Journal of
Marine Science
and Engineering

MDPI

Article

Spatial Characteristics and Duration of Extreme Wave Events around the English Coastline

Thomas Dhoop * and Travis Mason

Channel Coastal Observatory, European Way, Southampton SO14 3ZH, UK; travis.mason@noc.soton.ac.uk
* Correspondence: thomas.dhoop@noc.soton.ac.uk; Tel.: +44-023-8059-8468

Received: 11 December 2017; Accepted: 30 January 2018; Published: 2 February 2018

Abstract: This paper presents an analysis of the spatial characteristics and duration of extreme wave events around the English coast. There are five geographic regions which are affected as coherent units under extreme wave conditions, incorporating a sixth micro-wave climate region (western Lyme Bay). Characteristic storm tracks are associated with each region. Storms affecting the East region (North Sea coast) seldom impact other areas of England, whilst in contrast, storms affecting the Southwest or Northwest also have some impact on the Southeast. Average storm duration varies from 5 h in the Northwest to 14 h on the East coast north of the Humber. Storm duration exceeding 12.5 h in the Southwest and East (northern half) near guarantees that storm waves will span High Water, when it is of most significance for beach management operations. Storms along the East coast can be associated with anticyclonic conditions, as well as low pressure systems.

Keywords: wave extremes; coastal; spatial footprint; storm duration; English coast

1. Introduction

Waves, particularly when they coincide with high water levels, can cause beach erosion and damage to coastal structures and defenses, leading to social, economic, and environmental consequences [1], including danger to public safety [2]. For a long time, studies of storm tides have demonstrated that impacts from coastal processes under extreme conditions vary considerably along coastlines [3–6], while, more recently, a similar argument was made for the spatial variability of wave extremes and their relevance for the management of coastal hazards [7].

Previous research that has discussed the impact of extreme waves on coastlines has focused primarily on storm climate characterization [8–12] and the morphological impact on specific beaches [13–16] or regions [17]. On a larger scale, Malagon Santos et al. [7] considered a multi-site analysis of the UK coastline using return periods calculated from data from 18 buoys, of which seven were deep water locations. In this paper, we follow a similar approach but use a dense network of 40 wave buoys deployed around the English coast, which allows a higher-resolution spatial analysis and highlights some important variations, with consequent beach management and forecasting implications.

In addition to the magnitude and spatial extent of extreme wave events, their duration is also paramount because of the obvious relationship with impacts on beaches, dunes, and structures, etc., and from the fact that longer duration extreme wave events must by definition increase the potential for coincidence of the event with High Water [18]. Many of the wave impact studies on specific beaches and regions take the duration of individual events into account [10–15]. However, as yet, there has been no multi-site study that compares the duration of extreme wave events for different parts of the English coastline, despite being of particular interest for operational beach management. Furthermore, the large spatial footprint and long duration of some of the events discussed in this paper can present important financial and practical considerations for flood management, the insurance sector, infrastructure reliability, and emergency response [19]. For example, the effects of long duration, extreme waves on port operations along the English coast have potentially serious consequences for national supply chains [20].

The analysis in this paper is based on the wave data from a network of coastal wave buoys around the English coast deployed by the National Network of Regional Coastal Monitoring Programmes of England (Figure 1). Their coastal wave network concentrates on measurements in shallow water (typically 10 m above Chart Datum) where, traditionally, there were few long-term datasets available. The aims of the network include the generation of characteristic nearshore wave climates for the design of coastal defenses, evaluation of the performance of existing beach management schemes, and validation of numerical wave transformation models [21]. To date, the coastal wave network comprises 37 directional Waverider buoys (www.channelcoast.org, Southampton, UK). RWE Innogy UK Ltd. (www.rwe.com, Dolgarrog, UK) and Wave Hub Ltd. (www.wavehub.co.uk, Hayle, UK) also make available real-time and archived data from their wave buoys off north Wales and Cornwall, respectively. Record length exceeds 10 years at the majority of sites, extending to ~16 years along the eastern English Channel.

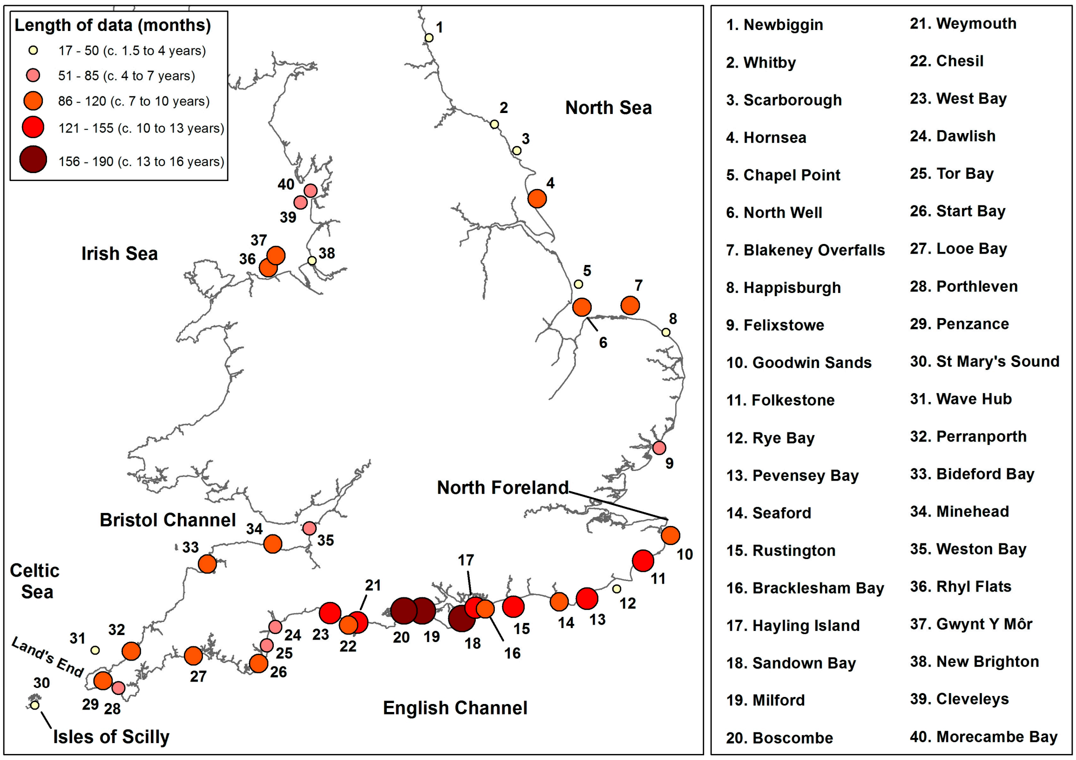


Figure 1. Location and deployment length of the wave buoys (with 90% monthly data return).

2. Methods

2.1. Wave Data

The rationale behind the location of the coastal wave network buoys is to provide site-specific wave information for beach management, rather than for generic nearshore wave data. However, the number of buoys currently deployed means that, in combination, they can produce a consistent, spatially-representative, shallow water wave climate of the English coast. Data from a total of 40 buoys was used, of which 37 are operated by the Regional Coastal Monitoring Programmes and three are industry-owned (Figure 1). The majority of the buoys are in water depths of about 10 m Chart Datum (CD), with only two sites (St Mary's Sound and Wave Hub) in ~50 m depth. All are Datawell's Directional Waverider (DWR) Mk III.

Wave parameters are derived from 30 min burst samples, every 30 min. Data transmission from the buoys is by HF (high frequency) radio and hence the processed parameters are derived by Datawell's "rfbuoy" software from the full spectrum (satellite transmission includes only a reduced number of spectral parameters). All processed parameters are subsequently quality controlled, monthly in arrears, by the Channel Coastal Observatory (CCO), using bespoke semi-automatic MATLAB routines, followed by a manual review. Full details of the CCO quality procedures are published by Mason and Dhoop [22]. Quality-control was particularly important for the highest storms at several sites, such as Bideford Bay, where waves were clearly depth-limited. All 1 Hz data and wave spectra were examined for the presence of artefacts, such as when the buoy "surfs" down the crest of large breakers, or when large waves breaking over the buoy "shock" the accelerometers, leading to artificially long and high wave traces approximately 2 min after the initial shock (Figure 2), which is the time-delay due to the electronic filters [23,24]. It should be noted that depending on when the initial "shock" occurs, the artefact may be reflected in the previous or following 30 min parameters, and therefore manual inspection of the 1 Hz data files is crucial. Wave parameters from any 30-min burst which showed evidence of contamination from very high or breaking waves were discarded.

