Swell Wave Progression in the English Channel: Implications for Coastal Monitoring

Thomas Dhoop, Charlie Thompson

Channel Coastal Observatory, National Oceanography Centre, Southampton, UK.

Corresponding author: Thomas Dhoop (email: thomas.dhoop@noc.soton.ac.uk)

Abstract

Energetic swell waves, particularly when they coincide with high water levels, can present a significant coastal hazard. To better understand and predict these risks, analysis of the sea levels and waves that generate these events and the resulting coastal impacts is essential. Two energetic swell events, neither of which were predicted by modelled flood forecasts, occurred in quick succession in the English Channel. The first event, on 30th January 2021, produced moderate significant wave heights at or just below the 0.25 year return period along the southwest English coast, but combined with significant swell caused overtopping at East Beach in West Bay and at Chesil Beach. The second event, on 1st February 2021, generated the highest wave energy periods measured at many locations along the southern English coastline and, at High Water, caused waves to run up over the promenades in Poole and Christchurch bays and caused overtopping at Hayling Island. Both events are described in detail and their spatial footprints mapped through joint return period analysis using a copula function. It is found that typical joint return period analysis of water level and significant wave height under-estimates potential impacts, while a joint consideration of water level and wave power describes the 31st January event better and a joint consideration of water level and energy period describes the 1st February event best. Therefore, it is recommended that energy period Te and wave power P are adopted for coastal monitoring purposes and that future studies further explore the use of both parameters for swell monitoring.

Keywords: Coastal Flooding, Copulas, Joint Return Periods

1. Introduction

Energetic swell waves in the English Channel, particularly when they coincide with high water levels, can present a significant coastal hazard, causing beach erosion and damage to coastal structures and defences (e.g. Draper and Bownas 1983, Sibley and Cox 2014, Palmer *et al*. 2014). Swell is defined as waves that have been generated in another region of the ocean and have propagated out of the area of generation. Typically, the longer-period waves generated by a low pressure system travel faster than the storm and therefore move out of the storm area (Draper and Bownas 1983). Waves that are not generated by local wind conditions may arrive without warning and without wind, therefore taking coastal users and managers by surprise, making swell waves a danger to public safety.

From time to time, the UK is subject to long-period swell waves originating from storms developing in the western Atlantic, southeast of Newfoundland. Typically, the energy dissipates over distance. However, in certain cases trapped fetch conditions occur when a depression moves roughly in the same direction and with the same speed as the main wave group, maintaining an input of energy into the longer period waves (Sibley and Cox 2014). The English Channel is a narrow tidal strait adjacent to a large fetch, the Atlantic Ocean, in which trapped fetch conditions can occur (Figure 1). Once swell waves pass through the relatively small window of the Western Approaches, Sibley and Cox (2014) suggest that they are refracted towards the coast by Hurd Deep which lies west to east, in the middle of the English Channel, but are also refracted as they come into shallow water near the coast.

This paper uses data from a dense network of wave buoys in the English Channel to describe two swell events that occurred in quick succession in the English Channel. The first on the 30th January and the second on 1st February 2021. Neither event was predicted by modelled flood forecasts, but both caused overtopping of defences along the English south coast, and took coastal engineers and managers by surprise. This analysis will evaluate non-traditional wave parameters as predictors of swell hazard and suggest ways to improve the monitoring of the latter phenomenon with the aim to better support decision making with regards to flood and coastal risk management and further assist modelling and prediction efforts.

The wave parameters typically used for the design of coastal structures are significant wave height Hs (in this paper, Hs refers to the spectrally-derived H_{m0}) and the zero up-crossing period Tz. Nonetheless, swell waves have long been appreciated as a contributor to the overtopping of beaches (Carr 1983, Draper and Bownas 1983, Bradbury *et al*. 2007), gravel beach recharge design (Bradbury *et al*. 2011) and the design of defence structures (Hawkes 1999). Indeed, swell conditions are now an integral part of runup and overtopping formulas for beaches (e.g. Poate et al. 2016) and a key consideration in the design of coastal defences (EurOtop 2018). Nonetheless, even in recent years, overtopping of defences due to swell events does occasionally occur and has been documented e.g. by Palmer et al. 2014 and Sibley and Cox 2014. It is important to remember that, although new tools have been developed to assess swell in the design of new assets, many aging assets around England were not designed for extreme long period swell events. Documenting and analysing the metocean conditions, sea levels and waves that continue to cause overtopping of beaches and defences is a useful exercise to better understand the threats presented by swell events and develop methods to better monitor and predict them.

The wave parameters typically used for operational beach monitoring are Hs and peak period Tp. In England these parameters are provided in real-time by the National Network of Regional Coastal Monitoring Programmes of England (NNRCMP, 2021), where a "storm alert threshold" is provided for Hs for each wave buoy deployed by the programme as a monitoring tool for coastal engineers and managers (Dhoop & Thompson 2018). Tp values provided on the website are used by some coastal engineers on the south coast of England to monitor for swell waves (pers. comm. Dr S. Cope, Coastal Partners Havant Borough Council). The wave data captured by the NNRCMP is also displayed on the CEFAS WaveNet website (2021) where CEFAS provides a five-day prediction, supplied by the Met Office, for most wave buoys. These data feed into the Met Office wave and tide surge models, and the

National Flood Forecasting Service which aims to provide sufficient time for coastal managers to prepare for flooding. The SWEEP Operational Wave and Water Level model is also available on the NNRCMP website (2021). The model was developed by the University of Plymouth Coastal Processes Research Group and provides a three-day forecast of waves, water levels and wave overtopping for the southwest coast of the UK. Both events described in this paper were under predicted by modelled forecasts and although Tp functioned as a good monitoring tool to notify engineers of when the swell arrived at a particular buoy, it did not provide a full appreciation of the energy contained in the swell.

In summary, certain swell events continue to prove difficult to predict and monitor. This paper describes the meteorological conditions of two such events and the waves and water levels that they produced. Besides the standard engineering parameters (Hs, Tp, Tz and Direction), two additional parameters are calculated. First, the energy period Te as an alternative to Tp as it is less subject to rapid changes. As the ratio of the first negative and zeroth moments of the wave spectrum $\left(T_e = \frac{m_1}{m_0}\right)$, the parameter represents more of the lower frequency energy in the spectrum whilst avoiding marked jumps in the time series, typical of Tp. Second, wave power P in an attempt to account for both wave height and wave period in a single parameter. The timing of the swell as it propagated through the Channel and the energy of the swell is then mapped along the English coastline.

However, phenomena such as overtopping, beach erosion and coastal flooding are often the result of the combined actions of two or more physical processes, most importantly water level and wave action. Therefore, the wave data is combined with water level data to assess the joint return periods achieved at each wave buoy site. The spatial extent of the swell events is evaluated by mapping the joint return periods of water level and one of three wave parameters: Hs, Te and P at each wave buoy. This is followed by a description of the overtopping that occurred at East Beach and Chesil on 30th January and at Poole and Christchurch Bays and Hayling Island on 1st February 2021.

Finally, recommendations for coastal monitoring and operational beach management purposes are discussed. It is suggested that it would be beneficial to add Te to the suite of standard wave parameters currently used in coastal monitoring. Realtime provision of both Tp and Te could provide a more holistic appreciation of a swell event. In addition wave power P, as a measure of both wave height and period, could be a valuable addition for those events where swell is combined with a significant amount of wind-generated waves, although in theory these could be monitored by observing both Hs and Te.

2. Data and Methods

2.1. Data Sources

In total, data from 20 wave buoys and seven tide gauges is analysed, allowing for a high-resolution description and analysis of the swell waves and water levels during the 30th January and 1st February events. To accomplish this, three datasets are used.

The first and primary dataset is the wave data from the fleet of coastal wave buoys deployed around the English coastline by the National Network of Regional Coastal Monitoring Programmes of England (NNRCMP). The network consists of 37 Datawell Directional Waverider (DWR) MkIII buoys and is funded by the Department for Environment, Food and Rural Affairs (DEFRA) through the Environment Agency. The raw Datawell (2020) 64-bin spectral files and quality-controlled archived data from the 18 wave buoys deployed along the English south coast are used (Figure 1). Spectrally-derived and archived parameters are quality controlled according to the procedures published by Mason and Dhoop (2017). The Rye Bay wave buoy is not used as it was (re)deployed on 26th February 2021 and therefore missed both events described in this paper. All buoys used in the analysis are in water depths of approximately 10 m Chart Datum (CD). The longest dataset is Milford-on-Sea (Hampshire) which starts in 1996 and the shortest is Porthleven (Cornwall) which starts in 2011. The mean data length for the wave buoys used is 15 years.

The second dataset of wave data is retrieved from CEFAS WaveNet, funded by DEFRA through the Environment Agency. From the 15 wave buoys deployed around the British Isles, the two Datawell DWR MkIII wave buoys deployed in the English Channel at Poole Bay and Hastings are used (Figure 1).

Where available, the full 64-bin spectral data is used to derive processed parameters. When not (yet) available, the Iridium telemetry data is used (less than 1% of all wave data used). The Iridium spectra have 27 frequency bins which can vary from spectrum to spectrum as they are calculated to best represent the specific dataset. All post-recovery and telemetry spectra is quality controlled according to the procedures outlined on the CEFAS website (Cefas 2021). The Poole buoy (Dorset) is located in 28 m CD water depth and the Hastings buoy (East Sussex) in 43 m water depth CD. The dataset from Hastings spans 19 years, while the dataset from Poole comprises 18 years' worth of measurements.

Water levels are retrieved from the UK National Tide Gauge Network, available from the British Oceanography Data Centre (BODC) archive. The network comprises 43 operational tide gauges and is owned by the Environment Agency (EA). The quality-controlled data from the seven tide gauges located along the English south coast are used (Figure 1). The longest record is at Newlyn (Cornwall), which started in 1915 and the shortest at Bournemouth (Dorset) which started in 1996. The mean data length for the tide gauges used is 51 years. Prior to 1993, data frequency was hourly and from January 1993 increased to 15-minutes.

2.2. Wave Power and Energy Period Calculations

Wave power represents the rate of transfer of energy through each metre of wavefront. In this study, wave power is used to account for wave height and wave period, which both have distinct and joint influences on coastal events, in a single parameter. Wave power is defined as (Folley 2016):

$$P = \frac{\rho g^2}{64\pi} {H_{m0}}^2 \, T_e \quad [1]$$

Where ρ is the density of seawater, taken as 1025 kg/m^3, g is acceleration by gravity at 9.81 m/s^2, H_{m0} ($H_{m0} = 4\sqrt{m_0}$) is the significant wave height based on m_0, the zero moment of the power spectrum, and Te the wave energy period.

Wave power is proportional to significant wave height squared and the wave energy period. However, most historical and ongoing wave measurement data typically only provide the spectral peak period

Tp and mean zero upcrossing period Tz as processed parameters and not the energy period Te needed to calculate wave power. This holds true for the wave data provided by both the NNRCMP and CEFAS WaveNet used in this study.

