



The influence of future weather pattern changes and projected sea-level rise on coastal flood impacts around the UK

Rachel J. Perks¹ · Dan Bernie^{1,2} · Jason Lowe^{1,3} · Robert Neal¹

Received: 17 August 2022 / Accepted: 29 January 2023 / Published online: 6 March 2023
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Abstract

When local extreme water levels surpass defences, the consequences can be devastating. We assess the importance of sea-level rise and future weather pattern changes on UK coastal flood impacts. Historical weather pattern classifications are matched with the observed skew surges and significant wave heights. Coastal-risk weather patterns are then defined as $\geq 1\%$ of events in the distribution exceeding the local warning threshold. We combine this methodology with projections of sea-level rise and weather pattern frequency occurrences, to determine the relative importance of each on future coastal risk. A deep low-pressure system situated to the west of Ireland (WP29) has the highest probability (6.3%) of exceeding Newlyn's present-day warning threshold; this is projected to increase under climate change to 46.2% by 2050 under RCP2.6. This work found that weather patterns associated with storm surges are increasing and decreasing in frequency; a synoptic situation causing windy conditions in the north of the UK (WP23) will increase by $> 40\%$ under RCP8.5 by the end of the century (2079–2090). When combining the impact of sea-level rise and changing frequency of weather patterns, this study found that sea-level rise dominates future coastal risk and is highly linked to the future emission scenarios. The need for successful adaptation, such as coastal defence improvements and early warning systems, will become even more important under the higher emission pathway. The most significant increases in coastal risk are found along the east coast, through the English Channel to the north Devon coastline.

Keywords Sea level · Storm surge · Waves · Weather patterns · Coastal risk

✉ Rachel J. Perks
rachel.perks@metoffice.gov.uk

¹ Met Office, Fitzroy Road, Devon EX1 3PB Exeter, UK

² Faculty of Health Sciences, University of Bristol, Bristol, UK

³ Priestley International Centre for Climate, University of Leeds, Leeds, UK

1 Introduction

The impact of climate change on the UK coast will exacerbate the already significant exposure to flooding and coastal erosion and may cause additional impacts such as saltwater intrusion into groundwater aquifers. In 1953, the east coast of the UK experienced a storm surge that caused extreme water levels that overflowed defences resulting in devastating consequences. Approximately 24,000 homes were flooded, 32,000 people were evacuated, costing over £1.2 billion, and tragically 307 people lost their lives (Haigh et al. 2017). In December 2013, Storm “Xaver” crossed the UK, generating similar extreme water levels. Through investment in defences and improved forecasting capabilities, the impact from this event was reduced, in comparison to the 1953 event. Despite these improvements, over two thousand homes and businesses and 6000 ha of agricultural land were flooded, leading to an estimated £44 to £83 million being spent on flood defence repairs and operations (Wadey et al. 2015). The most recent UK Climate Change Risk Assessment found that the risk to people from flooding remains high. In England, the number of people considered to be at significant risk of coastal flooding is projected to increase from 100,000 to 757,000 by the 2080s, under a 4 °C global warming scenario and with high population increases (Kovats and Brisley 2021).

Extreme sea levels result from a combination of any, or all, of the following: the local time-mean sea level, tides, storm surge and sea-surface waves. Global mean sea level has risen by approximately 0.20 m between 1901 and 2018. Between 1971 and 2018, sea level rose at an average rate of 2.30 mm/year, and more recently, between 2006 and 2018, this increased to 3.70 mm/year (Fox-Kemper et al. 2021). Observations show that rates of sea-level rise in the UK, approximately 3.60 mm/year for the period 1993–2019 (Kendon et al. 2022), are comparable to global rates. Storm surges are an increase in the sea-surface elevation above that of the astronomical tide, generated by barometric pressure and strong winds that can push water towards the coast. Haigh et al. (2016) stated that a moderate skew surge, of less than 1-in-5-year return period, in combination with a high spring tide can cause significant coastal flooding, more so than the largest skew surges which may occur during a neap tide. The largest waves in UK waters tend to be found on the Atlantic-facing coasts, where the large ocean fetch and strength of the westerly winds play an important role. A positive phase of the North Atlantic Oscillation usually drives a stronger jet stream which subsequently generates larger waves (Wolf et al. 2020) leading to greater erosion and damage to defences.

A small increase to the time-mean sea level can lead to a large impact on extreme events; for example, what is currently a 1-in-100-year flood event could become a 1-in-10-year event. The Intergovernmental Panel on Climate Change’s (IPCC) 6th Assessment Report (AR6) is “virtually certain” that global mean sea level will continue to rise over the twenty-first century (Fox-Kemper et al. 2021). Coastal sea-level projections for the UK are also expected to continue to rise, at least until the end of the twenty-first century under all representative concentration pathway (RCP) climate change scenarios (Palmer et al. 2018), although these are slightly smaller than the global average values due to the proximity of the UK to the Greenland ice sheet. Under RCP2.6 climate change scenario, sea level is expected to rise in the north (south) of the UK, by 0.10–0.50 m (0.30–0.70 m), while under RCP8.5, this is expected to increase to 0.30–0.90 m (0.50–1.10 m). Weeks et al. (2023) found the IPCC AR6 likely range projections and those from UKCP18 generally show good agreement, despite substantial advances in the underlying model simulations and methods, although there are some differences on post-2100 time horizons.

In some coastal regions, extreme sea levels could also be amplified further by changes in the frequency and severity of storms, which impacts the number and magnitude of storm surge or sea-surface wave events. Palmer et al. (2018) found both positive and negative trends in the storm surge magnitude at tide gauge sites in the UK. Using five RCA4-downscaled simulations, the coastal skew surge trends range from about -1.00 to about 0.70 mm/yr (which is about 10% of the projected time-mean sea-level rise). Furthermore, Palmer et al. (2018) used global and regional wave models to explore the projected changes in mean significant wave height (SWH) under RCP8.5, finding an overall decrease in UK coastal waters, but with some variation offshore. Projected changes in mean SWH are of the order ± 0.20 m (10% of the current SWH). Changing meteorological forcing has been found to play a substantial role at local scales (Vousdoukas et al. 2016), although typically they have not been well studied because it is difficult to develop robust simulations of changes to atmospheric circulation. Recently, improvements in the ability to simulate aspects of the North Atlantic atmospheric circulation, in models such as HadGEM3 as used here, provide cause for revisiting the issue.

The term “weather pattern” can be used to describe one of many circulation types over a defined region, which differs in its characteristics from other weather patterns over the same region and varies daily. One of the first classifications over the UK was completed by Lamb (1972), which described seven basic daily weather types: cyclonic, anticyclonic, northerly, easterly, southerly, westerly and north-westerly. More recently, the Met Office used cluster analysis to objectively derive a set of 30 weather patterns over the UK and surrounding European area (MO30; Neal et al. 2016). Circulation type classifications such as MO30 are used within operational weather forecasting, whereby multiple forecast scenarios from ensemble prediction systems (e.g. Buizza et al. 2007) are assigned to the closest matching weather pattern definition. This allows for daily weather pattern probabilities to be derived, covering the medium- to extended-range forecast period (~ 1 to 7 weeks). Objective verification of these forecasts over Europe (Ferranti et al. 2015; Neal et al. 2016; Büeler et al. 2021) shows useful skill at the synoptic scale on longer lead times than high-resolution (local scale) weather forecasts (Lewis et al. 2015).