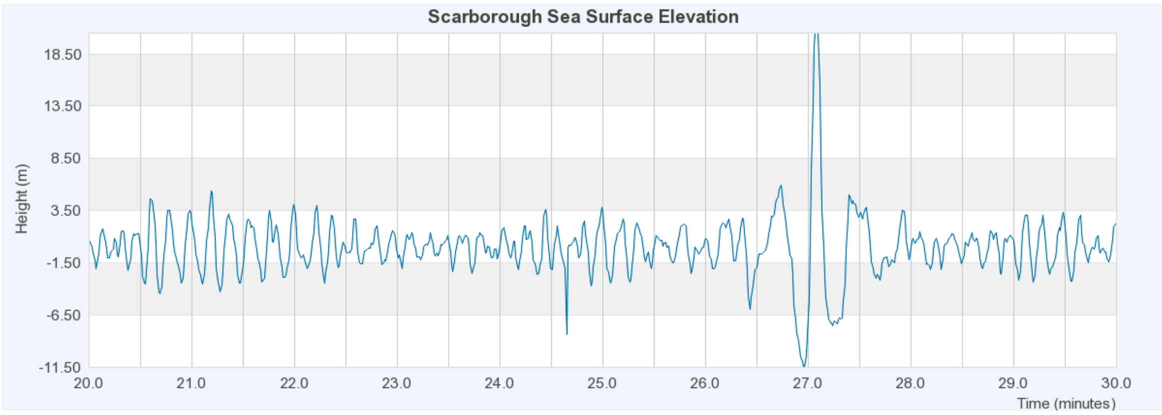


Figure 2. Ten-minute trace of 1.28 Hz data from the Scarborough wave buoy recorded on 13 January 2017 between 13:20 and 13:30UT. The spike between minutes 24 and 25 is the moment of shock to the accelerometers, leading to the apparent long and high wave artefact approximately 2 min after the initial shock.

Analysis used all measured data from the initial deployment of each buoy until 30 June 2017, so the record length varies from ~16 years (Milford-on-Sea) to 17 months (New Brighton). The median length across all measuring site records, meeting a minimum of 90% data return per month, was 102.5 months (>8.5 years).

2.2. Identification of Storms

For each site, significant wave height (H_S) return periods were calculated using the Peaks-over-Threshold (POT) method, with the threshold defined by the 95th percentile of all measured, quality-controlled data from each site, and with a 16-h storm separation window. A Weibull distribution was fitted to the extracted data set to produce H_S estimates for the 1 in 0.25, 1, 2, 5, 10, 20, and 50-year return periods [25].

The Weibull distribution has been used here for general conformity with many studies [26], although some more recent studies [7,27] use a generalized Pareto distribution (GPD) with the POT data. Caires [26] undertook a comparison of extremes calculation using a 20-year shallow water (19 m) dataset from the Netherlands using five different methods. She found that estimates using the POT/Weibull method fell into the middle of the POT-method ranges, but with narrower 95% confidence interval values. POT/GPD produced the lowest estimate for the 50-year return period

(8.30 m compared to 8.71 m for the Weibull/POT), but given the wide range of predictions produced by the different methods (8.30 m to 9.50 m), the more important factors may be record length and the overall wave conditions for the time series used for extremes analysis. For example, Mason and Bradbury [28] found that based on a seven-year subset of data, the addition of a further (particularly stormy) year led to a 7% increase in the 50-year return period H_S, whilst the addition of the same storm data to the full 16-year record resulted in only a 2% increase.

The calculated one-year return period H_S was used subsequently as the threshold to identify extreme wave events. The highest H_S measured during the continuous period where waves remained above the threshold was used to represent the conditions of that storm. Meteorological independence of individual storms was ensured by examining the Met Office's archived sea level pressure charts to confirm whether, for example, a storm spanning midnight, or two storms occurring within a 24-h day, were single or multiple storms.

The one-year return period threshold was found to be suitable to produce a sufficiently large sample of events, whilst only including those waves that can be considered "extreme" [7,29]. Furthermore, calculating return periods for each site effectively normalizes the significant wave heights achieved during a storm by removing the influence of local factors and water depth, and thus allowing for a regional comparison.

2.3. Spatial Footprints and Storm Tracks

The partitioning of the coast into regions affected coherently by storms was achieved by examining the spatial footprint of all 75 storms identified between 2004 and 2017. Regional partitioning was an iterative process, with the starting point being based on broadly east, south, or west coasts. With each broad region, a binary system was employed to define a coastline which was/was not affected by a storm, i.e., whether the storm exceeded the one-year return period or not. The "centroid" of the broad region was the site with the highest combined frequency/magnitude of storms. The regional partitioning emerged by mapping the extent of coast adjacent to the centroid site which was impacted by the same storm, thus identifying a range of spatially-extensive but regionally-exclusive storms. In this way, sections of coast which had a distinct and common behavioral response to extreme wave events were characterized. Examples of spatial footprints and their resultant geographical region are given in Figures 3 and 4 (see Section 3.1 below).

Storm tracks were digitized from the Met Office's sea level pressure charts, based on the location of the center of low pressure, at six-hourly intervals.

2.4. Duration

The duration of an extreme wave event is generally determined using two thresholds; an upper threshold to identify a particular storm, and a lower threshold to calculate the start time (moment of up-crossing) and end time (down-crossing) of the storm [30]. However, there is no general consensus in the literature as to how to attribute values to these two thresholds, and a wide variety of different definitions have been used [10–15].

In this study, storm duration thresholds have been selected based on coastal operational and engineering considerations; in the UK, long-term coastal engineering experience has shown that, on average, three or four storms per year have the potential to have significant impact for beach management. Accordingly, storm duration is selected to be the period when waves may be of operational significance, that is, above the 0.25-year return period, referred to henceforth as the "storm alert threshold". Hence, following the traditional method, storm duration is established via two thresholds: firstly, the one-year return period to define an individual storm (Section 2.2); and secondly, the period of time when H_S during the storm exceeded the storm alert threshold. Where a site had experienced a minimum of three individual storm wave events, the median storm duration was calculated.

3. Results

A total of 75 individual storms were identified between January 2004 and June 2017. Across 40 measuring sites, the storms generated a total of 244 extreme wave events, of which 25 exceeded the one-year return period threshold, and 22 exceeded the two-year, eight the five-year, five the 10-year, nine the 20-year, and six the 50-year return periods.

The 2013/2014 storm season stood out as having, by a large margin, the most individual storms (16 of the 75) and represented nearly 40% of the highest wave events. This unusual season, the waves it generated, and its impact on beaches along the south coast, have been discussed at length elsewhere [7,31–33].

3.1. Spatial Footprints and Storm Tracks

The results indicated that the coastline of England can be partitioned into five discrete coastal regions, each of which is impacted as a relatively coherent unit:

- East: North Sea coast from Newbiggin to North Foreland
- Southeast: Eastern half of the English Channel, from North Foreland to Portland Bill
- Southwest: Western half of the English Channel, from Portland Bill to Land's End and the Isles of Scilly
- Bristol Channel: Southern Celtic Sea coast from Land's End to Weston Bay
- Northwest: Northern Irish Sea coast from Llandudno to Morecambe Bay

Additionally, it was found that the southeast-facing coastline of western Lyme Bay has its own distinct "wave micro-climate" and is identified as a sixth region:

- West Lyme Bay: Exmouth to Start Point

Spatial footprints of individual extreme wave events are shown in Figures 3 and 4. Only the most significant storms are shown in these figures for clarity; the full dataset can be found in the Supplementary Material. Also plotted were the locations where the DWR's were operational, but where the measured waves did not reach the 0.25-year return period.