Although Te is not reported as a standard output parameter of a Datawell Directional Waverider MkIII, it can be derived from the raw spectral files from the buoy by calculating the first negative moment and the zeroth moment, where the frequency moment m_n of the spectrum is defined as:

$$m_n = \int f^n \, E(f) \, d \, f \qquad [2]$$

Where $E(f)$ is the frequency spectrum (m^2Hz^{-1}), f is the frequency and *d* is the frequency bandwidth (Hz).

The wave energy period Te can then be defined as the ratio of the first negative moment of the spectrum to the zero moment as given by equation 3.

$$T_{e=\frac{m_{-1}}{m_0}} \qquad [3]$$

Because Te is proportional to the first negative moment of the wave spectrum, the parameter gives more weight to the lower frequencies and therefore the longer periods in the spectrum than wave periods parameters such as Tp or Tz.

2.3. Univariate Extremes Analysis

To gauge the likelihood of the swell events discussed in this study, energy period (Te) return periods are calculated for each wave buoy site. To do this, a peaks-over-threshold approach with the threshold defined as the 99.5th percentile is used, with a 48 hour storm separation window, to create a sample of independent and identically distributed (iid) observations. A generalised Pareto distribution (GPD) is fitted to the sample and parameter estimates are derived using the maximum likelihood method (Coles 2001). Both the threshold and storm separation window are rules-of-thumb to make the analysis more efficient while still providing reasonable parameters for the analysis. The same parameters are used in analyses performed by the NNRCMP and are discussed in detail in Dhoop & Thompson 2018.

2.4. Joint Probability Analysis

The spatial extent of the swell events is examined by producing maps of the spatial footprint of the events based on the joint return period of water level combined with one of three different wave parameters; significant wave height Hs, energy period Te and wave power P, at each wave buoy.

Joint return periods between two time series are calculated using a bivariate copula function. Over the last fifteen or so years, copula functions have been widely used in coastal engineering to examine a combination of wave heights and periods (De Waal and Van Gelder 2005), storm surges and wind waves (Bernadino et al. 2013; Wahl et al. 2012) and sea level and wave height (Mazas and Hamm 2017). It should be noted that, as mentioned above, this study uses a number of heuristics to make the analysis easier to apply to all wave buoy sites while providing the most reasonable spatial footprint and does not attempt to provide any design characteristics for any particular location.

The following four-step methodology is implemented in MATLAB and is typical to UK coastal engineering as the same steps are used in the JOIN-SEA software (Hawkes et al 2002):

a. Data selection of the joint time series
b. Modelling of the marginal distributions
c. Analysis of the dependence structure
d. Estimation of joint return periods

2.4.1. Data Selection of the Joint Time Series

Samples for dependence modelling were extracted from concurrent time series of water levels and wave parameters using a multivariate threshold similar to Li et al. (2014). It is assumed that, in order for high and/or energetic swell waves to cause significant beach erosion, overtopping or coastal flooding at all wave buoy sites, they must occur at or around a high water level. Therefore, first a subsample of the 5% highest tides and their concurrent wave parameters is extracted. From this subsample, the sample for dependence modelling is extracted by applying a high threshold for the wave parameter (Figure 2). This threshold varies site by site and is determined by the desired sample size. It can be argued a sufficiently large sample is needed to capture dependence between variables. Therefore, we follow Mazas and Hamm (2017), and strive for 20 events per year (i.e. the shortest time series of 10 years has a desired sample size of 200 events).

Independent events are assured by applying a storm separation window of 48 hours. This window was adopted as a rule of thumb for all sites as a compromise between assuring independent observations and losing valid observations due to tightly clustered, but independent storms (e.g. the unusual 2013-2014 storm season, see Malagon Santos et al. 2017).

2.4.2. Marginal Distributions

The joint probability approach taken in this study uses a mixture distribution: an extreme value analysis is carried out for modelling the tail of the distributions of water level and the wave parameter, while the dependence (Section 2.4.3) is modelled from the sample of joint high water levels and the wave parameter derived in section 2.4.1.

Similar to the univariate extremes analysis described in section 2.3, for water level and each wave parameter, a threshold is set above which the exceedances are modelled by a GPD. The value of the threshold is again determined by the desired sample size. Following Bernardara et al (2014) and Mazas and Hamm (2017), 10 events per year are strived for (i.e. e shortest time series of 10 years has a desired sample size of 100 events). Independence is again assured by applying a storm separation window of 48 hours.

2.4.3. Dependence Structure

Dependence between water level and the wave parameter is measured using Kendall's rank correlation coefficient τ, a well-known nonparametric measure of dependence (e.g. Wahl et al 2012).

Following Sklar's theorem (1959), the joint cumulative distribution function $H_{X,Y} = \mathbb{P}[X \leq x, Y \leq y]$ can be described by the univariate marginal distributions of X and Y, F_X and F_Y, via a copula C:

$$H_{X,Y}(x, y) = C(F_X(x), F_Y(y)) \quad [4]$$

The copula function used in this study needs to be applicable to a large number of wave buoy sites with different wave climates and with potentially different levels of dependence between water level and the wave parameter. Because the calculated joint return periods need to be comparable to one another, a bivariate normal copula, or Gauss copula was used for all sites (as is used in the JOIN-SEA software, Hawkes et al. 2002). The Gauss copula is described by the dependence parameter θ (or correlation parameter) which is derived using the copulaparam function in MATLAB.

2.4.4. Estimation of Joint Return Periods

Joint return periods for each swell event are evaluated by plotting two peaks on a joint return period plot; (a) the peak of the wave parameter with the associated water level and (2) the highest water level during the event with its associated wave parameter (Figure 3). The plot is constructed by extracting the contours from the copula at nine intervals (2, 5, 10, 15, 20, 25, 50, 75 and 100 years joint return periods), shaped by the dependence parameter θ, while the marginal distributions calculated in section 2.4.2 inform the x and y axes. The highest joint return period achieved between the two peaks is considered the joint return period of the event.

The concept of return periods can be ambiguous, particularly in a bivariate context. Despite work by Serinaldi (2015) outlining the misinterpretations of return periods in a multivariate setting, return periods are still a staple when discussing probabilities in coastal engineering and are therefore still used in this study. For the sake of clarity, because the sampling strategy described in section 2.4.1

extracted exceedances of both water level and a wave parameter, the joint return periods in this work are to be understood as the return periods associated with the joint exceedances of both variables.

3. Results

3.1. 30th January 2021

3.1.1. Swell Generating Mechanism

To find the generating area for the swell measured on 30th January 2021, the UK Met Office synoptic analysis charts for the previous few days were examined. The chart for 12:00 UTC on 28th January 2021 shows a new depression southeast of Newfoundland (low 973 mb) (Figure 4, Table 1). This low quickly moved in a northeast direction and by 00:00 UTC, on 29th January it can be seen as a low that had deepened to 967 mb. Twelve hours later, the depression had continued its northeasterly movement at a slightly slower pace and persisted as a low at 968 mb. At this point, the westerly winds generating waves on its southern flank are conservatively estimated from the synoptic chart by the authors to be around 55-60 knots. Such wind speeds are not uncommon in an Atlantic storm. The low continued its northeasterly movement filling to 975 mb by 00:00 UTC on 30th January. Twelve hours later, the low was positioned west of Land's End and had filled to 981 mb. Finally, by 00:00 UTC on 31st January the remains of the depression centred over Nantes, in France.

3.1.2. Swell Propagation Through the Channel

To track the swell waves as they travelled through the English Channel, their first manifestation in peak period Tp is plotted on a timeline (x-axis on Figure 5). The first instances of Tp were site specific and in the range of 15.4s to 22.2s. The energy contained in the swell manifested at each wave buoy site is shown as the peak energy period that was achieved at the site during the event (y-axis on Figure 5). To investigate how common the swell measured at each wave buoy location is and to make the swell comparable between sites, the Te return period achieved at each site is calculated (circle size on Figure 5).

On 30th January, the swell first manifested at Porthleven at 14:00 UTC. Between 15:00 UTC and 15:30 UTC, the waves had reached Looe Bay and western Lyme Bay. By 16:30 UTC, West Bay and Chesil recorded the swell also. By 18:00 UTC the swell manifested in the Christchurch and Poole Bays. One hour later, the waves had refracted around the Isle of White and reached Hayling Island. The most easterly location where swell was visible in Tp was Seaford at 20:30 UTC. From its first measurement at Porthleven to the eastern most measurement at Beachy Head, the swell travelled about 430 kilometres in about 6.5 hours, moving at an average speed of 66 km/h or 36 knots. The highest return periods were achieved at the Looe Bay, West Bay and Chesil wave buoys.

Figure 5 shows that, at some buoys, the swell waves manifested in Tp later than one would expect based on their location and the timing of their detection at neighbouring buoys. This is the case at Penzance, Dawlish and Pevensey Bay. The primary reason for this is the prevalence of locally-generated wind waves in the spectra of those sites, hiding the swell component until the swell manifested strongly enough in the spectrum. A secondary reason may be that the buoys are all east-facing and it may therefore take some time for the swell to refract around to reach them.

3.1.3. Spatial Footprint

The spatial footprint of this event is mapped by calculating a number of joint return periods at each wave buoy site using a copula function, focusing on the time of primary concern when they occur at or around High Water. Joint return periods are calculated for water level and one of three wave parameters: significant wave height Hs, Energy period Te and wave power P.

Because the swell passed through the channel around High Water, the high water levels pushed the joint return periods above 1 in 2 years at all sites where the swell was observed (Figure 6). Looking closer at the joint water level and significant wave height Hs footprint, higher joint return periods were achieved between Porthleven in Cornwall and Tor Bay in West Lyme Bay (numbers 2 and 5 on Figure 1) with joint water levels and wave heights at Penzance, Looe Bay, Start Bay and Tor Bay (numbers 1, 3, 4 and 5 on Figure 1) exceeding the 1 in 5 year joint return period.

Investigating the joint water levels and energy periods Te achieved at the buoys, a 1 in 5 year joint return period was achieved at almost all instruments where the swell was measured, ranging from Porthleven in Cornwall to Seaford in East Sussex (numbers 2 and 17 on Figure 1).

Finally, examining the map of joint water level and wave power, the latter itself being a function of energy period Te and significant wave height Hs squared, high joint return periods were achieved at Porthleven (1 in 25 years) and Looe Bay (1 in 20 years) (numbers 2 and 3 on Figure 1). 1 in 5 year joint return periods were also exceeded at Start Bay, West Bay and Chesil (numbers 4, 7 and 8 on Figure 1). Further east, in the Christchurch and Poole Bays, the 1 in 5 year joint return period was exceeded at Poole Bay (number 11 on Figure 1), but not at the two buoys located closer inshore.