Once weather pattern characteristics are understood, in terms of their climatologies or impacts, it becomes possible to interpret forecast output and describe the likely consequences. Weather patterns have been exploited in several applications including assessing the likelihood of coastal flooding (Neal et al. 2018), extreme rainfall (Richardson et al. 2020), volcanic ash flow from Iceland (Harrison et al. 2022), lightning occurrence (Wilkinson and Neal 2021) and extreme wave heights for decision-making within marine industries (Steele et al. 2017, 2018). Weather pattern approaches have also been used to address climate timescale questions, such as assessing future changes in the frequency and persistence of different types (Pope et al. 2022).

This study uses a weather pattern approach, similar to Neal et al. (2018), to understand how sea-level rise and future changes in the large-scale atmospheric circulation may influence coastal flood risk around the UK. While the metrics of skew surge and SWH are suitable for a broadscale understanding of how climate change might alter the drivers of coastal flooding, future adaptation planning at any site will need to take account of local-scale coastal features and flood defences using detailed modelling of over-topping and inundation.

2 Data and methods

2.1 Input data

Data used to relate weather patterns to current coastal flood risk can be split into three types: (i) daily historical weather pattern classifications; (ii) residual and astronomical tide gauge data; and (iii) wave hindcast data. To examine future changes to coastal flood risk, additional data is required: (i) regional sea-level projections; and (ii) daily projected weather pattern classifications.

2.1.1 Weather patterns

This paper utilises the existing MO30 weather pattern classification (Neal et al. 2016; see Online Resource 1). These were derived from the 5° horizontal resolution European and North Atlantic Daily to Multi-decadal Climate Variability (EMULATE) mean sea level pressure (MSLP) dataset (Ansell et al. 2006) over a 154-year period, from 1850 to 2003 using an iterative clustering technique. Associated daily historical weather pattern classifications are representative of the overall synoptic conditions on each day. These are available between 1950 and 2020 and were derived by objectively assigning MSLP fields from the European Centre for Medium Range Weather Forecasting (ECMWF) ERA5 reanalysis (Hersbach et al. 2020; Bell et al. 2021) to the closest matching definition from the MO30. Weather pattern assignment is based on the reanalysis field and the weather pattern definition field with the smallest area weighted sum of squared differences using MSLP anomalies, also known as the pairing with the smallest “distance” (Neal 2022).

The classifications of future weather pattern frequency used in this study were produced using the UKCP Global ensemble (Pope et al. 2022) and using the same assignment techniques as Neal (2022). The UKCP Global (Met Office Hadley Centre 2018) 15-member perturbed-physics ensemble (PPE) is based on the GC3.05 configuration of the UK Met Office Global Coupled Model (Williams et al. 2017). This is a fully coupled version of the UK Met Office model featuring atmosphere and land (Walters et al. 2017), ocean (Storkey et al. 2017) and sea ice (Ridley et al. 2017) components. Each member in the ensemble was run from 1st December 1899 to 30th November 2099 at N216 horizontal resolution (60 km at the equator), forced under RCP2.6 and RCP8.5 emission scenarios.

2.1.2 Marine data

Tide gauge data from the British Oceanographic Data Centre (BODC) were used to calculate the daily maximum skew surge (hereafter skew surge) for the 20 Class A tide gauge locations used by Neal et al. (2018). The skew surge is the difference between the maximum observed sea level and the astronomical tide regardless of their timing. The length of the observational records varies between sites.

The community-developed WAVEWATCH III model produced the Met Office’s wave hindcast dataset (Tolman 2009). WAVEWATCH III is a third-generation spectral wave model, which was run based on Version 3.14. This comprises a global configuration (50 km resolution) using the default Tolman and Chalikov (1996) source terms, which in turn forces the Northeast Atlantic and European domain (8 km resolution) using WAVEWATCH Model (WAM) Cycle-4 source terms following tunings proposed by Bidlot (2012).

Hindcast output from the European domain was used to derive the daily maximum significant wave height (hereafter SWH) between 1980 and 2014. The SWH is the average of the highest third of the observed waves. The WAVEWATCH III sites are approximately 6–8 km offshore from the respective BODC tide gauge sites.

We consider the twenty-first-century sea-level projections under the RCP2.6, RCP4.5 and RCP8.5 emission scenarios; the regional sea-level projections are obtained from the United Kingdom Climate Projections 2018 (hereafter UKCP18) which are documented in the UKCP18 Marine Report (Palmer et al. 2018). These projections are derived from the climate model simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) which underpin much of the global mean sea-level projections of the IPCC's Fifth Assessment Report (AR5; Church et al. 2013). See Online Resource 2 for additional metadata, thresholds and projections for each of these datasets.

2.2 Baseline coastal risk

For each site, daily historical weather pattern classifications in the ERA5 reanalysis dataset were matched with the skew surge and the SWH values. The distribution of skew surges and SWHs among weather patterns is shown in Fig. 1 for Newlyn. To identify a coastal-risk weather pattern, initially, a warning threshold is defined. This is considered the 99.7th percentile skew surge or SWH across all weather patterns for each site, which can also be considered a 1-in-1-year return period (blue line in Fig. 1), which can have significant impacts when combined with a high tide (Haigh et al. 2016). For Newlyn, the warning threshold for skew surges is 0.48 m and for SWHs is 6.94 m. The percentage probability of a skew surge and SWH event exceeding the warning thresholds for each weather pattern and for each site is calculated (Fig. 2). A weather pattern is considered a risk at a specific site if $\geq 1\%$ of skew surge and SWH events exceed this level (bars exceeding the blue lines in Fig. 2). For Newlyn, the coastal-risk weather patterns based on both skew surges and SWHs are 29 and 30.

2.3 Impact of sea-level projections on coastal risk

Regional sea-level projections have been used to uplift the skew surge and the SWH datasets for each site (i.e. skew surge + sea-level projections and SWH + sea-level projections), but with no changes to the weather pattern frequency. The regional sea-level projections have been applied for each decade from 2050 to 2100. To ensure an appropriate comparison with the future weather pattern frequencies, regional sea-level projections for 2085 have also been applied, the central year for the future period (2069–2099). RCP2.6, RCP4.5 and RCP8.5 emission scenarios have been used. Following UKCP18, regional sea-level projections used here are based on the 5th, 50th and 95th percentile ranges of the underlying model simulations, for a given RCP scenario. The uplifted datasets have been used to assess (i) the impact on the baseline warning threshold and (ii) the increased probability of exceeding the baseline warning threshold, all under different emission scenarios and future year combinations.