Although distinct coastal units can be identified, in most cases, storms impacting one coastal unit also had some impact on another unit, although to a lesser extent:

- The East coast remained mostly isolated in terms of spatial impact
- In addition to its own storms, the Southeast incurred lesser effects from storms in the Southwest, Bristol Channel, and Northwest, i.e., most storms with a major impact on western Britain also had some impact on the southeast English Channel
- In all other regions, secondary impact storms were typically only from neighboring coastal units.

The tracks of those storms which had a significant spatial impact on the coastline, as defined by Figures 3 and 4, were identified for each of the coastal regions (Figure 5). Storm tracks which affected the East coast region typically moved into the North Sea, broadly southwards into the southern North Sea or German Bight; one track (17–18 December 2009) moved southwest-wards along the coasts of the Low Countries. In contrast to storms affecting the southern and western coasts, however, those impacting the East coast were not always associated with deep depressions; rather, in half of the cases, the strong winds resulted from steep pressure gradients between shallow depressions (c. 1001 to 1010 hPa) in the southern and central North Sea, and intense anticyclones (c. 1034 to 1039 hPa) further north, over Norway or Iceland.

The majority of storms that impacted the Southeast region tracked in a north-easterly direction, across a wide latitudinal band, while two storms re-curved towards the north-west over the Scottish mainland towards Iceland. There was no consistent track to produce the highest measured H_S, which could occur with the center of the low-pressure system situated almost anywhere across much of the English mainland, Ireland, and west of Scotland. Of the 12 storms affecting the Southeast, only five impacted the Southeast exclusively, when the center of low pressure was usually south of Bristol to The Wash.

Most of the storms impacting the Southwest also tracked in a north-easterly direction, but generally across slightly more northerly latitudes. The centers of the depressions when the highest H_S was measured were mostly concentrated west of the UK mainland, above and around Ireland, with the sole exception being the most southerly storm of 29–30 April 2012, which moved over the Brest peninsula and south into mainland France.

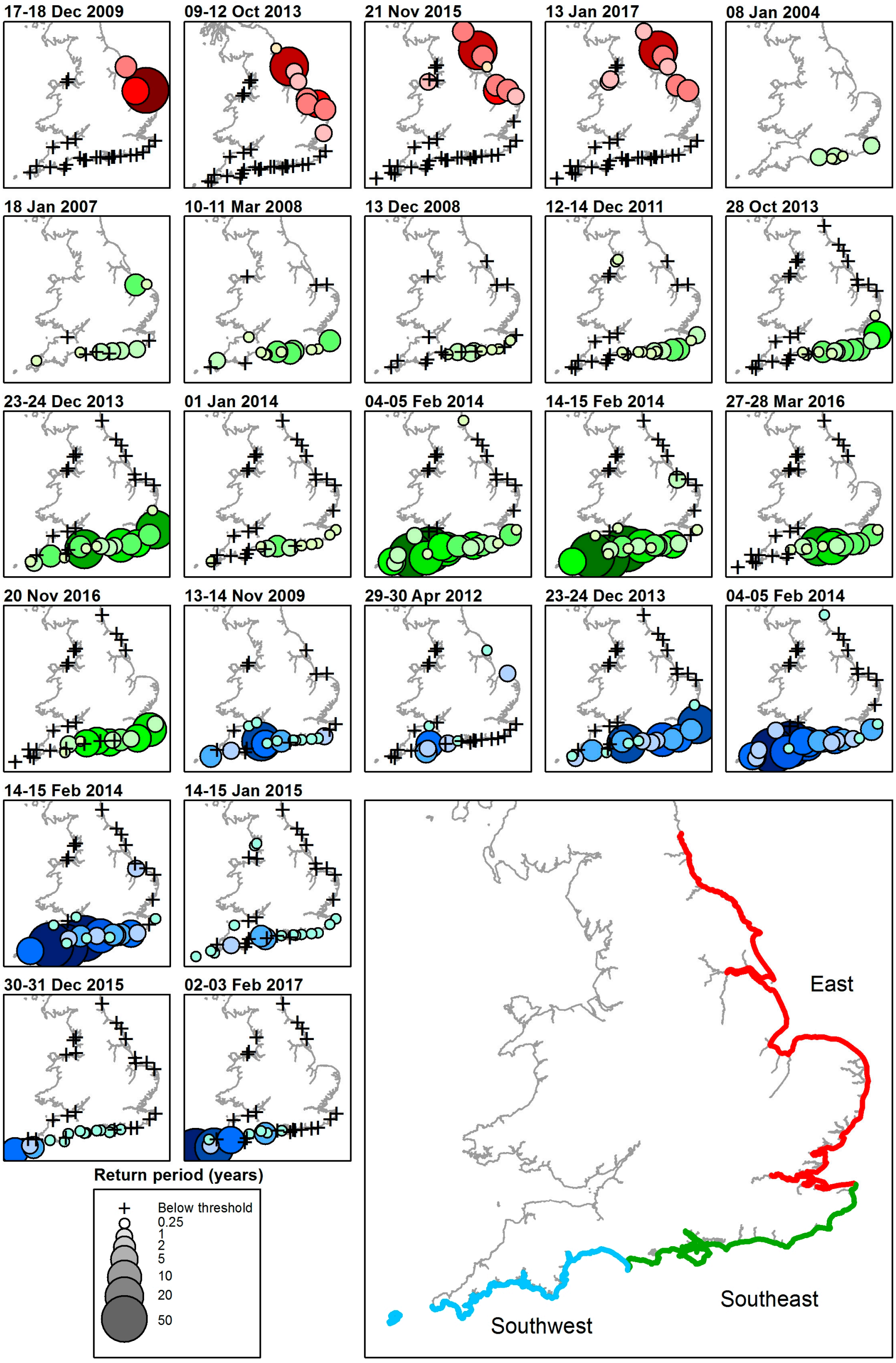


Figure 3. Spatial footprints of extreme wave events affecting at least three sites in the East, Southeast, and Southwest areas.