3.1.4. Impact at East Beach and Chesil

At East Beach in West Bay, small scale overtopping occurred during the 30th January swell event. The event came as a surprise and caused significant erosion, resulting in some 'cliffing' of the beach (Figure 7). However, it should also be noted that the crest width of the beach was already much reduced before the event. The 'cliffing' is believed to have been caused by the high content of fine material present in the shingle at the time. This was likely disturbed during the construction of a new rock revetment in 2019. Prior to this, the clean shingle had no cohesive properties. With time, it is expected the fine material will wash from the single (pers. comm. Martin Worley, Environment Agency).

Chesil Beach suffered notable overtopping with flooding around Chiswell and Brandy Row. Several cars were damaged and a significant amount of shingle was swept onto the promenade and street. The lower beach foreshore suffered from erosion whilst the upper beach experienced accretion, with material deposited just below the crest of the open beach and level with the top of the sea wall at Chesil Cove. It is possible this exacerbated the overtopping in places by providing a shingle ramp for wave runup, allowing water to overtop the sea wall (Dave Picksley, Environment Agency). The erosion at Chiswell can clearly be seen on the two photos taken before and after the event as part of the Southwest Regional Coastal Monitoring Programme's CoastSnap project (Figure 8).

3.2. 1st February 2021

3.2.1. Swell Generating Mechanism

To find the generating area for the swell measured on 1st February 2021, the UK Met Office synoptic analysis charts for the previous few days were again consulted. The chart for 00:00 UTC on 30th January 2021 shows a new depression southeast of Newfoundland (low 957 mb) (Figure 9, Table 2). This low moved in a northeast direction and by 12:00 UTC, on 30th January, it can be seen as a low that had filled to 962mb. Twelve hours later, the depression had continued its northeasterly movement at a slightly more rapid pace and continued to fill at 969 mb. At this point, the westerly winds on its southern flank are conservatively estimated from the synoptic chart by the authors to be around 55 knots, similar to the 30th January event and not uncommon for an Atlantic storm. The low continued its northeasterly movement filling to 978 mb by 12:00 UTC on 31st January. By 00:00 UTC on 1st February the depression had weakened and lost its identity, and was incorporated in a complex low pressure system, having filled to 987 mb. The final remains of the depression appear to be centred between Bremen and Dortmund, in Germany.

3.2.2. Swell Propagation Through the Channel

The first manifestation of the waves in peak period Tp (values were site-specific and ranged between 18.2s and 25s) is plotted against swell intensity (peak energy of the event), and Te return period (Figure 10).

On 1st February, the swell was first measured by the Porthleven buoy at 03:30 UTC and reached Looe Bay by 05:30 UTC. West Bay and Chesil were confronted with the swell around 06:30 UTC. By 07:30 UTC, the waves reached the Poole and Christchurch Bays. One hour later, the swell had refracted around the Isle of Wight and reached Hayling Island. At 11:30 UTC the swell reached Seaford at Beachy Head and by 12:00 UTC, the waves arrived at Folkestone which is the eastern most located wave buoy where the swell manifested in Tp. From their first measurement at Porthleven to the eastern most buoy where the swell manifested in Tp in Folkestone, the swell waves travelled about 510 kilometres in about 8.5 hours, travelling at an average speed of 60 km/h or 32 knots. The highest return periods were achieved at Boscombe, Poole Bay and Hayling Island.

Figure 10 shows that again, at some buoys, the swell waves manifested in Tp later than one would expect based on their location and when the neighbouring buoys registered the swell. This is the case at Penzance, Start Bay, Tor Bay, Dawlish, Chesil, Sandown Bay, Pevensey Bay and Hastings. A possible explanation is that the majority of these are east-facing sites where it would take some time for the swell to refract around to reach the particular wave buoy.

3.2.3. Spatial Footprint

Because waves are the most dangerous during high water levels, at each wave buoy, the joint return period of water level and one of three wave parameters is calculated: significant wave height Hs, energy period Te and wave power P.

As was the case during the 30th January event, because the swell passed through the channel around High Water at most wave buoy sites, the 1 in 2 year joint return period was exceeded at all locations (Figure 11). Examining the joint water level and significant wave height footprint, at no location was the 1 in 2 year joint return period exceeded, making it clear that wave heights did not contribute in any significant way to the event. The same pattern holds true for the joint return periods of water level and wave power; at no location was the 1 in 2 year return period exceeded.

In contrast, looking at the map showing joint water level and energy period Te, the 1 in 2 year return period was exceeded at all sites with the exception of Tor Bay (number 5 on Figure 1) on the southeast coast of Devon. At all other sites, at least the 1 in 5 year return period was exceeded with the 1 in 100 year return period exceeded at Boscombe in Poole Bay and at Hayling Island in the Solent (numbers 10 and 14 on Figure 1).

3.2.4. Impact at Christchurch and Poole Bay and Hayling Island

At Hayling Island, significant and dangerous overtopping occurred during the 1st February 2021 swell event. This was unexpected and caused flooding in the gardens along Southwood Road, although the flood defences managed to retain the majority of the overtopping within the promenade. In places, the waves flattened the crest of the beach which required emergency repairs and deployment of plant to reinstate the standard of protection (pers. comm. Dr A. Pearce, Coastal Partner Havant Borough Council) (Figures 12 & 13).

The 1st February swell event also caused a surprising amount of water to run up over the promenades in Poole and Christchurch Bays which likely cannot be just attributed to antecedent beach levels (pers. comm. Dr M. Wadey, Bournemouth, Christchurch and Poole (BCP) Council).

It is also worth mentioning that on 26th February 2021, part of the east wing of Hurst Castle, located on the Hurst Spit shingle bank, collapsed. Although the collapse is not a direct result of the two swell events described in this study – the foundations of the east wing were already severely undermined – the two swell events may have expedited the collapse.

4. Discussion

4.1. 30th January 2021

The reported significant impacts of the 30th January event are focused along the coastline of western Dorset. At East Beach in West Bay small scale overtopping and erosion occurred resulting in the ‘cliffing’ of the beach, although it should be noted that the beach was already depleted. Also at Chesil Beach notable overtopping occurred, damaging cars and moving significant amounts of shingle from the lower foreshore to the upper beach, onto the promenade and into the street.

The storm that generated the swell originated on 28th January as a new Atlantic depression southeast of Newfoundland which tracked due east, with forcing winds moving in a relatively straight line relative to the curvature of the earth which directed long-period swell waves directly towards the UK.

During the strongest storm development period, when the low was travelling across the Atlantic, trapped fetch conditions as described by Sibley and Cox (2014) may have occurred as the centre travelled at a speed between 28 and 36 knots with a gradient wind speed on the southern flank estimated at around 55-60 knots (Table 1), suggesting that the speed of movement of the low centre kept track with the group wave speed. However, the centre did not enter the English Channel, as around midday on 30th January, the storm changed direction bending south past Land's End towards Brittany in France.

When the swell first arrived at West Bay and Chesil between 16:30 UTC and 17:00 UTC, a surge of ~27.9cm was measured at the Weymouth NTSLF tide gauge. At the peak of the event, defined as when significant wave height Hs peaked at 3.49m at West Bay and 4.04m at Chesil, between 20:30 UTC and 21:30 UTC, the surge had dropped to ~14.65 cm. High Water occurred close to the peak at 20:00 UTC with a maximum water level of 1.32m OD on a spring tide. At West Bay, Peak period Tp peaked at 20s, energy period Te at 15s, wave power P at 86 kW/m^2 and peak wave direction was 210 degrees (southwest by south). At Chesil, Tp peaked at 22.2s, Te at 12.1s, P at 120 kW/m^2 and peak wave direction was 220 degrees (southwest).

The 30th January event was driven by a combination of swell entering the English Channel and low pressure centred west of Land's End generating high wave heights for the southwest regions of the English coastline. These conditions resulted in high wave powers generated at the Porthleven and Looe Bay wave buoys, exceeding the 1 in 20 and 1 in 15 years joint return periods for water level and wave power, respectively. Due to the nature of the event, the spatial footprint that captured the impact of the event best is the combined consideration of water level and wave power.

Two observations regarding the impact of wave heights during the event are worth pointing out. First, neither at West Bay nor Chesil, the two sites where overtopping was recorded, did significant wave height Hs exceed the storm alert threshold on the NNRCMP website, emphasizing again the well-established point that energetic long period waves are an important component of overtopping and beach erosion and are therefore important to monitor. Nonetheless, the second observation is that no overtopping was reported at either site during the even more energetic 1st February event, likely because significant wave heights were quite low (section 4.2.1). Other factors that likely influenced the different impacts of both swell events at West Bay and Chesil are the storm tracks and wave directions, but detailed analysis of these are outside the scope of this paper.

A final observation worth considering is that, when monitoring swell by tracking peak period Tp, the wind waves generated by the depression off Land's End managed to hide the swell in this parameter for a considerable amount of time at locations like Penzance and Dawlish before the swell peak became dominant in the wave spectrum.

4.2.1 1st February 2021

The reported impacts of the 1st February event are centred on the coastline of east Dorset and the Solent in Hampshire. At the Poole and Christchurch Bays, water ran up over the promenades and at Hayling Island, a significant amount of overtopping occurred, flattening the crest of the beach and requiring emergency repairs and deployment of plant on the beach.

The storm that generated the swell originated on 30th January as a new Atlantic depression southeast of Newfoundland. Also this storm tracked northeast with forcing winds travelling in a relatively straight line pushing long-period swell waves directly towards the British Isles. Again, trapped fetch conditions may have occurred as the storm crossed the Atlantic with the centre travelling at speeds between 33 and 39 knots with a gradient wind speed on the southern flank estimated at around 55-60 knots, suggesting the movement of the low kept track with the group wave speed. However, by 1st February, the depression had weakened and became incorporated in a complex low pressure system that moved across the English Channel, potentially continuing to feed the wave group passing through.

When the swell waves arrived at the buoys deployed in Poole Bay and at Hayling Island, at 07:30 UTC and 08:30 UTC respectively, a surge of ~ 32.7cm was measured at the Portsmouth NTSLF tide gauge.

At the peak of the event, defined as when energy period Te peaked at 18.7s at Boscombe and 20.6s at Hayling Island, between 12:30 UTC and 13:30 UTC, the surge dropped slightly to 27.1cm. High Water occurred one hour after the peak of the event at Boscombe and during the peak at Hayling Island with a maximum water level of 2.16m OD on a spring tide. At Boscombe, significant wave height Hs peaked at 1.42m, peak period Tp at 25s, wave power P at 11 kW/m^2 and peak wave direction was 186 degrees (south by west). At Hayling Island, Hs peaked at 1.92m, Tp at 25s, P at 29 kW/m^2 and peak wave direction was 180 degrees (south).

The 1st February event and its related impacts were entirely driven by the swell waves travelling through the Channel. The complex low travelling across the channel did not generate any significant wind speeds or wind waves. These conditions resulted in a calm weather day during which an exceptionally energetic swell passed through the channel, generating some of the highest energy period measurements on record at the buoys in the channel, but relatively low significant wave height measurements. Due to these conditions, the spatial footprint that captured the impact of this event best is the combined consideration of water level and energy period Te.

