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Assessment and comparison of extreme sea levels and waves during the 2013/2014 storm season in two UK coastal regions

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Abstract

The extreme sea levels and waves experienced around the UK's coast during the 2013/2014 winter caused extensive coastal flooding and damage. In such circumstances, coastal managers seek to place such extremes in relation to the anticipated standards of flood protection, and the long-term recovery of the natural system. In this context, return periods are often used as a form of guidance. We therefore provide these levels for the winter storms, as well as discussing their application to the given data sets and case studies (two UK case study sites: Sefton, northwest England; and Suffolk, east England). We use tide gauge records and wave buoy data to compare the 2013/2014 storms with return periods from a national dataset, and also generate joint probabilities of sea level and waves, incorporating the recent events. The UK was hit at a national scale by the 2013/2014 storms, although the return periods differ with location. We also note that the 2013/2014 high water and waves were extreme due to the number of events, as well as the extremity of the 5 December 2013 "Xaver" storm, which had a very high return period at both case study sites. Our return period analysis shows that the national scale impact of this event is due to its coincidence with spring high tide at multiple locations as the tide and storm propagated across the continental shelf. Given that this event is such an outlier in the joint probability analyses of these observed data sets, and that the season saw several events in close succession, coastal defences appear to have provided a good level of protection. This type of assessment should be recorded alongside details of defence performance and upgrade, with other variables (e.g. river levels at estuarine locations) included and appropriate offsetting for linear trends (e.g. mean sea level rise) so that the storm-driven component of coastal flood events can be determined. Local offsetting of the mean trends in sea level allows long-term comparison of storm severity and also enables an assessment of how sea level rise is influencing return levels over time, which is important when considering long-term coastal resilience in strategic management plans.

1 Introduction

Storm surges and flooding are a threat to low lying coastal zones, with risks increasing due to sea level rise (Haigh et al., 2010; Menéndez and Woodworth, 2010; Wahl et al., 2011) and floodplain development (Hanson et al., 2011; Stevens et al., 2014). Northwest Europe, in which the case studies described in this paper are located, has historically suffered terrible losses from coastal flooding (Lamb, 1991; Gönnert et al., 2001). In living memory the worst event was the 31 January–1 February 1953 North Sea floods, which killed > 2100 people, mostly in the Netherlands and along the UK east coast (Steers, 1953; McRobie et al., 2005; Baxter, 2005). Recent and deadly reminders of the threat of coastal flooding include: Hurricane Katrina, 2005 (floods on the US Gulf coast, > 900 people killed by flooding); Storm Xynthia, 2010 (French Atlantic coast, > 50 flooding fatalities); Hurricane Sandy, 2012 (US east coast 41 flooding fatalities); and Super Typhoon Haiyan, 2013 (Philippines) (Lapidez et al., 2015).

More recently in the UK and Ireland, the 2013/2014 autumn-winter period was exceptional for the continued sequence and extent of storms and floods – the stormiest in 143 years (Matthews et al., 2014), causing a cluster of extreme coastal sea levels (Wadey et al., 2014). The magnitude of these high waters and lack of recovery between events caused coastal erosion, damage to defences and flooding. This unusual "season" (BBC, 2014; Wadey et al., 2014) began with the St Jude Storm (27 October 2013), followed by extreme sea levels in early November, and ended on the 3 March 2014 with high tides and floods in the Channel Islands. The biggest coastal event of the season was the "Xaver Storm" (5–6 December 2013), with the storm surge and consequent floods affecting Wales, northwest England, the UK east coast, and the southeast English Channel. In total > 2800 properties across the UK were flooded in this event alone including > 800 in Boston (Lincolnshire). Storm waves and high sea levels impacted the west and south coast throughout early January 2014, then on 5–6 February 2014 waves overtopped and destroyed the Dawlish Railway in Devon, and on 10–15 February waves and surges continued to impact the south and west coasts. There were numerous flood incidences and calls to emergency services.

The aim of this paper is to inform coastal managers at two contrasting case study sites of the extremity of the sea levels and waves during this unusual season. This is because it has been widely perceived that despite the stress to which the coast was subjected during 2013/2014, defences greatly reduced the consequences of these storms. This type of assessment provides insight and discussion to whether defences performed to their anticipated standards of protection, and also informs future defence design. We primarily undertake this via the commonly applied concept of joint probability analysis to generate return periods (of high waters, waves or these combined), and compare 2013/2014 with previous seasons. Our specific objectives are to:

1. Identify the most extreme sea level and wave events of 2013/2014 relative to long-term records;
2. Identify temporal clustering of these events in the span of the available observed data;
3. Compare and contrast the case studies to identify different return period characteristics and consequences (caused by local variability in sea level, waves and coastal orientation relative to the storm track position);
4. Discuss implications for defence performance and coastal management.

