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

Bricheno, L.M.[1], Amies, J.D.[2], Chowdhury, P.[3], Woolf, D.[4] and Timmermans, B.[5]

1. National Oceanography Centre. Joseph Proudman Building, 6 Brownlow St, Liverpool, L3 5DA, UK
2. Met Office. Fitzroy Rd, Exeter, EX1 3PB, UK
3. Centre for Environment, Fisheries and Aquaculture, Science. Lowestoft, NR33 0HT, UK
4. Heriot-Watt University. Orkney Campus, Stromness, Scotland, KW16 3AN, UK
5. National Oceanography Centre. European Way, Southampton, SO14 3ZH, UK

Citation: Bricheno, L.M., Amies, J.D., Chowdhury, P., Woolf, D. and Timmermans, B. Climate change impacts on storms and waves relevant to the UK and Ireland. MCCIP Science Review 2023, 20pp.

doi: 10.14465/2023.reu09.str

Submitted: 10 2022

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 the north of the UK, 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 mechanisms.

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.
- Projections suggest the wintertime storm track could intensify 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.

SUPPORTING EVIDENCE

Introduction

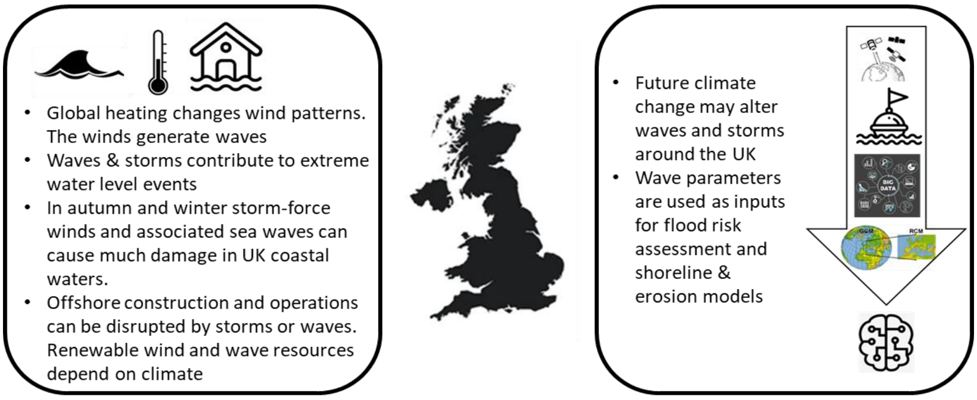
Storm-force winds and wind-driven sea waves can cause much damage in UK coastal waters, particularly in autumn and winter. Understanding the characteristics and variability of wave climate, and historical and projected future change, is an important consideration for sustainable development of coastal and offshore infrastructure, and management of coastal resources and ecosystems. Waves contribute directly to coastal flooding, and wave conditions are critical to shipping and offshore industry. 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 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. Bonaduce *et al*., 2022).

Wind-driven waves are created by the momentum input at the sea surface under local winds. These wind-sea waves then propagate as swells, with their effects being felt at great distances from generation. 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. Due to seasonal variation, waves around the UK are highest during the period October to March 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 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' within the cyclone (Clark and Gray, 2018).

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 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).

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 still water levels, and coastal flooding for the UK are detailed in companion report cards (Horsburgh, 2020; Haigh *et al*., 2022).



- Global heating changes wind patterns. The winds generate waves
- Waves & storms contribute to extreme water level events
- In autumn and winter storm-force winds and associated sea waves can cause much damage in UK coastal waters.
- Offshore construction and operations can be disrupted by storms or waves. Renewable wind and wave resources depend on climate

- Future climate change may alter waves and storms around the UK
- Wave parameters are used as inputs for flood risk assessment and shoreline & erosion models

Figure 1: *Storms and waves and their impacts*

What is already happening?

Atmospheric circulation and storminess

Long-term changes in storminess and waves should be related 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) and West Europe Pressure Anomaly (WEPA). On a global scale and informed by a dynamical understanding, the 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 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. 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.

On 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. Some other coasts are exposed to waves from the north or north-east and sea ice loss in the Arctic and the frequency of strong winds from this quarter are important.

There are also at least two lines of evidence that suggest that the 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

To investigate historical trends, we can use model 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 ERA5 (Hersbach *et al*., 2020). Several global datasets of historical wind waves have recently become available, e.g. Liu *et al*. (2021), Alday (2021), Ribal and Young (2019), and ECMWF (2019). These can be more accurate than 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 CCI. 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 2). Erikson *et al*. (2022) analyse a community ensemble of global wave models, to perform a meta-analysis of trends in global ocean wave hindcasts across a 35-year period between 1980 and 2014. They find spatially coherent patterns of change including downward trend in both winter and summer SWH across the North Atlantic (NA). The annual number of rough days (when daily maximum Hs 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.

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 within the variability, over various time periods. 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. 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).

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 sea. Wave heights may have been enhanced by an increase in persistence of westerly winds (Wolf and Woolf, 2006). Looking at a different period, Figure 2 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* 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. Castelle *et al*. was not an assimilating reanalysis (and is not shown in the figure, or part of (Timmermans *et al*. 2020. 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 choice of time period therefore has a strong influence over what trends are identified. 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.