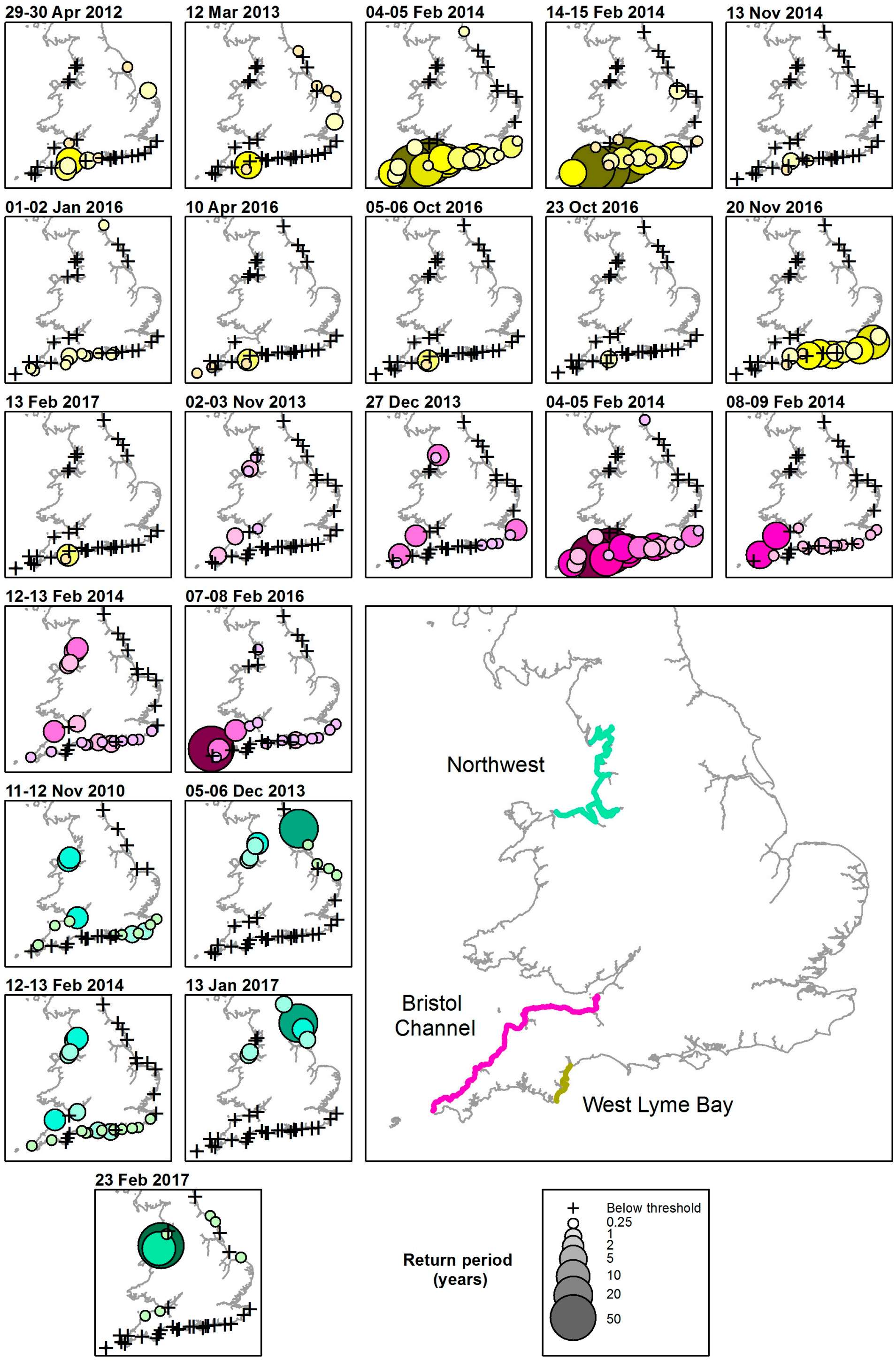


Figure 4. Spatial footprints of extreme wave events affecting at least two sites in the Bristol Channel and Northwest areas, and one site in West Lyme Bay.

The West Lyme Bay region was impacted by the same large north-easterly tracking storms which affected the majority of the Southeast and Southwest regions. However, there were five additional storms, generally with more southerly tracks but from a wide range of directions, which impacted West Lyme Bay but had minimal impact on the rest of the Southwest. When the highest H_S was generated, depressions tended to be located west of the Bay of Biscay, although the easterly and south-easterly winds generated from a shallow depression (c. 1017 hPa) in combination with an intense anticyclone (c. 1051 hPa) over southern Norway (as occurs in the East) could also affect West Lyme Bay (5–6 October 2016), whilst leaving the remainder of the western English Channel relatively unscathed.

All storms affecting the Bristol Channel followed a tight track across northern Britain, with the highest H_S occurring when the depression centers were off the west coast of Scotland.

The Northwest region was primarily impacted by storms tracking over the northern half of the UK, moving principally west to east, although one storm track originating in the Norwegian Sea and moving south along the eastern North Sea coast also produced storm waves in the Northwest (13 January 2017). The highest H_S measurements were usually generated with storm centers in the North Sea, but could also occur when the depression center was situated over the Northwest coast, e.g., 12–13 February 2014.

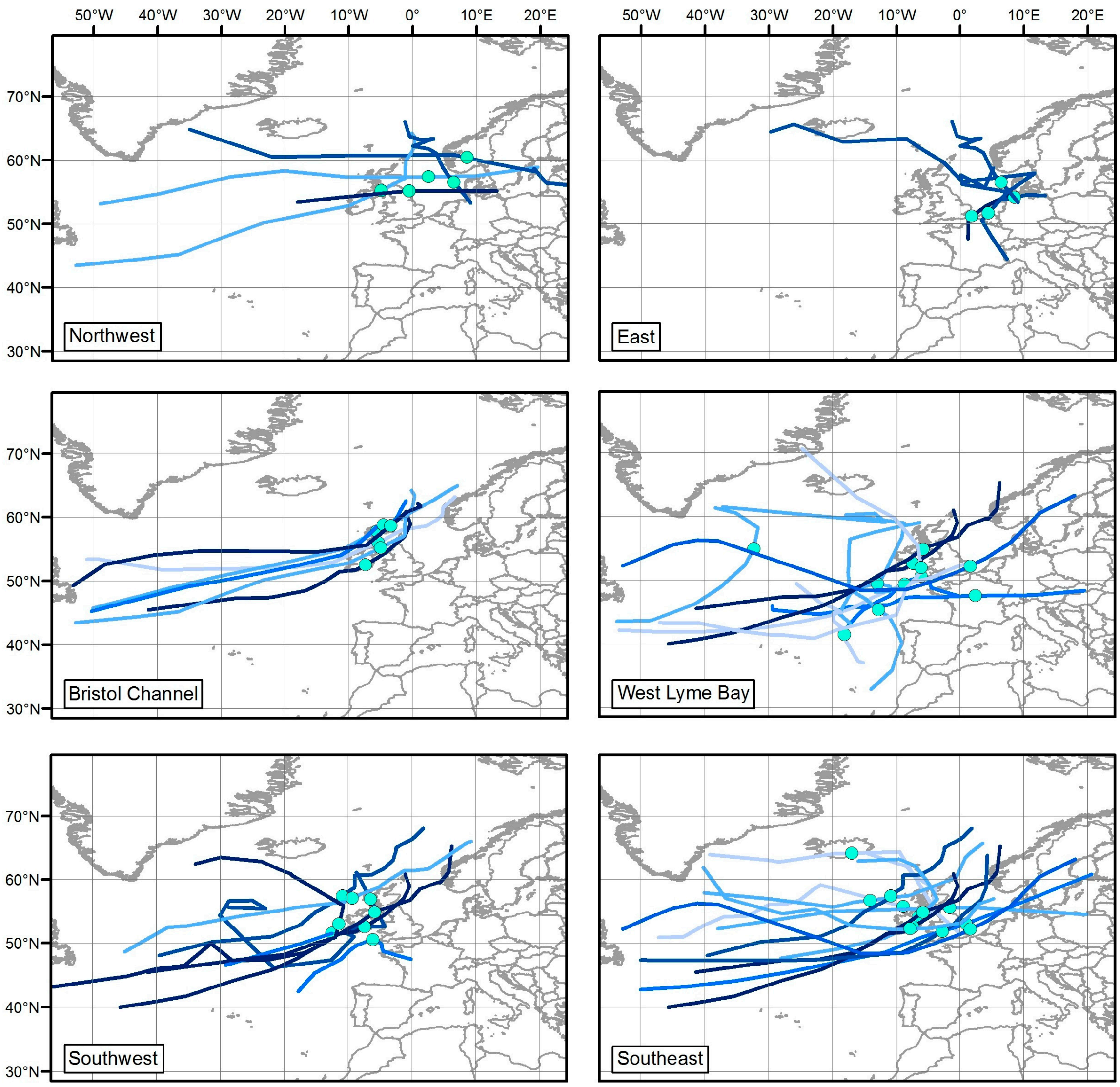
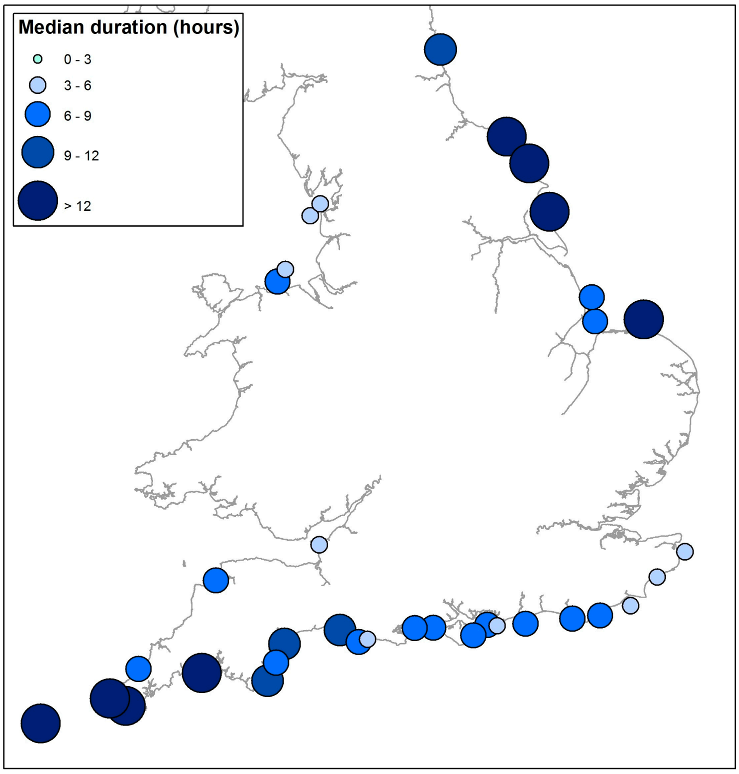


Figure 5. Storm tracks for the extreme wave events shown in Figures 3 and 4. The tracks are grouped according to the six discrete regions that were identified. The green circles indicate the location of the center of the low pressure system when the maximum significant wave height was recorded. Darker colored tracks represent longer return periods.