Implicit in this approach is the assumption that regional sea-level change has no impact on the skew surge, wave characteristics or the spatial pattern of the local tidal range (Palmer et al. 2018). We focus on the relative contributions to future risk from changing atmospheric circulation and regional sea-level rise; these are considered suitable metrics for a broadscale understanding of how climate change might alter the

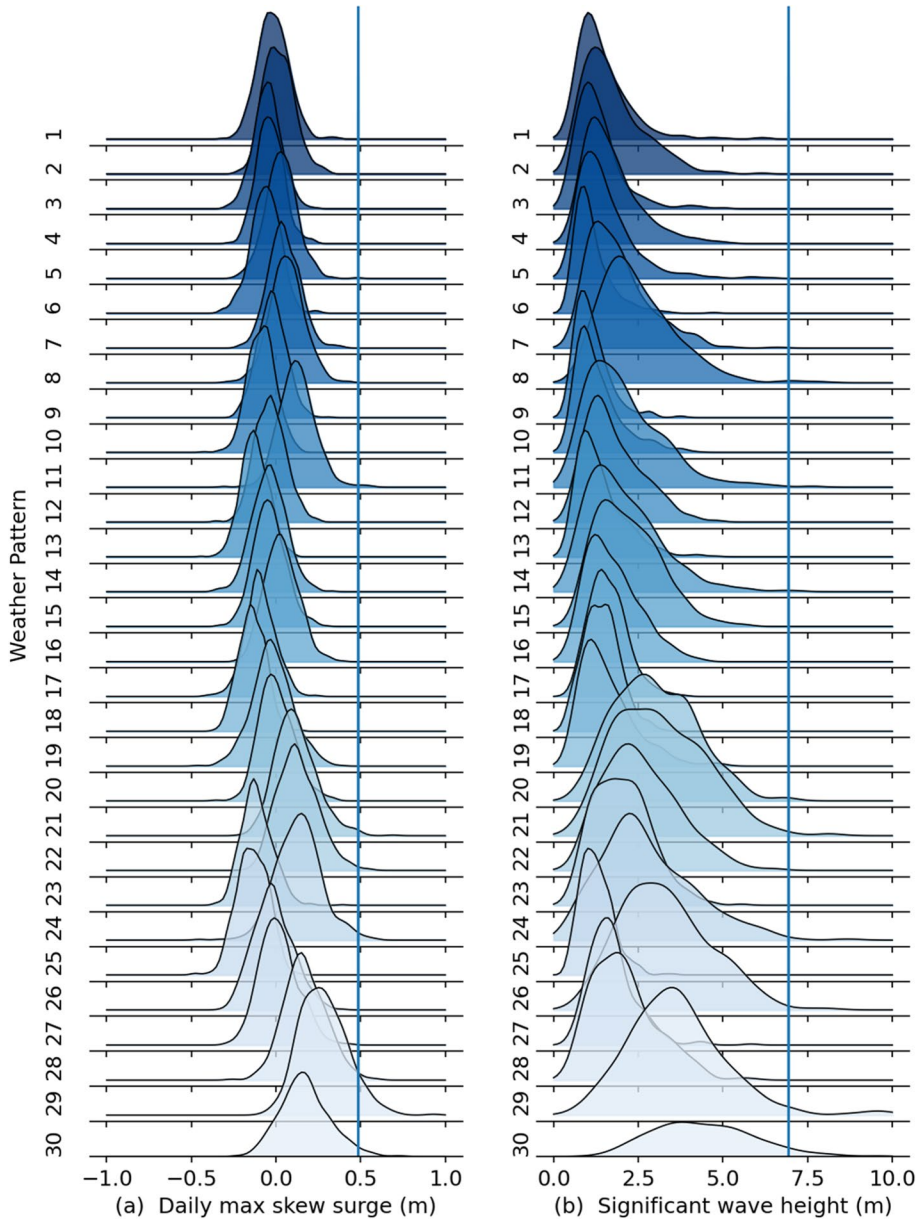


Fig. 1 Historical distribution of **a** daily maximum skew surge and **b** significant wave height, among the MO30 weather patterns at Newlyn. The vertical blue line on each subplot shows the 99.7th percentile of **a** daily maximum skew surge and **b** significant wave height climatology for the site (used as the warning threshold)

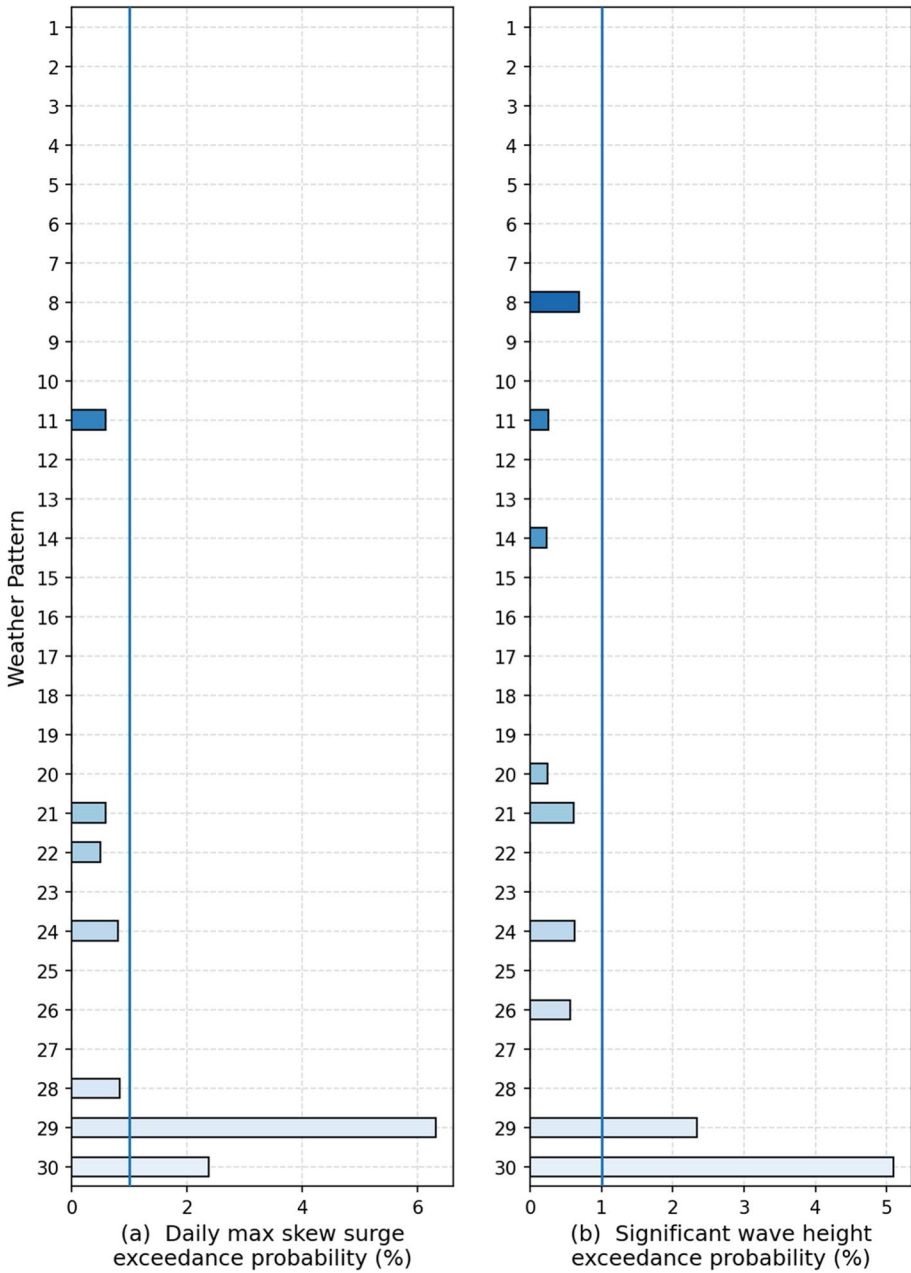


Fig. 2 The historical probability of **a** a skew surge event and **b** a significant wave height event, exceeding the warning threshold for Newlyn, 0.48 m and 6.94 m respectively. The vertical blue line on each subplot shows the 1% probability level; weather patterns are considered a risk when the exceedance probability surpasses this level