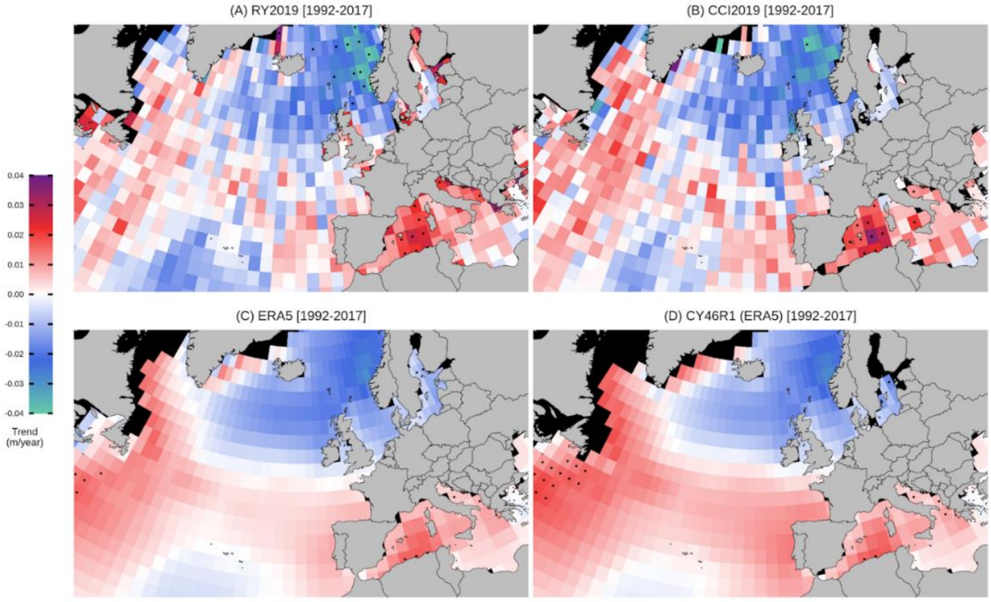


Figure 2: *Distribution of January-March SWH trend estimates on a 2°×2° grid over 1992–2017 for a selection of satellite and model reanalysis datasets. (a) RY2019, (b) CCI2019, (c) ERA5, and (d) CY46R1. Dots indicate grid cells where the trend coefficient is significant at the 1% level (replotted from 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.

Large ensemble runs can help quantify some sources of uncertainty (model structural uncertainty and internal climate variability). For example, Casas-Prat *et al*. (2022) demonstrate the North Atlantic's large internal climate variability, where different ensemble-members can show trends of the opposite signs for the same area. However overall, they conclude a negative trend for annual mean and maximum SWH.

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). 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 work by Wiggins *et al*. (2019,2020) considers 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.

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 emergent 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. Storm surges and their coastal impacts are covered in more detail in Haigh *et al*. (2022).

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 devised for the North Atlantic storm track, which remains an area of considerable uncertainty. 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, Harvey *et al*. (2020) show that successive Coupled Model Intercomparison Project (CMIP) studies have been mostly consistent in their projections of changes in the North Atlantic storm track, and changes include an increase in wintertime zonal winds at the latitude of UK. A recent study (Manning *et al*., 2022) projects an increase in the frequency of wind storms over Europe to 2100, with a specific and substantial contribution from sting jets. While in 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.

Our latest climate projections come from the CMIP6 (Eyring *et al*., 2016). Even some of the most advanced climate models, in the CMIP6 suite, struggle to represent the observed wintertime atmospheric circulation over the North Atlantic and Western Europe (Dorrington *et al*., 2021). The reduced ability of models to correctly simulate extreme events is often attributed to poor representation of regimes associated with persistent atmospheric blocking events, or variations in jet latitude. However, Dorrington *et al*. (2021) observed that CMIP6 has a considerably improved spatial regime structure, and a more trimodal eddy-driven jet when compared to CMIP5. CMIP6 still struggles with under persistent regimes, and too little European blocking, when compared to five re-analysis products.

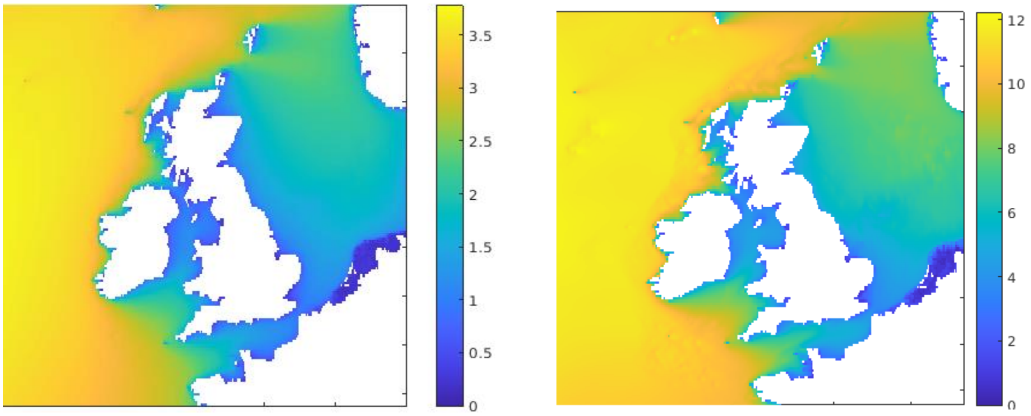
Oudar *et al*. (2020) evaluated the wintertime midlatitude atmospheric circulation in CMIP6 models and identified a tripole structure in the North Atlantic, where the zonal wind strengthens over Western Europe and decreases north and south. The zonal wind is observed to shift poleward in the Pacific 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 storm tracks need evaluation in detail for the CMIP6 models. Priestley *et al.* (2020) presents a representation of the winter and summer extratropical storm tracks in both hemispheres. Comparing the state of the storm tracks from 1979 to 2014 with ERA5 it was found that the main biases present in the previous generation of models (e.g. CMIP5) persist but to a lesser extent. CMIP6 exhibit some lessening of biases in the higher-resolution models, notably in the zonal tilt of the North Atlantic storm track. The low-resolution models tend to underestimate the frequency of high-intensity cyclones with all models simulating a peak intensity that is too low for cyclones in the southern hemisphere. In the northern hemisphere, most improvements can be attributed to increased horizontal resolution. Song *et al*. (2021) compared 14 CMIP6 models with ERA5. The comparison reveals that both the individual models and their ensemble mean can simulate the spatial distribution of the density of cyclone tracks with reasonable capability. The Atlantic zonal negative bias of track density is stronger in winter than in summer, while location-field-related and density-field-related variables (i.e. cyclolysis, cyclogenesis, track, and lowest centre pressure densities) of Arctic cyclones are generally better represented in winter than in summer.