3.2. Storm Duration

Median storm duration around the coast of England is shown in Figure 6. The region with the shortest storms was the Northwest, with a duration of about 5.5 h. The median duration of storms affecting the Bristol Channel was 7 h, and 6 h in the eastern English Channel (Southeast). Storms along the western English Channel as a whole, including West Lyme Bay, had a median duration of 13 h but increased consistently to 14 to 17 h westwards from Looe Bay.

Storms along the East coast as a whole lasted around 12 h. However, although the East functions as a relatively coherent unit in terms of the spatial footprints of storms and storm tracks, storm duration is different within the coastal unit; north of the Humber, storms consistently last about 14 h, while along the East Anglian coast, median duration falls to 8.5 h.



Region	Median duration (hours)	Chance of extreme waves spanning High Water
East	12.0	97%
Southeast	6.0	50%
Southwest	13.0	100%
West Lyme Bay	10.0	81%
Bristol Channel	7.0	56%
Northwest	5.5	44%

Figure 6. Median duration of storms along the English coastline.

4. Discussion

4.1. Regional Partitioning

Observational data was used to better understand the spatial extents of extreme wave events around the English coastline over the past 16 years. Spatial footprints can help better inform flood management, the insurance sector, emergency response, and infrastructure resilience planning [19,20], particularly when considered in tandem with similar work on extreme sea levels and surge events [27].

Furthermore, spatial footprints determined from long-term measured conditions can be used to facilitate a more informed set of boundaries for extreme wave and flood modelling.

In general, the regional partitioning defined here followed the overall pattern of regions identified by Malagon Santos et al. [7] for the UK coastline, other than for the Southwest Peninsula. The higher density of wave buoys used in this study gave clear evidence that north Cornwall and south Cornwall are two distinct regions as regards storm waves and, furthermore, north Cornwall and the Bristol Channel were a coherent unit as regards spatial impact and the duration of storms. Accordingly, Land's End was found to be a more suitable boundary between the two regions. This study found that the Isles of Scilly, as represented by the St Mary's Sound DWR, fitted better with the Southwest spatial footprints, but the DWR is sited to the south of the Isles; without measurements, it is unclear whether the north of the islands would be better represented by the Southwest or the Bristol Channel/Southern Celtic Sea regions.

Identification of the micro-region of West Lyme Bay within the overall Southwest negates the need to split the southern England coastline at Start Point, as suggested by Malagon Santos et al. [7], in preference to Portland Bill, since any storm affecting the Southwest also tended to have some impact in West Lyme Bay, in addition to the West Lyme Bay exclusive storms.

The analysis presented here is principally concerned with wave extremes as defined by significant wave height, but at Chesil (which is fully exposed to the Southwest), long period swell waves approaching exclusively from the Atlantic are of major significance for overtopping and coastal flooding [34,35]. Swell waves can advance much further east, reaching Pevensey Bay on occasion [36], but in terms of the spatial impact of storm waves, Portland Bill typically marks the boundary between the eastern and western sections of the English Channel. Chesil, therefore, remains broadly within the Southwest region, in contrast to the nearby Weymouth Bay DWR, where the sheltering effect of Portland Bill restricts the storms to those affecting the whole Southeast area, together with the high magnitude 2013/2014 winter storms which impacted the entire Channel coast. However, the "special case" of Chesil is discussed further in Section 4.4 below.

4.2. Storm Duration

At a regional scale, the differential duration of extreme wave events is of particular importance for operational beach management, in light of the semi-diurnal tidal regime of the UK. The major operating concerns for high waves are twofold: firstly, the danger to life and property from wave overtopping and coastal flooding; and secondly, damage to sea defenses, where beach lowering in front of seawalls can lead to undermining of the foundations and subsequent damage or even collapse of the structure, as happened in Dawlish in 2014 [37,38] and at Folkestone in 2015. So, for beach operations, high waves are only of immediate concern if they span the period 1 or 2 h either side of High Water. Therefore, the 14-h median storm duration for the North Sea coast north of the Humber effectively means it is near certain that storm waves will coincide with the upper part of the tidal cycle at some stage, with a ~70% likelihood for the southern North Sea coast.

In contrast, there is only a ~50% chance of the storm spanning High Water in the Southeast, Bristol Channel, and Northwest. Interestingly, median storm duration in the Southwest, including West Lyme Bay, exceeds the 12.5 h tidal cycle, near guaranteeing waves occurring around High Water, in particular west of Looe Bay.

The median duration lengths in the western and southern regions in England typically result from the relative exposure or shelter of the coastline to the passage of fast-moving low-pressure systems originating in the Atlantic (Figure 6). For example, the median 13 h duration for the Southwest is heavily weighted by long-lasting storms measured by all DWR's from the Isles of Scilly to Looe Bay, all of which are exposed to waves from the SSW to westerly quadrant, either directly or refracted, whilst on the north Cornwall coast, the sheltering effect of Ireland tends to truncate the period of higher waves once the storm track moves further north. Along the North Sea coast, in contrast, the low-pressure systems tend to slow down and hence the broadly linear coastline is exposed to wave-generating systems for much longer. The long median storm duration is also influenced by the presence of autumn and winter anticyclones over Norway or northern Britain, as discussed below.

4.3. Storm Generation Mechanisms

Two distinct modes of storm generation were identified: firstly, the more prevalent storms associated with the passage of a deep mid-latitudes depression along the polar front; and secondly, a small sub-set of six (of 75) storms associated with anticyclones, where the largest pressure gradient (typically 25–30 hPa) was between a high pressure system to the north and an area of shallow low pressure further south (see Figure 7 which illustrates the three anticyclonic storms with the largest spatial footprint). These pressure gradients are of a similar magnitude to those experienced during the passage of low-pressure systems. Furthermore, given the quasi-stationary nature of large high-pressure systems, the associated higher winds around the edge and blocking of low pressure systems from the west means that they can lead to long periods of extreme storm waves. For example, the anticyclonic storm which impacted the East coast on 11 October 2013 (Figure 7, track no. 3) was the longest measured storm at Whitby (25 h), Scarborough (28 h), Happisburgh (19 h), and Felixstowe (13.5 h). A similar anticyclonic storm on 18 December 2009 (Figure 7, track no. 2) generated a 19.5 h storm at Hornsea (the Scarborough, Whitby, and Newbiggin buoys were not deployed in 2009). Overall, the five anticyclonic-generated events affecting the East coast together caused 16 of the 52 individual extreme wave events over the one-year return period, and constituted over half of the longest-duration events.