The selected sites are Sefton (a district in northwest England), and Suffolk (a county on the east coast). These sites have several attributes that make them appropriate case studies to identify storm-tide levels in relation to defence management. At both sites there is active coastal monitoring by coastal managers; hence this research provides storm thresholds to compare with past and future observations to inform shoreline management planning. These two case studies each have different coastal orientations and contrasting fetch limitations. Both sites are considered to experience some of the

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largest surges (> 2 m) within the UK (Lennon, 1963; Heaps, 1983) and host a variety of natural and manmade defences (Dolphin et al., 2007; Dissanayake et al., 2014).

The structure of this paper is as follows: Sect. 2 will provide a background (case study areas and 2013/2014 storms), Sect. 3 describes the data and methods, Sect. 4 provides the results for each objective, Sect. 5 discusses the results comparing the two contrasting study sites and the applications for managers, and Sect. 6 presents the conclusions.

2 Background

The two case studies, the locations of which are shown in Fig. 1, are summarised here. The Sefton case study site, in the context of shoreline management in England and Wales lies where Liverpool Bay management cells or "process cells" (Motyka and Brampton, 1993; Cooper and Pontee, 2006) 11a and b meet. This region borders the eastern Irish Sea and extends for 36 km between the Mersey and the Ribble estuaries. This coastline has a diverse range of environments, including: estuaries, tidal flats, saltmarshes, rapidly eroding dunes, defended shorelines, recreational beaches, urban areas and unspoilt and protected environments of high touristic value (Esteves et al., 2012). The coast is extensively monitored and managed; and the area is an internationally important nature conservation site which supports a declining population of Red Squirrels and Natter Jack Toads (Plater and Grenville, 2010). The Sefton coast is west facing and is situated in the enclosed basin of the eastern Irish Sea – and typically experiences extreme waves and surge under southwest to north-westerly wind condition (Pye and Blott, 2008). Extreme significant wave heights during storms can exceed 5 m; storm surges can exceed 2 m and the mean spring tidal range is 8.3 m (at Princes Pier, Liverpool). The storms that characteristically cause most impact on this coast are when a depression tracks across the Irish Sea from west to northwest, creating veering winds south-westerly to westerly over the longest fetches for surge and wave generation to the eastern Irish Sea (Brown et al., 2010). The dominantly recreational beach

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at Formby (Sefton) includes a notoriously fast eroding dune system, with a predicted annual rate of 4 m yr^{-1} over the next century, although during the 2013/2014 storms alone, over 13 m was lost (NT, 2014; Smith, 2014). The coastal dune systems here are amongst the largest in the UK, extending 16 km alongshore, 4 km inland and up to 30 m high (hence acting as a flood defence), and covering 21 km^2 (Esteves et al., 2012). Recovery since the recent 2013/2014 storms has included reinstating access routes to the beach and erecting new dune fences. The 5 December 2013 storm surge event and 3 January 2014 were associated with the worst damage during 2013/2014 (Smith, 2014). The 5 December event also caused floods within the Mersey Estuary: overall 19 businesses were flooded and 4 domestic properties (Wirral, 2014): at the Dell, Rock Ferry and also at Woodside. Further downstream the promenade between Seacombe and New Brighton was subject to overtopping causing damage to the promenade surfacing, railings and wave return units particularly towards New Brighton. At New Brighton flooding caused major disruption.

The Suffolk case study site (which forms the management cells 3c) borders the southern North Sea, and has approx. 78 km of shoreline (excluding tidal rivers), with two of its key urban areas at each end, Lowestoft to the north, Felixstowe to the south. Felixstowe has one of the largest container ports in Europe. The county's landscape is dominated by agriculture and is important to the national energy supply: the Sizewell nuclear power stations (one decommissioned, another active, and a third planned) lie behind the gravel barrier coast between Dunwich and Minsmere (EADT, 2013) which is an area of complex morphological evolution and nature conservation (Pye and Blott, 2006, 2009). The Suffolk coast is southeast facing and situated in the open North Sea basin. Extreme wave and surge conditions are typically associated with winds from the north to northeast (Pye and Blott, 2006). Suffolk's wave exposure is greatest to the north, with potential for extreme significant wave heights > 4 m. Storm surges of > 2 m have been recorded at Lowestoft which has a mean spring tidal range of 1.94 m (tidal range increases from north to south). Dominant offshore wave directions tend to be from the north-northeast and south-southwest, and net wave energy at the shoreline tends to be from the east (RoyalHaskoning, 2010).