The 1st February event is close to a schoolbook example of the dangers swell events pose, especially during a calm day. At the Poole and Christchurch Bays, waves unexpectedly running up the promenades are a danger to the public, while at Hayling Island the swell significantly flattened the beach crest. Furthermore, the swell entered at an angle in the channel, and was energetic enough, to travel all the way through, still being distinctly visible in the data from the Folkestone buoy in Kent.

4.3. Implications for Coastal Monitoring

The two consecutive but quite different swell events documented in this paper present an opportunity for coastal monitoring programmes to reflect on how waves, and in particular swell waves, are measured and reported.

Currently, long-period swell monitored through measurements is primarily done by observing (or setting an alert for) peak period Tp. Because Tp is defined by the period at the wave spectrum peak it is subject to rapid changes. Moreover, if there are more than two distinct frequency components of similar peak energy, the time series of Tp can appear to fluctuate markedly. These properties of the parameter can be advantageous and will typically result in swell being first picked up in this parameter. However, as was the case at some locations during the 30th January event, swell can also remain hidden in Tp if sufficient wind waves are generated for the wind wave peak on the spectrum to dominate the swell peak. A solution to this is to partition the wave spectrum into its wind and swell components and focus on the peak period for the swell component only, thereby excluding any contamination of wind-wave energy. However, because the lower frequencies in a standard (Datawell) wave spectrum are not as finely-resolved, relatively large step-changes in a time series of Tp swell will remain. Such a bimodal wave spectrum is typically referred to as a bimodal sea state and is monitored post hoc by the NNRCMP by calculating the occurrence of bimodal seas as a monthly percentage (Mason & Dhoop 2018) and is available as a regularly updated spreadsheet (NNRCMP 2021).

A well-established tool for wave monitoring is the definition of a threshold condition, such as the storm alert threshold defined on the real-time data pages of the NNRCMP website. A similar threshold condition could prove useful for swell monitoring. However, the rapidly-changing nature of Tp makes this parameter unsuitable for such use. In an attempt to quantify the energy contained in the swell events discussed in this paper, the energy period Te is found to provide a much smoother time series. As the ratio of the first negative and zero moments of the wave spectrum, the parameter represents more of the lower frequency energy in the spectrum whilst avoiding marked jumps in the time series.

Figure 14 shows a time series of peak period Tp and energy period Te as measured by the wave buoys at West Bay, Chesil, Boscombe and Hayling Island covering both swell events discussed above. In red, a horizontal line was added as an indicative 'swell alert threshold' at the 0.25 year return period for energy period. The threshold was chosen to mimic the 0.25 years return period threshold used for significant wave height Hs by the NNRCMP. The reasoning being that, on average, four times per year conditions occur which have the potential to move a significant quantity of beach material. The threshold condition applied in Figure 14 appears to function relatively well; the threshold is exceeded at West Bay and Chesil during both events, while at Boscombe and Hayling Island the threshold is exceeded only during the 1st February event, matching the findings in this paper.

As Mason *et al*. (2008) had suggested before, the addition of energy period Te to the current set of wave parameters provided as an industry standard in coastal monitoring could prove beneficial to monitoring swell in the future. An additional benefit of Te is that it is the standard wave period used for wave run-up and overtopping formulae (van de Meer 2008) and may therefore be of particular use to calibrate and provide a check on overtopping models. A complication to this end is that Te is typically not a standard output of most wave measuring instrumentation. Nonetheless, it can be derived from the wave spectrum, a dataset already provided by most providers of wave data (e.g. CEFAS, NNRCMP) in England, in a straightforward manner. Alternatively, the parameter can be derived from additional instrument specific parameters (for an example using Datawell DWR MkIII parameter outputs, see Appendix 1).

It is also worth noting that, despite the irregularities noted in sections 3.1.2 and 3.2.2, swell propagates through the English Channel from west to east in a progressive manner. Up to a point, it is therefore possible to receive a couple of hours early warning of incoming swell at those locations further east up the Channel by monitoring Tp and Te at more westerly located wave buoys. Furthermore, by partitioning the wave spectrum in its wind and swell components and by monitoring the peak period of the swell component only, it is possible to avoid swell remaining hidden due to a wind-wave peak dominating the spectrum. A closer examination of the time dependencies between Tp, Tp swell and Te at different locations along the southern English coastline could prove useful for coastal monitoring purposes.

Finally, while it is perfectly reasonable to be well-informed about both swell events by monitoring Hs in tandem with energy period Te, once the latter is provided as a parameter for monitoring purposes, it is a relatively small effort to also provide wave power as a parameter that incorporates both wave height and period. Wave power P is particularly useful when a swell event is combined with locally generated waves such as the 30th January event.

5. Conclusions

Energetic swell waves, particularly when they coincide with high water levels, can present a significant coastal hazard. Two such events occurred in quick succession in the English Channel. The first, on 30th January 2021, was driven by a combination of swell entering the English Channel and a depression centred west of Land's End generating moderate wave heights for the southwest regions of the English coastline. The event caused overtopping at East Beach in West Bay and at Chesil Beach.

The second event, on 1st February 2021, was entirely driven by the swell waves travelling through the English Channel. A complex low travelled across the channel but did not generate any significant wind speeds or wave heights. The event generated some of the highest energy period measurements on record at the buoys deployed in the channel and caused waves to run up over the promenades in Poole and Christchurch Bays and caused overtopping and flattening of the beach crest at Hayling Island.

Spatial footprints of both events were generated through joint return period analysis of water level combined with one wave parameter; significant wave height Hs, energy period Te or wave power P. The water level at which a swell event occurs will significantly contribute to the severity of the impact of that event in terms of overtopping or beach erosion. Te was calculated to provide a smoother time series for swell monitoring than Tp. As the ratio of the first negative and zero moments of the wave spectrum, the energy period represents more of the lower frequency energy in the spectrum whilst avoiding marked jumps in the time series. Wave power P was calculated in an attempt to account for both wave heights and wave period in a single parameter.

The 31st January swell event, with its significant contribution of moderate wave heights due to the low centred off Land’s end was best described by the joint return periods of water level and wave power. The 1st February event is almost entirely driven by swell and therefore best captured by the joint return periods of water level and Te.

Finally, Te was found to be a valuable addition to the standard wave parameters used to describe the two swell events under discussion. Te, providing a smoother time series than the rapidly changing Tp, allowed for improved quantification of the swell energy and has the potential for threshold setting for ‘swell alerts.’ The parameter could also prove useful in supporting modelling efforts, in particular overtopping models, by providing a check on predictions. It is therefore recommended that Te is considered for inclusion in the arsenal of wave parameters currently used for coastal monitoring and beach management purposes. Also wave power P, as a measure of both wave height and period, could be a valuable addition for those events where swell is combined with a significant amount of wind-generated waves, although in theory these could be monitored by observing both Hs and Te. Inclusion of these parameters will ensure that those swell events with the potential to impact coastal flooding and erosion, but which aren’t currently captured in standard flood warning models, can be more closely monitored.

Conflict of interest statement

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank Dr Sam Cope and Dr Andy Pearce from the Coastal Partners team at Havant Borough Council, Dr Matthew Wadey from Bournemouth, Christchurch and Poole Council, Jack Eade from Jacobs, and Martin Worley and Dave Picksley from the Environment Agency for the information and images they provided. The authors also thank Robin Newman from Fugro for providing valuable feedback on an early draft of this paper.

The National Network of Regional Coastal Monitoring Programmes (NNRCMP) is funded by the Department for Environment, Food and Rural Affairs (DEFRA) through the Environment Agency. Data is made available under Open Government License. The analysis also included data provided by CEFAS which is also funded by DEFRA through the Environment Agency. Data is licensed under the Cefas WaveNet Non-Commercial License v1.0. This study also uses data from the National Tidal and Sea Level Facility, provided by the British Oceanographic Data Centre and funded by the Environment Agency.

Contributor's statement

Thomas Dhoop conceptualised the study, performed the analysis and wrote the original draft of the paper. Charlie Thompson provided supervision over the work, and reviewed and edited the original draft.

Funding statement

The Channel Coastal Observatory, as part of the National Network of Regional Coastal Monitoring Programmes (NNRCMP) is funded by the Department for Environment, Food and Rural Affairs (DEFRA) through the Environment Agency.

Data availability statement

The wave data used in this study, provided by the NNRCMP is publicly available under open government license from www.coastalmonitoring.org. The wave data provided by CEFAS is publicly available under the Cefas WaveNet Non-commercial License v1.0 from www.wavenet.cefas.co.uk. The tide data provided by the National Tide and Sea Level Facility is publicly available through the British Oceanographic Data Centre (BODC) from www.ntslf.org.

References

Bernardara, P., Mazas, F., Kergadallan, X., and Hamm, L. 2014. A two-step framework for over-threshold modelling of environmental extremes. Nat. Hazards Earth Syst. Sci. **14**: 635-647. doi:10.5194/nhess-14-635-2014

Bradbury, A., Mason, T. and Poate, T. 2007. Implications of the spectral shape of wave conditions for engineering design and coastal hazard assessment – Evidence from the English Channel. *In* 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium. http://www.waveworkshop.org/10thWaves/ProgramFrameset.htm

Bradbury, A., Stratton, M. and Mason, T. 2011. Impacts of wave climate with bi-modal wave period on the profile response of gravel beaches. *In* The Proceedings of Coastal Sediments 2011. *Edited by* J.D. Rosati, P. Wang and T.M. Roberts. World Scientific Publishing, Singapore, pp. 2004-2018. doi.org/10.1142/9789814355537_0151

Carr, A. 1983. Chesil beach: environmental, economic and sociological pressures. Geogr. J. **149**: 53-62. doi.org/10.2307/633342

CEFAS, 2021. https://www.cefas.co.uk/data-and-publications/wavenet/ Access: 12 May 2021.

Coles, S.G. 2001. An Introduction to Statistical Modelling of Extreme Values. Springer, London, UK. 209 pp.