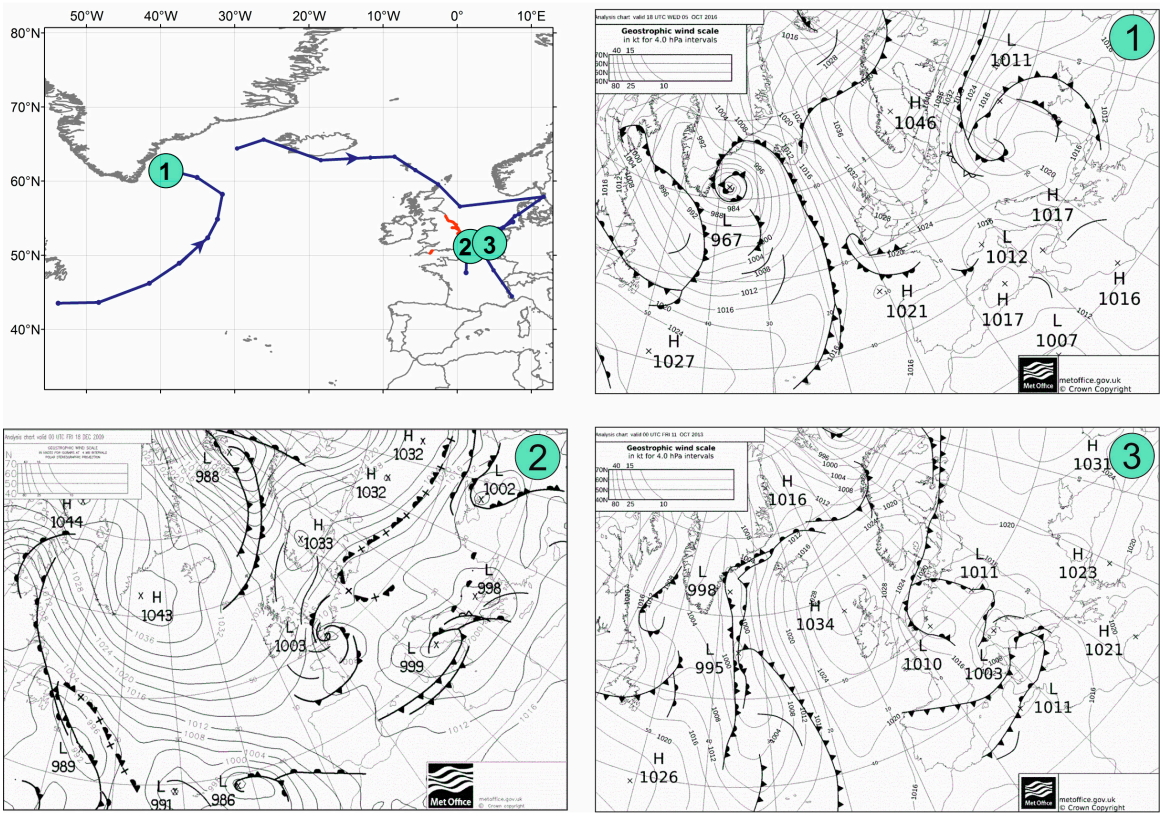


Figure 7. Tracks of storms caused by large pressure gradients between a high-pressure system to the north and a shallow area of lower pressure further south.

By default, storm waves associated with this generating mechanism are not associated with low barometer readings, nor with a "named storm", and affect only the east coast or western Lyme Bay (see below). Early forecast of these meteorological conditions may be a useful alert for coastal engineers and managers.

4.4. Region-Specific Considerations

In West Lyme Bay, five of the eleven storms affected the area exclusively with no impact elsewhere around the English coast. The meteorological conditions for four of these five storms were fairly slow moving, complex low-pressure systems, originating in the western Atlantic tracking from either north or south, with a moderately deep depression (~985 hPa) centered at the storm peak off the Southwest Approaches (Figure 8, storm no. 1 to 4). This geographical configuration of pressure systems generated the easterly or south-easterly wave conditions which are effectively onshore for the beaches of western Lyme Bay. Since the prevailing wave direction is from the southwest, including for over half of the storms affecting western Lyme Bay, the beaches are generally in equilibrium with south-westerly waves. As a result, storm waves from the easterly quadrant can lead to rapid re-shaping of the beach, either by cross-shore sediment transport, or resulting in wholescale beach rotation as reported at Slapton Sands [39].

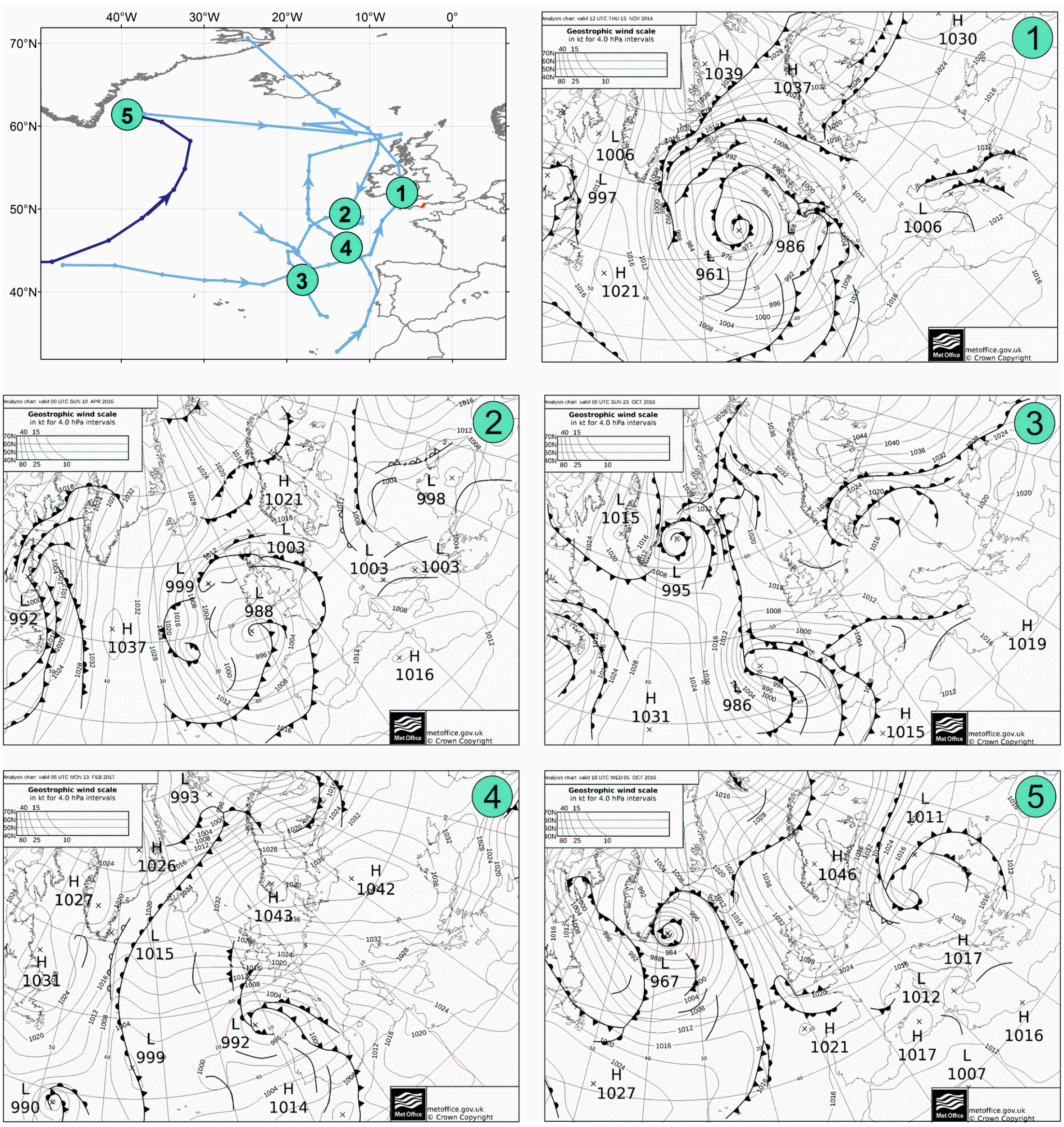


Figure 8. Tracks of storms affecting only West Lyme Bay. The associated pressure charts show the situation around the time when the highest waves were generated.

As with the majority of storms affecting the English coast, all storms affecting western Lyme Bay as discussed above were associated with the polar front. The remaining single storm affecting West Lyme Bay exclusively (Figure 8, storm no. 5) was derived from an intense anticyclone over central Norway, sufficiently extensive and long-lasting to be considered a "blocking-high" and generating a 9-h storm of due easterly waves on 5 October 2016.