The Suffolk coast around Dunwich and Sizewell has experienced major changes during the past two millennia, with significant loss of land caused by marine erosion (Pye and Blott, 2006). On this shoreline, local inshore wave heights, period, and approach angle are strongly controlled by the morphology of the coastline, and by the offshore bathymetry. The importance of the offshore Sizewell-Dunwich bank, which reduces wave energy reaching the coast, varies alongshore due to different shoaling (or even breaking) over the variable elevation and width of the bank (Tucker et al., 1983). The worst event in living memory was during the floods of 31 January–1 February 1953, when 45 people were killed in Suffolk. This storm characterised the worst conditions to impact this area of coast, a deep Atlantic depression which passed to the north of Scotland and moved southeast down the North Sea. The northerly gales on the western side of this depression forced sea water south at the time of high tide, causing a surge, whilst the wind field veered from northerly to northeast over the longest fetches generating extreme waves at the coast. The most severe 2013/2014 event in Suffolk was 5 December 2013, which flooded 231 properties in the county. At Lowestoft 143 commercial and 90 residential properties were affected (compared with 400 properties in 1953). Almost 170 properties were flooded in the Waveney District, with some breaches as large as 30 m wide (SDC, 2014; SFCN, 2014). A total of 22 breaches were reported across the county causing severe flooding and in one example the hamlet of Woodbridge was “cut off” (BBC, 2013a). Failure of the sea defences at Blythburgh caused the closure of the A12 road, the vital link between Lowestoft and Ipswich. Rail services between Lowestoft and Norwich, and Lowestoft and Ipswich were disrupted as a consequence of flooding at Lowestoft Central and damage to the signalling network. The Lowestoft to Ipswich line was closed for eleven days after the surge (SDC, 2014; SFCN, 2014). Ipswich and Felixstowe escaped substantial damage but Waldringfield suffered significant flooding.

3 Data and methods

Both Sefton and Suffolk have wave recording devices located nearby (Directional Waverider® MkIII). These are part of the WaveNet system of nearshore wave buoys deployed since 2002 (Fig. 2), and maintained for the Environment Agency (EA) and Department of Environment Food and Rural Affairs (DEFRA) by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS). One of these wave buoys is offshore from Sefton, near the Liverpool Bar Light in 22 m water depth. This has now provided over 12 complete years of directional wave observations. The Suffolk data used here are from the Sizewell wave buoy in 18 m water depth and has been operational for approximately 6 years. The data time series is provided at 30 min temporal resolution. Available at both sites are observed sea level time series from the UK's "Class A" network of tide gauges, managed by the National Tide and Sea Level Facility (NTSLF), owned and funded by the EA, and data is quality controlled and archived by the British Oceanographic Data Centre (BODC). 15 min data values are available for January 1993 onwards and hourly values prior to 1993 (Fig. 2). The sampling frequency of these time series were not changed (i.e. interpolated) for this analysis (so any levels quoted may be directly obtained from the raw data). These sampling rates filter out high frequency seiches, swell and wind waves. UK tide gauges are regularly levelled and checked. The BODC's archived data is accompanied by flags which identify problematic data and we also undertook secondary checks. The closest tide gauge to Sefton is Liverpool (surrounding gauge data at Heysham and Llandudno is briefly discussed), and the wave buoy is 16 km offshore. For the Suffolk case study we use data from the Lowestoft tide gauge, and the Sizewell waverider buoy which is 4 km offshore.

We separated the observed sea level record (SL) into its main component parts (Pugh, 2004): mean sea level (MSL); astronomical tide; and non-tidal residual (see also Wadey et al., 2014). We refer to the "skew surge" which is the difference between the elevation of observed high water and the corresponding value of the predicted tidal peak – a more relevant concept to flood risk than residuals elsewhere in the tidal cycle (Horsburgh and Wilson, 2007). To assess return periods of each high water, we use a UK-wide assessment of the joint probability of tide and skew surge from the Environment Agency's national extreme value statistics for sea level (Batstone et al., 2013; McMillan et al., 2011a). These return periods are referenced to a 2008 mean sea level (MSL) baseline; therefore we offset the total water levels to remove the influence of sea level rise on the extreme water levels relative to the year 2008 (see Wadey et al., 2014) (Fig. 3). Over these multi-decadal observations, this provides a better isolation of the storm-tide driven component responsible for causing the extreme high waters. For this we use the linear SLR trend calculated at each site: at Llandudno this is +2.41 mm yr^{-1}, at Liverpool +2.66 mm yr^{-1}, at Heysham +1.56 mm yr^{-1}, and at Lowestoft +2.35 mm yr^{-1}. The higher rates are artefacts of the short records: mean sea level rise at Liverpool assessed by Woodworth et al. (2009) suggests a lower long term (since 1901) trend of +1.4 mm yr^{-1}; whilst the UK's longest record (Newlyn since 1915) suggests a rate of approx. +1.8 mm yr^{-1} (Araújo and Pugh, 2008; Wadey et al., 2014) similar to the average global rate. However, it should also be noted that since the 1990s satellite altimetry suggests higher recent global averaged rates in the order of +3 mm yr^{-1} (Church and White, 2006); whilst in the UK, there are regional variations in sea level trends, mainly due to uplift/subsidence of land with different geological and glacial history (Shennan and Horton, 2002; Bradley et al., 2009).