Datawell. 2020. Datawell Waverider Reference Manual. Datawell BV. https://www.datawell.nl/Portals/0/Documents/Manuals/datawell_manual_dwr-mk3_dwr-g_wr-sg_2020-02-01.pdf

De Waal, D. and Van Gelder, P. 2005. Modelling of extreme wave heights and periods through copulas. Extremes. **8.4**: 345-356. Doi.org/10.1007/s10687-006-0006-y

Dhoop, T. and Thompson, C. 2018. Extreme Value Analysis for NNRCMP Coastal Wave Data. Channel Coastal Observatory. https://coastalmonitoring.org/reports/index.php?link=&dla=download&id=1517&cat=266/Extreme_Value_Analysis_for_CCO_Coastal_Wave%20Data_TN03.pdf

Draper, L. and Bownass, T. 1983. Wave devastation behind Chesil beach. Weather. **38**: 346-352. doi.org/10.1002/j.1477-8696.1983.tb04822.x

EurOtop. 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

Folley, M. 2016. The wave energy resource. *In* Handbook of Ocean Wave Energy. *Edited by* A. Pecher and J. Kofoed. Springer, Cham, Switzerland. pp. 43-79. doi.org/10.1007/978-3-319-39889-1_3

Hawkes, P.J. 1999. Mean overtopping rate in swell and bimodal seas. Proc. Instn Civ. Engr Wat., Marit. & Energy. **136**: 235-238. doi.org/10.1680/iwtme.1999.31987

Hawkes, P.J., Gouldby, B.P., Tawn, J.A. and Owen, M.W. 2002. The joint probability of waves and water levels in coastal engineering design. J. Hydraul. Res. **40**: 241-251. doi.org/10.1080/00221680209499940

Li, F., van Gelder, P.H.A.J.M., Ranasinghe, R., Callaghan, D.P. and Jongejan, R.B. 2014. Probabilistic modelling of extreme storms along the Dutch coast. Coastal Engineering. **86**: 1-13. doi.org/10.1016/j.coastaleng.2013.12.009

Malagon Santos, V., Haigh, I. and Wahl, T. 2017. Spatial and temporal clustering analysis of extreme wave events around the UK coastline. J. Mar. Sci. Eng. **5**.28. doi.org/10.3390/jmse5030028

Mason, T. and Dhoop, T. 2018. Occurrence of bimodal seas around the English coastline. Technical Note TN02. National Network of Regional Coastal Monitoring Programmes of England.

https://coastalmonitoring.org/reports/index.php?link=&dla=download&id=1518&cat=266/Occurrence_of_Bimodal_Seas_around_the_English_Coastline_TN02.pdf

Mazas, F. and Hamm, L. 2017. An event-based approach for extreme joint probabilities of waves and sea levels. Coastal Engineering. **122**: 44-59. doi.org/10.1016/j.coastaleng.2017.02.003

NNRCMP, 2021. https://coastalmonitoring.org/ Access: 12 May 2021.

Palmer, R., Nicholls, R.J., Wells, N.C., Saulter, A., Mason, T. 2014. Identification of 'energetic' swell waves in a tidal strait. Continental Shelf Research. **88**: 203-2015. doi.org/10.1016/j.csr.2014.08.004

Poate, T.G., McCall, R.T. and Masselink, G. 2016. A new parameterisation for runup on gravel beaches. Coastal Engineering. **117**: 176-190. doi.org/10.1016/j.coastaleng.2016.08.003

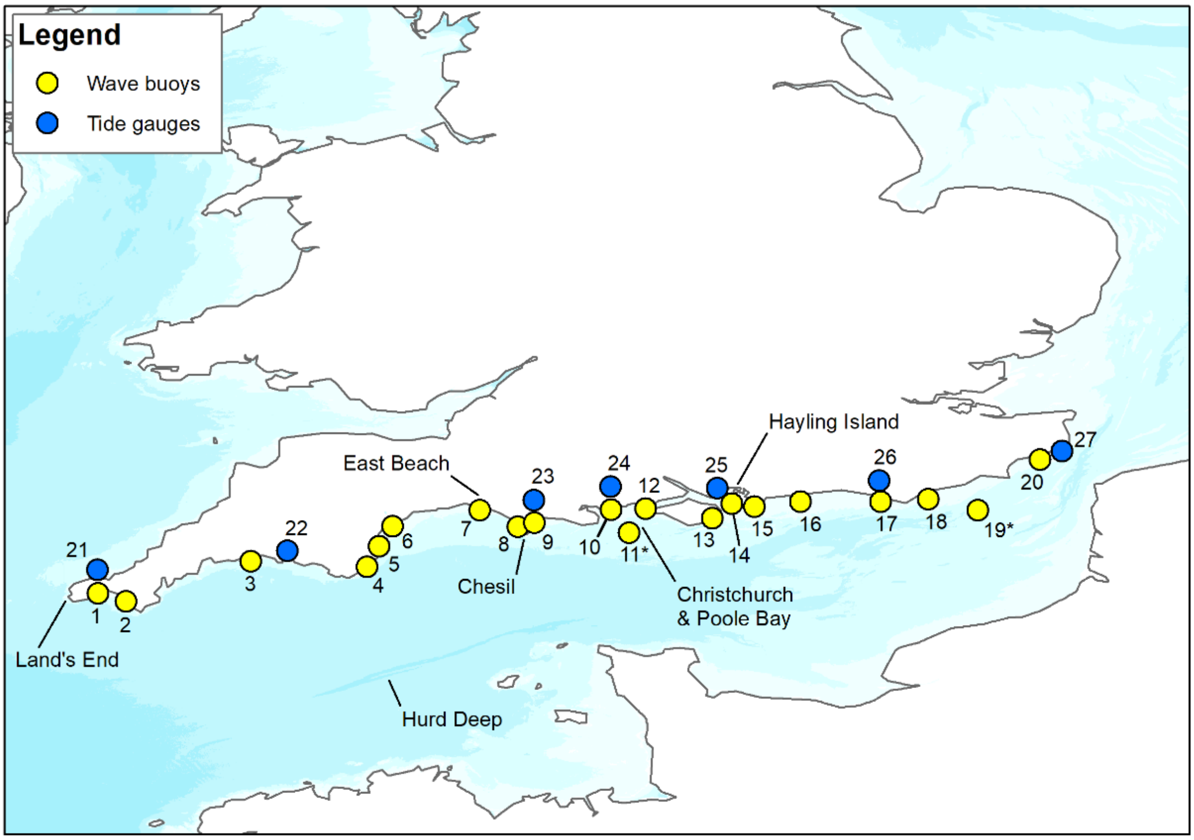
Serinaldi, F. 2015. Dismissing return periods. Stoch. Environ. Res. Risk Assess. **29**: 1179-1189. doi.org/10.1007/s00477-014-0916-1

Sibley, A. and Cox, D. 2014. Flooding along the English Channel coast due to long-period swell waves. Weather **69**: 59-66. doi.org/10.1002/wea.2145

Sklar, A. 1959. Fonctions de repartition à n dimensions et leurs marges. Publications de l'Institut Statistique de L'Université de Paris. **8**: 229-230.

Wahl, T., Mudersbach, C. and Jensen, J. 2012. Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas: a multivariate statistical approach based on copula functions. Nat. Hazards Earth Syst. Sci. **12**: 495-510.

Tables and Figures



Wave buoys:			Tide gauges:
1. Penzance	8. Chesil	15. Bracklesham Bay	21. Newlyn
2. Porthleven	9. Weymouth	16. Rustington	22. Devonport
3. Looe Bay	10. Boscombe	17. Seaford	23. Weymouth
4. Start Bay	11. Poole Bay*	18. Pevensey Bay	24. Bournemouth
5. Tor Bay	12. Milford	19. Hastings*	25. Portsmouth
6. Dawlish	13. Sandown Bay	20. Folkestone	26. Newhaven
7. West Bay	14. Hayling Island		27. Dover

Figure 1: Locations of the wave buoys and tide gauges used in this study. All wave buoys are owned and operated by the NNRCMP, except those indicated with an asterisk which are owned and operated by CEFAS. All tide gauges are owned and operated by the UK National Tide Gauge Network.

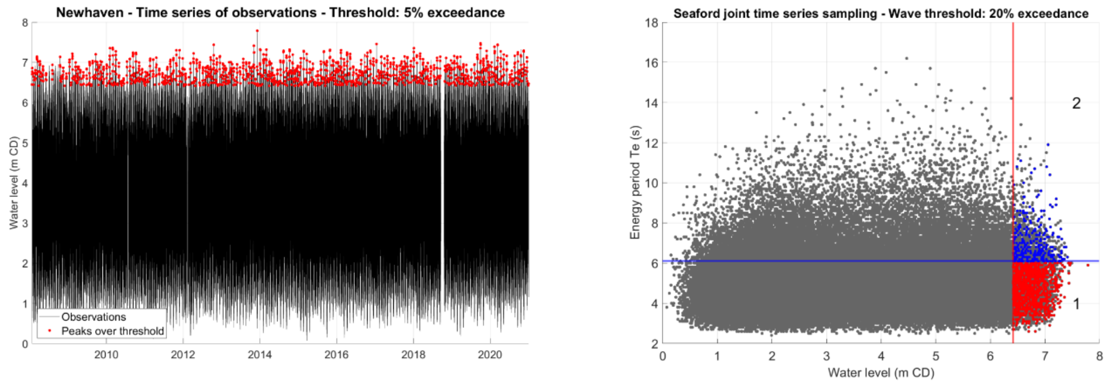


Figure 2: Sample of high water levels extracted via peaks over threshold from the concurrent sample of water levels at Newhaven and waves from the Seaford DWR (left).

From the sample of high water levels from Newhaven (quadrants 1 + 2), a subsample is extracted for dependence modelling by applying a high threshold for energy period Te from the Seaford DWR (blue line, 20% exceedance in this example), resulting in the sample represented by the blue markers in quadrant 2 (right).

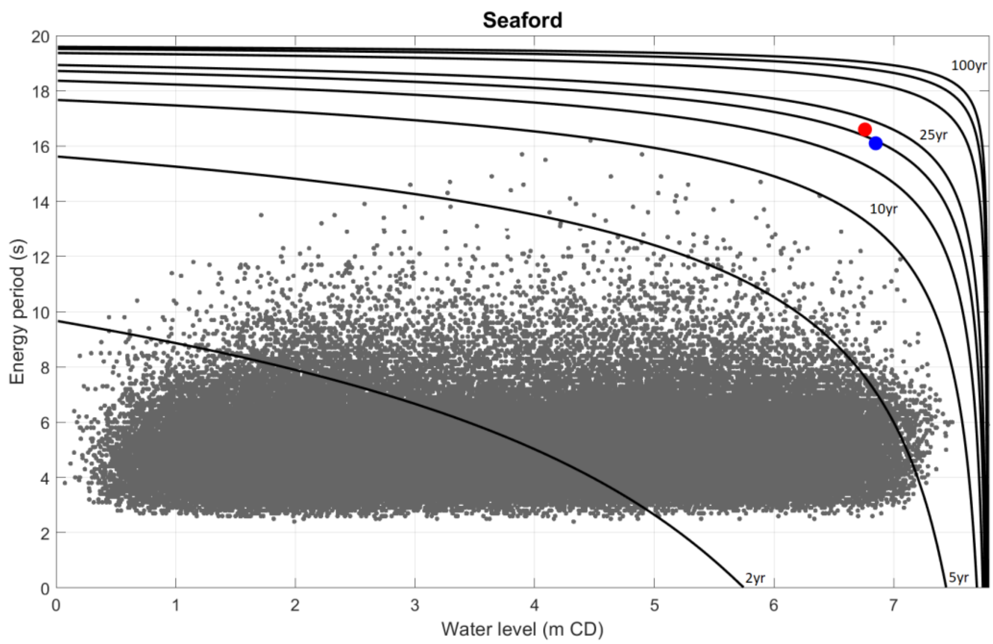


Figure 3: Joint return period plot of water level and energy period Te. In red, peak Te is indicated with the associated water level. In blue, the highest water level during the event is indicated with the associated Te. The values are from the 1st February 2021 swell event.