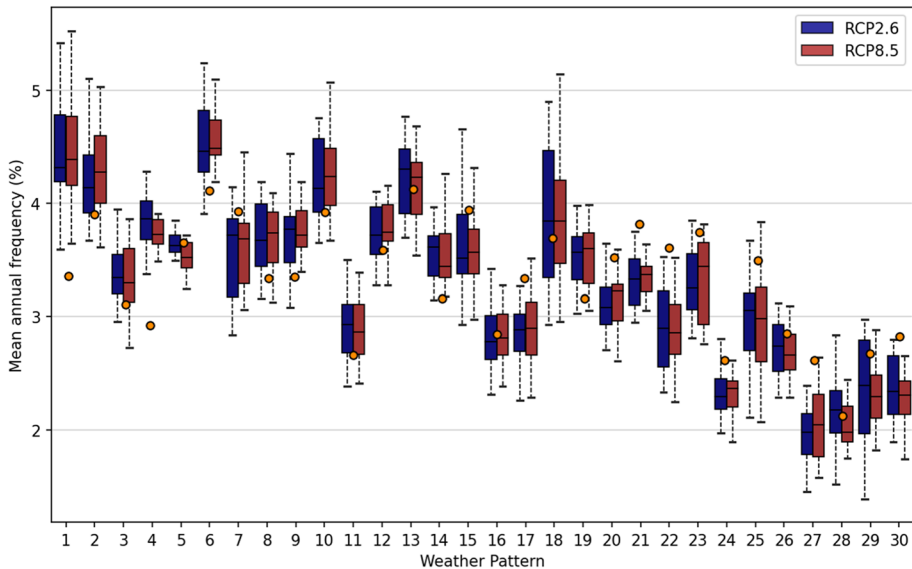


Fig. 3 Mean annual frequencies for the MO30 weather patterns from the UKCP Global 15-member PPE under emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the historical period (1989–2019) in comparison to the weather pattern frequencies from the ERA5 reanalysis (orange dots) for the same period. Boxes show the 25th, 50th and 75th percentiles; whiskers show maximums and minimums. Data source: Pope et al. (2022) and Neal (2022)

drivers of coastal flooding. It is recommended that future adaptation planning at any site will need to take account of local-scale coastal features and include modelling of wave transformation, over-topping and inundation, particularly as bottom friction affects wave breaking (Wolf et al. 2020).

2.4 Future changes to atmospheric storminess

The average daily occurrence of each weather pattern in the UKCP Global 15-member PPE is assessed on annual timescales for an historical and future period. In this study, the historical period spans 1989–2019 and the future period spans 2069–2099. For each member in the ensemble, the annual frequency is calculated as the number of times each weather pattern occurs against the total number of days in the year (including leap years). The mean annual frequency is then calculated for each data period and ensemble member. As the frequency of occurrence of each weather pattern is calculated as a percentage, to compare the changes in each of the patterns, results are presented as ensemble median percentage change, following Pope et al. (2022).

This approach assumes that the MO30 classifications are appropriate at the end of the century. The UKCP Global 15-member PPE has been validated in this respect and is discussed in Section 2.4.1.

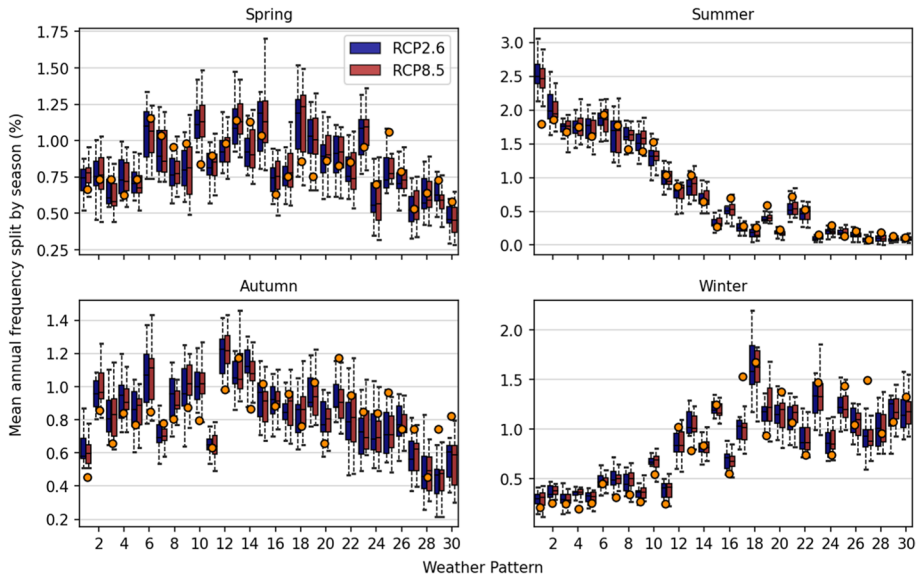


Fig. 4 Mean annual frequencies split by season for the MO30 weather patterns from the UKCP Global 15-member PPE under emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the historical period (1989–2019) in comparison to the weather pattern frequencies split by season from the ERA5 reanalysis (orange dots) for the same period. Boxes show the 25th, 50th and 75th percentiles; whiskers show maximums and minimums. Data source: Pope et al. (2022) and Neal (2022)

2.4.1 Validation of UKCP global model weather patterns

To validate the UKCP Global 15-member PPE, a simple comparison of weather pattern frequencies is made between the PPE and the ERA5 reanalysis dataset for the historical period. Figure 3 shows good agreement between the modelled and observed datasets. The main outliers are weather pattern one (hereafter WP1, where the number is interchangeable for each of the 30 patterns) and WP4 which are both associated with very low coastal risks, and so are not an important issue for the present study. This good agreement is also shown on seasonal timescales; Fig. 4 shows the mean annual frequencies split by season (DJF, MAM, JJA, SON). For WP1, the cause of the outlier on annual timescales is due to a poor representation in summer. Despite the good correspondence between the historical frequencies, to use them as a proxy for coastal risk for future projections, we need to establish that the MO30 weather patterns do not change appreciably over time.