Wave events were defined as the peak in significant wave height (H_s) of a storm event, each event being separated by at least 24 h and above a level of the 1 in 1 wave return period level. A national swell wave return period data set exists (McMillan et al., 2011b) but at each case study site the locally generated wind waves are important for causing higher total sea states, hence we applied a Weibull distribution in an extreme value analysis of observed wave height. This generated return periods from the observed wave event time series and also a 30 year model hindcast (provided by CEFAS – c.f. Leonard-Williams and Saulter, 2013) at the Waverider® locations (Table 1). It is clear that the longer 30 year hindcast data has higher H_s levels for each return period.

Since longer data is required for extreme event analysis we used the 30 year levels to identify wave height return levels for observed events. Due to fetch limitations in the eastern Irish Sea higher return periods are associated with a small increase in the wave height. Figure 4 provides a perspective of wave events and the corresponding wave periods – we acknowledge that ideally a fuller assessment of wave events would incorporate period, direction and duration.

For the joint probability assessment (Fig. 5) we created a dataset of every high water (HW) and corresponding H_s at the time of each high water. For Sefton this was data from the wave and tide recorders at Liverpool, and for Suffolk the wave buoy at Sizewell and tide gauge at Lowestoft. We calculated the joint probability of high water elevations and wave heights occurring together from this dataset using the JOINSEA software (Hawkes and Gouldby, 1998; Hawkes et al., 2002) which has been extensively applied and validated (Hawkes and Svensson, 2003). Fundamentally this approach is based upon principles that are also described in Coles and Tawn (1990). Generalised Pareto Distributions are fitted to the top few percent of the marginal variables (i.e. wave heights and coincident sea levels), and dependence models – a single Bi-Variate Normal (BVN) Distribution and a mixture of two BVNs are applied to the observed data to generate a large sample of random pairs of wave heights and sea levels, which are based on the fitted distributions, and with the same statistical characteristics as the input data. This allows 1000s of years of sea conditions to be simulated with fitted distributions, extremes and dependences. Extreme values are calculated below the upper tails of statistical distributions defined in the software. However in our case studies, due to the requirement for a seamless dataset of combined waves and high waters, the datasets are shortened by the limited length of the wave observations. Therefore the resultant return periods should to be treated with caution beyond the 10 year level. At Liverpool this was a data set of 6836 high waters (with corresponding wave height) and at Suffolk this was 4030 records. Due to the short time scale of observations, a sea level rise offset to modify the HW elevation relative to the first year of observations has not been

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included (initial tests showed this to have nominal effect on return period across these short data sets).

To assess the temporal nature of the high water and wave events during the 2013/2014 storm season we analyse the frequency of events above the 1 in 1 year return levels. The objective is to determine if 2013/2014 was indeed unusual in terms of the "clustering" of distinct sea level and wave extremes, and also to identify if the overall duration of high sea and waves levels during this season is considered extreme compared with other seasons. In the UK extreme storm events tend to occur between Oct and Apr (Wadey et al., 2014); hence to compare year-on-year durations of clusters of events we define "seasons" for year on year comparison as an assessment of events occurring between the 1 July of one year and the 30 June of the following year.

4 Results

4.1 Sea level and wave height return periods

Objective 1, to summarise the large water level and wave events of 2013/2014, is addressed firstly for Sefton then Suffolk. Each event during the winter cluster is associated with a return level for water level (WL), wave height (WH) and the joint water level-wave level (JL). Extreme events during the 2013/2014 season are identified at each location if the water level exceeds the 1 in 1 threshold defined by McMillan et al. (2011a), or if the wave height exceeds the 1 in 1 threshold (Fig. 4) defined by the 30 year wave hindcast (Table 1), or if the combined water level-wave conditions exceed the joint 1 in 1 threshold (Fig. 5).

