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The temporal clustering of storm surge, wave height, and high sea level exceedances around the UK coastline

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Abstract

The temporal clustering of storms presents consecutive storm surge and wave hazards that can lead to amplified flood and erosional damages; thus, clustering is important for coastal stakeholders to consider. We analyse the prevalence of storm clustering around the UK coastline by examining the temporal and spatial characteristics of storm surge, wave height, and high still sea level exceedances at the 1 in 1- and 5-year return levels. First, at the inter-annual timescale, we show that there are periods of high/low exceedance counts on national and regional scales. Elevated annual counts of exceedances with smaller magnitudes can occur without a respective signal of higher-magnitude exceedances. Secondly, at the intra-annual timescale, we show that high proportions of exceedances are clustering over short timescales. Storm surge, wave height and still sea level exceedances occurring < 50 days after the prior exceedance at a given site account for between ~ 35–44% and ~ 15–22% of all exceedances at the 1 in 1- and 5-year return levels, respectively. Still sea levels have the highest proportion of exceedances clustered in quick succession, with ~ 25% of 1 in 1-year exceedances occurring < 2 days after the previous at the same site. Spatially, for UK storm surges and still sea levels, the North Sea has the lowest proportion of clustering, whereas the North Atlantic and Bristol Channel have the highest. For English wave records, the highest proportions of clustering are found in the North Sea for exceedances of a lower magnitude and the English Channel for exceedances of a higher magnitude. These findings illuminate the prevalence of the clustering of coastal hazards around the UK—helping coastal stakeholders evaluate the threat of surges, waves, and sea levels clustering over short periods.

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1 Introduction

Coastal areas represent a small percentage of the world's land surface (~2%) but contain a disproportionately high proportion of the world's population. Kulp and Strauss (2019) estimated that 1 billion people currently occupy land < 10 m above current high tides levels with 230 million of those living on land < 1 m above high tide levels. Over the last century, over 8 thousand people have been killed and 1.5 million people are affected annually by high sea levels on average (Bouwer and Jonkman, 2018). Mean global flood losses in 2005 for the world's major coastal cities were estimated at ~$6 billion per year; this is predicted to rise to $60–63 billion per year in 2050 even if adaptations maintain constant flood probability (Hallegatte et al. 2013). Without adaptation to sea-level rise, up to 4.6% of the global population is expected to be flooded annually in 2100, with expected annual losses of such flooding being up to 9.3% of the global gross domestic product (Hinkel et al. 2014). Currently, around 24% of sandy beaches around the world are eroding (Luijendijk et al. 2018), and increased lengths of coastline will be exposed to increased erosion risk in the future (Vousdoukas et al. 2020).

The United Kingdom (UK) coastal zone is home to over 5.3 million people in English and Welsh towns alone (Office for National Statistics, 2020), and holds great value to the economy, culture, and the environment. Annual average economic damages from coastal flooding in the UK are estimated to be £540 million (Sayers et al. 2015) and 28% of the English & Welsh coastline is already experiencing rapid erosion (Masselink et al. 2020). Therefore, improving the understanding of the causes and related impacts of coastal flooding and erosion is of great importance for effective adaptation and management strategies.

In this paper we focus on the temporal 'clustering' (i.e. events occurring one after another in close succession) of storm surges, wave heights, and high still sea levels around the UK coast, which can strongly influence coastal flooding and erosion. These are driven by storm clusters (also referred to as storm sequences), where multiple extratropical cyclones pass through the same location in a given time period (Dacre and Pinto, 2020). The issues associated with storm clustering were brought to the fore in the UK during the extreme winter season of 2013/14 (Spencer et al. 2015; Wadey et al. 2014; Haigh et al. 2016). Multiple, intense extratropical storms impacted the UK coastline during this winter period, with an average of 1 intense storm every 2.5 days in December-February (Priestley et al. 2017b). Storm clustering could lead to amplified flood and erosion damage as the attritional effects of the temporal clustering of high still sea levels, storm surges and waves are augmented by a lack of recovery or repair time. Therefore, not accounting for clustering could lead to a potential underestimation of coastal flood and erosion risk. Furthermore, rising mean sea levels driven by climate change and possible changes in storminess (Dangendorf et al. 2017; Nerem et al. 2018; Garner et al. 2018; Fox-Kemper et al. 2021) will likely lead to increased clustering of storm surges, waves, and high still sea levels, further exacerbating the impacts of flooding and erosion. Therefore, improved understanding of storm clustering around the coastlines of the UK is crucial in mitigating against storm damages into the future and assisting coastal management and planning.

Over the last decade, studies have started to examine storm clustering from a storm surge, wave and/or high still sea level perspective. For example, Godoi et al. (2018) and Stephens et al. (2020) assessed clustering in high still sea levels and waves around the coastline of New Zealand and linked this to patterns of mean sea level anomaly and large-scale ocean–atmosphere oscillations. In the UK, Wadey et al. (2014) and Haigh et al. (2016) undertook assessments of the temporal clustering of high still sea levels and storm

surges, and Malagon Santos et al. (2017) and Dhoop and Mason (2018) assessed clustering in waves. These studies showed that extreme wave events can cluster over short periods (Malagon Santos et al. 2017), whereas high still sea levels are governed by the timescale of spring-neap tidal variations (Haigh et al. 2016). The majority (86%) of high still sea levels are caused by high spring tides that coincide with a moderate skew surge (difference between the maximum sea level and the maximum tidal level within a tidal cycle, irrespective of their timing) (Haigh et al. 2016). Spatially, similar storm tracks have been shown to have broad, regional-scale footprints of high still sea levels and waves (Haigh et al. 2016; Malagon Santos et al. 2017; Dhoop and Mason, 2018). However, high still sea levels that occur in close succession (<4 days) typically affect different parts of the UK coastline (Haigh et al. 2016). Whereas the number of days between extreme wave events were found to be similar among sites from the same region (Malagon Santos et al. 2017). The impact of the clustering of storm surges, waves and high still sea levels at the coast is varied and determined by a variety of site- and event-specific factors affecting beach vulnerability (Eichentopf et al. 2019). These complex site- and event-specific factors determine exactly how a storm cluster affects a beach, but studies have shown that the cumulative erosional effects of a storm sequence can be greater than a single more powerful storm (e.g. Karunarathna et al., 2014; Dissanayake et al. 2015). Research has also found that particularly stormy seasons can have long lasting impacts on beach morphology—Atlantic coast beaches in Europe affected by the extreme 2013/14 winter season had not recovered 4 years later (Dodet et al., 2019).

Our overall aim in this paper is to assess the nature of temporal clustering of storm surges, wave heights, and high still sea levels in measured and modelled time-series at sites around the UK coast. We build on the earlier work of Haigh et al. (2016), Malagon Santos et al. (2017) and Dhoop and Mason (2018) but instead of analysing surges/still sea levels and waves separately, we analyse them together using a consistent approach. We also undertake an analysis at each gauge site individually, whereas these 3 previous studies focused on analysis of extreme events across sites, making it more difficult to quantify whether clustering is an issue at an individual site. We also extend the previous studies by comparing and contrasting measured and modelled hindcast time series. Utilising hindcast records of sea levels and waves is common in the literature and here we assess their utility by evaluating their ability to accurately capture what has been observed at the coast over interannual timescales.

We have 2 specific main objectives with 1 sub-objective, as follows:

1. To assess the characteristics of clustering on interannual timescales, determining in which periods clustering was most apparent;

   a. To evaluate the performance of modelled hindcast data in capturing these temporal and spatial patterns of exceedances; and

2. To examine the characteristics of clustering on intra-annual timescales, analysing the number of days between consecutive exceedances.

We undertake our analysis considering and contrasting measured and modelled still sea level records at 46 tide gauge sites, and wave datasets at 43 sites around the UK coast. We identify all storm surge, wave heights and high still sea levels that exceed 2 thresholds, namely, the 1 in 1-year threshold and the 1 in 5-year threshold. We choose the 1 in 1-year threshold to represent levels that are common enough to be present throughout

the time-series and to ensure a higher number of exceedances are identified, thus allowing clustering to be more readily identified. The 1 in 5-year thresholds represent more extreme levels that are less frequent. The 1 in 5-year level also ensures high still sea levels arise as a result of a storm surge, and not solely a large astronomical tide (lunar perigean cycle causes tides to reach a maximum every 4.4 years; Haigh et al. 2011). To assess clustering on interannual timescales, we examine the number of exceedances of storm surges, wave heights and high still sea levels each'storm year' period. Note, a storm year is defined as being from 1st July to 30th of June the next year and when we refer to annual periods, we are referring to this July to June of the next year period. We do this to encompass the northern hemisphere winter storm season, as well as any exceedances that occur outside of the season. We assess how well the modelled hindcasts capture the characteristics of storm clustering, compared to the measured records. To assess clustering on intra-annual time-scales, we examine the number of days between consecutive exceedances.

2 Data

Six main data sources are used in this study and are described below. The first dataset we use is high-frequency measured still sea level records from the UK National Tide Gauge Network, which comprises 43 operational 'A-class' tide gauges around the coast of the UK. 'A-class' gauges are those that are monitored and maintained to a high standard for scientific research. Note, these include a small number of tide gauges that are no longer operational, but for which historical records are available. Still sea levels refer to changes in the sea surface height driven by astronomical tides, storm surges and mean sea level, but excluding wind waves. The records were downloaded from the 46 gauges for which there was processed data (the 43 operational 'A-class' gauges plus 3 historical gauges). This was obtained from the British Oceanographic Data Centre (BODC), which is responsible for the monitoring, data retrieval, and quality control of the tide gauge network. The tide gauge network forms part of the UK Coastal Flood Forecasting (UKCFF) service, a partnership formed by the Environment Agency (EA), Scottish Environment Protection Agency (SEPA), Department for Agriculture and Rivers Agency Northern Ireland (RANI) and Natural Resources Wales (NRW). Values flagged as suspect by the BODC quality control were excluded from the datasets. The still sea levels were converted relative to ordnance datum Newlyn (ODN). Data are provided to the end of July 2021, with values prior to 1993 in hourly temporal intervals, and values after 1993 in 15-min intervals. The longest and shortest data records are Newlyn (106 years) and Moray Firth (10 years), respectively. The average data length is 45 years and the average data coverage after flags are removed is 81.3%. The location and durations of the tide gauge sites are listed in Tables 1 and 2 and locations are shown in Fig. 1a.

The second dataset consisted of modelled hindcast still sea levels from the Coastal Dataset for the Evaluation of Climate Impact (CODEC). CODEC consists of a historical climate period (1979–2018) and a future climate period (2040–2100), under different climate change scenarios. To create the historical dataset (CODEC-ERA5), which is used in this research, the third generation Global Tide and Surge Model (GTSMv3.0) was forced with tidal-generating forces with a set of 60 frequencies and 10-m wind speeds and atmospheric pressures from the Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate (ERA5) (Hersbach et al. 2020). GTSMv3.0 is a depth-averaged hydrodynamic model that is built from the unstructured Delft3D Flexible Mesh software. CODEC-ERA5

Table 1 Information on the EA tide gauge study sites and the statistics of 1 in 1-year sea level and storm surge exceedances at each site