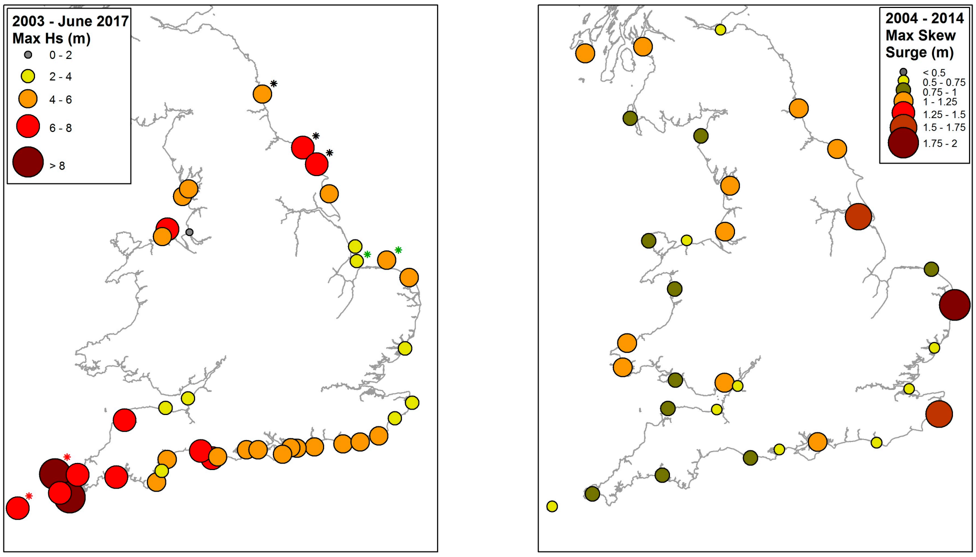
Chesil DWR, meanwhile, is the only site where waves exceeded at least the storm alert threshold from almost any storm occurring along the English Channel. Of the 18 storms measured by the Chesil DWR, half were common to both regions and a further eight storms occurred in common with the Southeast region, whilst only a single storm was in common with the Southwest alone. For beach operations at Chesil, therefore, the storm forecast for sites as far eastwards as Newhaven may be relevant as a warning of some lesser impacts west of Portland Bill.

The Northwest is the least exposed to repeated storms, with only five events that affected two sites or more since 2010, four of which also had some impact in either the Bristol Channel or North Sea. The storm durations are also some of the shortest experienced along the English coastline. Yet the storm of 23 February 2017 (Storm "Doris") was a one in 50-year event on the north Wales coastline (as recorded by the Gwynt Y Môr DWR), with only a relatively minor impact elsewhere in England, in terms of extreme wave conditions. The storm center tracked rapidly due eastwards across Northern Ireland and Cumbria. This illustrates clearly that although the frequency of extreme waves is lower than for the other regions and indeed, with a tidal range of up to 10 m, the likelihood of high waves coinciding with High Water in this area is consequently quite low given the short storm duration, coastal flooding and damage can be significant. The relatively concentrated pattern of storm tracks identified here may aid future forecasting of potential coastal flooding in this area. Similarly, the Bristol Channel area is only affected by a narrow band of storm tracks.

4.5. National Considerations

Coastal forecasting and analysis in the UK is heavily weighted towards the prediction of tidal surges, particularly in view of the notable extreme water levels recorded along the North Sea coast on 5/6 December 2013 [29,40,41]. For other coastal regions, however, particularly the Southeast and Southwest (including West Lyme Bay), tidal surges exceeding ~1 m are uncommon, as illustrated in Figure 9, which shows the maximum skew surge recorded at the Class A tide gauge sites between 2004 and 2014 (data extracted from Haigh et al. [42]), together with the spatial distribution of maximum H_S measurements. In the Southeast and especially the Southwest and southern Celtic Sea/Bristol Channel areas, serious damage and risk to property and life tend to be associated with wave action (beach erosion and/or run-up and overtopping) spanning High Water as the primary factor, rather than or supplemented by extreme water levels generated by surges.

Even along the East coast, where much effort is expended on surge prediction, wave action can be shown to be of similar importance for beach management as extreme water levels. In addition, the identification of the East coast as a region impacted as a relatively coherent unit, and subject to long-lasting extreme wave events (especially north of the Humber) is an important argument for the inclusion of wave processes when considering hazards to port operations, which has so far been neglected.



(**a**) (**b**)

Figure 9. Maximum significant wave height measured by the wave buoy network (**a**) and maximum skew surge measured by the UK National Tide Gauge Network (**b**). The black asterisk indicates a buoy in ~15–20 m CD water depth, the green asterisk a buoy in ~2–30 m CD water depth, and the red asterisk a buoy in ~50 m CD water depth. All other buoys are in 1–15 m CD depth. Maximum skew surges were measured between 2004 and 2014, and were extracted from Haigh et al. [42].

5. Conclusions

The coastline of England can be partitioned into five regions each of which is impacted by storms in a coherent manner, along with a sixth, micro-region (West Lyme Bay) which experiences additional storms which have no impact on the remainder of the English Channel. Characteristic storm tracks can be associated with each coastal region.

The Southwest region as a whole experiences the highest waves and longest duration storms, closely followed by the east coast, north of the Humber. Median storm duration in these areas exceeds 13 h and, accordingly, extreme waves typically span High Water.

Although much less prevalent than polar front storms, the anticyclonic-generated storms that affect the east-facing English coastlines are of a similar magnitude but a much longer duration, due to the generally more stationary nature of high-pressure systems, and are therefore of significance for operational coastal management.

This research should further confidence in the link between forecast storm tracks and spatial footprints. Consequently, this can provide vital early warning for immediate beach operations where even an additional 12-h notice is beneficial for arranging specialized machinery for beach reworking to prevent potential damage to infrastructure; or, conversely, that such machinery is unlikely to be needed. Similarly, the potential spatial footprint could prove particularly important for the logistics behind the deployment of emergency response units or temporary barriers for coastal flooding. Furthermore, the duration of storms is an important and somewhat neglected variable when assessing potential danger to public and private infrastructure by the insurance sector and in assessments of infrastructure reliability.

Supplementary Materials: Supplementary materials can be found at www.mdpi.com/2077-1312/6/1/14/s1.

Acknowledgments: The National Network of Regional Coastal Monitoring Programmes is funded by the Department for Environment, Food and Rural Affairs (DEFRA). Data from the wave buoys at Wave Hub, Rhyl Flats, and Gwynt Y Môr were kindly provided by Wave Hub Ltd. and RWE Innogy Ltd.