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 some parts of the North Sea. 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.

The latest high-resolution wave projections for the UK coast were made under UKCP18 (Palmer *et al*. 2018). For the 21st Century, 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. High resolution wave simulations suggest that the changes in the climatology of waves over the 21st Century is sensitive to the position of the storm track, and differs depending on the exposure of the coastline. For exposed coasts, the changes in waves are dominated by the global response to climate change through the 21st Century. For sheltered coastal regions, the changes in waves are dominated by the local weather variability over the 21st Century.



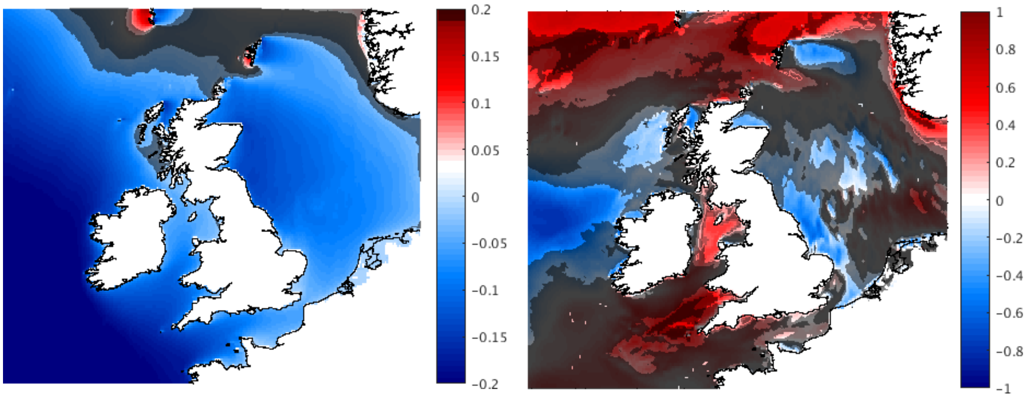


Figure 3: *Historical conditions (top) and projected changes (below) in future mean (left) and AnnMax (right) SWH (m). Areas masked in black have a confidence below 50% and those masked in grey a confidence below 75 % (left) Middle century. (right) End century, Representative Concentration Pathway RCP8.5. (After Bricheno and Wolf, 2018, and Palmer* et al.*, 2018.)*

Bricheno and Wolf (2018) use dynamical downscaling to make higher resolution future wave climate projections for UK forced by the EC-Earth climate model. Increases in the annual maximum and 99th percentile wave height as large as 0.5–1 m are observed in some areas, but with a more complex spatial pattern. An increase in waves to the north of Scotland is also observed, mainly caused by a reduction in sea ice. Widening of the probability density function is observed, suggesting an increased intensity of rare high-wave events in the future.

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. It is also important to note that only a subset of the CMIP5 models were used in this part of the assessment limiting the confidence of the findings.

Wave properties other than SWH are also projected to change in the future. Mean wave period is projected to decrease around the UK of 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 – to come from an increasingly clockwise around the UK. Changes are of the order 3-5 degrees by the end of the century, however these projections are not statistically significant.

Coastal impacts

Waves are a primary driver of coastal evolution and as such changing wave and storm climates will affect shoreline erosion around the UK. Wave bulk 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*., 2022). 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).

Wave contributions to total water level are made up of wave setup (time mean dynamic elevation of sea level due to wave breaking) and swash (waterline oscillations at the time scale of individual waves and wave groups) (Dodet *et al*., 2019). Wave setup can be a substantial contributor to regional departure from global mean sea level. In projections for 2081–2100 for UK coastlines, the trend in the contribution of wave setup contribution to coastal mean sea level change is negative (Melet *et al*., 2020).

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). For renewable energy from offshore wind and waves, the resource is directly related to storms and waves. Scott *et al.* (2021) examine inshore wave climate at 63 locations throughout the United Kingdom and Ireland for the period of 1980–2017. They show that 73% of the inshore waves are directionally bimodal. They find that winter-averaged expressions of six leading atmospheric indices are strongly correlated with both total and directional winter wave power (peak spectral wave direction) at all studied sites.

Malagon 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. Brown *et al*. (2016) discuss the evolution of coastal systems in the aftermath of the winter of 2013/2014, when there were several severe storms tracking across the UK. 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. Some parts of the coast have changed their state (passed a tipping point) so they may be more vulnerable to future storms and overtopping by waves.

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. 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 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 setups 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). 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).