At Sefton 14 instances of extreme conditions are identified (Table 2). Out of these 6 are considered extreme due to the sea levels, 3 are considered extreme due to the wave heights and 13 are considered extreme due to the joint water-wave level conditions. At this site, considering water levels and waves together increases the return period value assigned to the event, compared with when the water levels and waves are taken in isolation. The water level return periods of McMillan et al. (2011a) approximate the largest water level event at Liverpool tide gauge (5 December 2013 12:30 GMT) as a 1 in 44 year return period. This was the largest event in the database at Liverpool, a record dating back to 1992, and is 0.33 m higher than the event previously considered as the largest, which was the 10 February 1997. When considering the offset in HW elevation due to the local trend in mean sea level there is little reduction in the sea level return periods for these events. The largest wave height during 2013/2014 was also on 5 December 2013 at the same time (12:30 GMT), with a significant wave height of 4.55 m and period of 6.9 s. This was rated as a 1 in 5 year event on the basis of the 30 year model hindcast (Table 1). The next largest wave event of the season occurred on 3 November 2013 (H_s) 4.30 m, T_z 7.6 s). The largest event in the observational data set was a wave height of 5.43 m measured on 8 February 2004. The fact such large wave conditions coincided with high water meant that this event was rare. The analysis of the observed combined 12 year sea level and wave record confirmed that this was the largest joint water-wave level in the 2013/2014 season and in this data set. The veering W-NW wind directions during the morning rising tide (see Figs. 7 and 8) caused large wave and surge conditions for Liverpool, which when combined with one of the largest spring tides due to the timing a year before the maxima in the nodal cycle resulted in an extreme sea level. This coincidence at high water level, due to the spring tide and large skew surge, and wave height increases the probability estimates for the isolated conditions to an estimated joint probability of > a 200 year return period event. On the 1–3 February 2014, and in other events, smaller storm wave conditions occurred but were prolonged over multiple tidal HWs, creating consecutive instances of extreme joint water–wave level conditions.

The neighbouring tide gauges of Llandudno and Heysham (either side of Liverpool: Heysham is 55 km north of Sefton and Llandudno is 55 km southwest of Sefton) are also affected by the same high water levels and storm events. The 5 December 2013 event stands out at all of these sites, although the 3 January 2014 HW was the largest of 2013/2014 at Llandudno and Heysham. Using the SLR offset values, the 5 December 2013 was a 1 in 15 year HW at Llandudno and 1 in 4 year HW at Heysham, respectively ranked as the 4th and 3rd largest events in these records; whereas the 3 January 2014 HW was a 1 in 17 and 1 in 9 year HW respectively. Events on 10 February 1997 and 1 February 2002 were more extreme HWs at Llandudno and Heysham than they were at Liverpool, and at Heysham larger than any 2013/2014 HW.

At Suffolk (Table 3) 9 time instances occur when extreme conditions are identified. Out of these 2 are considered extreme due to the water levels, 2 are extreme due to the wave heights and 8 are extreme due to the joint water-wave level conditions. For the 10–12 October 2013 storm, and the high waters on 6 and 19 December it is clear that considering water levels and waves together increases the return period value assigned to the event (compared with the water level and waves return periods taken in isolation). Using the sea level elevation return periods of McMillan et al. (2011a) the largest water level event at Lowestoft, was on 5 December 2013 at 22:30 GMT and was a 1 in 196 year return period. This was the largest event in the database at Lowestoft, a record dating back to 1964, 0.55 m higher than the event previously considered as the largest on the 29 September 1969. However the HW of 31 January 1953 (which is not in the BODC database) was up to 0.18 m larger according to the observations of Rossiter (1954). The 5–6 December 2013 event caused the two highest joint water-wave level values of 2013/2014 at Suffolk on consecutive high tides. The extreme water level is most influential upon the large return period in the first instance and large waves most influential upon the return period in the second instance (Figs. 5 and 7). On the latter tide the wave conditions increased the HW return level at 11:30 GMT 6 December from a 1 in 2 year sea level to a 1 in 15 year joint water-wave level occurrence. Less damage was experienced on the second tide although waves overtopped onto promenades on the 6 December (e.g. https://www.youtube.com/watch?v=vTE5o3M7JF0). When considering the offset in HW elevation due to the local trend in mean sea level there is a greater reduction in the joint water-wave level for the high return period on the 5 December 2013, while the lower return period on the 6 December 2013 is unaffected. The estimated joint probability of this event at a 1 in 75 year return period is large, but the small wave heights at the time of HW cause a lower return level than when considering water level in isolation. The largest wave height event during 2013/2014 was at 22:30 GMT 14 February 2014 with a significant wave height of 3.94 m and period of 6 s, rated as a 1 in 5 year event on the basis of the 30 year model hindcast. This did not occur during a big storm-tide and hence was not associated with an extreme water level on the east coast. Therefore the joint water-wave level return period is less than the wave return level in isolation at 1 in 2 years; although this particular storm was extreme and caused flooding on the south coast of England ("The Valentines Night Storm"). This event at the Sizewell wave buoy is exceeded by the largest H_s in the record of 4.72 m measured on 10 March 2008 – interestingly these big wave events (but not big surges) in Suffolk (10 March 2008 and 14 February 2014) coincide with extreme surge and flood events on the south coast (c.f. Wadey et al., 2013). The largest wave period (7.6 s) in the Sizewell record was during 2013/2014 following the Xaver Storm, and occurred during the night of 6–7 December 2013.