To carry out this assessment of stationarity, we make use of two weather pattern assignment statistics developed by Neal et al. (2016): *distance* and *correlation*. In brief, distance describes how closely each weather pattern represents the atmospheric pressure of the model output and correlation describes the fit in the location of weather features between the weather pattern and model output. When considering coastal risk, an additional metric was developed: pressure anomaly difference (PAD; Neal et al. 2018). This is the grid point difference between the mean sea-level pressure anomalies in the weather pattern and the model output. A positive (negative) value of PAD suggests the model output has a higher (lower) pressure than the assigned weather patterns, which translates to a lower (higher) likelihood of large skew surges.

Using each of these fitting statistics, further validation of PPE for the historical and future periods has been completed and the results are shown in Online Resources 3. We find no indication of non-stationarity in the weather pattern simulations by PPE, with the differences between the model and observations in the historical period larger than the temporal trend within the PPE. There are some exceptions to this with some weather patterns better represented by specific ensemble members. However, we judge the data suitable for the purposes of our coastal risk analysis.

2.5 A combined proxy approach

This study calculated the coastal risk proxy, CR , to provide an indication of the combined risk from marine and atmospheric conditions.

$$CR = \sum_{i=0}^{30} P(S_i > T) f_i$$

Initially, the probability of skew surge or SWH events, S_i , exceeding the baseline warning threshold, T , for that site is calculated, where i is the weather pattern number. This is combined with the frequency, f_i , of that weather pattern's occurrence. The sum across all weather patterns is considered the coastal risk proxy.

This study's baseline, the observed coastal risk proxy, is the combination of the skew surge or SWH exceedance values and the weather pattern frequencies from the ERA5 reanalysis dataset. For example, in Newlyn, the probability of skew surge events exceeding the baseline warning threshold for WP1 is 0.00% and the frequency of occurrence for WP1 is 3.40%. The product for WP1 is therefore 0.00%. When completed for all 30 weather patterns and summed across them, the observed coastal risk proxy equates to 0.33%.

To verify the historical circulation patterns produced by the UKCP Global 15-member PPE, the observed coastal risk proxy is compared with the combination of the skew surge or SWH exceedance values and the historic weather pattern frequencies from the PPE. This combination is compared with the combination of the skew surge or SWH exceedance values and the future weather pattern frequencies from the PPE, to assess the impact of changing frequencies of weather patterns. The impact of sea-level rise is examined by combining the future sea-level conditions (skew surge and SWH uplifted with regional sea-level projections to 2085, following the method set out in Section 2.3) and the historical weather pattern frequencies from the PPE and comparing this with the combination using the present-day sea-level conditions. The combined impact of sea-level projections and the changing frequency of weather patterns on coastal risk has also been assessed for each site. Here, the future sea-level conditions are combined with the future weather pattern frequencies. See Online Resource 4 for a summary of the coastal risk proxies developed in this study.

3 Results

3.1 Impact of sea-level projections on coastal risk based on skew surge

The impact of sea-level projections on coastal risk can be considered in several ways. Firstly, to retain the present-day level of risk experienced at each site, the impact of sea-level change on a local warning threshold is assessed. For each of the 20 Class A tide gauge sites,

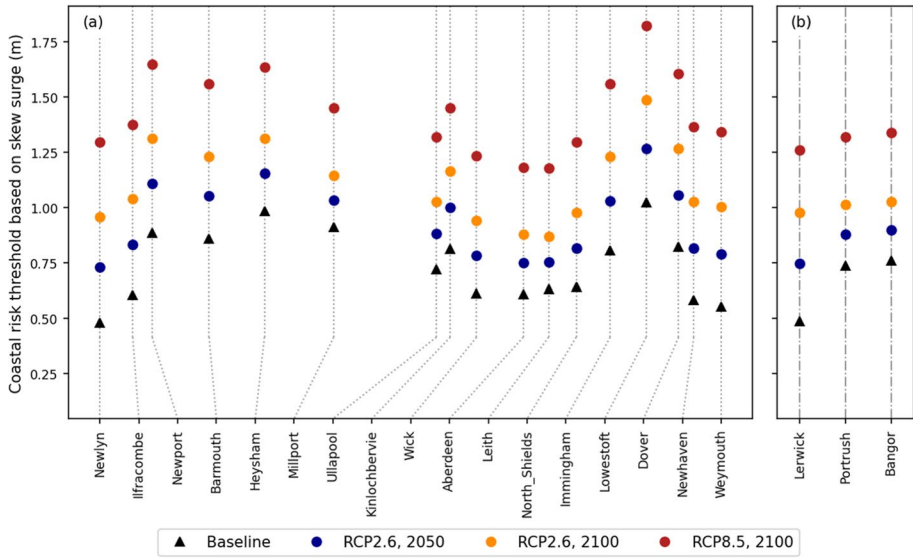


Fig. 5 Coastal-risk warning threshold based on skew surge for study locations around the UK coastline. The baseline warning threshold (black triangle) is based on the 99.7th percentile skew surge value across all days in the sample irrespective of weather pattern classification. The uplifted warning thresholds are shown for future years under emission scenarios as indicated in the legend. The horizontal separation between vertical lines **a** is proportional to the distance around the mainland coast as defined by the chainage. Where a chainage value is not available, **b** vertical lines are equidistant

a coastal-risk threshold based on skew surge under present-day and future sea-level projections and on different time horizons was calculated. Figure 5 shows how the baseline warning thresholds, based on the 99.7th percentile, change when accounting for sea-level projections to 2050 and 2100 under RCP2.6 and RCP8.5 emission scenarios. The horizontal separation between vertical lines in Fig. 5a is proportional to the distance around the mainland coast as defined by the chainage. Where a chainage value is not available as in Fig. 5b, vertical lines are equidistant.

For all future time horizons and under all emission scenarios, the coastal-risk threshold is expected to increase. The smallest increase is expected at Leith, equating 0.12 m in 2050 under RCP2.6, while the largest increase is expected at Newlyn, equating 0.81 m in 2100 under RCP8.5. While there are some variations in the baseline coastal-risk threshold based on skew surge, the largest increases as a direct result of sea-level rise are seen in the south of the UK, while the smaller increases are in the north; the spatial pattern of these changes correlates with the spatial pattern of sea-level projections.

Secondly, the impact of sea-level change would have on the probability of a skew surge event exceeding the present-day warning threshold and therefore indicate the potential future risk if no changes were made to coastal defences. The probability of exceeding the present-day warning threshold has been calculated for all 20 Class A tide gauge sites, for each decade from 2050 to 2100 under scenarios RCP2.6, RCP4.5 and RCP8.5. The analysis here will focus on Newlyn, for sea-level projections to 2100 under RCP2.6 and RCP8.5 (Fig. 6).