The importance of natural variability in storminess over the next few decades above that of either climate-change-induced changes or mean sea-level rise is demonstrated by Horsburgh *et al*. (2021). The study uses artificially synthesised storms to create ‘grey swan’ events, which represent plausible events within the range of natural variability but outside of the observational record, showing that potential storm events capable of generating more extreme waves and storm surges than have been observed are likely to occur without any climate-driven changes.

Data quality and bias correction
Inconsistencies within and between datasets complicate interpretations of historical trends. Methods to reduce those inconsistencies are essential, and improvements have been made in the field of bias correction. Lemos *et al.* (2020a) studied systematic biases in wave climate simulations, exploring different bias correction methods commonly used for climate impact variables (e.g. precipitation, temperature), and the analysis of bias-corrected wave climate projections. Under the RCp8.5 scenario, a bias-corrected 8-member ensemble was analysed for a future timescale of 2081–2100. The results indicate the significance of bias correction in both the ensemble estimation of mean SWH projected changes and in the ensemble spread magnitude. The outcomes indicate the need for a quantile-based bias correction, able to deal with extreme events, which have a disproportionate impact in coastal processes. In another study by Lemos *et al.* (2020b) the relevance of a quantile-based bias-correction method in the estimation of the future projected changes in global wave climate was explored. They used the empirical Gumbel quantile mapping (EGQM) and empirical quantile mapping (EQM) methods for bias correction. The original SWH biases (annual mean, and extreme mean: mean above the 99th quantile) showed a consistent overestimation over the period of 1979–2005 relative to ERA5, especially in the extratropical latitudes of both hemispheres for extreme SWH values. A generalised overestimation was also shown for the mean wave period (Tm), for the mean wave direction (MWD), the highest biases in both hemispheres were shown to be present along the tropical and subtropical latitudes. The correction (EGQM method for SWH and Tm, and EQM method for MWD), reduced biases by between two and three orders of magnitude, to values generally below 0.01m, 0.01 s, and 0.2° for SWH, Tm and MWD, respectively. 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).

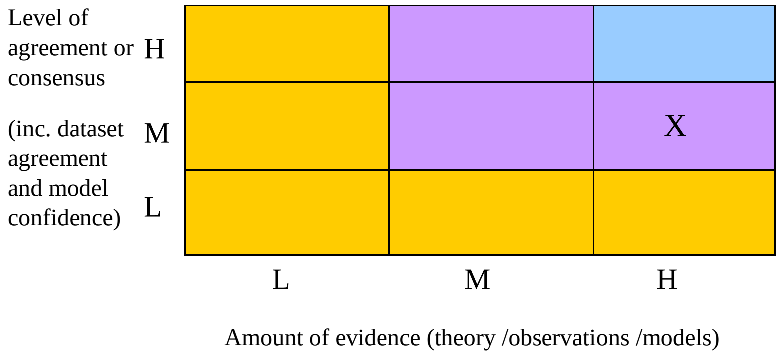
Modelling techniques Traditionally, spectral wave and hydrodynamic models have been run separately, with no hydrodynamic forcing of the wave models. However, it is becoming increasingly clear that coupling improves behaviour and accuracy, and the importance of waves is more recognised. For example, Bonaduce *et al*. (2020) found the wave-induced component of sea-level can contribute up to 20% of total water level during extreme events. 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 waves. 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.

CONFIDENCE ASSESSMENT

What is already happening?



Level of agreement or consensus

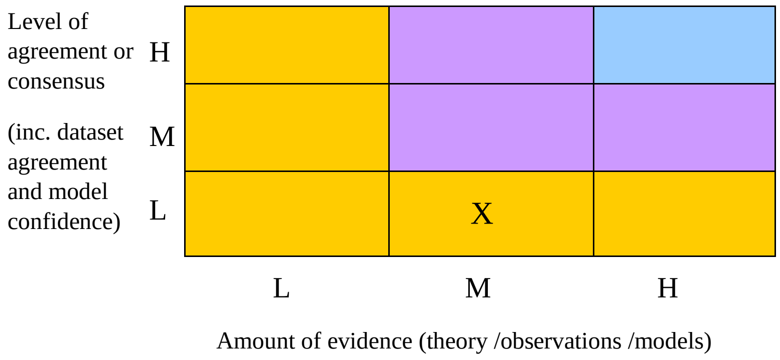
(inc. dataset agreement and model confidence)

	L	M	H
H			
M			X
L			

Amount of evidence (theory /observations /models)

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 is unclear which of those currently available for wave climate is the most reliable.

What could happen in the future?



Level of agreement or consensus

(inc. dataset agreement and model confidence)

	L	M	H
H			
M			
L		X	

Amount of evidence (theory /observations /models)

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.

REFERENCES

Alday, M., Accensi, M., Ardhuin, F. and Dodet, G. (2021) A global wave parameter database for geophysical applications. Part 3: Improved forcing and spectral resolution. *Ocean Modelling*, **166**, 101848.

Amores, A. and Marcos, M. (2020) Ocean Swells along the Global Coastlines and Their Climate Projections for the Twenty-First Century. *Journal of Climate*, **33**(1), 185–199. doi: 10.1175/JCLI-D-19-0216.1

Aksenov, Y., Popova, E.E., Yool, A., Nurser, A.J.G., Williams, T.D., Bertino, L. and Bergh, J. (2017) On the future navigability of Arctic sea routes: high-resolution projections of the Arctic Ocean and sea ice. *Marine Policy*, **75**, 300–317. doi: 10.1016/j.marpol.2015.12.027

Aksenov, Y., Rynders, S., Feltham, D.L., Hosekova, L., Marsh, R., Skliris, N., Bertino, L., Williams, T.D., Popova, E., Yool, A. and Nurser, A.J. (2022) Safer operations in changing ice-covered seas: Approaches and perspectives. In *IUTAM Symposium on Physics and Mechanics of Sea Ice*, Springer, Cham., pp. 241-260.

