et al. (2023) also noticed a west-east variability in likely coincidence of high river levels and storm surge around the coast of UK.

Data quality and bias correction

Inconsistencies within and between datasets complicate interpretations of historical trends. Methods to reduce those inconsistencies are essential. For example Lemos *et al. (*2020a) indicate the significance of bias correction in both the ensemble estimation of mean SWH projected changes and in the ensemble spread magnitude. Lemos *et al.* (2020b) find a quantile-based bias-correction method reduced biases by between two and three orders of magnitude. The bias-corrected projected changes show decreases in the North Atlantic Ocean that are more pronounced during local winter.

The accuracy of SWH trends from the long-term multi-mission altimetry record has also been shown to be limited by the composite nature of the dataset (Young *et al*., 2022). Potential issues with data buoys that are typically used as the 'gold standard' for in-situ measurement of sea state, continue to be identified (Collins *et al*., 2022). Considerable effort is being focussed on better understanding the range of uncertainties that affect these various data sources (Dodet *et al*., 2022). Disagreement in long term trends found in re-analysis versus observations has been linked to changes in the re-analysis data assimilation methods that took place in the earlier part of the record (Meucci *et al*. 2020).

Modelling techniques Traditionally, spectral wave and hydrodynamic models have been run separately, with no hydrodynamic forcing of the wave models. However, it is becoming increasingly clear that coupling improves behaviour and accuracy, and the importance of waves is more recognised. For example, Bonaduce *et al*. (2020) found the wave-induced component of sea-level can contribute up to 20% of total water level during extreme surge events in shallow UK seas, particularly the North Sea. Interactions between wave and atmosphere can also impact surface winds and storm progression. Including this process explicitly in coupled models can reduce sea-surface wind speed (e.g. Wu *et al*., 2019).

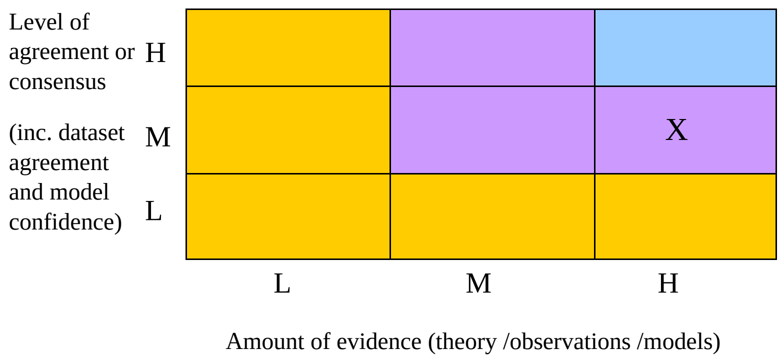
The majority of General Circulation Models (GCMs) do not include wave parameters as a standard output. However, the First Institute of Oceanography-Earth System Model version 2.0 (FIO-ESM v2.0), a GCM coupled with an ocean wave model, was developed and participated in CMIP6 (Bao *et al*., 2020; Song *et al*., 2020). Comparison against ERA5 re-analysis data showed that SWH and mean direction (Dm) were generally in good agreement, however spectrum peak wave period (Tp) and zero-crossing wave period (Tz) were less well represented in the model (Song *et al*., 2020). Regional biases were also noted over the North Atlantic, with annual mean SWH approximately 0.5 m higher than ERA5.

In recent years, the use of machine learning methods as a statistical approach to predict wave properties has been increasingly demonstrated. Studies have applied machine-learning techniques to determine wave conditions over a domain from limited observations (e.g., Sánchez *et al*., 2018; Shamshirband *et al*., 2020; Chen *et al*., 2021), or for short-term wave forecasting, out to 24–72 hours ahead, using either observational data (e.g., buoy observations) or primary variables from a physics- based model (e.g., wind and wave boundary conditions) as inputs (e.g., Ibarra-Berastegi *et al*., 2015; Oh and Suh, 2018; O'Donncha *et al*., 2019; Mooneyham *et al*., 2020; Pirhooshyaran and Snyder, 2020). Use to date of machine learning techniques to project future wave climates on longer timescales is more limited, and they are more successful for wind-dominated than swell dominated wave fields. The open seas around the UK, particularly along the western coasts, are influenced by remotely generated swell, necessitating consideration of the atmospheric setup over a much larger domain and posing a greater challenge for this type of approach.

Since, the greatest impacts can be a result of a few rare events, it is important to consider what “might occur” not just the statistics of the historical record and individual projections. The UNprecedented Simulated Extreme ENsemble (UNSEEN) method enables that analysis by increasing the sample size, and applied to wind storms (Maddison et al., 2024) combined with the use of a storm severity index “SSI” (Cornér et al., 2024) to capture the impact provides greater insight into potential impacts. High-impact, low-likelihood or “HILL” events proposed by Wood et al. (2023) capture worst-case, but plausible storylines caused by the crossing of a climate system tipping-point. For example an AMOC collapse is considered a HILL event which could result in an abrupt northward shift and strengthening of the Northern Hemisphere Hadley cell and intensification of the northern midlatitude eddy-driven jet (Orbe et al., 2023)

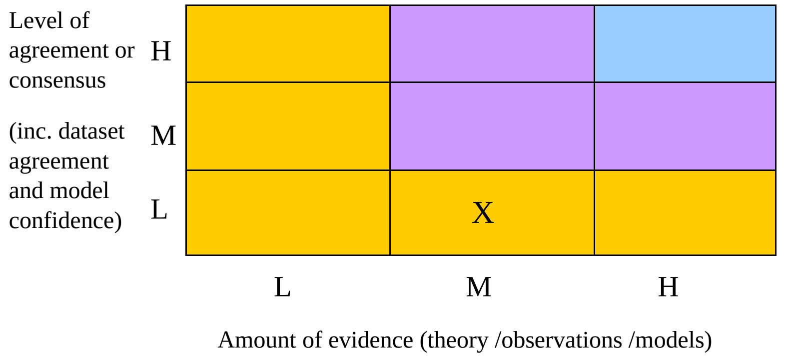
CONFIDENCE ASSESSMENT

What is already happening?



Long term observations of the atmosphere (e.g. sea level pressure and winds) reveal a great deal of variability at time scales from multi-decadal to intra-annual for a century or more, with an increase in jet strength and multi-decadal variability in recent decades. However, attribution of changes is more difficult, with models unable to reproduce those trends. Changes in wind speed statistics are associated with variability in storm track, jet strength and the intensity of cyclones, but no persistent trend is apparent. While our evidence base has continued to grow, with longer observational datasets and more model re-analysis available, there is not a consensus in the trend in SWH, which is highly sensitive to seasonality and short-term variability. No dataset or re-analysis is perfect and it remains unclear which of those currently available for wave climate is the most reliable.

What could happen in the future?



The future changes depend on model projections, which have improved on moving from CMIP5 to CMIP6 but still have shortcomings when representing the most intense storms. There are still quite substantial differences between different climate models, but new higher-resolution models promise better representation of storms. Meta-analysis through e.g. COWCLIP has led to better understanding and quantification of intra-model uncertainty, and helped identify areas of (no) consensus.

KEY CHALLENGES AND EMERGING ISSUES

- There is inconsistency between models, in-situ observations, and remotely sensed wave data.
- We need to improve the simulation of storms in climate models.
- We need to improve understanding of how North Atlantic storms and blocks respond to external forcing.
- We need to use new techniques: meta-analysis and statistical methods to reduce historical and future uncertainty.

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