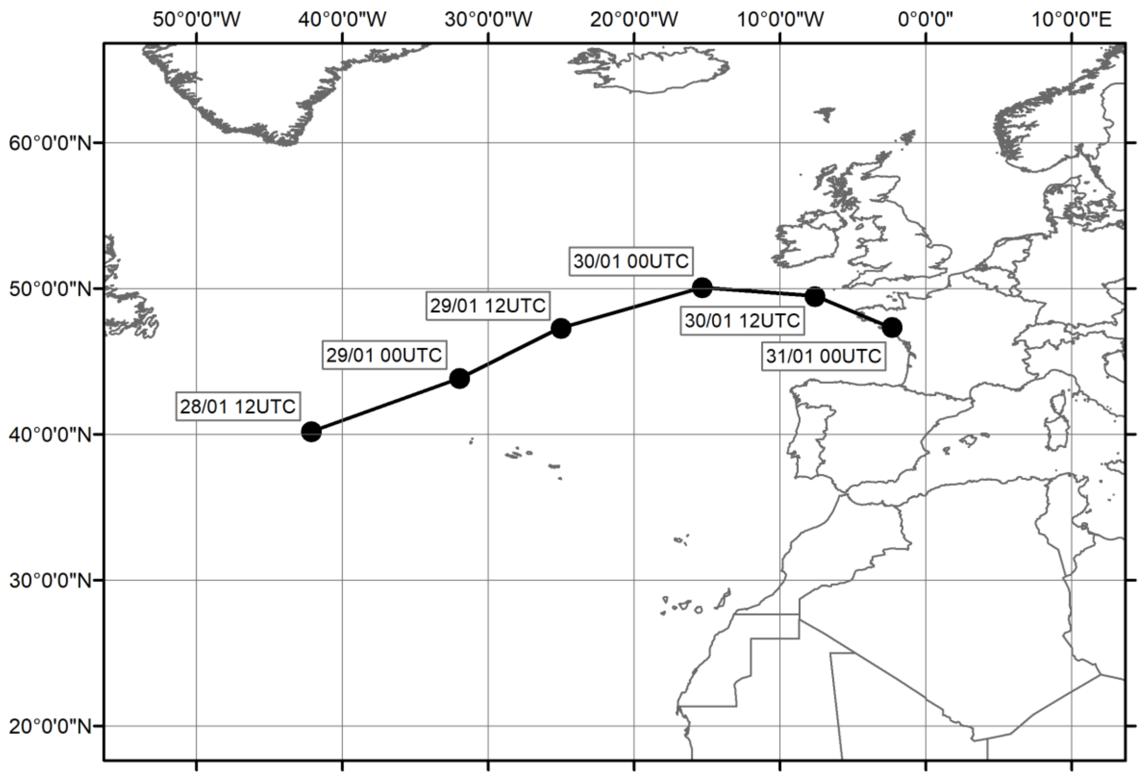
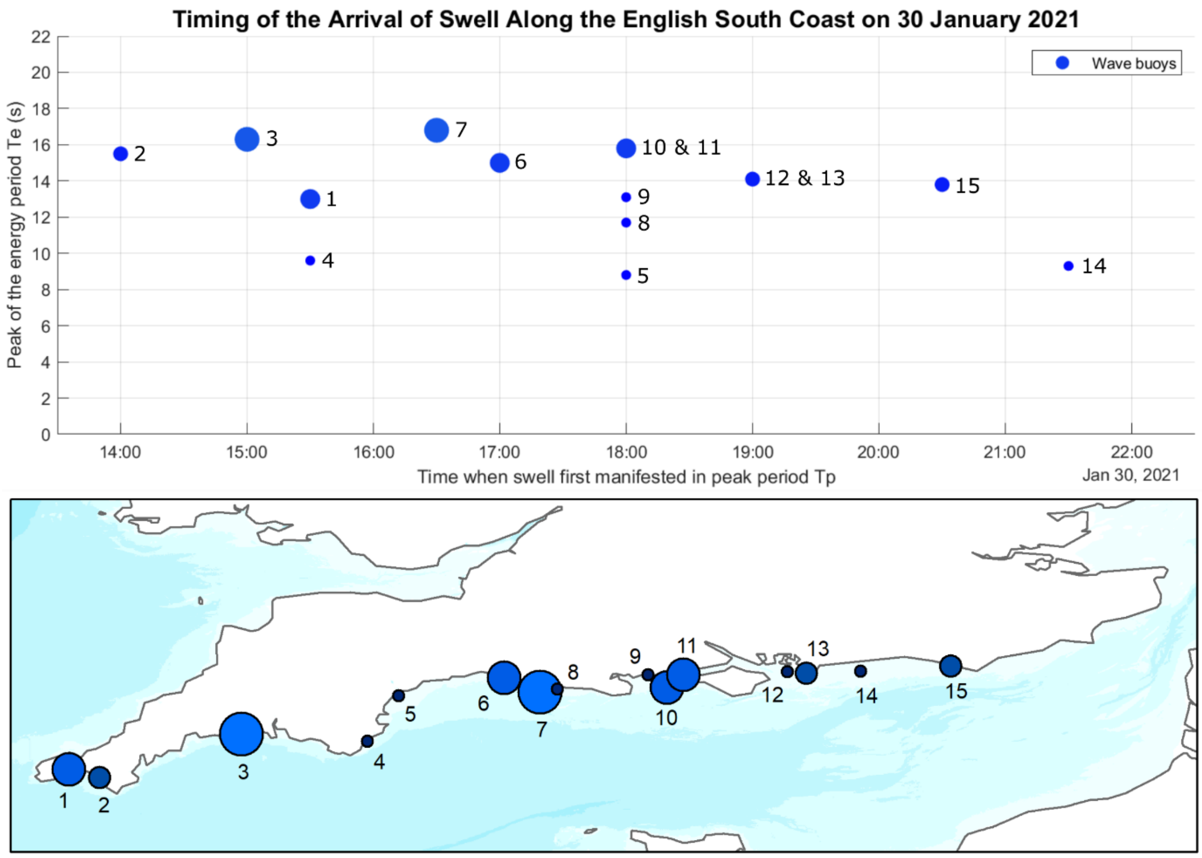


Figure 4: Storm track of the 30th January 2021 swell event.

Date / Time (UTC)	Barometric Pressure (mb)	Latitude / Longitude	Km	Km/h / knots
28/01 12:00	973	40°N, 40°W	-	-
29/01 00:00	967	44°N, 32°W	798	67 / 36
29/01 12:00	968	47°N, 25°W	629	52 / 28
30/01 00:00	975	50°N, 15°W	811	68 / 36
30/01 12:00	981	50°N, 08°W	498	42 / 22
31/01 00:00	993	48°N, 03°W	427	36 / 19

Table 1: Time, central pressure, position, distance travelled and estimated average speed of movement of the depression for the 30th January 2021 event.



Site	Return Period	Site	Return Period	Legend
1. Penzance	1 year	9. Boscombe	Bel. thr.	Below 0.25 year
2. Porthleven	0.25 year	10. Poole Bay	1 year	0.25 year
3. Looe Bay	2 year	11. Milford	1 year	1 year
4. Start Bay	Bel. thr.	12. Hayling Island	Bel. thr.	2 year
5. Dawlish	Bel. thr.	13. Bracklesham Bay	0.25 year	
6. West Bay	1 year	14. Rustington	Bel. thr.	
7. Chesil	2 year	15. Seaford	0.25 year	
8. Weymouth	Bel. thr.			

Figure 5: The swell propagating through the English Channel on 30th January 2021. The x-axis denotes when swell first manifested in peak period Tp, the y-axis shows the peak energy period Te achieved during the event. The size of the markers gives an indication of the Te return period achieved at the site. On the map, the size of the marker is relative to the Te return period achieved at each wave buoy site.

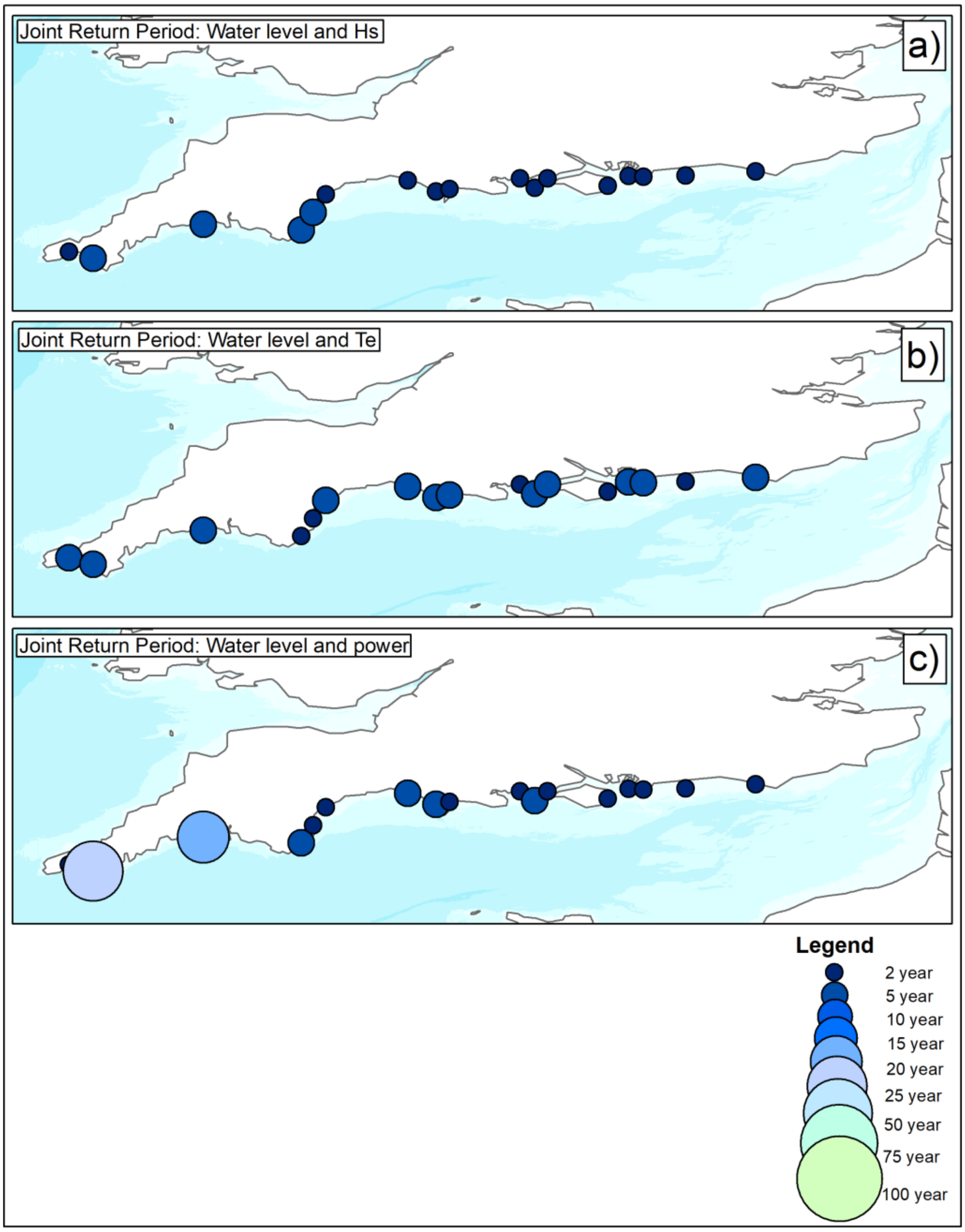


Figure 6: Spatial footprints of the 30th January 2021 swell event. The size of the markers is congruent with the joint return period achieved at the site. The spatial extent of the swell events is shown by mapping the joint return periods of water level and one of three wave parameters: significant wave height Hs (a), energy period Te (b) and wave power P (c).