Baker, A.J., Hodges, K.I., Schiemann, R.K. and Vidale, P.L. (2021) Historical variability and lifecycles of North Atlantic midlatitude cyclones originating in the tropics. *Journal of Geophysical Research: Atmospheres*, **126**(9), p.e2020JD033924.

Bao, Y., Song, Z. and Qiao, F. (2020) FIO-ESM Version 2.0: Model Description and Evaluation. *Journal of Geophysical Research: Oceans*, **125**(6), e2019JC016036. doi: 10.1029/2019JC016036

Bonaduce, A., Staneva, J., Grayek, S., Bidlot, J.R. and Breivik, Ø. (2020) Sea-state contributions to sea-level variability in the European Seas. *Ocean Dynamics*, **70**(12), 1547-1569.

Bricheno, L.M. and Wolf, J. (2018) Future wave conditions of Europe, in response to high-end climate change scenarios. *Journal of Geophysical Research: Oceans*, **123**(12), 8762-8791.

Brown, Jennifer M.; Prime, Thomas; Phelps, Jack J.C.; Barkwith, Andrew; Hurst, Martin D.; Ellis, Michael A.; Masselink, Gerd; Plater, Andrew J. 2016 Spatio-temporal variability in the tipping points of a coastal defense. Journal of Coastal Research, SI:75. 1042-1046. https://doi.org/10.2112/SI75-209.1

Casas-Prat, M. Wang, X.L., Mori, N. Feng, Y., Chan, R. and Shimura, T. (2022) Effects of Internal Climate Variability on Historical Ocean Wave Height Trend Assessment. *Frontiers in Marine Science*, **9**. www.frontiersin.org/articles/10.3389/fmars.2022.847017/full

Calafat, F.M., Wahl, T., Tadesse, M.G. and Sparrow, S.N. (2022) Trends in Europe storm surge extremes match the rate of sea-level rise. *Nature*, **603**, 841-845.

Castelle, B., Dodet, G., Masselink, G. and Scott, T. (2017) A new climate index controlling winter wave activity along the Atlantic coast of Europe: The West Europe Pressure Anomaly. *Geophysical Research Letters*, **44**(3), 1384–1392. doi: 10.1002/2016GL072379

Castelle, B., Dodet, G., Masselink, G. and Scott, T. (2018) Increased winter-mean wave height, variability, and periodicity in the northeast Atlantic over 1949–2017. *Geophysical Research Letters*, **45**(8), 3586–3596. doi: 10.1002/2017GL076884

Ceres, R.L., Forest, C.E. and Keller, K. (2017) Understanding the detectability of potential changes to the 100-year peak storm surge. *Climatic Change*, **145**(1), 221-235.

Chen, J., Pillai, A. C., Johanning, L. and Ashton, I. (2021) Using machine learning to derive spatial wave data: A case study for a marine energy site. *Environmental Modelling & Software*, **142**, 105066. doi: 10.1016/j.envsoft.2021.105066

Clark, P.A. and Gray, S.L. (2018) Sting jets in extratropical cyclones: A review. *Quarterly Journal of the Royal Meteorological Society*, **144**(713), 943-969.

Collins, M., Sutherland, M., Bouwer, L., Cheong, S.-M., Frölicher, T., Jacot Des Combes, H. et al. (2019), Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (eds. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska et al.). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 589-655. https://doi.org/10.1017/9781009157964.008

D'Agostini, A. Bernardino, M. and Soares, C.G. (2022) Projected wave storm conditions under the RCP8.5 climate change scenario in the North Atlantic Ocean. *Ocean Engineering*, **266**(3) https://doi.org/10.1016/j.oceaneng.2022.112874.

Dodet, G., Piolle, J.F., Quilfen, Y., Abdalla, S., Accensi, M., Ardhuin, F., Ash, E., Bidlot, J.R., Gommenginger, C., Marechal, G. and Passaro, M. (2020) The Sea State CCI dataset v1: towards a sea state climate data record based on satellite observations. *Earth System Science Data*, **12**(3), 1929-1951.

Dodet, G., Abdalla, S., Alday, M., Accensi, M., Bidlot, J. and Ardhuin, F. (2022) Error characterization of significant wave heights in multi-decadal satellite altimeter product, model hindcast and in situ measurements, using triple collocation technique. *Journal of Atmospheric and Oceanic Technology*, 887-901.

Dorrington, J., Strommen, K. and Fabiano, F., (2021). How well does CMIP6 capture the dynamics of Euro-Atlantic weather regimes, and why. Weather and Climate Dynamics Discussions, 2021, pp.1-41

Earl, N., Dorling, S., Hewston, R. and Glasow, R. (2013) 1980–2010 Variability in U.K. Surface Wind Climate. *Journal of Climate*, **26**, 1172−1191.

ECMWF (2019). PART VII: ECMWF wave model. In *Official IFS Documentation CY46R1*. ECMWF, Reading, UK. https://www.ecmwf.int/node/19311

Erikson, L., Morim, J., Hemer, M., Young, I., Wang, X., Mentaschi, L. *et al*. (2022) Global ocean wave fields show consistent regional trends between 1980 and 2014 in a multi-product ensemble. *Communications Earth & Environment*, **3**(320).