The 6 years of available observed joint water-wave level data indicated that the largest event (in the 2013/2014 season and in this data set) was on the 5 December 2013, also the largest in over 11 years of observed data on the opposing UK coast in Sefton. These JOINSEA return period outputs are commensurate with actual coastal event extremities observed in the case study regions, and much more realistic in terms of a timeline perspective of coastal impact than the sea level and wave return periods in their respective isolation. The Sefton data produces a joint water level-wave probability of > 200 years for the 5 December 2013. Whilst we reiterate caution with the short data length we could find no record of a more severe flood or erosion event in living memory, hence such as large return period is plausible. In Suffolk, the same event is widely regarded as "the most serious surge and flood to hit the east coast for 60 years" e.g. (BBC, 2013b) – i.e. since 31 January 1953. Therefore, the "1 in 75 year" joint water level wave estimate at Lowestoft is again proportionate with this statement in terms of coastal impacts.

4.2 The temporal clustering of events

The second objective, is to assess the temporal clustering and duration of extreme sea levels and waves. At Sefton, the assessment based upon the Liverpool tide gauge and wave buoy observations (Table 2) lists 14 time instances of water level and/or wave extremes during the 2013/2014 cluster that resulted from 6 different storm periods (the extremes are defined as those when conditions are greater than an annual probability of occurrence according to the respective statistical methods).

From the perspective of sequences in extreme water levels (by associating a return period with the twice daily high waters – HWs) the 2013/2014 season was the most extreme season on record at Liverpool: there were 6 HWs greater than the annual return period threshold (with or without offsetting for SLR either side of the year 2008) and if HW is offset to remove the local SLR trend there are 5 events above the 1 in 1 year HW extreme (Fig. 6). Previously the most clustered extreme HW season was 2006/07 for HWs above the 1 in 1 year threshold (with or without offsetting for SLR either side of the year 2008). The season of 2013/2014 was the second most extreme for HW clustering in the longer Heysham record (Fig. 6), with 3 events above the 1 in 1 year level (whether offset for SLR or applying the 2008 baseline MSL return periods), outdone by 1988/89 which saw 4 events above this threshold. When looking at the 1 in 5 year return period threshold, 2013/2014 is the most extreme at Liverpool and Llandudno, whilst at Heysham there has not been more than one event above this threshold per season. Interestingly, at Liverpool the water level was above the 1 in 1 year threshold (2008 MSL) for a total of 5.3 non-consecutive hours during the 2013/2014 events – the previous longest duration of exceedance was 2.25 non-consecutive hours in 2006/07 season.

From the time series plot of wave height, period and 1 in 1 and 1 in 5 H_s thresholds in Fig. 4, it is seen that 2013/2014 does not stand out as particularly extreme in the 2002–2014 Liverpool wave record (Figs. 4a and b), with 3 time instances of large H_s relating to separate storm events (using > the 1 in 1 year return period from the 30 year hindcast data). 2007/08 was more clustered with 5 events above this threshold. The JOINSEA assessment of water-wave level joint probability (Fig. 5) suggests 13 time instances > a 1 in 1 year return period, 7 of which are not extreme when sea level or waves are assessed independently. This is the highest such seasonal cluster in this record (since 2002) – the previous maxima was 10 events > the 1 in 1 year level (2006/07). The 2013/2014 season is even more extreme when it is considered that there are 4 events easily in excess of the 1 in 10 year return period (again the previous maxima was 2006/07 with two above this level).