Author Contributions: T.D. conceived the study, performed the analysis, and co-wrote the paper. T.M. provided technical oversight and co-wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jonkman, S.N.; Vrijling, J.K. Loss of life due to floods. *J. Flood Risk Manag.* **2008**, *1*, 43–56. [CrossRef]
2. Wolf, J. Coupled wave and surge modelling and implications for coastal flooding. *Adv. Geosci.* **2008**, *17*, 19–22. [CrossRef]
3. Battjes, J.A.; Gerritsen, H. Coastal modelling for flood defence. *Philos. Trans. R. Soc. Lond. A Math. Phys. Eng. Sci.* **2002**, *360*, 1461–1475. [CrossRef] [PubMed]
4. McInnes, K.L.; Hubbert, G.D.; Abbs, D.J.; Oliver, S.E. A numerical modelling study of coastal flooding. *Meteorol. Atmos. Phys.* **2002**, *80*, 217–233. [CrossRef]
5. Lewis, M.; Horsburgh, K.; Bates, P.; Smith, R. Quantifying the uncertainty in future coastal flood risk estimates for the UK. *J. Coast. Res.* **2011**, *27*, 870–881. [CrossRef]
6. Lewis, M.; Schumann, G.; Bates, P.; Horsburgh, K. Understanding the variability of an extreme storm tide along a coastline. *Estuar. Coast. Shelf Sci.* **2013**, *123*, 19–25. [CrossRef]
7. Malagon Santos, V.; Haigh, I.D.; Wahl, T. Spatial and temporal clustering analysis of extreme wave events around the UK coastline. *J. Mar. Sci. Eng.* **2017**, *5*, 28. [CrossRef]
8. Dolan, R.; Davis, R.E. An intensity scale for Atlantic coast northeast storms. *J. Coast. Res.* **1992**, *8*, 840–853.
9. Lemm, A.J.; Hegge, B.J.; Masselink, G. Offshore wave climate, Perth (Western Australia), 1994–96. *Mar. Freshw. Res.* **1999**, *50*, 95–102. [CrossRef]
10. Shand, T.D.; Goodwin, I.D.; Mole, M.A.; Carley, J.T.; Browning, S.; Coghlan, I.G.; Harley, M.D.; Peirson, W.L.; You, Z.-J.; Kulmar, M.A. NSW coastal storms and extreme waves. In *Water Research Laboratory Technical Report*; University of New South Wales: Sydney, Australia, 2010. Available online: http://www.coastalconference.com/2010/papers2010/Tom%20Shand%20full%20paper.pdf (accessed on 10 June 2017).
11. Mendoza, E.T.; Jimenez, J.A.; Mateo, J. A coastal storms intensity scale for the Catalan sea (NW Mediterranean). *Nat. Hazards Earth Syst. Sci.* **2011**, *11*, 2453–2462. [CrossRef]
12. Amaroli, C.; Ciavola, P.; Perini, L.; Calabrese, L.; Lorito, S.; Valentini, A.; Masina, M. Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy. *Geomogphology* **2012**, *143–144*, 34–51. [CrossRef]
13. Corbella, S.; Stretch, D.D. Multivariate return periods of seas storms for coastal erosion risk assessment. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 2699–2708. [CrossRef]
14. Almeida, L.P.; Vousdoukas, M.V.; Ferreira, Ó.; Rodrigues, B.A.; Matias, A. Thresholds for storm impacts on an exposed sandy coastal area in southern Portugal. *Geomorphology* **2012**, *143–144*, 3–12. [CrossRef]
15. Masselink, G.; Austin, M.; Scott, T.; Poate, T.; Russell, P. Role of wave forcing, storms and NAO in outer bar dynamics on a high-energy, macro-tidal beach. *Geomorphology* **2014**, *226*, 76–93. [CrossRef]
16. Castelle, G.; Marieu, V.; Bujan, S.; Splinter, K.D.; Robinet, A.; Sénéchal, N.; Ferreira, S. Impact of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy coast: Beach and dune erosion and megacusp embayments. *Geomorphology* **2015**, *238*, 135–148. [CrossRef]
17. Plomaritis, T.A.; Benavente, J.; Laiz, I.; Del Río, L. Variability in storm climate along the Gulf of Cadiz: The role of large scale atmospheric forcing and implications of coastal hazards. *Clim. Dyn.* **2015**, *45*, 2499–2514. [CrossRef]
18. MacClenahan, P.; McKenna, J.; Cooper, J.A.G.; O'Kane, B. Identification of highest magnitude storm events over western Ireland on the basis of wind speed and duration thresholds. *Int. J. Climatol.* **2001**, *21*, 829–842. [CrossRef]
19. Cabinet Office. National Risk Register of Civil Emergencies. 2015. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf (accesed on 10 June 2017).
20. Achuthan, A.; Roan, J.; Fujiyama, T. Resilience of the Food Supply to Port Flooding on East Coast. DEFRA Project FO0454; Synthesis Report; 2015. Available online: http://randd.defra.gov.uk/Document.aspx?Document=13179_SynthesisReport.pdf (accessed on 10 June 2017).
21. Saulter, A.; Bunney, C.; Li, J.G.; Palmer, T. Process and resolution impacts on UK coastal wave predictions from operational global-regional wave models. In Proceedings of the 15th International Workshop on Wave Hindcasting and Forecasting and 6th Coastal Hazard Symposium, Liverpool, UK, 10–15 September 2017. Available online: http://www.waveworkshop.org/15thWaves/ (accessed on 18 September 2017).

22. Mason, T.; Dhoop, T. *Quality Assurance & Quality Control of Wave Data*; Channel Coastal Observatory: Southampton, UK, 2017. Available online: http://www.channelcoast.org/ccoresources/dataqualitycontrol/ (accessed on 12 November 2017).
23. Andernach, M.; Rijkswaterstaat, Haarlem, The Netherlands. Personal communication, 2014.
24. Stoker, E.; Datawell, Haarlem, The Netherlands. Personal communication, 2014.
25. Dhoop, T.; Mason, T. A comparison of extremes analyses of observational coastal wave data. *Proc. Inst. Civ. Eng. Marit. Eng.* **2018**, under review.
26. Caires, S. Extreme Value Analysis: Wave Data. JCOMM Technical Report No. 51. 2011. Available online: https://library.wmo.int/pmb_ged/jcomm-tr_57_en.pdf (accessed on 2 January 2018).
27. Haigh, I.D.; Wadey, M.P.; Wahl, T.; Ozsoy, O.; Nicholls, R.J.; Brown, J.M.; Horsburgh, K.; Gouldby, B. Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK. *Sci. Data* **2016**, *3*, 160107. [CrossRef] [PubMed]
28. Mason, T.; Bradbury, A.P. The St Jude's Storm—Just the start. In Proceedings of the Coastal Management, Amsterdam, The Netherlands, 8–9 September 2015. [CrossRef]
29. Wadey, M.P.; Brown, J.M.; Haigh, I.D.; Dolphin, T.; Wisse, P. Assessment and comparison of extreme sea levels and waves during the 2013/2014 storms season in two UK coastal regions. *Nat. Hazards Earth Syst. Sci.* **2015**, *15*, 2209–2225. [CrossRef]
30. Harely, M. Coastal Storm Definition. In *Coastal Storms: Processes and Impacts*; Paolo, C., Coco, G., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2017; pp. 1–22.
31. Bradbury, A.P.; Mason, T. *Review of South Coast Beach Response to Wave Conditions in the Winter of 2013–2014*; Channel Coastal Observatory: Southampton, UK, 2014. Available online: http://www.channelcoast.org/reports (accessed on 12 November 2017).
32. Masselink, G.; Castelle, B.; Scott, T.; Dodet, G.; Suanez, S.; Jackson, D.; Floc'h, F. Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe. *Geophys. Res. Lett.* **2016**, *43*, 2135–2143. [CrossRef]
33. Scott, T.; Masselink, G.; O'Hare, T.; Saulter, A.; Poate, T.; Russell, P.; Davidson, M.; Conley, D. The extreme 2013/2014 winter storms: Beach recovery along the coast of England. *Mar. Geol.* **2016**, *382*, 224–241. [CrossRef]
34. Draper, L.; Bownass, T.M. Unusual waves on European coasts, February 1979. In Proceedings of the 18th Coastal Engineering Conference, Cape Town, South Africa, 14–19 November 1982. Available online: https://journals.tdl.org/icce/index.php/icce/article/view/3630 (accessed on 12 November 2017).
35. Sibley, A.; Cox, D. Flooding along English Channel coast due to long-period swell waves. *Weather* **2014**, *69*, 59–66. [CrossRef]
36. HR Wallingford. Modelling Shingle Beaches in Bimodal Seas, Development and Application of Shingle-B. 2016. Available online: http://www.channelcoast.org/ccoresources/shingleb/ (accessed on 12 November 2017).
37. Sibley, A.; Cox, D.; Titley, H. Coastal Flooding in England and Wales from Atlantic and North Sea Storms during the 2013/2014 Winter. *Weather* **2015**, *70*, 62–70. [CrossRef]
38. Dawson, D.; Shaw, J.; Roland Gehrels, W. Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England. *J. Transp. Geogr.* **2016**, *51*, 97–109. [CrossRef]
39. De Alegria-Arzaburu, A.R.; Masselink, G. Storm response and beach rotation on a gravel beach, Slapton Sands, UK. *Mar. Geol.* **2010**, *278*, 77–99. [CrossRef]
40. Wadey, M.P.; Haigh, I.D.; Brown, J.M. A century of sea level data and the UK's 2013/2014 storm surges: An assessment of extremes and clustering using the Newlyn tide gauge record. *Ocean Sci. Discuss.* **2014**, *11*, 1995–2028. [CrossRef]
41. Wadey, M.P.; Haigh, I.D.; Nicholls, R.J.; Brown, J.M.; Horsburgh, K.; Carroll, B.; Gallop, S.L.; Mason, T.; Bradshaw, E. A comparison of the 31 January–1 Feburary 1953 and 5–6 December 2013 coastal flood events around the UK. *Front. Mar. Sci.* **2015**, *2*, 84. [CrossRef]
42. Haigh, I.D.; Ozsoy, O.; Wadey, M.P.; Nicholls, R.J.; Gallop, S.L.; Wahl, T.; Brown, J.M. An improved database of coastal flooding in the United Kingdom from 1915 to 2016. *Sci. Data* **2017**, *4*, 170100. [CrossRef] [PubMed]