ESA (2019). European Space Agency Climate Change Initiative for Sea State: Project website and data access. Retrieved 2019-07-10, from http://cci.esa.int/seastate

Eyring, V., Bony, S. Meehl, G. A,. Senior, C. A. Stevens B, Stouffer, R. J. and Taylor K. E. (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscentific Model Development*, **9**, 1937–1958. doi: 10.5194/gmd-9-1937-2016

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L. *et al*. (2021), Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds* V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger *et al.*), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. doi: 10.1017/9781009157896.011

Gulev, S.K. and Grigorieva, V. (2004) Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research Letters*, **31**, L24302. doi: 10.1029/2004GL021040

Gulev, S.K., Grigorieva, V., Sterl, A. and Woolf, D. (2003) Assessment of the reliability of wave observations from voluntary observing ships: Insights from the validation of a global wind wave climatology based on voluntary observing ship data. *Journal of Geophysical Research*, **108**(C7), 3236. doi:10.1029/2002JC001437

Haigh, I.D., Nicholls, R.J., Penning- Roswell, E. and Sayers, P. (2020) Impacts of climate change on coastal flooding, relevant to the coastal and marine environment around the UK. *MCCIP Science Review* 2020, 546–565. http://archive.mccip.org.uk/media/2032/23_coastal_flooding_2020.pdf

Haigh, I.D., Dornbusch, U., Brown, J., Lyddon, C., Nicholls, R.J., Penning-Rowsell, E. and Sayers, P. (2022) Impacts of climate change on coastal flooding, relevant to the coastal and marine environment around the UK. *MCCIP Science Review* 2022, 18 pp.

Harvey, B.J., Shaffrey, L.C. and Woollings, T., (2015). Deconstructing the climate change response of the Northern Hemisphere wintertime storm tracks. Climate dynamics, 45, pp.2847-2860.

Harvey, B.J., Cook, P., Shaffrey, L.C. and Schiemann, R. (2020) The response of the northern hemisphere storm tracks and jet streams to climate change in the CMIP3, CMIP5, and CMIP6 climate models. *Journal of Geophysical Research: Atmospheres*, **125**(23), p.e2020JD032701.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz‐Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146**(730), 1999-2049.

Hilton, D., Davidson, M. and Scott, T. (2020) Seasonal predictions of shoreline change, informed by climate indices. *Journal of Marine Science and Engineering*, **8**(8). https://doi.org/10.3390/JMSE8080616

Hochet, A., Dodet, G., Ardhuin, F., Hemer, M. and Young, I. (2021) Sea State Decadal Variability in the North Atlantic: A Review. *Climate*, **9**(12), 173.

Horsburgh, K., Rennie, A. and Palmer, M. (2020). Impacts of climate change on sea-level rise relevant to the coastal and marine environment around the UK. *MCCIP Science Review* 2020, pp.116-131.

Horsburgh, K., Haigh, I.D., Williams, J. *et al*. (2021) "Grey swan" storm surges pose a greater coastal flood hazard than climate change. *Ocean Dynamics*, **71**, 715–730. doi: 10.1007/s10236-021-01453-0

Ibarra-Berastegi, G., Saénz, J., Esnaola, G., Ezcurra, A. and Ulazia, A. (2015) Short-term forecasting of the wave energy flux: Analogues, random forests, and physics-based models. *Ocean Engineering*, **104**, 530–539. doi: 10.1016/j.oceaneng.2015.05.038

Izaguirre, C., Losada, I. J., Camus, P., Vigh, J. L. and Stenek, V. (2021) Climate change risk to global port operations. *Nature Climate Change*, **11**(1), 14–20. doi: 10.1038/s41558-020-00937-z

Jaroszweski, D., Wood, R., and Chapman, L. (2021) Infrastructure. In *The Third UK Climate Change Risk Assessment Technical Report*. (eds Betts, R.A., Haward, A.B. and Pearson, K.V.) Prepared for the Climate Change Committee, London.

Lemos, G., Menendez, M., Semedo, A., Camus, P., Hemer, M., Dobrynin, M. and Miranda, P.M. (2020a) On the need of bias correction methods for wave climate projections. *Global and Planetary Change*, **186**, p.103109.

Lemos, G., Semedo, A., Dobrynin, M., Menendez, M. and Miranda, P.M. (2020b) Bias-corrected CMIP5-derived single-forcing future wind-wave climate projections toward the end of the twenty-first century. *Journal of Applied Meteorology and Climatology*, **59**(9), 1393-1414.

Li, X.M. and Huang, B. (2020) A global sea state dataset from spaceborne synthetic aperture radar wave mode data. *Scientific ata*, **7**(1), 1-12. www.nature.com/articles/s41597-020-00601-3

Liu, Qi, Babanin, A.V., Rogers, W.E., Zieger, S., Young, I.R., Bidlot, J-R., Durrant, T. *et al.* (2021) Global wave hindcasts using the observation-based source terms: description and validation. *Journal of Advances in Modeling Earth Systems*, **13**(8).

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G. and Fung, F. (2018) UKCP18 science overview report. Met Office Hadley Centre: Exeter, UK.

Manning, C., Kendon, E.J., Fowler, H.J., Roberts, N.M., Berthou, S., Suri, D. and Roberts, M.J. (2022) Extreme windstorms and sting jets in convection-permitting climate simulations over Europe. *Climate Dynamics*, **58**(9), 2387-2404.

Marcos, M., Calafat, F.M., Berihuete, Á. and Dangendorf, S. (2015) Long-term variations in global sea level extremes. *Journal of Geophysical Research: Oceans*, **120**, 8115–8134. doi: 10.1002/2015JC011173

Malagon Santos, V., Haigh, I.D. and Wahl, T., 2017. Spatial and temporal clustering analysis of extreme wave events around the UK coastline. Journal of Marine Science and Engineering, 5(3), p.28.