At Suffolk, from the assessment based upon the Lowestoft tide gauge and Sizewell wave buoy observations, Table 3 identifies 9 time instance during the 2013/2014 season that resulted from 6 different storms. In terms of water level, the HWs associated with the Xaver Storm (5 December 2013) are the only two during 2013/2014 above the 1 in 1 year probability threshold; and only the first HW exceeds the 1 in 5 year threshold. The previous maximum number of > 1 in 1 year HWs per season was 5 in 1973/74; and in 1992/93 there were 2 HWs > the 1 in 5 year level (Fig. 6). Two events were also above a 1 in 1 year return period purely from a wave height perspective (using return periods developed from the 30 year hindcast data, Fig. 4c), but 2007/08 was more clustered with 5 events above this threshold. The joint water-wave level probability suggested that 9 events in the 2013/2014 season were > 1 in 1 year return period (2 of which were the extreme sea levels of 5–6 December 2013). Note that 6 of these events require the water-wave level joint probability approach to define them as extreme (i.e. they are not extreme when sea level or waves are assessed independently). 2013/2014 is more clustered than the other years of February 2008 to July 2013, when there was previously a total of only 4 events above the 1 in 5 year return period (2 of which were in March 2008).

5 Discussion

5.1 Comparison of the case study sites

The third objective is to compare and contrast the case study sites. First we focus on the winter 2013/2014 season. Starting with the sea level analysis we find that the Liverpool tide gauge in 2013/2014 recorded a greater cluster of extreme sea level instances: 7 of which were > 1 in 1 year compared with only 2 events above this threshold at Lowestoft. Furthermore, at Liverpool the extreme high waters were spread out over time, from December to March; whereas both extreme sea level instances in Suffolk were on consecutive days, linked to the 5–6 December 2013 Xaver storm and surge. However, the 5–6 December 2013 sea level event at Lowestoft was far more extreme (with an almost 1 in 200 year return period high water followed by a 1 in 1 year HW on the next tide, compared with a single 1 in 40 year HW at Liverpool).

From a wave height perspective, the records are relatively short, and at neither location can 2013/2014 be considered the most extreme at these sites if waves are assessed independently. Both sites have seen larger wave height peaks (03:30 GMT 8 February 2004 at Liverpool, 10:30 GMT 10 March 2008 Sizewell) and more persistent seasons of large wave heights. In terms of joint water-wave level probability, waves changed the HW return periods at both sites to either higher/lower levels (compared with taking HW and wave return periods in isolation). This is most noticeable when the coincidence of waves is taken into consideration for the 5 December event. This event is unusual due to its national scale impact – different UK locations tend to be susceptible to extremes and coastal floods, from different storm tracks.

We focus upon the 5–6 December 2013 event as an example to discuss the different coastal response to the same storm. This event was extreme nationally due to the storms timing relative to high water spring tide, and the veering winds over the UK. In Liverpool the storm track created large waves and a large surge, which due to the timing relative to the tide created an extreme skew surge. Whereas the window of opportunity for a large sea level and wave event at Liverpool is relatively limited, due to the big tidal range; at Suffolk the surge is a long wave and coincidence of the surge with spring tide allowed for two successive extreme water level events. Large North Sea surges tend to be from storms that generate a high water level gradient in the northern North Sea and track southwards along the coast – such as that of 31 January 1953 (the biggest North Sea event in living memory). On 31 January 1953 the Irish Sea was also extremely stormy (resulting in the sinking of the Princess Victoria, killing 133 people), but there is no mention of flooding – one reason being that peak high tides were at a smaller phase than during the storms of December 2013. For the wide-scale flood impact seen in December 2013, the storm track (that eventually creates a surge in the North Sea) needs to coincide with spring tides on the west coast of the UK (i.e. in our example the Irish Sea). However, at Sefton the waves on 5 December 2013 were not as extreme as is possible due to the rapid variation in wind direction, which caused time-limited wave growth – the winds veered N-NW during the morning. Similarly, the waves and the wind-component of surge in Suffolk was not as extreme as possible – the wind was offshore at the time of high water (Fig. 7) and the low pressure centre did not track southwards as close to the coast as for example during the larger surge and waves of 1953. Storm tracks that are known to generate the most severe wind, wave and surge conditions in the Irish Sea are less likely to impact the North Sea, even if coincidental with spring tide. This is because SW-W fetches are associated with the worst conditions in the eastern Irish Sea, whilst the large (> 8 m) tidal range controls extreme water levels (Brown et al., 2010). Extreme sea levels in the North Sea, and specifically at Lowestoft with its small 2 m spring tidal range, are more determined by large storm surges.