Study site	Nearest CODEC grid node				Data length	Data coverage (%)	Storm surge						Still sea level offset by MSL					
	Longitude	Latitude	Longitude	Latitude			Number of days between exceedances						Number of days between exceedances					
							Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
All Sites (average)					45y 7mo	81.3	47.2	25.3	1.4	2259.4	319.7	188	51.7	22.2	1.6	2618.4	343.4	151.3
Lerwick	-1.14	60.15	-1.12	60.10	62y 6mo	78.5	48	24	1	4621	390.9	95.1	42	18	1	4297	436.8	104.5
Wick	-3.09	58.44	-3.05	58.47	56y 6mo	91.8	30	19	0.7	1482.6	322.8	237	76	24	1	1183.6	137.4	30.5
Moray Firth	-4.00	57.60	-4.02	57.63	10y 11mo	74.6	22	13	1.3	667.1	225.9	278.6	12	10	18.1	1682	533.6	463.2
Aberdeen	-2.08	57.14	-2.06	57.17	91y 6mo	74.6	35	21	1	1911.3	345.6	193.1	30	17	1	1788	407.5	219.4
Leith	-3.18	55.99	-3.20	55.99	40y 6mo	85.7	95	49	0.8	6996	361.2	260.6	39	24	1	11370	837.7	360.2
North Shields	-1.44	55.01	-1.43	55.04	75y 6mo	82.7	32	18	1	2130	342.7	251.2	98	20	1	1212.6	106.2	28
Whitby	-0.61	54.49	-0.59	54.49	41y 6mo	81.5	52	26	1	2482.2	370.9	113.3	20	12	1	2922	681.6	192.5
Immingham	-0.19	53.63	-0.07	53.81	68y 6mo	81.8	37	25	1	1180.7	387.3	325.6	36	19	1	1923.1	387.3	192.5
Cromer	1.30	52.93	1.33	52.92	48y 6mo	79.0	112	55	0.7	2187.8	337.6	223.7	119	57	1	1816	314.3	162.5
Lowestoft	1.75	52.47	1.75	52.45	57y 6mo	95.8	45	17	0.7	1511.3	208.4	18.4	25	13	1	2067.5	361.8	177
Felixstowe	1.35	51.96	1.38	51.98	29y 11mo	85.6	27	17	1	1742.9	399.7	311.3	46	19	1	1739.9	229	87.5
Harwich	1.29	51.95	1.31	51.92	67y 6mo	78.9	29	16	1.9	2099.7	337.6	81.5	56	20	1	1404.6	187.9	74
Sheerness	0.74	51.45	0.74	51.50	69y 6mo	62.4	60	37	1.2	2189.2	334.7	291.4	49	28	1	2584.5	408.2	234.4
Dover	1.32	51.11	1.31	51.12	97y 6mo	76.3	51	24	0.8	776.3	196.8	80.8	46	19	1	4932.5	319	55.9

Table 1 (continued)

Study site		Nearest CODEC grid node			Data length	Data coverage (%)	Storm surge						Still sea level offset by MSL					
									Number of days between exceedances						Number of days between exceedances			
	Longitude	Latitude	Longitude	Latitude			Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
Newhaven 0.06	50.78	0.02	50.78	39y 6mo	95.0		30	18	1.7	1593	318.5	266.5	19	11	8.3	2449.5	383.9	235.2
Portsmouth -1.11	50.80	-1.09	50.74	30y 6mo	92.6		66	40	1.6	2871.2	366.4	298.9	39	27	1	2288.5	509.1	321.7
Bournemouth -1.87	50.71	-1.90	50.71	25y 6mo	67.2		56	41	0.8	1487	372.8	336.3	67	38	1	1868.4	309.7	221.5
St. Helier -2.12	49.18	-2.09	49.17	29y 6mo	85.1		79	46	1.6	1708.2	310.6	176.2	42	31	1	3294	603.9	326
Weymouth -2.45	50.61	-2.47	50.57	30y 6mo	82.1		79	35	0.9	3234.7	308.4	142.8	25	17	4.1	3337	638.5	488.3
Devonport -4.19	50.37	-4.18	50.33	34y 6mo	89.8		42	30	1.7	1458.3	350.7	324.9	85	34	1	1110.6	174.2	75.5
Newlyn -5.54	50.10	-5.50	50.11	106y 6mo	88.2		32	20	6.4	1039.6	284	306.8	80	21	1	1079.1	128.4	30.5
St. Marys -6.32	49.92	-5.71	50.11	45y 6mo	67.5		31	22	3.5	1071.5	330.4	322.3	29	12	1	2125	368	134.5
Ilfracombe -4.11	51.21	-4.08	51.22	53y 6mo	79.1		33	17	1.1	1470	262.6	68	36	12	1	1241.6	240.9	162.5
Hinkley Point -3.13	51.22	-3.10	51.20	31y 6mo	86.3		32	15	0.9	1497.9	268.8	62.9	50	17	1	2125	177.8	55.4
Portbury -2.73	51.50	-2.81	51.51	13y 6mo	48.4		60	33	0.8	2126.4	354.9	267.6	93	36	1	1818	226.5	81.8
Avonmouth -2.71	51.51	-2.81	51.51	51y 3mo	79.1		59	33	1.6	4713	348.6	92.6	54	32	1	3307	375.3	164.5
Newport -2.99	51.55	-2.97	51.54	28y 6mo	73.1		67	31	0.8	2557.6	316.5	81.4	68	27	1	2998.5	366	106.6
Mumbles -3.98	51.57	-3.99	51.57	32y 11mo	61.2		33	15	0.8	1809.2	283.6	38.1	11	6	1	3113.4	912.4	260.3

Table 1 (continued)

Study site	Nearest CODEC grid node						Storm surge						Still sea level offset by MSL					
							Number of days between exceedances						Number of days between exceedances					
	Longitude	Latitude	Longitude	Latitude	Data length	Data coverage (%)	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
Milford Haven	-5.05	51.71	-5.08	51.66	68y 6mo	79.8	29	14	1	2627.4	342.5	85.2	104	18	1	1403	96.3	27.4
Fishguard	-4.98	52.01	-4.97	52.02	58y 6mo	84.9	103	48	1.1	3302.8	318.4	84.4	63	36	1	5154	531.1	206.5
Barmouth	-4.05	52.72	-4.07	52.71	30y 6mo	65.5	28	15	1.4	1809.7	350.4	303.8	49	19	1	1842.9	206.1	36.5
Holyhead	-4.62	53.31	-4.62	53.27	57y 6mo	86.2	44	23	1.4	1556.3	269.4	233.4	50	23	1	2703.5	291.4	134
Llandudno	-3.83	53.33	-3.79	53.31	50y 6mo	87.4	71	35	0.7	2449.6	308.7	51.1	42	28	1	1875	534.1	369
Liverpool	-3.02	53.45	-3.07	53.49	30y 6mo	80.4	46	26	2.1	1143.4	300.5	109.9	54	29	1	1745.7	263	61.1
Heysham	-2.92	54.03	-2.91	54.05	57y 6mo	80.2	7	4	1.9	770.3	309.6	285.8	14	6	1	1075.4	173.8	76.6
Port Erin	-4.77	54.09	-4.75	54.06	29y 6mo	93.9	35	15	0.9	4773.8	332	64.3	45	17	0.9	4348.6	256.8	44.7
Workington	-3.57	54.65	-3.57	54.66	29y 6mo	95.3	61	33	1.8	1797.8	307.2	81.1	75	31	1	1876	257.7	56.2
Bangor	-5.67	54.66	-5.68	54.69	26y 8mo	68.1	49	25	0.7	2216.3	335.3	266.3	86	27	1	2376.5	181.2	28
Portpatrick	-5.12	54.84	-5.12	54.84	53y 6mo	85.7	32	18	3	1473.4	351.4	308.5	46	19	1	2096	242.4	61.6
Portrush	-6.66	55.21	-6.63	55.22	26y 6mo	86.6	46	26	1.4	2212.8	390	309	103	35	1	1818	191.5	28.2
Port Ellen	-6.19	55.63	-6.20	55.61	32y 11mo	93.1	51	31	0.7	1875.5	401.8	329.5	94	38	1	2126	211	58
Millport	-4.91	55.75	-4.93	55.70	43y 6mo	83.9	31	15	1.6	1075.3	233.1	79.6	30	13	1	1749.2	242.4	25.9
Tobermory	-6.06	56.62	-6.10	56.76	31y 6mo	87.7	30	18	1.6	1824.6	292	294.4	26	16	1.6	2172.5	356.2	309.5
Ullapool	-5.16	57.90	-5.37	57.96	55y 6mo	84.4	72	29	1.5	10522.8	341.2	44	39	20	1	10522.9	634.9	228.5

Table 1 (continued)

Study site	Nearest CODEC grid node				Data length	Data coverage (%)	Storm surge						Still sea level offset by MSL					
	Longitude	Latitude	Longitude	Latitude			Exceedance count	Number of days between exceedances					Exceedance count	Number of days between exceedances				
								Number of seasons with exceedances	Min.	Max.	Avg.	Median		Number of seasons with exceedances	Min.	Max.	Avg.	Median
Stornoway	-6.39	58.21	-6.32	58.17	45y 6mo	84.5	49	23	0.7	803.8	191.5	74.4	40	19	1	1682	243.1	133.5
Kinloch-bervie	-5.05	58.46	-5.12	58.48	30y 6mo	86.4	12	7	0.9	1080.6	290.8	95.2	25	6	1	798.5	119.4	28.7

has a resolution of 1.25 km along the European coast. The nearest grid node to each EA tide gauge site was selected and the still sea levels extracted at a 10-min temporal resolution. More detailed information about CODEC can be found in Muis et al. (2020). The location of the CODEC grid points closest to the tide gauge sites are shown in Fig. 1a.

The third dataset comprised of return periods for still sea levels. The annual exceedance probabilities for all tide gauge sites in the UK National Tide Gauge Network were gained from the EA's 'Coastal flood boundary conditions for the UK: update 2018' (CFB) report (Environment Agency, 2018). The return periods range from 1-year to 10,000-years. The CFB report (2011) created a new statistical method, the Skew Surge Joint Probability Method (Bastone et al. 2013), that was used to estimate return periods and levels for the majority of the UK National Tide Gauge Network. The 2018 update to the first CFB report utilised 10 years of additional data to extend the tide gauge records and made significant improvements to the statistical methods. Exceedance probabilities were calculated for missing tide gauge sites, such as those in Northern Ireland, and the temporal interpolation of return periods/levels from the hindcast reduced to 2 km or less.

The fourth dataset consisted of wave measurements obtained from the National Network of Regional Coastal Monitoring Programmes of England (NNRCMP). This database contains 52 wave sites around the English coastline: 42 directional waverider buoys (DWR); 6 wave radars (WaveREX); 3 step gauges; and 1 pressure array. NNRCMP wave data were chosen over other UK buoy networks, such as WaveNet from the Centre for Environment, Fisheries and Aquaculture (CEFAS), as the NNRCMP buoys tend to be closer to the shore and as such are more suitable for the characterisation of events affecting the coastline. However, this limits the analysis to England. Data are delivered in 30-min intervals and each site is also provided with return periods/levels. Operational wave sites have data up to the end of September 2021. The West Anglesey wave buoy was omitted as it does not have quality-controlled data available. Values flagged by NNRCMP quality control were excluded from the research, as well as 6 further sites whose exceedance probabilities have not been calculated. These sites were: Sandown Pier; Lymington; Swanage Pier; Teignmouth Pier; Port Isaac; and Severn Bridge. The longest and shortest data records are Milford (25 years) and New Brighton (1.7 years), respectively. The average data length is 11 years and the average data coverage after flags are removed is 92.8%. The locations and durations of the wave sites are listed in Table 3 and locations are shown in Fig. 1b.

The fifth dataset we use was modelled hindcast significant wave heights (Hs) from ERA5. ERA5 replaced ERA-Interim and is based on the Integrated Forecasting System (IFS) Cy41r2. For waves, ERA5 has a much higher resolution of 40 km compared to its predecessor (100 km). Data are provided at an hourly temporal resolution from 1979 up to current day with a latency of around 5 days. In this research, we use wave data from the 1st January 1979 to the 1st January 2020. The availability of data back through time gives a far longer time period of wave data than any of the UK buoy networks. This data is also gap-free, coincident with the CODEC dataset, and allows for analysis anywhere around the UK coastline. We extracted data from the nearest grid point to each NNRCMP wave site to give comparable time-series. More information about the wave hindcast can be found in Hersbach et al. (2020). The location of the ERA5 grid points closest to the NNRCMP wave sites are shown in Fig. 1b.

The sixth dataset comprised of return periods for measured observations of high wave heights. These were obtained from NNRCMP. These exceedance probabilities are calculated by fitting a generalised pareto distribution onto observations designated through the peak-over-threshold method that is combined with a storm separation window (Dhoop and Thompson, 2018).