Under current atmospheric conditions, WP29 and WP30 can be considered a coastal-risk weather pattern for Newlyn, where $\geq 1\%$ of skew surge events exceed the warning threshold of 0.48 m (Fig. 2). By 2050, it is expected this will also include WP2, WP5, WP7, WP8,



Fig. 6 The probability of exceeding the present-day site threshold based on skew surge among weather patterns at Newlyn, accounting for decadal sea-level projections as indicated in the legend, under emission scenarios **a** RCP2.6 and **b** RCP8.5. Coastal-risk weather patterns are currently defined as those that exceed the 1% level

WP11, WP16, WP19, WP20, WP21, WP22, WP24, WP26, WP27 and WP28 under RCP2.6 (Fig. 6a) and all MO30 weather patterns by the end of the century under RCP8.5 (Fig. 6b). Taking the pattern with the highest probability of exceeding the warning threshold, which could be considered the most serious pattern in the present day (WP29), the exceedance probability is expected to increase from 6.30% (baseline) to 46.20% by 2050 under RCP2.6 and further to 76.80% by 2100 under RCP8.5. See Online Resources 5 for the results of the impact of sea-level change on the coastal-risk thresholds based on SWH.

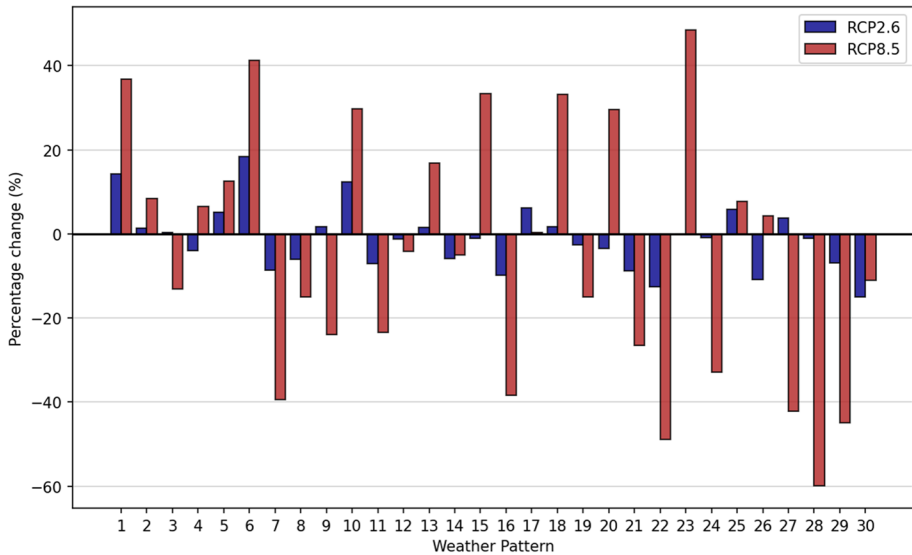


Fig. 7 UKCP Global 15-member PPE median percentage change in annual frequency of the MO30 weather patterns from the historical period (1989–2019) to the future period (2079–2090) under emission scenarios RCP2.6 (blue) and RCP8.5 (red)

3.2 Future changes to atmospheric storminess

Future changes to atmospheric storminess can be considered by assessing the projected changes to MO30 weather pattern frequency. For each member in the UKCP Global 15-member PPE, the percentage change in the mean annual frequency of weather pattern occurrence is calculated between the historical period (1989–2019) and the future period (2079–2090). The results here are shown using the median value across the ensemble.

Figure 7 shows the ensemble median percentage change in mean annual frequency for each of the MO30 weather patterns under RCP2.6 and RCP8.5 scenarios. This shows significant differences across weather patterns and between emission scenarios. Using an illustrative threshold of $\pm 20\%$ change in the frequency of occurrence, no weather patterns show an annual increase or decrease under scenario RCP2.6. However, under RCP8.5, seven patterns exceed the 20% threshold, and ten patterns exceed the -20% threshold. WP13, WP14, WP19, WP20, WP23, WP24 and WP26 have been associated with storm surges in the UK (Neal et al. 2018), and Fig. 7 shows that these patterns are both increasing and decreasing in frequency. The most significant of these changes is shown to be for WP23, with a greater than 40% increase in the frequency of occurrence under RCP8.5.

Figure 8 shows the ensemble median percentage change in mean seasonal frequency for each of the MO30 weather patterns under RCP2.6 and RCP8.5 emission scenarios; as with the annual frequency, this shows significant differences across weather patterns. Most notably, WP13 is increasing in frequency in spring, WP19 is increasing in frequency in summer while decreasing in autumn and winter, while WP20 is decreasing in frequency in summer while increasing in autumn and winter. The magnitude of changes under RCP2.6 is smaller than those in RCP8.5; however, for WP27, the percentage change in summer frequency is slightly larger for RCP2.6 than RCP8.5.

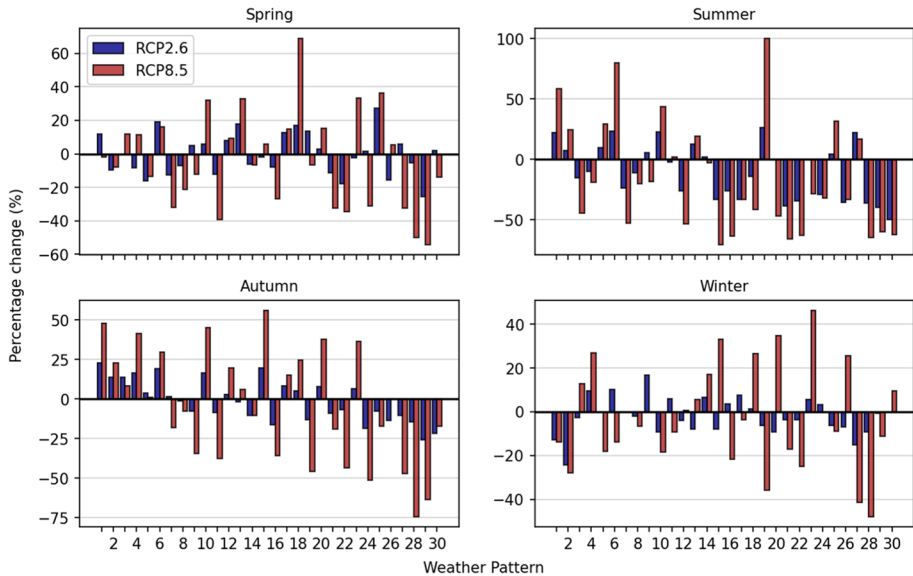


Fig. 8 UKCP Global 15-member PPE median percentage change in seasonal frequency of the MO30 weather patterns from the historical period (1989–2019) to the future period (2079–2090) under emission scenarios RCP2.6 (blue) and RCP8.5 (red)

3.3 Combined impact of time-mean sea-level rise and atmospheric storminess changes on coastal risk based on skew surge

The combined impact of time-mean sea-level rise and changes to atmospheric storminess on coastal risk has also been assessed (hereafter coastal risk proxy). The observed coastal risk proxy based on skew surge has been calculated for each site (black triangles in Fig. 9) which is between 0.19 and 0.33%. Figure 9_{a+b} shows good agreement between the coastal risk proxy developed using the present-day skew surge exceedance probabilities and historical weather pattern frequencies from the PPE under emission scenarios RCP2.6 (blue) and RCP8.5 (red) and the observed coastal risk proxy (black). When using the historical weather pattern frequencies, under RCP2.6 (RCP8.5), the coastal risk proxy is between 0.17 and 0.30% (0.16 and 0.29%). This shows a relatively similar risk to all sites around the UK coastline, with a slightly increased risk in Newlyn and Lowestoft and a slightly lower risk in Ilfracombe.