Masselink, G., Austin, M., Scott, T., Poate, T. and Russell, P. (2014). Role of wave forcing, storms and NAO in outer bar dynamics on a high-energy, macro-tidal beach. *Geomorphology*, **226**, 76–93. doi: 10.1016/J.GEOMORPH.2014.07.025

Melet, A., Almar, R., Hemer, M., Le Cozannet, G., Meyssignac, B. and Ruggiero, P. (2020). Contribution of Wave Setup to Projected Coastal Sea Level Changes. *Journal of Geophysical Research: Oceans*, **125**(8), e2020JC016078. doi: 10.1029/2020JC016078

Mentaschi, L., Vousdoukas, M. I., Voukouvalas, E., Dosio, A. and Feyen, L. (2017) Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophysical Research Letters*, **44**(5), 2416–2426. doi: 10.1002/2016GL072488

Mercè Casas-Prat, Xiaolan L. Wang, Nobuhito Mori, Yang Feng, Rodney Chan and Tomoya Shimura (2022) Effects of Internal Climate Variability on Historical Ocean Wave Height Trend Assessment *Frontiers in Marine Science* volume 9

Meucci, A., Young, I.R., Aarnes, O.J. and Breivik, O. (2020a) Comparison of wind speed and wave height trends from twentieth century models and satellite altimeters. *Journal of Climate*, **33**(2), 611–624. doi: 10.1175/JCLI-D-19-0540.1

Montaño, J., Coco, G., Cagigal, L., Mendez, F., Rueda, A., Bryan, K. R. and Harley, M. D. (2021) A multiscale approach to shoreline prediction. *Geophysical Research Letters*, **48**(1), e2020GL090587. doi: 10.1029/2020GL090587

Mooneyham, J., Crosby, S.C., Kumar, N. and Hutchinson, B. (2020) SWRL Net: A Spectral, Residual Deep Learning Model for Improving Short-Term Wave Forecasts. *Weather and Forecasting*, **35**(6), 2445–2460. doi: 10.1175/WAF-D-19-0254.1

Morim, J., M.A. Hemer, X.L. Wang, N. Cartwright, C. Trenham, A. Semedo, *et al*. (2019) Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, **9**, 711-718.

Morim, J., Trenham, C., Hemer, M., Wang, X.L., Mori, N., Casas-Prat, M., Semedo, A., Shimura, T., Timmermans, B., Camus, P. and Bricheno, L. (2020) A global ensemble of ocean wave climate projections from CMIP5-driven models. *Scientific Data*, **7**(1), 1-10.

Morim, J., Vitousek, S., Hemer, M., Reguero, B., Erikson, L., Casas-Prat, M., Wang, X.L., Semedo, A., Mori, N., Shimura, T. and Mentaschi, L. (2021) Global-scale changes to extreme ocean wave events due to anthropogenic warming. *Environmental Research Letters*, **16**(7), p.074056.

Morrow, R., Fu, L-L., Ardhuin, F., Benkiran, M., Chapron, B., Cosme, E., d'Ovidio, F. *et al*. (2019) Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) mission. *Frontiers in Marine Science*, **6**, 232.

Muis, S., Apecechea, M.I., Dullaart, J., de Lima Rego, J., Madsen, K.S., Su, J., Yan, K. and Verlaan, M. (2020) A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. *Frontiers in Marine Science*, **7**, 263. doi: 10.3389/FMARS.2020.00263/BIBTEX

National Academies of Sciences, Engineering and Medicine (2016) *Attribution of Extreme Weather Events in the Context of Climate Change*. Washington, DC: The National Academies Press. doi: 10.17226/21852

O'Donncha, F., Zhang, Y., Chen, B. and James, S. C. (2019) Ensemble model aggregation using a computationally lightweight machine-learning model to forecast ocean waves. *Journal of Marine Systems*, **199**, 103206. doi: 10.1016/j.jmarsys.2019.103206

Oh, J. and Suh, K. D. (2018). Real-time forecasting of wave heights using EOF – wavelet – neural network hybrid model. *Ocean Engineering*, **150**(February), 48–59. doi: 10.1016/j.oceaneng.2017.12.044

Oudar, T., Cattiaux, J. and Douville, H., (2020). Drivers of the northern extratropical eddy-driven jet change in CMIP5 and CMIP6 models. Geophysical Research Letters, 47(8), p.e2019GL086695.

Palmer, M., Howard, T., Tinker, J., Lowe, J., Bricheno, L., Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J. and Pickering, M. (2018) UKCP18 marine report, The Met Office, UK. www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

Patra, A., Min, S. K. and Seong, M. G. (2020) climate variability impacts on global extreme wave heights: seasonal assessment using satellite data and ERA5 reanalysis. *Journal of Geophysical Research: Oceans*, **125**(12), e2020JC016754. doi: 10.1029/2020JC016754

Pirhooshyaran, M. and Snyder, L.V. (2020) Forecasting, hindcasting and feature selection of ocean waves via recurrent and sequence-to-sequence networks. *Ocean Engineering*, **207**, 107424. doi: 10.1016/j.oceaneng.2020.107424

Pleskachevsky, A., Tings, B., Wiehle, S., Imber, J. and Jacobsen, S., (2022). Multiparametric sea state fields from synthetic aperture radar for maritime situational awareness. Remote Sensing of Environment, 280, p.113200.