Table 2 Information on the EA tide gauge study sites and the statistics of 1 in 5-year sea level and storm surge exceedances at each site

| Study site | Nearest CODEC grid node | | | | Data length | Data coverage (%) | Storm surge | | | | | | Still sea level offset by MSL | | | | | |
| | Longitude | Latitude | Longitude | Latitude | | | Exceedance count | Number of seasons with exceedances | Number of days between exceedances | | | | Exceedance count | Number of seasons with exceedances | Number of days between exceedances | | | |
									Min.	Max.	Avg.	Median			Min.	Max.	Avg.	Median
All Sites (average)					45y 7mo	81.3	9.8	8.6	137.4	3995.8	1288	879.4	8.6	6.8	251	4242.3	1588	1324.5
Lerwick	-1.14	60.15	-1.12	60.10	62y 6mo	78.5	14	12	5.1	4622	1146.1	440.1	5	5	104.5	2996.5	1384.4	1218.3
Wick	-3.09	58.44	-3.05	58.47	56y 6mo	91.8	4	4	772.3	2649.2	1863	2167.7	13	9	1	2644.5	760.4	346
Moray Firth	-4.00	57.60	-4.02	57.63	10y 11mo	74.6	4	4	828.6	1820.6	1240.2	1071.3	1	1				
Aberdeen	-2.08	57.14	-2.06	57.17	91y 6mo	74.6	8	7	9.4	2577.7	1374.1	1394.7	5	4	31.1	6230	2403.9	1677.3
Leith	-3.18	55.99	-3.20	55.99	40y 6mo	85.7	20	18	2.1	9574.2	1784.6	718.3	9	8	266.5	12580.6	3979.2	2695.3
North Shields	-1.44	55.01	-1.43	55.04	75y 6mo	82.7	5	5	318.8	6576.7	2182.8	917.8	16	10	1	2922	670.4	192
Whitby	-0.61	54.49	-0.59	54.49	41y 6mo	81.5	11	9	4.3	6962.1	1822.9	672.5	4	3	58	6171	3518.7	4327
Immingham	-0.19	53.63	-0.07	53.81	68y 6mo	81.8	9	8	42	5814.5	1548	966.6	5	4	1.5	6557.6	2816.6	2353.7
Cromer	1.30	52.93	1.33	52.92	48y 6mo	79.0	22	17	2	8042.4	1784.3	1394.2	18	14	1	11573.4	1932.5	1462
Lowestoft	1.75	52.47	1.75	52.45	57y 6mo	95.8	12	8	2.1	3344.5	800.3	399.2	2	2	1846	1846	1846	1846
Felixstowe	1.35	51.96	1.38	51.98	29y 11mo	85.6	6	6	463	2167.6	1177.5	1095.9	5	4	42.5	3231.4	1657.1	1677.3
Harwich	1.29	51.95	1.31	51.92	67y 6mo	78.9	8	7	4.1	4755.4	1291.5	724	13	8	1	2536.4	835.4	422.3
Sheerness	0.74	51.45	0.74	51.50	69y 6mo	62.4	14	12	3.4	4762.2	1262.2	747.5	7	7	799.1	4353.9	2259	2179
Dover	1.32	51.11	1.31	51.12	97y 6mo	76.3	11	10	49.2	2862.4	839.5	580.5	10	9	74.5	6731	1509.4	666.6

Table 2 (continued)

Study site	Nearest CODEC grid node			Data length	Data coverage (%)	Storm surge						Still sea level offset by MSL					
	Longitude	Latitude	Latitude			Exceedance count	Number of seasons with exceedances	Number of days between exceedances				Exceedance count	Number of seasons with exceedances	Number of days between exceedances			
								Min.	Max.	Avg.	Median			Min.	Max.	Avg.	Median
Newhaven	0.06	50.78	50.78	39y 6mo	95.0	6	6	113.3	5000.6	1391	666.2	2	2	341	341	341	341
Portsmouth	-1.11	50.80	50.74	30y 6mo	92.6	14	14	373.3	2575.8	1285.4	1046.5	8	8	59.5	6143	2305.5	2287.5
Bournemouth	-1.87	50.71	50.71	25y 6mo	67.2	12	12	113.4	4790.6	1519.1	774.9	14	13	74.5	4694.5	1328.7	783.5
St. Helier	-2.12	49.18	49.17	29y 6mo	85.1	15	14	307.8	6084.3	1730.4	988.8	8	8	739	6084.5	3174.7	2583
Weymouth	-2.45	50.61	50.57	30y 6mo	82.1	13	12	55.3	3967.2	1542.9	947.3	2	2	2925.6	2925.6	2925.6	2925.6
Devonport	-4.19	50.37	50.33	34y 6mo	89.8	9	9	351.3	2218.7	1176.5	787	8	7	221.5	3688.9	1609.3	1547.4
Newlyn	-5.54	50.10	50.11	106y 6mo	88.2	8	7	243.2	2582.2	1053	1112.5	7	6	29	2614.5	1028.5	908.5
St. Marys	-6.32	49.92	50.11	45y 6mo	67.5	7	7	47.3	3275.2	1384	1205.1	7	4	1	4353.9	1282	759.5
Ilfracombe	-4.11	51.21	51.22	53y 6mo	79.1	6	6	392.3	2167.3	1177.5	1036	4	3	1	3633	1939	2182.9
Hinkley Point	-3.13	51.22	51.20	31y 6mo	86.3	8	7	44.3	4079	1000.9	440.2	5	5	432.6	2836	1542.7	1451.2
Portbury	-2.73	51.50	51.51	13y 6mo	48.4	11	10	7.5	5885.9	1835.7	1291.1	13	11	31.1	5817	1529.6	1173.2
Avonmouth	-2.71	51.51	51.51	51y 3mo	79.1	16	13	4.1	2898.1	899.9	408.1	9	8	31.1	2196.9	1049.9	878.7
Newport	-2.99	51.55	51.54	28y 6mo	73.1	15	13	4.2	3254.6	1359	1269.3	16	13	1	5183	1618.4	1625.6
Mumbles	-3.98	51.57	51.57	32y 11mo	61.2	5	5	10.8	2929.7	1113.5	756.8						

Table 2 (continued)

Study site	Nearest CODEC grid node				Storm surge								Still sea level offset by MSL					
	Longitude	Latitude	Longitude	Latitude	Data length	Data coverage (%)	Exceedance count	Number of seasons with exceedances	Number of days between exceedances				Exceedance count	Number of seasons with exceedances	Number of days between exceedances			
									Min.	Max.	Avg.	Median			Min.	Max.	Avg.	Median
Milford Haven	-5.05	51.71	-5.08	51.66	68y 6mo	79.8	8	6	2	4126.4	1247.6	1073.5	28	13	1	2287.5	358.2	162.5
Fishguard	-4.98	52.01	-4.97	52.02	58y 6mo	84.9	18	15	5.3	7349.9	1724.8	756.1	11	11	739	5533.9	2071.7	1485.5
Barmouth	-4.05	52.72	-4.07	52.71	30y 6mo	65.5	5	3	4.6	2255.5	1096.1	1062.1	10	7	1	3278	854.7	665
Holyhead	-4.62	53.31	-4.62	53.27	57y 6mo	86.2	10	8	34.2	4469.4	1085.4	707.9	7	7	30	6143	1828.5	1077
Llandudno	-3.83	53.33	-3.79	53.31	50y 6mo	87.4	10	8	0.9	3298.3	1171.7	766.3	12	9	1	5785.9	1560.9	1074.9
Liverpool	-3.02	53.45	-3.07	53.49	30y 6mo	80.4	9	9	383.7	2207.9	1229.6	1081.4	9	8	8.2	3205	1183.5	1092.5
Heysham	-2.92	54.03	-2.91	54.05	57y 6mo	80.2	2	1	125.8	125.8	125.8	125.8	1	1				
Port Erin	-4.77	54.09	-4.75	54.06	29y 6mo	93.9	6	6	658.2	2207.9	1301.5	780.7	8	6	47.5	2511.7	929.9	732.8
Workington	-3.57	54.65	-3.57	54.66	29y 6mo	95.3	8	8	43.1	5141	2283.3	1005.6	15	12	2.1	4739	1228.6	728.9
Bangor	-5.67	54.66	-5.68	54.69	26y 8mo	68.1	9	7	4.7	5940.1	1699.1	1157.1	17	13	1	2568	943.4	769
Portpatrick	-5.12	54.84	-5.12	54.84	53y 6mo	85.7	7	7	392.2	2988.6	1462.6	1470.3	5	5	1046.9	3278.5	2093.1	2023.5
Portrush	-6.66	55.21	-6.63	55.22	26y 6mo	86.6	11	7	1.4	2117.7	765.3	586.4	16	11	1	5539.6	1291.3	735.9
Port Ellen	-6.19	55.63	-6.20	55.61	32y 11mo	93.1	14	13	6.7	4037.4	1356	1382.7	16	14	26.4	4789.7	1291.4	1048.5
Millport	-4.91	55.75	-4.93	55.70	43y 6mo	83.9	6	5	25.8	2521.7	1105.6	724.1	5	4	3.1	4353.9	1649.2	1119.9
Tobermory	-6.06	56.62	-6.10	56.76	31y 6mo	87.7	7	6	8.4	1467.1	609.2	540.2	4	4	690.9	2587.6	1826.7	2201.5
Ullapool	-5.16	57.90	-5.37	57.96	55y 6mo	84.4	17	16	22.3	10918.2	1513.2	799	4	3	18.1	2287.5	1010.4	725.6

Table 2 (continued)

| Study site | Nearest CODEC grid node | | | | Data length | Data coverage (%) | Storm surge | | Number of days between exceedances | | | | Still sea level offset by MSL | | Number of days between exceedances | | | |
	Longitude	Latitude	Longitude	Latitude			Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
Stornoway	-6.39	58.21	-6.32	58.17	45y 6mo	84.5	10	9	25.9	4388.2	883.6	408.1	8	6	29	2614.5	886	770.6
Kinloch-bervie	-5.05	58.46	-5.12	58.48	30y 6mo	86.4	3	1	2.5	4.3	3.4	3.4	2	1	29	29	29	29

3 Methodology

3.1 Data preparation

In this paper we first focus on analysing time-series of: (1) storm surges; (2) significant wave height; and (3) still sea level, offset by mean sea level (MSL) rise. We focus mainly on the first two time-series, as storm surges and waves are stochastic and primarily driven by meteorology—they therefore are most strongly influenced by storm clustering. In contrast, still sea levels include the deterministic tidal component driven by astronomical forces. However, as it is the still sea level (e.g. tides plus storm surges) realised at the coast that drives coastal flooding and erosion, we also consider clustering in still sea level.

The data preparation consists of 2 main steps. The first step involves generating time-series of different components of sea level, as follows: (1) the non-tidal (i.e. storm surge) component of still sea level, (2) significant wave height, and (3) still sea levels offset by MSL rise. Significant wave height time-series were provided directly by the data source and we use the raw measurements. The other 2 time-series were calculated, as described below. The second step was to calculate the exceedance probabilities (i.e. return period levels) of each new time-series.

In the first step, we derive the 2 records not provided by the data sources, namely; (1) the non-tidal residual, which mostly contains the storm surge component, and (2) still sea levels offset by MSL rise. To extract the first time-series, the non-tidal residual, we computed the astronomical tidal component and removed this from the measured still sea level record. To meet the harmonic analysis assumption of stationarity, the still sea levels for this analysis had already been offset by MSL, as described below. The tidal component was calculated using the MATLAB Unified Tidal Analysis and Prediction Functions (U-Tide) (Codiga 2022), using a separate analysis for each calendar year. For any year containing < 50% data, the constituents from the nearest year containing > 50% of data were used. The tidal component for each gauge was then removed from the observed still sea level, to leave the non-tidal residual. The modelled hindcast data were already provided with the tidal component from the data source, so this was removed from the modelled still sea levels to obtain the modelled non-tidal residual. Hereafter, we use the term surge, or storm surge, to refer to the non-tidal residual.

Because mean sea levels have risen around the UK coast (Hogarth et al. 2021), we would expect there to be more high still sea level exceedances in recent decades; and this is what we observe in the data. The rise of MSL brings the 'base' still sea level higher, therefore meaning that less input is required from the storm surge component of still sea levels to raise the overall levels above critical thresholds. As smaller storm surges are more common than large storm surges, with a rise in MSL you would expect to see a consequent rise in threshold exceedances. Thus, for the second time-series, we remove the influence of MSL rise, so that storm clustering can be better compared without the MSL influence which biases extreme events to more recent years. To offset observed still sea levels, MSL trends at each tide gauge site were estimated using a linear regression method utilised by multiple previous sea levels studies (Woodworth et al. 2009; Haigh et al. 2009, 2015, 2016). This method interpolates linear annual mean sea level trends at tide gauges to hourly time-series and then removes them. This leaves the interannual mean sea level variability. Hereafter, still sea level refers to still sea level offset by MSL rise.