For most sites, the future weather pattern frequencies result in a slight decrease in the coastal risk proxy (Fig. 9_{c+d}) in comparison to the historical period (Fig. 9_{a+b}), whereas there is a notable increase in the coastal risk proxy at all sites due to the impact of sea-level projections (Fig. 9_{e+f}), with some sites showing a much larger change than others. The coastal proxy developed using future sea-level conditions (skew surge and sea-level projections to 2085) and the future weather pattern frequencies under RCP2.6 and RCP8.5 is shown in Fig. 9_{g+h}. This shows that the impact of sea-level projections on the coastal risk proxy dominates with respect to the changing frequency of weather patterns from the historical to the future period. When accounting for sea-level projections to 2085 and future weather pattern occurrence under RCP2.6 (RCP8.5), the coastal risk proxy is between 0.71 and 34.65% (2.84 and 80.56%) across

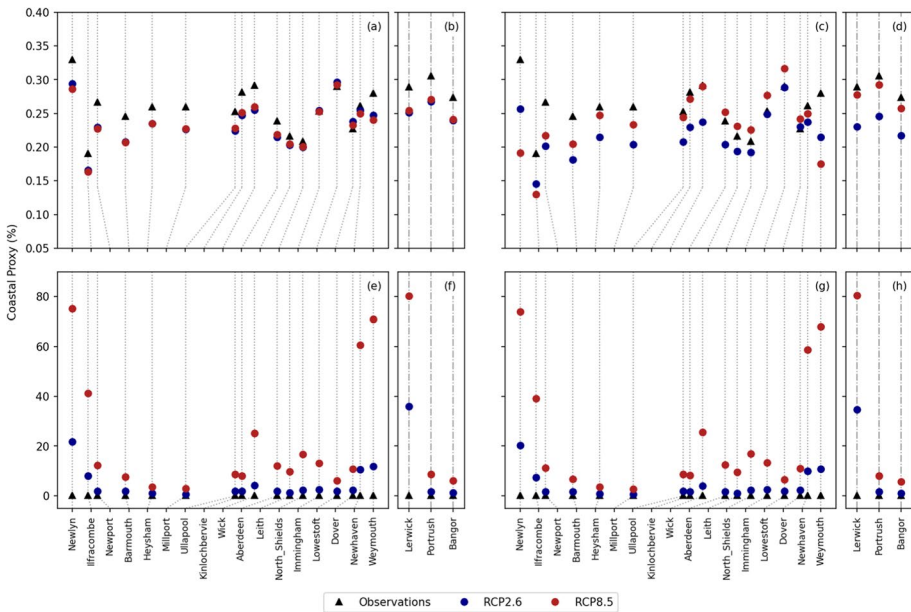


Fig. 9 Coastal proxy based on skew surge for study locations around the UK coastline, for four combinations: **a, b** present-day exceedance probability and historical weather pattern frequency (1989–2019), **c, d** present-day exceedance probability and future weather pattern frequency (2079–2090), **e, f** exceedance probability at 2085 and historical weather pattern frequency (1989–2019) and **g, h** exceedance probability at 2085 and future weather pattern frequency (2079–2090). The observed coastal proxy and future coastal proxies under emission scenarios are shown as indicated in the legend. The horizontal separation between vertical lines (**a, c, e, g**) is proportional to the distance around the mainland coast as defined by the chainage. Where a chainage value is not available (**b, d, f, h**), vertical lines are equidistant

all sites considered in this study. Significant increases in the coastal risk proxy can be seen on the east coast of the UK from Wick to Dover, through the English Channel and inclusive of the north Cornwall and Devon coastlines. Smaller increases are shown at locations within the Irish Sea and along the West coast of Scotland.

3.4 Combined impact of time-mean sea-level rise and atmospheric storminess changes on coastal risk based on SWH

Figure 10 shows the coastal risk proxy based on SWH. This shows good agreement between the UKCP Global 15-member PPE and the observed coastal risk proxy based on ERA5, albeit a slight under prediction across many sites in the English Channel and Irish Sea. The present-day coastal risk proxy based on SWH is relatively equal across all sites (Fig. 10_{a+b}). In general, there is a slight reduction in risk across most sites due to the impact of changing weather pattern frequencies (Fig. 10_{c+d}) as was found for skew surges, but with greater variability. Sea-level rise has a much greater impact with respect to the changing frequency of weather patterns (Fig. 10_{e+f}), most notably for Newport. This is in line with the results for skew surge but to a much smaller magnitude. The combined impact of sea-level projections and future weather pattern occurrence (Fig. 10_{g+h}) shows a slight reduction in the coastal risk proxy.

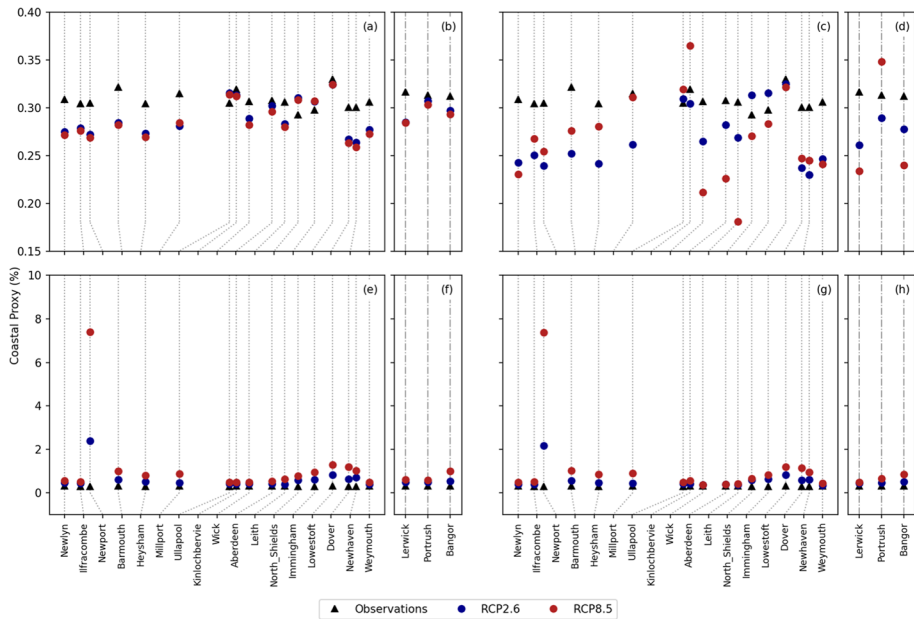


Fig. 10 Coastal proxy based on significant wave height for study locations around the UK coastline, for four combinations: **a, b** present-day exceedance probability and historical weather pattern frequency (1989–2019), **c, d** present-day exceedance probability and future weather pattern frequency (2079–2090), **e, f** exceedance probability at 2085 and historical weather pattern frequency (1989–2019) and exceedance probability at 2085 and future weather pattern frequency (2079–2090). The observed coastal proxy and future coastal proxies under emission scenarios are shown as indicated in the legend. The horizontal separation between vertical lines (**a, c, e, g**) is proportional to the distance around the mainland coast as defined by the chainage. Where a chainage value is not available (**b, d, f, h**), vertical lines are equidistant

The coastal risk proxies based on skew surge and SWH for each of the sea level and weather pattern combinations under RCP2.6 and RCP8.5 can be seen in Online Resources 6.