Figure 7: Beach erosion at East Beach, West Bay on 1st February 2021. Photo by the Environment Agency.

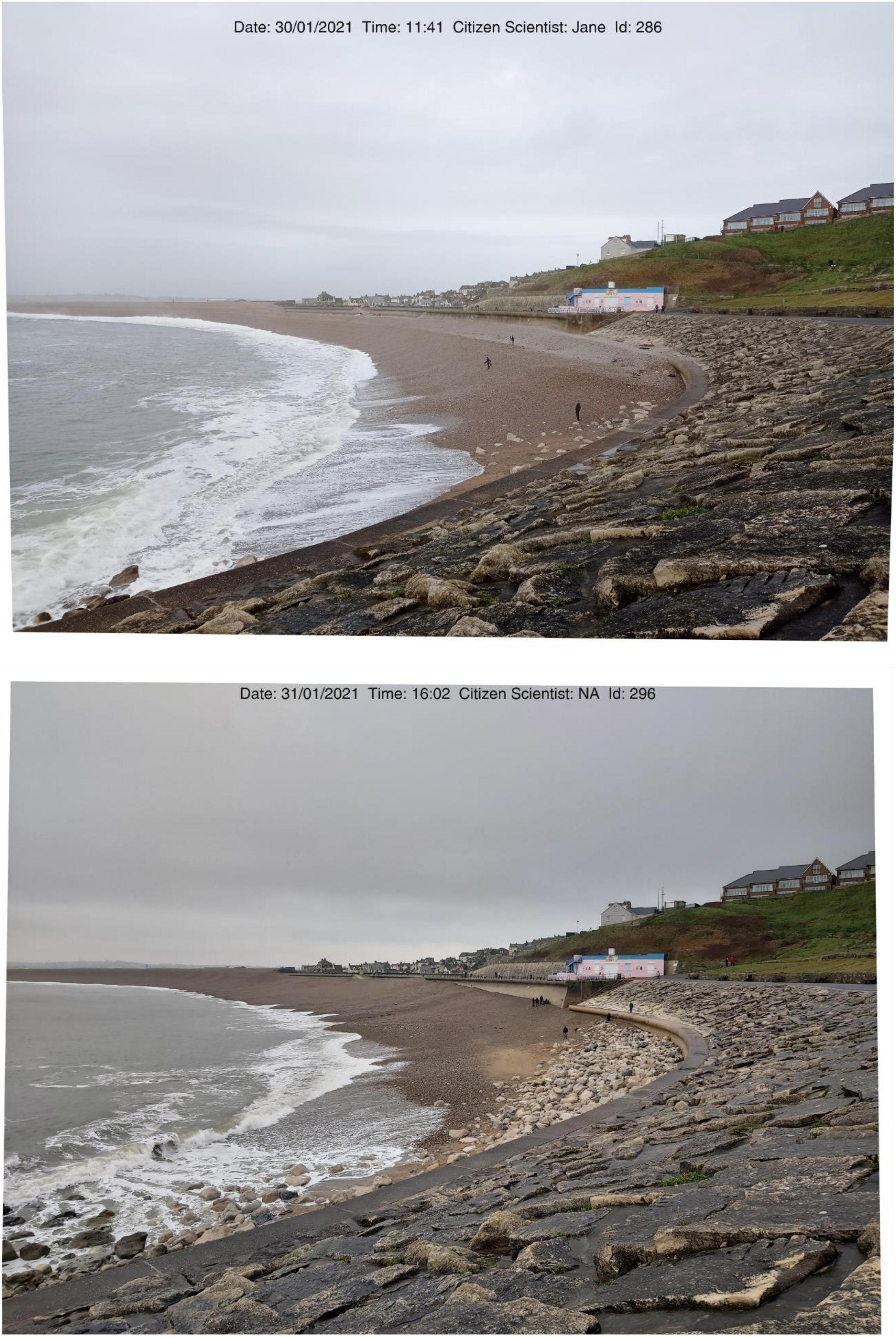


Figure 8: Erosion at Chesil Beach. The top photo was taken on 30th January, the bottom photo on 31st January 2021. Photo by the Southwest Regional Coastal Monitoring Programme CoastSnap Project.

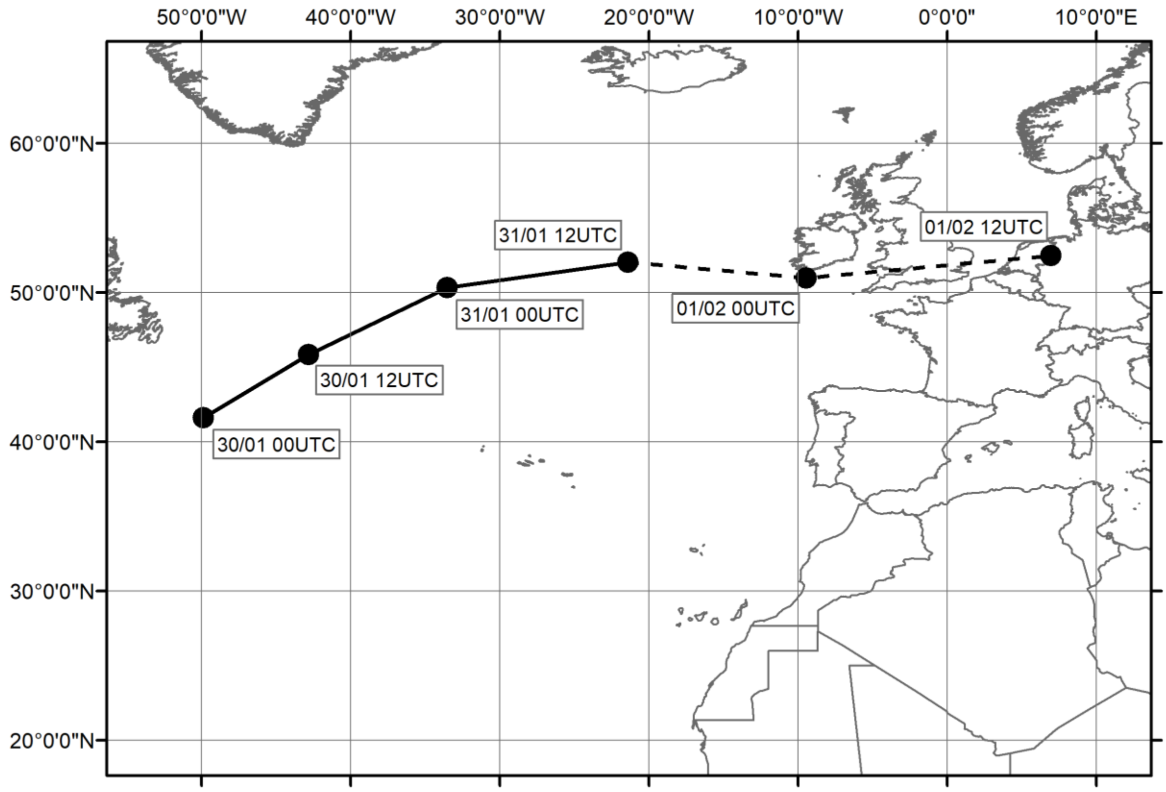
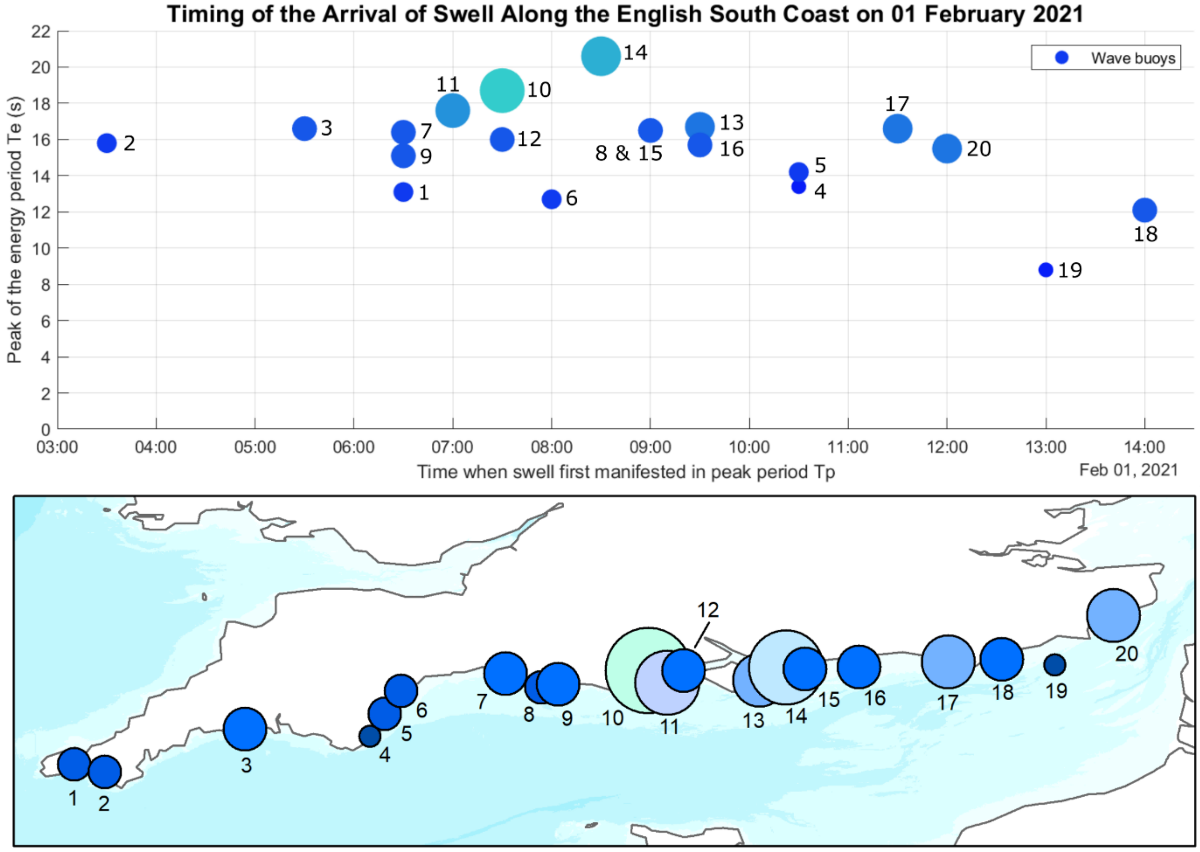


Figure 9: Storm track of the 1st February 2021 swell event. The hashed line is the track once the depression had lost its identity and became a complex low.