In a second step, we identify all the exceedances at each site, in the 3 time-series we analyse, at or above the 1 in 1- and 5-year return level thresholds. Return levels are
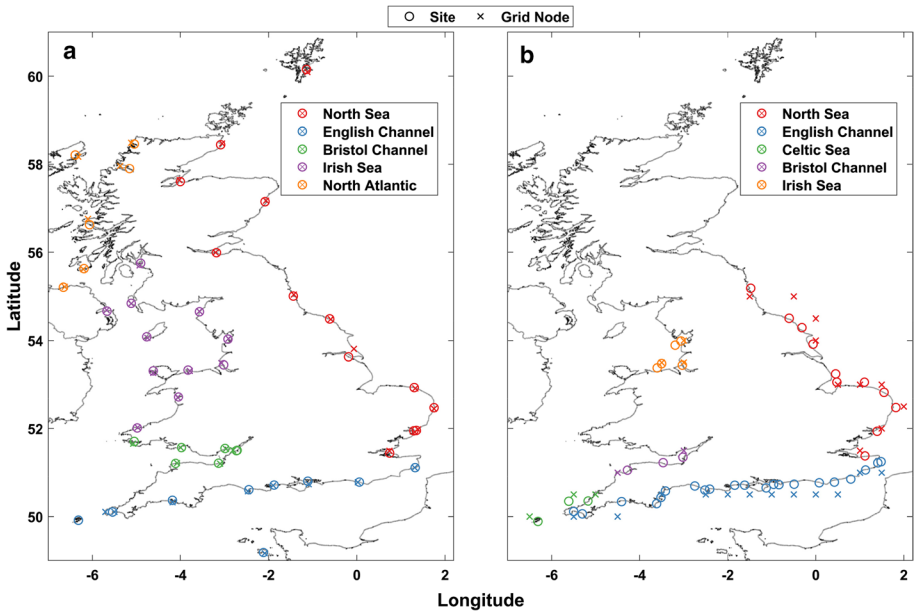
Fig. 1 **a** Site locations of EA tide gauges and the CODEC grid points closest to each tide gauge, and **b** site locations of NNRCMP wave sites and the ERA5 grid points closest to each tide gauge. The sites are grouped into 5 main regions geographically

available for the measured still sea level and wave height records, but not for the measured non-tidal residual or for the modelled hindcast time-series. Hence, we computed our own return levels for these datasets. We use a similar method to that of Dhoop and Thompson, (2018); using the peaks-over thresholds method (POT), we extracted all data above the 99th percentile. To decluster the data, and ensure unique peaks were identified, we used the 'storm window' approach of Haigh et al. (2016). We removed all values that were within plus or minus 16 h of each peak value. This period was chosen, as most storm surges last for approximately 32 h (see Supplementary Figure S1 and S2). We fit a generalised pareto distribution to the identified peaks at each site to gain estimates for return levels. Example time-series of measured storm surge, significant wave height and high still sea levels are shown in Fig. 2 for Newhaven (tide gauge) and Seaford (wave buoy), along with the levels identified to be above the chosen thresholds.

3.2 Interannual timescale analysis

Next, we address the first objective, which is to assess the characteristics of clustering around the UK coast on interannual timescales. To do this we analyse the spatial and temporal characteristics of storm year annual counts of exceedances. The storm year period was selected as extending from the 1st July to the 30th June the following year. Annual exceedances at or above the 1 in 1- and 5-year return level threshold of each measured and modelled parameter were counted at each site. An example is shown for Newhaven (tide gauge) and Seaford (wave buoy) in Fig. 3. The timings of all measured exceedances were then aggregated to show when in the year they occurred (see Supplementary Figure

S3). The Annual counts for each site were collated and presented together to show changes around the UK. Tide gauges around the UK were grouped into the 5 broad regions shown in Fig. 1a that represent different parts of the UK coastline. The wave sites around England were also grouped into 5 regions shown in Fig. 1b that represent broad portions of the English coast. The higher density of wave sites meant that 13 NNRCMP sites shared the same nearest ERA5 grid node as a neighbouring site. Modelled data were compared to the measured data to assess how well the hindcasts represented periods with a high number of exceedances. For the surge and still sea level time-series, we focus on the time period of 1979–2021 as it includes the time period from the CODEC dataset and measured data availability before this period is relatively sparse. For the waves time-series, we also focus on the same time-period as it includes the time period of the modelled ERA5 dataset. However, the short wave records of measured data means that most sites only have data availability from the early 2010's and interannual change for all regions can only be discussed for the last decade.

3.3 Intra-annual timescale analysis

Finally, we address the second objective, which is to examine the characteristics of clustering on the intra-annual timescale. To achieve this, we analyse the number of days between consecutive exceedances. This was carried out for all parameters and sites at the 1 in 1- and 5-year threshold before being aggregated together for UK-wide and regional analysis. Modelled data were not included in the second objective due to the differences seen between measured and modelled data while undertaking the first objective, as is discussed later in the paper.

4 Results

4.1 Interannual (storm year annual exceedances)

The first objective is to assess the characteristics of clustering around the UK coast on interannual timescales and evaluate the performance of the modelled hindcasts at capturing these characteristics. To do this we assess the number of exceedances per storm year from 1979/80 to 2021/22 above the 1 in 1- and 5-year thresholds in each of the three measured and modelled time-series and examine how this varies in time and space (across sites). The number of exceedances at or above the 1 in 1- and 5-year thresholds are plotted in Figs. 4, 5 and 6 for surge, wave height and still sea level, respectively. In each of these 3 figures the: 1 in 1-year exceedances are plotted in panels (a) and (b) and 1 in 5-year exceedances in panels (c) and (d); and measured data is plotted in figure panels (a) and (c) and the modelled data in panels (b) and (d). In these 3 figures, time (i.e. storm years 1979/90 to 2021/22) is represented on the x-axis and each site gauge is represented as a block on the y-axis, with the number of exceedances represented by a colour shading. On the y-axis the sites are plotted clockwise around the coast from Lerwick (at the top) for surges and still sea levels, and from Newbiggin for wave heights. The horizontal lines (blue: surges, red: wave heights and still sea levels) indicate the 5 regions shown in the inserted maps on the left side and in Fig. 1. The total number of exceedances, and the number of storm years containing an exceedance for each site, are listed in Tables 1 and 2 for tide gauges and Table 3 for wave sites. Below we present the results, first for surges, then waves, and then still sea levels.

Table 3 Information on the NNRCMP study sites and the statistics of significant wave height exceedances at each site

| Study site | Nearest ERA5 grid node | | | | Data length | Data coverage (%) | 1 in 1-year return level | | | | | | 1 in 5-year return level | | | | | |
	Longitude	Latitude	Longitude	Latitude			Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
All Sites (average)					11y 5mo	93.9	13.1	7.7	16.9	965.9	325.5	244.9	2.6	2.1	443.4	1193.5	776.6	716
Newbiggin	-1.48	55.19	-1.5	55	7y 9mo	96.8	23	6	0.7	456.5	86.6	1.3	3	1	1.4	15	8.2	8.2
Whitby	-0.61	54.50	-0.5	55	8y 2mo	87.2	8	5	16.1	478.4	296.4	316	2	2	419.4	419.4	419.4	419.4
Scarborough	-0.32	54.29	0	54.5	8y 2mo	89.3	6	5	16.3	922.8	508.4	419.4	2	2	419.4	419.4	419.4	419.4
Hornsea	-0.06	53.92	0	54	12y 9mo	97.9	5	4	0.7	2157.5	1017.6	956.1	1	1				
Chapel Point	0.45	53.25	0.5	53	8y 10mo	88.4	9	7	30	771.7	338.4	272.8	4	4	607.1	1190.9	847.4	744.1
North Well	0.48	53.06	0.5	53	14y 6mo	86.6	16	9	1.2	1393	333.4	192	6	5	7.7	1393	795.4	771.5
Blakeney Overfalls	1.11	53.06	1	53	14y 6mo	90.9	11	10	54.4	1044.2	483.9	477.9	1	1				
Happisburgh	1.55	52.83	1.5	53	8y 10mo	83.8	6	5	30	1109.1	514.4	607.1	2	2	2542.1	2542.1	2542.1	2542.1
Lowestoft	1.82	52.48	2	52.5	4y 11mo	79.4	8	4	0.7	360	112.2	42.4	2	2	364.3	364.3	364.3	364.3
Felixstowe	1.40	51.94	1.5	52	8y 10mo	90.0	12	6	1	742.7	262.8	200.3	2	2	2675.7	2675.7	2675.7	2675.7
Herne Bay	1.12	51.38	1	51.5	9y 2mo	86.5	9	6	14.6	1176.3	378.1	187.1	4	3	42.4	2574.6	963.1	272.2
Goodwin Sands	1.49	51.25	1.5	51	12y 9mo	97.9	18	8	3.1	1077.1	214	53.7	3	2	56.8	1021.2	539	539
Deal Pier	1.41	51.22	1.5	51	9y 2mo	94.0	8	5	1	741.7	373.9	465.6	2	2	466.6	466.6	466.6	466.6

Table 3 (continued)

Study site	Nearest ERA5 grid node						1 in 1-year return level						1 in 5-year return level					
	Longitude	Latitude	Longitude	Latitude	Data length	Data coverage (%)	Exceedance count	Number of seasons with exceedances	Number of days between exceedances				Exceedance count	Number of seasons with exceedances	Number of days between exceedances			
									Min.	Max.	Avg.	Median			Min.	Max.	Avg.	Median
Folkestone	1.13	51.06	1	51	17y 8mo	95.9	15	10	3.2	1372.6	392.5	287.5	5	4	43.1	2114.7	794.2	509.6
Rye Bay	0.79	50.85	1	51	12y 6mo	94.9	7	3	1.7	417.5	184.4	176.8	1	1				
Pevensey Bay	0.42	50.78	0.5	50.5	17y 8mo	96.3	20	12	1.8	1075.4	325	277.9	4	2	56.9	825	373	237.2
Seaford	0.08	50.77	0	50.5	13y 2mo	96.2	17	11	2	692	294.6	327.9	4	4	53	772.1	522.4	741.9
Rustington	-0.49	50.73	-0.5	50.5	17y 8mo	96.8	18	10	1.9	1789.6	364.6	99	4	4	52.9	772.1	522.4	742.1
Brackelsham Bay	-0.84	50.72	-1	50.5	12y 7mo	97.5	11	5	3.7	1434.6	363.1	52.8	1	1	0	0	0	0
Hayling Island	-0.96	50.73	-1	50.5	17y 8mo	96.9	28	16	1.9	758.5	217.9	100.3	3	2	9.4	772.1	390.8	390.8
Sandown Bay	-1.13	50.65	-1	50.5	17y 8mo	98.8	20	10	0.7	1836.9	321.7	112.8	4	3	237	2939.6	1335.1	828.7
Milford	-1.61	50.71	-1.5	50.5	24y 10mo	92.7	25	15	3.1	1462.3	367.7	155	5	4	9.4	4130.7	1579.5	1088.9
Boscombe	-1.84	50.71	-2	50.5	17y 8mo	97.9	12	6	2.4	1845.4	555.6	278	2	1	237	237	237	237
Weymouth	-2.41	50.62	-2.5	50.5	14y 3mo	98.2	12	7	4.9	686	327.9	415.8	3	2	237	782.1	509.5	509.5
Chesil	-2.52	50.60	-2.5	50.5	15y 2mo	90.5	15	10	3.1	1002.5	311.4	78	3	2	9.5	43.5	26.5	26.5
West Bay	-2.75	50.69	-2.5	50.5	14y 4mo	96.5	15	12	3.1	984.5	344.5	323.1	3	2	9.3	43.4	26.4	26.4
Dawlish	-3.42	50.58	-3.5	50.5	10y 3mo	98.3	10	5	9.9	645.8	309.8	323.1	2	2	645.8	645.8	645.8	645.8

Table 3 (continued)

Study site	Nearest ERA5 grid node						1 in 1-year return level						1 in 5-year return level					
							Number of days between exceedances						Number of days between exceedances					
	Longitude	Latitude	Longitude	Latitude	Data length	Data coverage (%)	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
Tor Bay	-3.52	50.43	-3.5	50.5	12y 8mo	90.1	20	8	0.7	982.8	169	112.4	2	2	1078.5	1078.5	1078.5	1078.5
Start Bay	-3.62	50.29	-3.5	50.5	13y 11mo	97.7	12	9	1.2	834.9	425.5	330.3	3	2	10	1476.1	743.1	743.1
Looe Bay	-4.41	50.34	-4.5	50	11y 9mo	98.5	9	7	9.4	1089.5	329.7	348.2	2	1	9.4	9.4	9.4	9.4
Porthleven	-5.31	50.06	-5.5	50	9y 5mo	97.1	12	8	3.1	616.9	280.9	349.3	1	1				
Penzance	-5.50	50.11	-5.5	50	13y 11mo	98.3	19	11	0.8	1041.5	242.1	52.2	2	1	9.9	9.9	9.9	9.9
St. Mary's Sound	-6.31	49.89	-6.5	50	6y 10mo	96.2	7	4	66.7	400.4	241.6	233.9	1	1				
Wave Hub	-5.61	50.35	-5.5	50.5	2y 11mo	95.8	4	3	5	616.2	231.6	73.7	1	1				
Perranporth	-5.17	50.35	-5	50.5	14y 4mo	96.6	20	12	1.7	1372.8	254.8	89.7	5	5	92.4	2154.1	919.5	715.8
Bideford Bay	-4.28	51.06	-4.5	51	11y 9mo	96.0	9	6	1	778.4	279.6	49.6	2	2	2191.7	2191.7	2191.7	2191.7
Minehead	-3.47	51.23	-3	51.5	14y 3mo	93.5	15	10	1.5	749	325.1	327	3	3	112.3	704.7	408.5	408.5
Weston Bay	-3.02	51.35	-3	51.5	11y 6mo	96.1	18	9	2.5	766.3	231.6	198.1	3	3	1191.1	1306	1248.5	1248.5
Rhyl Flats	-3.60	53.38	-3.5	53.5	13y 9mo	94.6	14	7	14.5	1104.9	306.5	225.7	2	2	703.1	703.1	703.1	703.1
Gwynt y Môr	-3.50	53.48	-3.5	53.5	12y 1mo	88.5	14	7	32.5	1086.9	252.9	198.9	1	1				