4 Discussion and conclusion

This work has updated the base case for identifying coastal risk in the UK by combining the skew surge and significant wave height (SWH) values with the daily weather pattern from ERA5 reanalysis. Coastal-risk weather patterns were defined for 20 sites following Neal et al. (2018) as those where $\geq 1\%$ of skew surge or SWH events exceed the site’s warning threshold (99.7th percentile). The results presented here indicate about two to three weather patterns are considered a coastal risk at each site in the baseline set-up, which is consistent with the work of Neal et al. (2018). Here, we focus on the relative contributions of time-mean sea-level rise and changing frequency of weather patterns to assess changes in coastal risk and have developed a coastal risk proxy. These metrics are considered suitable for a broadscale understanding of how climate change might alter the drivers of coastal flooding. A key assumption of this study is that regional sea-level change has no

impact on the skew surge, wave characteristics or the spatial pattern of the local tidal range (Palmer et al. 2018).

Risk-based decision-making is highly important across a variety of sectors from port authorities and related transport networks to national and local councils with an interest in coastal resilience and flood risk management strategies. To retain the present-day level of risk experienced, regional sea-level projections were found to increase the local warning thresholds based on skew surge at all sites across the UK, under all emission scenarios and future time horizons considered. The largest of these local warning threshold increases are seen in Newlyn and the smallest in Leith. This is in line with the spatial pattern of sea-level change documented by Palmer et al. (2018). The changes in these site-specific thresholds could be used as an input to adaptation planning, specifically flood risk reduction measures such as raising dikes, implementing new flood reservoirs, or opting to abandon coastal areas.

Currently, the Met Office Flood Forecasting Centre¹ uses information on coastal-risk weather patterns alongside site-specific forecasts to alert the responder community to the possibility of an impactful event. Neal et al. (2018) found several weather patterns that were typically associated with storm surges, namely weather pattern (WP) 13, WP14, WP19, WP20, WP23, WP24 and WP26. Of these, WP23 shows the most impactful change (increasing in frequency), which has significant practical and financial implications for the coastal flood forecasting sector. Furthermore, as a direct consequence of regional sea-level rise by 2085 under the representative concentration pathway (RCP), climate change scenario RCP2.6, on average eight weather patterns, can be considered a risk across the study locations increasing to 15 weather patterns under RCP8.5. Yet with adequate forewarning of potential future risk such as what has been presented here, it offers the ability for informed planning. Targeted model development and a greater focus on early warning systems could be a beneficial adaptation measure.

Specific weather types have been linked to high impact fluvial flooding (Pope et al. 2022) and compound flooding in estuaries along North Atlantic coastlines (Camus et al. 2022). Extreme sea levels are the result of the interaction between the local time-mean sea level, the tides, the storm surge and sea-surface waves, the latter of which are a direct consequence of cyclonic systems that vary in size, speed and trajectory. These systems are also associated with intense precipitation. For example, an unusual sequence of storms impacted the UK over the winter of 2013/2014, resulting in exceptional extreme water levels and record-breaking precipitation totals (Haigh et al. 2016). These storms caused devastating compound flooding and an estimated £2.5 billion in damages. This work has highlighted the risk associated with sea-level rise and changing frequency of weather patterns, suggesting the impacts from compound flooding are likely to increase over the coming decades. Coastal cities are expected to continue to grow (Committee on Climate Change, 2018), meaning that more people will also be at risk of compound flooding. It is recommended that future adaptation planning should account for local-scale coastal features and include modelling of wave transformation, over-topping and inundation.

Throughout this study, the benefit of mitigation can be seen from the differences in risk between the RCP2.6 and RCP8.5 emission scenarios. This result was found for both skew surges and SWH, however to a smaller magnitude for SWH, likely because the

¹ Flood Forecasting Centre—GOV.UK (www.gov.uk)

historical distribution of SWH among weather patterns is much wider than that of skew surges. When accounting for sea-level projections to 2085 and future weather pattern occurrence, the coastal risk proxy based on skew surge across all sites considered in this study is between 0.71 and 34.65% under RCP2.6 and between 2.84 and 80.56% under RCP8.5. This implies that meeting strong emission mitigation policies will significantly reduce the coastal risk at all locations around the UK coast; however, coastal adaptation and protection measures (as discussed) are still essential to protect people and places. The need for successful adaptation will become even more important under the higher emission pathway RCP8.5, which is in line with the findings of Vousdoukas et al. (2016).

Assuming there will be no changes to the current UK defences, a key finding of this work is that the time-mean sea-level rise has a much larger contribution to the coastal risk proxy than the changing frequency of weather patterns. The dominance in the changes to time-mean sea level in affecting extreme water levels, over changes in the skew surge or wave components (a direct consequence of synoptic conditions), was also found by Howard et al. (2019) using a different approach. It is not possible, however, to directly relate this to changes in future impacts as a significant skew surge event does not always correspond with a high tide. Future work could consider how changes in the coastal-risk weather patterns translate into a higher likelihood of more frequent or more severe flooding, which will also have implications for the insurance and re-insurance sectors due to the increase in flood losses. Additionally, the current study has produced results for 20 of the 46 Class A tide gauges around the UK; when considering impact-based work, it may be beneficial to extend this work for the remaining tide gauges and have results closer to the area of interest.

This work has assessed the impact of sea-level rise and changing frequency of weather patterns on coastal risk within the UK. It would also be interesting to apply this methodology to other locations across the globe. For example, weather pattern definitions have been developed for India to represent precipitation variability (Neal et al. 2020, 2022) and Southeast Asia to consider tropical variability and heavy precipitation (Howard et al. 2022). Weather pattern approaches such as these and what has been presented here show promising potential in extending the useful skill of the medium- to extended-range forecast period (~ 1 to 7 weeks) for a variety of forecasting and climatic applications.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-023-03496-2>.

Acknowledgements RP, DB and JL acknowledge the Strategic Priority Fund for U.K. Climate Resilience. We also thank the two reviewers for the all the time taken to help review this work.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by RP. The first draft of the manuscript was written by RP and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the UK Research & Innovation (UKRI) Strategic Priorities Fund UK Climate Resilience programme. The programme is co-delivered by the Met Office and NERC on behalf of UKRI partners AHRC, EPSRC and ESRC. RN was supported by the Met Office Hadley Centre Climate Programme funded by BEIS and Defra.

Data availability The data inputs used in the study are appropriately referenced in the text. The datasets generated during the study are going to be made available by the end of the review process.

Declarations

Conflict of interest The authors declare no competing interests.

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