Priestley, M.D., Ackerley, D., Catto, J.L., Hodges, K.I., McDonald, R.E. and Lee, R.W. (2020) An overview of the extratropical storm tracks in CMIP6 historical simulations. *Journal of Climate*, **33**(15), 6315-6343.

Ribal, A. and Young, I.R. (2019) 33 years of globally calibrated wave height and wind speed data based on altimeter observations. *Scientific Data* **6** (1), 1-15.

Sainsbury, E.M., Schiemann, R.K., Hodges, K.I., Shaffrey, L.C., Baker, A.J. and Bhatia, K.T. (2020) How important are post-tropical cyclones for European windstorm risk? *Geophysical Research Letters*, **47**(18), p.e2020GL089853.

Sánchez, A.S., Rodrigues, D.A., Fontes, R.M., Martins, M.F., Kalid, R. de A. and Torres, E.A. (2018). Wave resource characterization through in-situ measurement followed by artificial neural networks' modeling. *Renewable Energy*, **115**, 1055–1066. doi: 10.1016/j.renene.2017.09.032

Scott, T., McCarroll, R.J., Masselink, G., Castelle, B., Dodet, G., Saulter, A., Scaife, A.A. and Dunstone, N. (2021) Role of atmospheric indices in describing inshore directional wave climate in the United Kingdom and Ireland. *Earth's Future*, **9**(5), e2020EF001625. doi: 10.1029/2020EF001625

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., *et al.* (2021). Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.

Shamshirband, S., Mosavi, A., Rabczuk, T., Nabipour, N. and Chau, K-W. (2020) Prediction of significant wave height; comparison between nested grid numerical model, and machine learning models of artificial neural networks, extreme learning and support vector machines. *Engineering Applications of Computational Fluid Mechanics*, **14**(1), 805–817. doi: 10.1080/19942060.2020.1773932

Song, Z., Bao, Y., Zhang, D., Shu, Q., Song, Y. and Qiao, F. (2020) Centuries of monthly and 3-hourly global ocean wave data for past, present, and future climate research. *Scientific Data*, **7**(1), 1–11. doi: 10.1038/s41597-020-0566-8

Song, J.N., Fu, G., Xu, Y., Han, Z.Y., Sun, Q.Z. and Wang, H., (2021). Assessment of the capability of CMIP6 global climate models to simulate Arctic cyclones. Advances in Climate Change Research, 12(5), pp.660-676.

Timmermans, B.W., Gommenginger, C.P., Dodet, G. and Bidlot, J.R. (2020) Global wave height trends and variability from new multimission satellite altimeter products, reanalyses, and wave buoys. *Geophysical Research Letters*, **47**(9), p.e2019GL086880.

Turki, I., Baulon, L., Massei, N., Laignel, B., Costa, S., Fournier, M. and Maquaire, O. (2020) A nonstationary analysis for investigating the multiscale variability of extreme surges: case of the English Channel coasts. *Natural Hazards and Earth System Sciences*, **20**(12), 3225-3243.

Wiggins, M., Scott, T., Masselink, G., Russell, P. and Valiente, N.G. (2019) Regionally-coherent embayment rotation: behavioural response to bi-directional waves and atmospheric forcing. *Journal of Marine Science and Engineering*, **7**(4) , 116.

Wiggins, M., Scott, T., Masselink, G., McCarroll, R. J. and Russell, P. (2020) Predicting beach rotation using multiple atmospheric indices. *Marine Geology*, **426**, 106207. https://doi.org/10.1016/j.margeo.2020.106207

Williams, M.O. (2005) Wave Mapping in UK Waters. HSE RR392, 30 pp. www.hse.gov.uk/research/rrhtm/rr392.htm

Williams, M.O. (2008) Wave Mapping in UK Waters. Supporting document. HSE RR621, 38 pp. www.hse.gov.uk/research/rrhtm/rr621.htm

Wohland, J., Folini, D. and Pickering, B. (2021) Wind speed stilling and its recovery due to internal climate variability. *Earth System Dynamics*, **12**(4), pp.1239-1251.

Wolf, J. and Woolf, D.K. (2006) Waves and climate change in the north-east Atlantic. *Geophysical Research Letters*, **33**(6).

Wolf, J., Woolf, D. and Bricheno, L. (2020) Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. *MCCIP Science Review* 2020, 132–157. doi: 10.14465/2020.arc07.saw

Woollings, T., Franzke, C., Hodson, D.L.R., Dong, B., Barnes, E.A., Raible, C.C. and Pinto, J.G. (2015) Contrasting interannual and multidecadal NAO variability. *Climate Dynamics*, **45**, 539–556. doi: 10.1007/s00382-014-2237-y

Wu, L., Breivik, O. and Rutgersson, A. (2019) Ocean-wave-atmosphere interaction processes in a fully coupled modeling system. *Journal of Advances in Modeling Earth Systems*, **11**, 3852-3874. doi: 10.1029/2019ms001761

Young, I.R. and Ribal, A. (2019) Multiplatform evaluation of global trends in wind speed and wave height. *Science*, **364** (6440), 54.

Young, I.R. and Ribal, A. (2022) Can Multi-Mission Altimeter Datasets Accurately Measure Long-Term Trends in Wave Height? *Remote Sensing*, **14**(4), p.974.

Zappa, G., Hoskins, B.J. and Shepherd, T.G. (2015) Improving climate change detection through optimal seasonal averaging: The case of the North Atlantic Jet and European precipitation. Journal of Climate, 28, 6381–6397.