Table 3 (continued)

Study site	Nearest ERA5 grid node				Data length	Data coverage (%)	1 in 1-year return level						1 in 5-year return level					
									Number of days between exceedances						Number of days between exceedances			
	Longitude	Latitude	Longitude	Latitude			Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median	Exceedance count	Number of seasons with exceedances	Min.	Max.	Avg.	Median
New Brighton	-3.03	53.44	-3	53.5	1y 8mo	89.2	2	2	340.1	340.1	340.1	340.1						
Cleveleys	-3.20	53.89	-3	54	9y 9mo	96.9	11	9	31.7	700.5	295.9	317.8	3	2	31.7	2592.3	1312	1312
Morecombe Bay	-3.06	53.99	-3	54	9y 9mo	98.1	13	8	1	616	188.3	83.2	1	1				

4.1.1 Storm surge

First, we consider the measured storm surge component, shown in Fig. 4a, c. Without clustering, one might expect the 1 in 1-year exceedance to be reached each year at every site. However, it is evident in Fig. 4a that some storm years have multiple 1 in 1-year exceedances across multiple sites, and some storm years have no exceedances at certain sites and in certain regions. The 2013/14 storm year is the clear standout with the majority of UK gauges having elevated counts of threshold exceedances. Spatial coherence among sites in each of the 5 regions is apparent; i.e. if 1 site has a high number of exceedances, this is likely also apparent at the other sites within that region. Furthermore, in most storm years, exceedance counts are high across 2 or more of the 5 regions during the same period; at the 1 in 1-year level there is no storm year when exceedance counts are higher for just 1 of the 5 regions alone, implying that annual clustering impacts on large spatial scales across the UK. Surge exceedances at or above the 1 in 1-year level at each site are listed in Table 1. At all sites, the number of storm years when there was an exceedance is far less than the total number of years of data available, showing again that annual clustering is strongly prevalent in surge time-series. There were 161 storm surges exceedances in the 2013/14 storm year at or above the 1 in 1-year return level with 40 of the 42 operational tide gauges experiencing an exceedance in this period. 33 (29) gauges experienced 2 (3) or more exceedances in 2013/14. The storm years at the 1 in 1-year return level threshold that have similar high counts of exceedances across a large spatial coverage are the 1992/93 and 2006/07 periods. The 2006/07 storm year saw 114 storm surge exceedances across 41 out of 44 operational gauges for the 1 in 1-year level. In 1992/93, there was a similar number of storm surge exceedances (115) at the 1 in 1-year level, but these exceedances were across 32 out of 40 operational UK gauges. The 1992/93 storm year was the beginning of a 9-year period (1992/93–2001/02) which contained 7 out of the top 10 storm years on record in terms of total number of UK-wide storm surge exceedances at or above the 1 in 1-year return level threshold. Other periods of elevated exceedance counts occur with smaller spatial footprints. The 2011/12 storm year saw the second largest number of 1 in 1-year surge exceedances in North Sea gauges. This was despite 5 of the 12 operational gauges having no exceedances. The other UK regions during this period, except the Irish Sea, saw relatively low counts of exceedances relative to the rest of the time period (1979–2021) and the number of operational gauges.

At the 1 in 5-year return level threshold (Fig. 4c), the rarity of exceedances of this magnitude is apparent, as expected given the higher threshold, with long periods of few exceedances for large parts of the UK coastline and a much smaller overall count of exceedances (Table 2). Similar to the results from the 1 in 1-year threshold, some spatial coherence among sites in each of the 5 regions is apparent. However, with the exception of the 2013/14 storm year, exceedance counts are typically only higher across 1 or 2 of the 5 regions. This implies that meteorological forcing generally results in the annual clustering of smaller magnitude exceedances on a national scale, whereas the annual clustering of higher magnitude exceedances occur on a more local scale and are likely more reliant on storm paths. At the 1 in 5-year return level threshold, the 2013/14 storm year remains the most significant on record with 52 storm surge exceedances. 33 of the 42 operational tide gauges saw at least 1 surge exceedance. The 1992/93 storm year has the second highest annual total of 1 in 5-year surge exceedances (32), but the spatial coverage is reduced. All but 3 of the surge exceedances occurred across 16 North Sea and North Atlantic tide gauges. Interestingly, the 2006/07 storm year that had a high number of 1 in 1-year return

level surge exceedances does not have a matching signal at the 1 in 5-year return level. Each region has numerous multi-year periods where zero, or very few, exceedances were recorded. For example, between 2003/04 and 2018/19 in the English Channel, 1 in 5-year surge exceedances were only recorded in the 2013/14 storm year. There are also periods where it is evident that few exceedances occurred across the entire UK tide gauge network. The early-mid 1980's saw many storm years containing few exceedances, but there were 18 or more tide gauges that were not yet operational in this period. In contrast, some recent storm years where nearly all tide gauges were operational recorded few surge exceedances at the national scale. The 2003/04 storm year recorded only 2 surge exceedances at only 1 gauge, the storm years of 2016/17 and 2019/20 only saw 1 exceedance each, and the 2009/10 storm year recorded no surge exceedances across all operational UK gauges.

The annual counts of the corresponding modelled storm surge extremes from the CODEC hindcast, at or above the 1 in 1-year and 1 in 5-year return level are shown in Fig. 4b, d, respectively. Interestingly, although the CODEC hindcast has been extensively validated against measured still sea level data (with small root mean square errors and mean absolute errors in the high-frequency time-series; see Muis et al. 2020), the counts in surge exceedances above thresholds do not appear to closely agree. This would suggest that while the hindcast accurately captures the mean characteristics of measured still sea level well, the more extreme surge levels are not as accurately predicted at the gauge locations. For the coincident time period (1979/80–2018/19), it is apparent that CODEC underestimates the total number of exceedances across all gauges at the 1 in 1-year return level (1771 to 1502 exceedances), and the 1 in 5-year return level (382 to 179 exceedances), relative to the measured data. Differences in measured versus modelled total counts are also likely to be greater than stated, as there is a significant proportion of measured data missing due to non-operational tide gauges, whilst the modelled hindcast provides continuous gap-free data throughout the time period. Although there is some coherence between the measured annual storm surge exceedances and CODEC in relation to some of the periods of low, or no counts at the 1 in 1-year return level, the hindcast tends to overestimate the spatial footprint. The most evident difference between the modelled hindcast and the measured surge exceedances is the lessened signal of the 2013/14 storm year. It remains as one of the most significant periods but does not dominate the record like in the measured surge record. Instead, the most significant storm year in the modelled hindcast records is 1989/90. At the 1 in 1- (5-) year return level, 158 (37) surge exceedances were recorded across 40 (27) sites, whereas in 2013/14 there were 147 (31) exceedances across 44 (29) sites.

4.1.2 Wave

Next, we consider wave heights. The annual counts of measured high significant wave heights at each of the 45 waves site, at or above the 1 in 1-year and 1 in 5-year return level are shown in Fig. 5a and c, respectively. Due to the relatively short duration of measured wave data, it is more difficult to characterise interannual change. As with surge, the 2013/13 storm year stands out, with spatial coherence among sites being apparent in each of the 5 regions. The general pattern of wave exceedances is comparable to surge exceedances from the corresponding English tide gauges, but there is a greater number of neighbouring wave sites recording exceedances with the higher spatial density of wave sites. At the 1 in 1-year return level (Fig. 5a), numbers of exceedances are fairly consistent across all regions throughout the short record, with only the 2012/13 storm year having a high
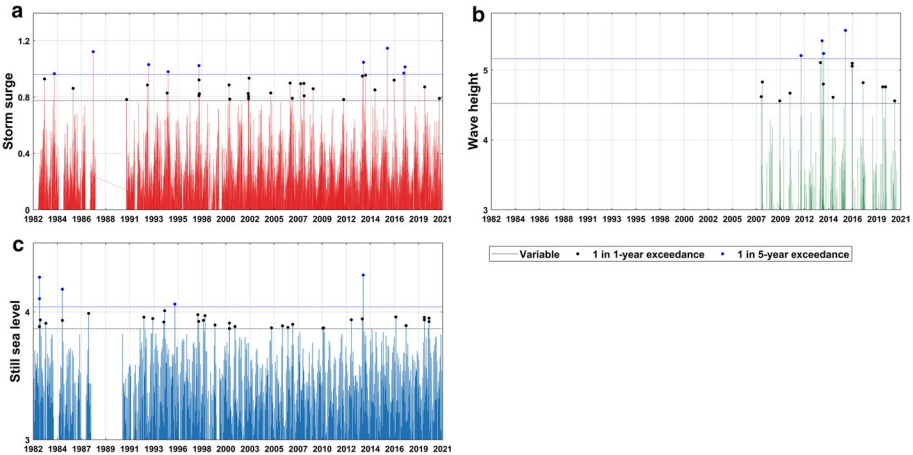
Fig. 2 Timeseries example of **a** storm surges at Newhaven, **b** significant wave height at Seaford, and **c** still sea levels (offset for MSL) at Newhaven—all parameters shown in metres (m). The timeseries are plotted with 1 in 1- and 5-year exceedances highlighted

number of sites not experiencing an exceedance with most sites being operational. At the 1 in 5-year return level (Fig. 5c), the North Sea sites appear to more consistently experience storm years with exceedances, but this is difficult to characterise relative to the particularly short data lengths. For example, Chapel Point has 4 storm years with a wave height exceedance at or above the 1 in 1-year level out of only 9 storm years in its record (Table 3). Sites in the English Channel have been operational for longer and show that periods of elevated counts of 1 in 5-year wave height exceedances can be preceded and/or followed by periods of no exceedances. There were only eight 1 in 5-year exceedances recorded between 2003/04 and 2012/13 across all operational sites in the English Channel and just 1
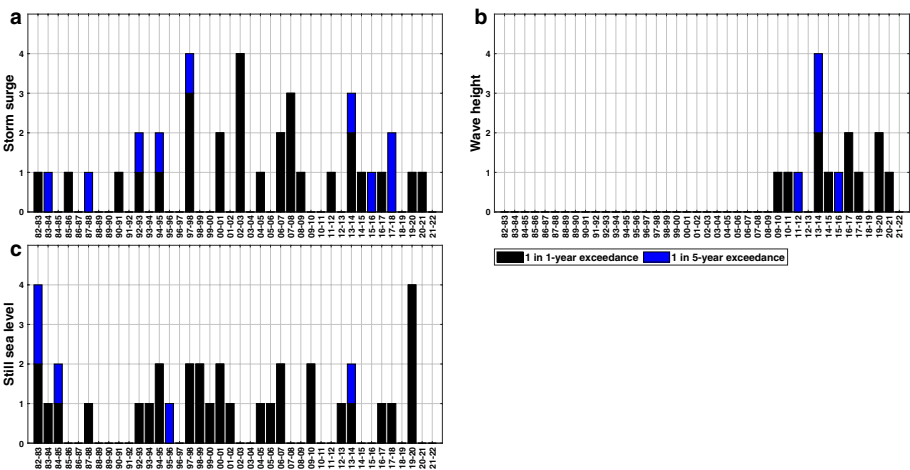
Fig. 3 Seasonal counts of exceedances above the 1 in 1- and 1 in 5-year return level for: **a** storm surges at Newhaven, **b** significant wave heights at Seaford, and **c** still sea levels at Newhaven

exceedance occurred between 2018/19 and 2020/21. In contrast, the extreme storm year of 2013/14 produced significantly higher exceedance counts in the English Channel. At both 1 in 1- and 5-year return levels, the 2013/14 period has the highest number of exceedances across all sites and most instances of a site experiencing > 1 exceedances in a storm year. This primarily occurred in English Channel wave sites. Across all sites and storm years of measured wave height data, ~ 25% of all 1 in 5-year exceedances happened at English Channel sites in the 2013/14 period.