Date / Time (UTC)	Barometric Pressure (mb)	Latitude / Longitude	Km	Km/h / knots
30/01 00:00	957	42°N, 50°W	-	-
30/01 12:00	962	46°N, 43°W	740	62 / 33
31/01 00:00	969	50°N, 34°W	854	71 / 38
31/01 12:00	978	52°N, 21°W	863	72 / 39
01/02 00:00	987	51°N, 10°W	842	70 / 38
01/02 12:00	993	52°N, 07°E	-	-

Table 2: Time, central pressure, position, distance travelled and estimated average speed of movement of the depression for the 1st February 2021 event.



Site	Return Period	Site	Return Period
1. Penzance	1 year	11. Poole Bay	10 year
2. Porthleven	1 year	12. Milford	2 year
3. Looe Bay	2 year	13. Sandown Bay	5 year
4. Start Bay	0.25 year	14. Hayling Island	20 year
5. Tor Bay	1 year	15. Bracklesham Bay	2 year
6. Dawlish	1 year	16. Rustington	2 year
7. West Bay	2 year	17. Seaford	5 year
8. Chesil	1 year	18. Pevensey Bay	2 year
9. Weymouth	2 year	19. Hastings	0.25 year
10. Boscombe	50 year	20. Folkestone	5 year

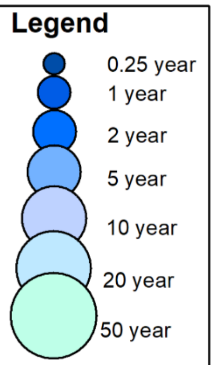


Figure 10: The swell propagating through the English Channel on 1st February 2021. The x-axis denotes when swell first manifested in peak period Tp, the y-axis shows the peak energy period Te achieved during the event. The size of the markers give an indication of the Te return period achieved at the site. On the map, the size of the marker is relative to the Te return period achieved at each wave buoy site.

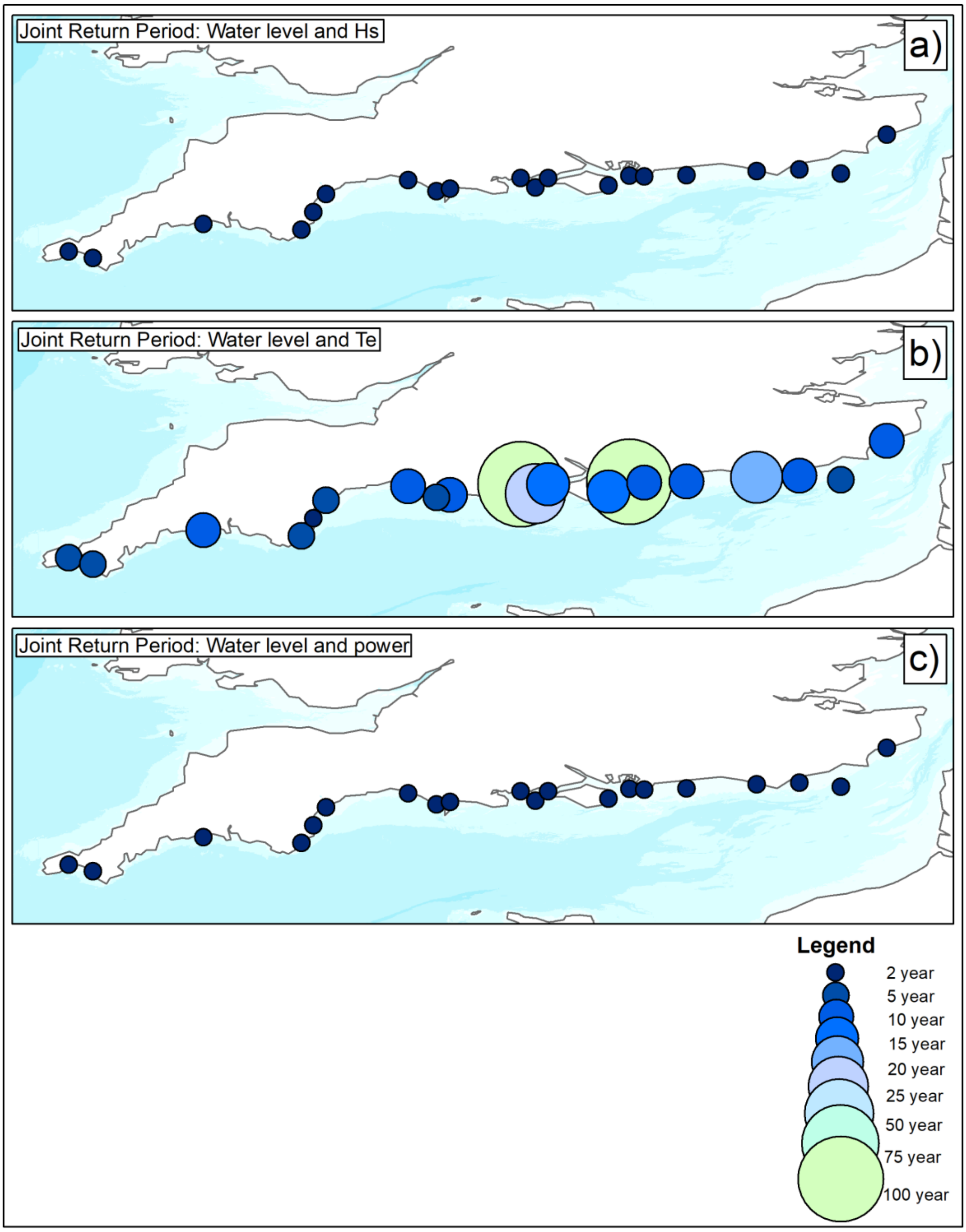


Figure 11: Spatial footprints of the 1st February 2021 swell event. The size of the markers is congruent with the joint return period achieved at the site. The spatial extent of the swell events is shown by mapping the joint return periods of water level and one of three wave parameters: significant wave height Hs (a), energy period Te (b) and wave power P (c).

Figure 12: Overtopping at Hayling Island on 1st February 2021. Photo by Havant Borough Council.

Figure 13: Plant is deployed at Hayling Island for emergency repairs to the beach. Photo by Havant Borough Council.

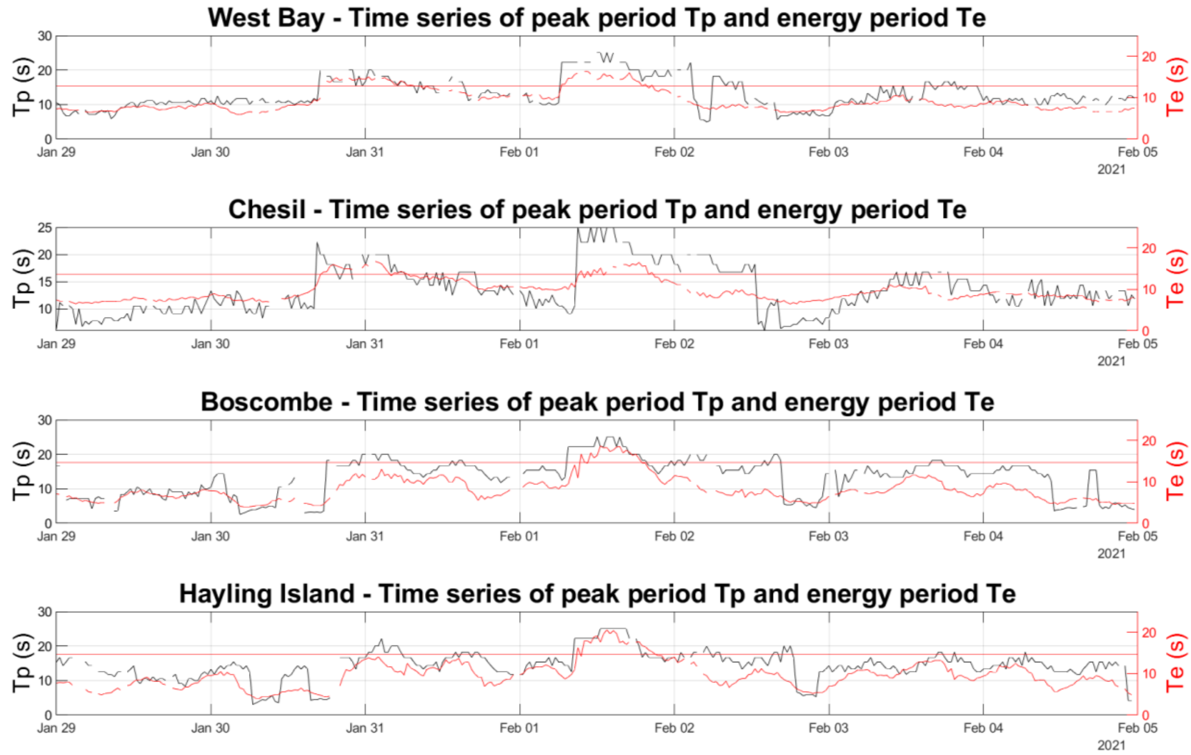


Figure 14: Time series of peak period Tp (black) and energy period Te (red) at those sites with reported impacts from the 30th January and 1st February swell events. The red horizontal line represents the 0.25 year return period for energy period Te as an indicative swell alert threshold.

Appendix 1

The wave energy period Te can be defined as the ratio of the first negative moment of the spectrum to the zeroth moment as given by equation A1.

$$T_{e} = \frac{m_{-1}}{m_0} \qquad \text{[A1]}$$

When knowledge of the full wave spectrum is not available, the energy period Te can still be derived from the full spectral parameter output of a Datawell MkIII buoy, specifically the periods Tdw2 and T1. What Datawell refers to as Tdw2 is the wave period Tm(-1,1) and is defined as the square root of the ratio of the first negative moment of the spectrum to the first moment as given by equation A2.

$$T_{dw2} = \sqrt{\frac{m_{-1}}{m_1}} \qquad \text{[A2]}$$

What Datawell refers to as T1 is the mean wave period or Tm(0,1) and is defined as the ratio of the zeroth moment of the spectrum to the first moment as given by equation A3.

$$T_1 = \frac{m_0}{m_1} \qquad \text{[A3]}$$

The wave energy period Te can therefore be calculated from the standard spectral analysis output of a Datawell Directional Waverider MkIII by reformulating equation A1 as:

$$T_e = \frac{m_{-1}}{m_0} = \frac{{T_{dw2}}^2}{T_1} \qquad \text{[A4]}$$