The annual exceedance counts of the modelled high significant wave heights from the closest ERA5 hindcast grid node to the corresponding wave site, at or above the 1 in 1-year and 1 in 5-year return level are shown in Fig. 5b and d, respectively. There are fewer ERA5 grid nodes than NNRCMP wave sites due to the coarse resolution of the ERA5 wave hindcast. It is important to note that spatial coherence between sites in the modelled data will be strengthened by the fact that 13 sites share the same ERA5 grid nodes. Due to short wave records, the modelled data can only be contrasted to the measured data for the last ~ 10–15 years. The 2013/14 storm year has a high number of counts and a large spatial footprint at both return levels. However, similar to the modelled surge component, the 1989/90 storm year has a higher total of exceedance counts than 2013/14, but it cannot be validated whether this is unusual using the measured data (as it was with surge levels), due to the limited record of measured wave data which doesn't go this far back in time at most sites. After the 2013/14 storm year, the model underestimates the number of exceedances by 173 at the in 1-year level and 46 at the 1 in 5-year level when compared to the measured data. As expected, there are some clear similarities in the general patterns seen between the ERA5 hindcast wave heights and the ERA5-forced CODEC surge exceedances as both are primarily driven by the meteorology of the ERA5 reanalysis. At the 1 in 1-year return level, the ERA5 annual exceedances closely resemble the CODEC annual exceedances at the English tide gauges. One of the most noteworthy differences is the strong wave signal in 1979/80 which is not seen at most English tide gauges in the modelled surges. Interestingly, when discounting the shared wave grid nodes and focusing on the 30 distinct English wave grid nodes analysed in the ERA5 hindcast, compared to 46 UK grid nodes analysed in the CODEC hindcast, the modelled wave data have 58 more exceedances than the surge hindcast at the higher 1 in 5-year return level threshold. The modelled annual exceedances of wave heights also have a higher level of spatial coherence, with 4 more storm years having 6 or more neighbouring sites all experiencing at least 1 exceedance, despite the lower overall number of sites. This further highlights the smaller spatial scales associated with the annual clustering of higher magnitude exceedances.

4.1.3 Still sea level

Finally, we consider high still sea levels (e.g. tide plus surge, offset by MSL rise). The number of still sea level exceedances at or above the 1 in 1-year and 1 in 5-year per storm year, is shown in Fig. 6a and c for the measured data at each of the 46 tide gauge sites. As with storm surges and waves, the 2013/14 period is the most significant storm year on record for the total number of UK-wide measured high still sea level exceedances at both the 1 in 1- and 5-year return level threshold. There were 175 (68) high still sea level exceedances across 39 (34) of the 42 operational tide gauges at the 1 in 1- (5-) year return level. It is rare for a site to experience more than one 1 in 5-year still sea level exceedance in a storm year yet in 2013/14 this was the case for 21 gauges. The 2006/07 storm year had
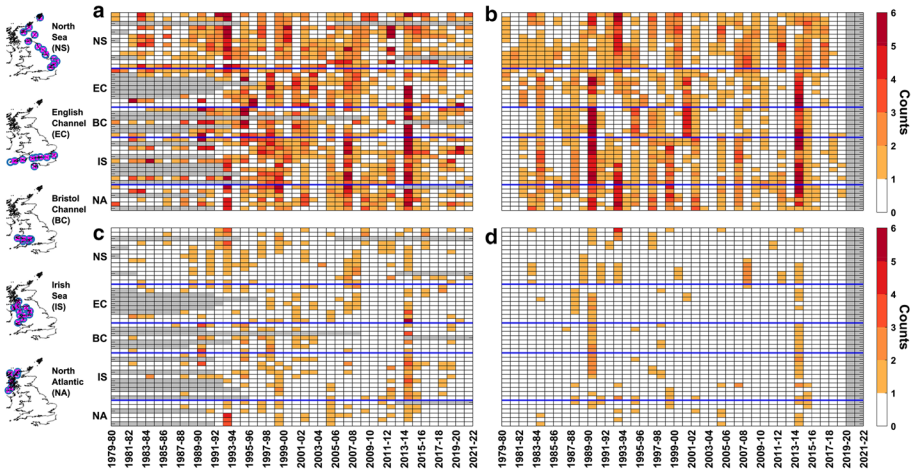
Fig. 4 Seasonal counts of storm surge exceedances from 1979/80. Panels (**a**) and (**c**) contain measured data from EA tide gauges and panels (**b**) and (**d**) contain modelled data from CODEC. The top panels (**a**, **b**) show counts at the 1 in 1-year return level and the bottom panels (**c**, **d**) show counts at the 1 in 5-year return level. The modelled data is from grid nodes closest to the corresponding tide gauge. The left-side panels illustrate the regional partitioning with blue circles being the tide gauges and red crosses being the corresponding grid nodes. This partitioning is further highlighted in the blue lines on the main panels. Grey shading indicates periods of no data availability
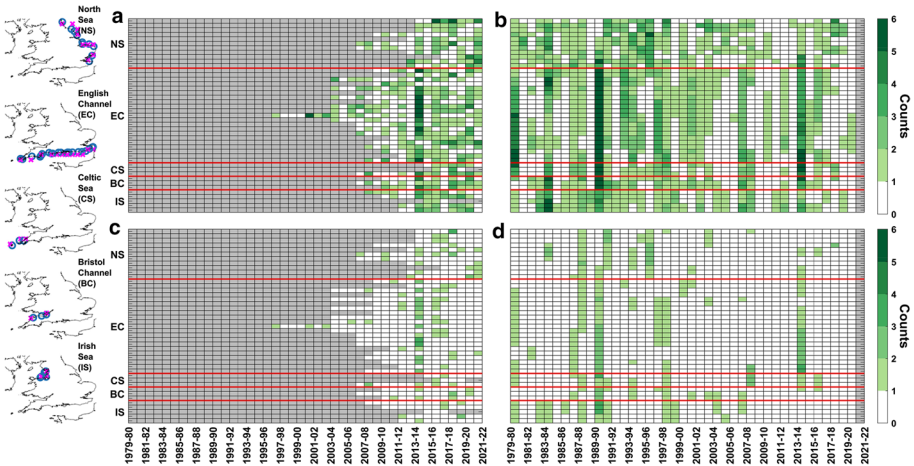
Fig. 5 Seasonal counts of significant wave height exceedances from 1979/80. Panels (**a**) and (**c**) contain measured data from NNRCMP wave sites and panels (**b**) and (**d**) contain modelled data from ERA5. The top panels (**a**, **b**) show counts at the 1 in 1-year return level and the bottom panels (**c**, **d**) show counts at the 1 in 5-year return level. The modelled data is from grid nodes closest to the corresponding wave site. The left-side panels illustrate the regional partitioning with green crosses being the wave sites and pink asterisks being the corresponding grid nodes. This partitioning is further highlighted in the red lines on the main panels. Grey shading indicates periods of no data availability
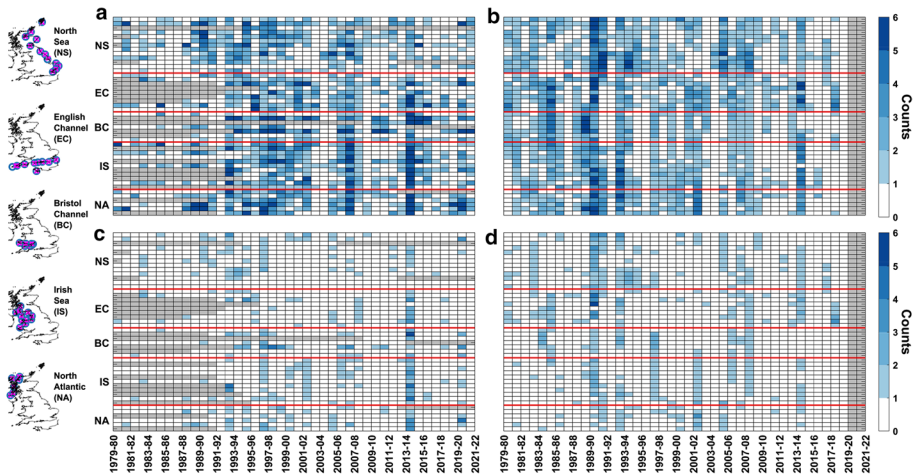
Fig. 6 Seasonal counts of still sea level (offset for MSL rise) exceedances from 1979/80. Panels (**a**) and (**c**) contain measured data from EA tide gauges and panels (**b**) and (**d**) contain modelled data from CODEC. The top panels (**a**, **b**) show counts at the 1 in 1-year return level and the bottom panels (**c**, **d**) show counts at the 1 in 5-year return level. The modelled data is from grid nodes closest to the corresponding tide gauge. The left-side panels illustrate the regional partitioning with blue circles being the tide gauges and red crosses being the corresponding grid nodes. This partitioning is further highlighted in the red lines on the main panels. Grey shading indicates periods of no data availability

the second highest count of 1 in 1-year still sea level exceedances, experiencing 149 across 40 of 44 operational gauges. However, as with storm surges, this period does not have a matching signal of 1 in 5-year return level exceedances. Only fifteen 1 in 5-year high still sea level exceedances were recorded across 12 gauges. Numerous 1 in 1-year return level exceedances that are clustered in the 1993/94 to 2001/02 period (Fig. 6a) are also not represented to a similar extent at the 1 in 5-year return level. There are clear differences in the measured still sea levels compared to the measured annual storm surge exceedances (Fig. 4a and c). Storm years that contain storm surge exceedances on local and regional scales do not necessarily have a corresponding signal of still sea level exceedances. At the lower 1 in 1-year return level, there are 254 more measured still sea level exceedances than storm surge exceedances (Table 1). All regions except the North Sea recorded stiller sea level exceedances than storm surge exceedances in the record. It is evident from Figs. 6a and 4a that the higher number of still sea level exceedances are clustered spatially and temporally to a larger extent than the storm surge exceedances, as there is a greater number of storm years with no still sea level exceedances at regional and national scales. The 9-year period (1992/93–2001/02) which contains 7 out of the top 10 storm years on record for 1 in 1-year return level surge exceedances, however, does also contain 7 of the top 10 storm year for high still sea level exceedances (6 matching storm years). Conversely, at the higher 1 in 5-year return level threshold (Fig. 6c), there were 44 more storm surge exceedances than high still sea level exceedances in the record (Table 2). This is despite both the North Atlantic and Bristol Channel regions recording higher still sea level exceedances than storm surge exceedances. The North Sea saw the highest number of storm surge exceedances (121) and the greatest difference between the numbers of still sea level exceedances (44 more surge exceedances, 26 more than the next largest regional difference in the English Channel) at the 1 in 5-year return level.

The number of modelled 1 in 1- and 5-year high still sea level exceedances (again offset by MSL rise) from the CODEC hindcast is shown in Fig. 6b and d for the grid nodes closest to each tide gauge. For the total count of exceedances across all gauges, the CODEC hindcast appears to better represent still sea level exceedances than surge exceedances at both 1 in 1- and 5-year thresholds for the coincident time period. At the 1 in 1-year return level (Fig. 6b), CODEC slightly underrepresents the measured data by a difference of 94 still sea level exceedances, whilst at the 1 in 5-year return level (Fig. 6d) CODEC slightly overestimates with 118 more modelled still sea level exceedances. The modelled still sea level data are consistent with some of the patterns seen across the modelled data for surges and waves. When exceedances occur in the modelled data, they tend to affect multiple neighbouring sites. The modelled still sea level data have more than double the number of storm years where 10 or more neighbouring tide gauges experience at least one 1 in 1-year exceedance. The 2013/14 storm year has a particularly reduced signal in the modelled still sea levels, despite having the third highest total count for a storm year; there were 87 (38) fewer exceedances compared to 1989/90. Like with surge levels, there is some coherence between measured and modelled still sea levels in relation to period of low, or no counts.

4.2 Intra-annual: Days-between exceedances

The second objective is to examine the characteristics of clustering on intra-annual timescales. To achieve this, we analyse the number of days between consecutive exceedances at or above the 1 in 1- and 5-year return levels for each of the 3 parameters, at each gauge site. We do this only for the measured datasets and the entirety of the measured data records available. As highlighted in Sect. 4.1, there are key differences in the modelled hindcast datasets when compared to the measured datasets in the annual count patterns of storm surge, wave height, and high still sea level exceedances.

The number of days between consecutive measured exceedances that occur within 365 days of the previous exceedance, at or above the 1 in 1- and 5-year thresholds, is shown in Fig. 7a, b for surge levels, 7c, d for wave heights, and 7e, f for still sea levels, for each gauge site available. Consecutive events occurring within 365 days of each other are evident at both return level thresholds. However, it is clear that there are many more examples at the lower 1 in 1-year return level, where numerous exceedances occurred within 365 days of the last. In each of the 3 parameters, there are a number of exceedances that occurred within very small time periods (i.e. < 3 days apart) for the 1 in 1-year threshold. Interestingly, there are many exceedances of still sea level at or less than 1 day, and between 6 and ~ 10 days (Fig. 7e); a feature not present in the surge (Fig. 7a) and wave (Fig. 7c) results. This is likely a result of the spring neap tidal cycle and confirms the findings of Haigh et al. (2016); when storms are separated by 4–8 days, 1 will always occur during neap tide, and the combined still sea level, even with a large storm surge, is unlikely to be high enough to lead to a high still sea level. As expected, given the higher threshold, there are much fewer exceedances occurring within shorter periods at the 1 in 5-year level, particularly in the surge and wave records.

The total number of exceedances and the minimum, maximum, median, and average number of days between consecutive exceedances for each site are listed in Tables 1 and 2 for tide gauges and Table 3 for wave sites. At the 1 in 1-year return level, the clustering of exceedances is prevalent. For example, there are 1793 still sea level exceedances that occur across all 45-gauge sites within 365 days of the last exceedance. However, at the 1 in 5-year return level, the clustering of exceedances becomes far less apparent. Only ~ 7% of the 1793

still sea level exceedances at or above the 1 in 1-year are at or above the 1 in 5-year level. A similar proportion of 1 in 5-year exceedances is shown across the other parameters analysed when compared to their respective 1 in 1-year return level exceedance totals (~7% for surges, ~8% for waves). Nevertheless, the proportions of 1 in 5-year exceedances occurring in quick succession is still of significance given the rarity of exceedances of this magnitude. Importantly, all parameters have the highest number of the exceedances occurring on short temporal scales in the periods of highest data availability. Therefore, it is likely that due to the drop off in data availability before the 1990's for tide gauge data, and the late 2000's for wave data, that a significant number of exceedances have been missed. The gap between many consecutive exceedances may also consequently be overestimated. Despite this, it is clear that significant numbers of exceedances are clustering over short periods.

Next, we consider the percentage of consecutive exceedances around the UK occurring at 6 different chosen timescales, namely: < 1–3 days, 3–14 days, 14–50 days, 50–100 days, 100–365 days, and ≥ 365 days. Results are shown in Fig. 8 for the 3 parameters, for both the 1 in 1- and 5-year thresholds. For all parameters, the majority (> 65%) of 1 in 1-year exceedances occur within 365 days of the previous exceedance. Importantly, significant proportions occur on far shorter timescales. At the 1 in 1-year threshold, approximately ~24% (~44%) of still sea level exceedances occur within 3 (50) days of the previous exceedance whereas ~10% of storm surge exceedances occur within 3 days and ~26% (~39%) occur within 14 (50) days of the previous exceedance. Approximately ~20% (~35%) of wave height exceedances occur within 14 (50) days. Of the still sea level exceedances occurring within 2 weeks of the last, ~75% occur in less than 2 days (Supplementary Figure S4). At the 1 in 5-year return level, exceedances occurring within 365 days of the previous exceedance account for ~26% of surge exceedances and ~34% of still sea level exceedances. Although there are 33 examples of quick succession still sea level exceedances occurring within 14 days of the last exceedance, all but 1 occurred within 4 days of the previous exceedance.

The percentages of consecutive exceedances at the 6 specified timescales are shown in Fig. 9a–e for surge and still sea level, but this time averaged across the sites within the specific 5 UK regions (shown in Fig. 1a) and again for all sites (Fig. 9f). Spatially, clustered periods of 1 in 1-year exceedances account for similar proportions of consecutive exceedances across all UK regions; there are negligible differences between regions. The regions that have the smallest proportions of successive 1 in 1-year still sea level exceedances occurring within 365 days of the previous exceedance are the North Sea and English Channel. The Bristol Channel and North Atlantic have the highest proportions occurring within 365 days of the prior exceedance. Both regions have over half of still sea level exceedances occurring within 50 days of the last exceedance. At the higher 1 in 5-year return level, the North Sea has the smallest proportions of exceedances occurring within 365 days of the previous exceedance for both still sea level and surge parameters. Only ~21% of still sea level exceedances and ~17% of surge exceedances occur within 365 days of the prior exceedance. The Bristol Channel has the highest proportions for the 2 parameters. Despite no 1 in 5-year still sea level exceedances occurring in the Bristol Channel within 14 days of each other, ~60% occur within 365 days of the last. Conversely, the Bristol Channel has a high proportion of 1 in 5-year surge exceedances occurring within 14 days of each other (~17%). North Atlantic gauges have no still sea level exceedances occurring within 3–14 or 50–100 days of the last. Nevertheless, the North Atlantic still has the second highest proportion of exceedances (~33%) occurring within 365 days of the prior exceedance. The North Atlantic has a higher percentage (~21%) of 1 in 5-year surge exceedances occurring within 14 days of the previous exceedance than the North Sea has exceedances occurring

within 365 days of the last (~ 17%), yet North Atlantic gauges record no instances of a 1 in 5-year surge exceedance occurring within either 14–50 days or 50–100 days of the previous exceedance.

The percentage of consecutive exceedances at the 6 specified timescales are shown in Fig. 10 for significant wave height; as the NNRCMP data is only for England, the data is averaged across the sites in 5 main English regions (Fig. 10a–e, the regions are shown in Fig. 1b) and again for all sites (Fig. 10f). The results must be approached with some caution, as some regions have a low number of sites, and the overall wave record length is short. Most of the wave sites are found in the English Channel, and these tend to also have the longest records. However, for the measured exceedances, the North Sea has by far the highest percentage (~ 20%) of 1 in 1-year exceedances occurring < 1–3 days after the previous exceedance, when compared to the other English regions. The other regions have ~ 14–21% of consecutive exceedances occurring within 14 days of the previous—except for the Irish Sea which only experiences ~ 4% of exceedances in < 1–3 days of the prior exceedance and no exceedances within 3–14 days. At the 1 in 5-year return level, the differences become starker as the greater rarity of these exceedances combine with the short records. The Irish Sea exhibits no exceedances within 14 days of the previous exceedance, the Celtic Sea has no exceedances within 50 days of the prior, and the Bristol Channel has no exceedances within 100 days of the prior. ~ 5 (~ 11%) of North Sea 1 in 5-year return level exceedances occur within 3 (14) days of the previous exceedance, whereas the English Channel has no exceedances within 3 days of the previous exceedance but has ~ 18% occurring within 14 days.

5 Discussion

We used measured and modelled still sea level and wave data to quantify the prevalence of storm clustering in surges, waves and still sea levels around the UK on interannual and intra-annual timescales. Analysis of interannual clustering around the UK showed that all parameters (i.e. surges, wave heights and still sea levels) exhibit consecutive storm years that contain high counts of exceedances, as well as consecutive storm years that contain low counts of exceedances. There are periods where significantly more exceedances are found compared to other storm years, such as 2006/07 or 2013/14—which is the stormiest on record (Matthews et al. 2014) and saw widespread coastal flooding due to extreme sea levels and waves (Haigh et al. 2016). Our results reaffirm this, with the season's high number of exceedances and large spatial footprint being unmatched across all measured parameters. These periods of varying counts of exceedances are likely linked to changes in the large-scale ocean-atmospheric patterns that have been shown to affect the prevalence of UK storm surges and waves, such as the North Atlantic Oscillation (NAO) or West Europe Pressure Anomaly (WEPA) (*e.g.* Woodworth et al. 2007; Castelle et al. 2017; Malagon Santos et al. 2017).

Importantly, there are storm years where numerous exceedances at the 1 in 1-year return level do not have a closely matched signal at the 1 in 5-year return level. For example, 2006/07 recorded 149 still sea levels at or above the 1 in 1-year level, but only 15 of those still sea levels were at or above the higher 1 in 5-year level. This clustering of lower magnitude events is important for beach recovery mechanisms as it has been shown that moderate to high energy winter wave conditions can be essential to morphological recovery at certain beaches whilst stalling recovery at others (Scott

et al. 2016; Dodet et al. 2019; Harley et al. 2022). With MSL continuing to rise into the future, these clusters of exceedances will be either of a higher magnitude or occur even more frequently through time as they will be associated with smaller surge events than currently observed—the vast majority of UK sea level exceedances at the 1 in 5-year return level are caused by moderate, rather than extreme, skew surge events that occur at high spring tides (Haigh et al. 2016). Consequently, understanding how the clustering of storms of a lower magnitude occurs in the atmosphere would be of interest as the literature investigating the atmospheric conditions responsible for the clustering of midlatitude storms has focused on only the most intense storms (e.g. Pinto et al. 2014; Priestley et al. 2017a, 2020; Dacre and Pinto, 2020).

There is a level of spatial coherence for exceedances shown among regions around the UK coast—if a site were to experience a storm surge, wave height, or still sea level exceedance in a storm year, it is likely that neighbouring sites in that region will also experience an exceedance in that period. This spatial coherence supports other research that has identified broad regional footprints of storm events (Haigh et al. 2016) and has been utilised in the risk assessments underpinning UK resilience planning (DEFRA, 2017). Incorporating the high levels of temporal clustering seen in this research into the synthetic scenarios created for the 'National Risk Assessment: Coastal Flooding Impact Analysis' (2017) would also allow for the sensitivity of impacts in the national scenarios to be tested against the arrival of storms in sequences.

A key finding of this work is that significant proportions of storm surge, wave height and still sea level exceedances are clustered on intra-annual timescales. As expected, exceedances of a lower-magnitude tend to cluster more than those of a higher-magnitude. Storm surge exceedances occurring within 50 days of the previous exceedance account for ~40% and ~15% of exceedances at or above the 1 in 1-year, and 1 in 5-year return level, respectively. Despite having a smaller storm window, which can allow for more quick succession clustering to be recorded, our analysis similar to that of Malagon Santos et al. (2017) resulted in lower proportions of 1 in 1-year wave height exceedances occurring within 4, 8, and 20 days of the last event when compared to their results. A similar proportion of wave exceedances occurred within 4 days of the previous event (~12% compared to ~16%), but we find only ~22% occurring within 20 days compared with Malagon Santos et al.'s (2017) ~50%. In contrast, we identify significant further clustering in still sea levels than Haigh et al. (2016). With our updated data record, we find 32 pairs of still sea levels that exceed the 1 in 5-year return level whilst Haigh et al. (2016) found 7; although, they focused on events across sites, whereas we focus on individual sites, so a direct comparison is not possible. We find that still sea levels cluster more than storm surges and waves, with ~25% (~9%) of all consecutive 1 in 1- (5-) year still sea level exceedances occurring within 4 days of the last and ~83% (~78%) of these exceedances occurring within 2 days. At both return levels, over half of all still sea level exceedances occurring within 28 days of the prior exceedance happen within 2 days. These quick-succession exceedances are likely to be a result of astronomical high tides either exceeding the threshold or raising the still sea level enough so that lower-magnitude storm surges raise the sea levels above critical thresholds. This is shown by the far higher number of 1 in 1-year storm surge exceedances occurring within 2 days of the last (123 pairs) compared to the 1 in 5-year exceedances (2 pairs).
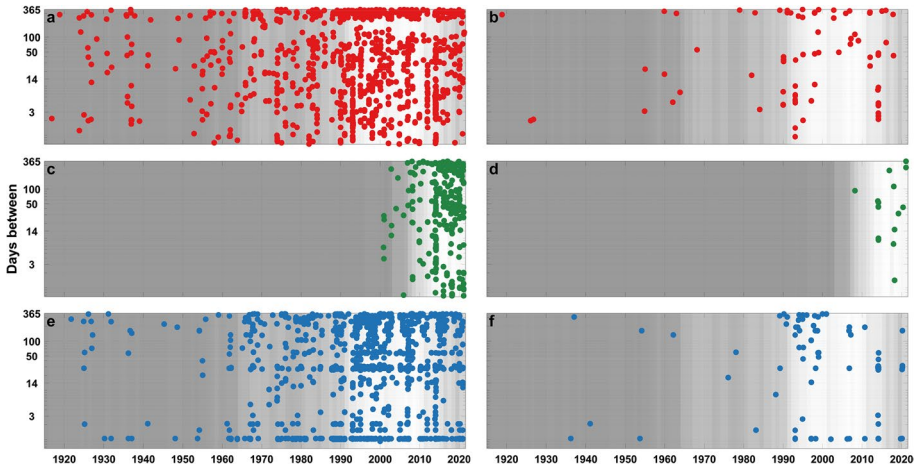
Fig. 7 Number of days between consecutive measured (**a**, **b**) storm surge, (**c**, **d**) significant wave height and (**e**, **f**) still sea level exceedances that occur in less than 365 days. The number of days is calculated for consecutive exceedances at individual sites and then collated. The left panels (**a**, **c**, **e**) are the number of days between consecutive 1 in 1-year return level exceedances whereas the right panels (**b**, **d**, **f**) are for consecutive 1 in 5-year return level exceedances. Grey shading indicates the number of sites where 50% of data within that year is available. The darker the grey the fewer sites have at least 50% data coverage for that year

Our analysis shows that storm surge exceedances are not always concurrent with still sea level exceedances. As discussed above, this is expected as high still sea levels are driven primarily by high spring tides and moderate, rather than extreme, surges (Haigh et al. 2016). The spring/neap tidal cycle was shown in Haigh et al. (2016) to prevent consecutive 1 in 5-year still sea level events occurring within 4–8 days of each other as one would always fall on neap tide. This tidal cycle leads to many 'misses' where extreme surge events do not coincide with extreme still sea levels as the combined sea level is not raised high enough. We found only one instance of 1 in 5-year still sea level exceedances occurring within 4–8 days of each other, but we did find 29 1 in 1-year still sea level exceedances occurring in this window. These represent particularly extreme surge events that raise still sea levels above the 1 in 1-year return level even at neap tide.

Our comparison between the measured and modelled datasets illustrated some of the important problems associated with using modelled hindcasts for the analysis of extremes. There are significant challenges in accurately modelling extreme events (Sillmann et al. 2017) and any model will inherit the uncertainties associated with the forcing used to drive the model. The modelled datasets used here accurately represented the general statistics of the measured data (as illustrated by the good level of validation; see Muis et al. 2020) but, as we show here, they do not capture some of the interannual and intra-annual signals and patterns in the exceedance levels. For instance, it is unclear why the stormiest period on record (2013/14) for still sea level, storm surge and significant wave height exceedances was not characterised to the same extent in the modelled data of those parameters. Nevertheless, hindcasts are the only method of gaining gap-free continuous data around the coast
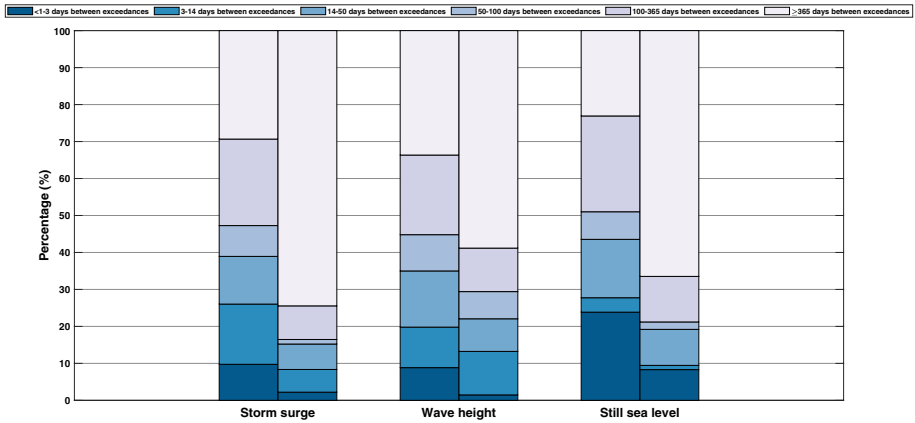
Fig. 8 Percentage of consecutive measured surge, significant wave height, and still sea level exceedances around the UK occurring at different timescales. The number of days is calculated for consecutive exceedances at every individual site and then collated. For each pair of stacked bars, the left bar is for 1 in 1-year return level exceedances and the right bar is for 1 in 5-year level exceedances
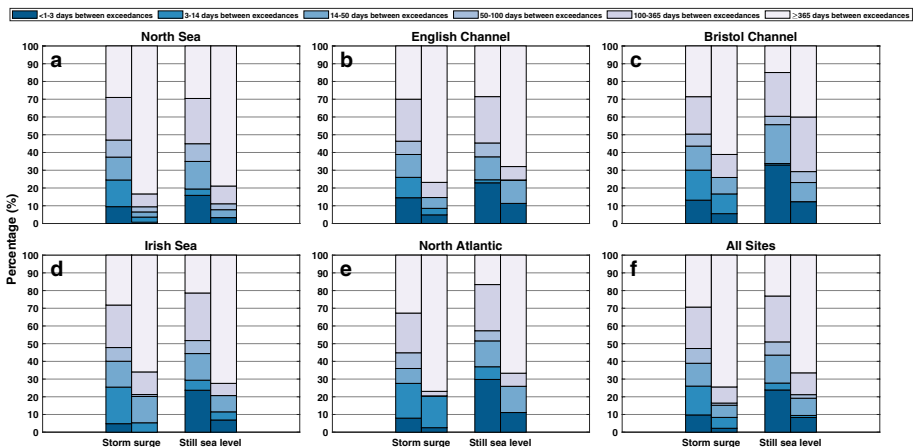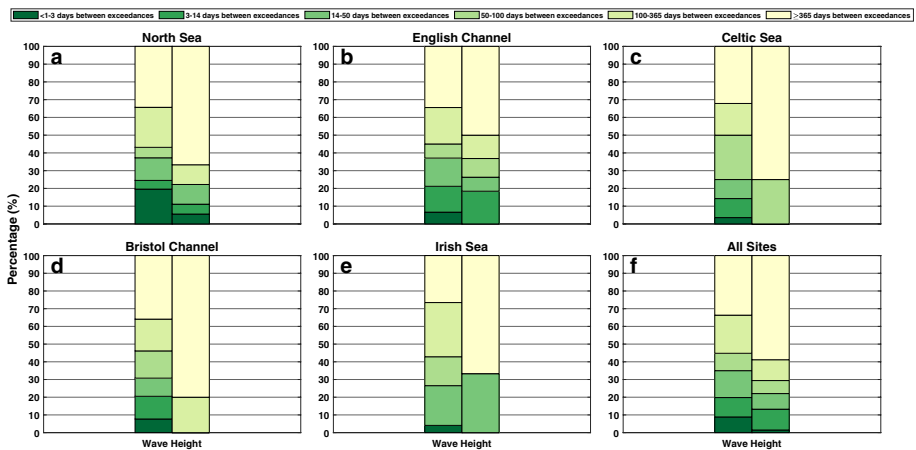

Fig. 9 Percentage of consecutive surge and still sea level exceedances occurring at different timescales for different regions of the UK shown in Fig. 1a. These regions are **a** North Sea, **b** English Channel, **c** Bristol Channel, **d** Irish Sea, **e** North Atlantic and **f** all regions together. The number of days is calculated for consecutive exceedances at individual sites and then collated by region. For each pair of stacked bars, the left bar is for 1 in 1-year return level exceedances and the right bar is for 1 in 5-year level exceedances

(and at ungauged sites), which is particularly important considering the short data record lengths of UK wave buoys.

A key limitation of our study is the lack of data availability through time. This is a common problem for the research of extreme natural hazards, but it is compounded in clustering research due to the further rarity of the phenomenon. Wave data are mainly limited to

the last decade and any analysis further back in time relies on modelled hindcasts. The varying data lengths of tide gauges also present the possibility of data bias when analysing the days between consecutive exceedances. Repeating the intra-annual (days between) analysis for tide gauge sites with > 30 years of data produces similar results to that of all sites (see Supplementary Figure S5). This indicates that the results are not significantly biased by sites with short data lengths and present an adequate portrayal of extremes through time. As the wave sites have far shorter data record lengths, an element of data bias must be considered in wave height results. The use of non-English wave buoys would improve this research, but wave buoys found in other parts of the UK (such as WaveNet's) are mainly further offshore and therefore unsuitable for this research. Although we have a higher density of sites for English regions when compared to the tide gauge network, we are missing key UK regions. For example, there are no wave sites in the North Atlantic nor on the northern coastline of the Bristol Channel—2 important regions of clustering identified from the still sea level and surge analysis.

This analysis focused on storm surges, significant wave heights and still sea levels. Other parameters, such as long period swell waves and total water level can also affect coastal flooding (e.g. Sibley and Cox, 2014) and understanding how these cluster across the UK would be of interest. The ERA5 wave hindcast contains wave swell and could also be used to create a novel dataset of total water level far longer than is possible with measured wave data. This extended dataset of total water levels around the UK coastline will be of particular interest as wave-induced water levels represent the maximum potential hazard from the compound effects of sea levels and waves. Further work could also examine the specific storm durations, severities and chronologies of the clusters found here. Such characteristics have been shown to greatly affect morphological response (Eichentopf et al. 2019) and analysis on this subject would help explain the extent that the exceedance clustering found in this research is affecting the UK coastline.

Fig. 10 Percentage of consecutive significant wave height exceedances occurring at different timescales for different regions of the UK shown in Fig. 1b. These regions are **a** North Sea, **b** English Channel, **c** Celtic Sea, **d** Bristol Channel, **e** Irish Sea and **f** all regions together. The number of days is calculated for consecutive exceedances at individual sites and then collated by region. For each pair of stacked bars, the left bar is for 1 in 1-year return level exceedances and the right bar is for 1 in 5-year level exceedances

6 Conclusions

In this paper we assessed the temporal characteristics of the clustering of storm surges, waves and high still sea levels around the UK coastline. We identified exceedances at or above the 1 in 1- and 1 in 5-year return level on two timescales: interannual and intra-annual.

We used annual counts of exceedances to identify interannual clustering across the time series and the spatial footprint of clustered periods. We compared measured datasets to modelled hindcast datasets and highlighted the issues surrounding the use of modelled data for the analysis of storm clustering. Exceedances are not consistent through time and there are significant periods with and without exceedances, at our two chosen thresholds. There is a level of spatial coherence between sites around different regions of the UK with elevated annual counts of exceedances frequently occurring across neighbouring sites in a given region. It is important to account for this when assessing the risk of events aggregated at large scales; for example, to inform insurance industry resilience or national emergency preparedness. The 2013/14 period is the most extreme storm year on record, with exceptional high counts across all parameters at both the 1 in 1- and 5-year return levels. Some storm years, such as 2006/07, also saw high numbers of exceedances at the lower 1 in 1-year return level without a matching high signal at the 1 in 5-year return level.

We then examined the number of days between consecutive exceedances to quantify the proportion of exceedances that cluster over intra-annual timescales within a storm year. We compared this between regions to classify differences between the levels of clustering around the UK coast. A key finding is that within storm years containing multiple exceedances, significant proportions of these occur in quick succession; storm surge, wave and still sea level exceedances occurring within 50 days of the previous exceedance account for ~ 35–44% and ~ 15–22% of exceedances at or above the 1 in 1-year and 5-year return level, respectively. The clustering of storms is apparent in all regions of the UK but is more prevalent in the North Atlantic and Bristol Channel, and less prevalent in the North Sea.

This research has demonstrated the prevalence of clustering of extreme coastal storm parameters at different temporal scales. It shows that coastal communities are likely to face multiple storm surge, wave and still sea level exceedances in stormy years, and that neighbouring regions are also likely to experience this as well during that period. This highlights the non-stationarity of extreme environmental return periods and the challenges associated with assigning these to individual events. The criticality of clustering of storms in quick succession for amplifying damage and limiting recovery of the natural and built coastal defence system has many implications for coastal stakeholders, be it for the repeated closure of storm surge barriers, event allocation and multiple payouts for insurers, or for higher levels of emotional distress within coastal communities that have been associated with repeat flooding (Lamond, 2014). Developing a greater understanding of the timescales on which storm surges, waves and still sea levels cluster allows for improved preparedness in emergency planning and will better support coastal resilience and adaptation measures. This is particularly pertinent to allow for fast, effective, post-event, actions to be taken in a future where a rapid increase in event frequency and clustering should be expected as MSL, and associated tide levels, continue to rise.

Declarations

Conflict of interests The authors have no competing interests to declare.

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