At Liverpool the coincidence of large storm waves on the 5 December 2013 at the peak of the storm-tide increased the event extremity above that of the still water level categorisation alone, to beyond a 200 year return period. Contrastingly at Lowestoft the lack of extreme waves at the time of high water lowers water level return period to a water-wave level a 1 in 75 year return period. At Liverpool the surge (Fig. 8a) and large waves (Fig. 8b) peak closely in time, due to close orientation of the fetches that generate extreme conditions for both variables, and are coincident with the time of the peak astronomical tide, which is unusual, but crucial since the tidal range (predicted at 8.9 m during this event) is the main factor in causing extreme water levels at this site. The waves and surge diminished by the following low water. It is worth noting that next biggest 2013/2014 event at Sefton: the 1 in 75 year joint water-wave level occurrence on 3 January 2014, was much smaller (0.36 m smaller peak high water, and H_s of approx. half the size of 5 December 2013), but is a "notable" event (i.e. it caused some coastal damage at Sefton) because of the magnitude of the tide and moderately large waves that persisted for several days (i.e. until the 6 January – Table 2).

At Lowestoft, the situation on the 5–6 December 2013 was very different because the surge component (the key mechanism for extreme sea levels at this location) is as large as the tidal range (approx. 2 m). The surge is also more prolonged than at Liverpool due to the nature of the long wave, and that the wind was constant from the northwest (during the 6 December): the non-tidal residual (primarily consisting of storm surge) remained at > 1 m high for (2 tidal cycles) over 18 h, which is why the morning high water of 6 December was also extreme. Unlike at Sefton, the waves and surge were not as coupled, with the peak H_s occurring around midday due to the SW winds, dropping by the time the surge and tide had propagated into the North Sea causing a peak in water level at the same location, but this time under NE wind conditions. While the surge levels drop after HW the waves recorded at Sizewell begin to build again (as the wind direction at the Suffolk coast aligns from NW towards the N) causing a second extreme joint water-wave level. However, if the local wind had been stronger and more northerly during the 5 December evening HW, this could have both added to the surge height and wave conditions – an onshore storm (as in 1953) would have caused more severe damage (SDC, 2014). The bimodal wave climate at this location lead to the multiple instances of large wave events as the storm winds veered from SW to N. During SW wind-wave events this location is unlikely to experience large surge levels, the joint occurrence of large waves and surge is more likely to occur during NW to NE veering winds. In this case the slow veering towards a more northerly direction delayed the secondary peak in waves coinciding with the peak surge level.

5.2 Coastal defence performance

The fourth objective is to discuss, in relation to the analysis presented here and general reports of flooding and damage, how the coastal defences at these case studies performed. We reiterate that the return periods shown for our case studies, particularly those for waves and the joint water-wave level assessment should be treated with caution due to the short length of the data sets that were applied. Further challenges include that detail of the defences (e.g. structural design and condition assessments) are not available; return period definitions change with new data, events and analysis methods; and naturally variable systems (e.g. beach levels, offshore bars, intertidal mudflats) also provide defence (and are not incorporated into our assessment).

The UK's coast is extensively managed via a risk-based approach, which includes aiming for specified standards of protection (SoP) at different locations, based upon the potential consequences (e.g. property losses, risk to life) of defence failure. The cost-benefit or risk analysis would typically use design conditions referenced to hydraulic load(s) (e.g. river flow, storm-tide level or wave height) return period. Nationally standardised protection followed the Waverley Report in response to the 1953 floods, whereby flood defences were set to withstand a 1 in 100 year still water level (Alcock, 1984). Coastal flood defence design standards are now (since approx. 1980s) more commonly based upon joint sea level and wave conditions, and are often between 50 to 100 years (c.f. Hames and Reeve, 2007). These standards require defences to limit damage and overtopping from storms to a level that will be reached or exceeded on average once during a period matching the design standard. Implied in more recent risk management and insurance policy is that coastal flood defence schemes should not breach (i.e. collapse or break open) given a 1 in 200 year "tidal event" (DCLG, 2009), although wave overtopping onto promenades and seawalls and "localised flooding" is often accepted. Design standards for some area are more stringent, for example a 1 in

1000 year level for London (e.g. Ramsbottom et al., 2006) and 1 in 10 000 for power stations (e.g. Wilby et al., 2011). The indicative "tidal" floodplain in which risk is managed by the EA, and the most frequently used categorisation in planning and flood management is typically defined by an envelope of land that is exposed (i.e. would flood without defences) to a 1 in 200 year annual probability flood (EA, 2009). Meanwhile "Flood Re", a fund to provide affordable flood cover to high risk properties, will pay out on reinsurance claims up to the limit equivalent to a 1 in 200 year level of claims (Defra, 2013). A knowledge of extreme events (e.g. including the timing and magnitude of respective components of tide, surge, MSL and waves) and their return periods, can inform appropriate levels of defence. In both case study locations engineered schemes vary in their design, thus knowing the storm severity at a location allows the robustness of different designs to be monitored to inform future plans to optimise engineered structures. Categorising these storms to provide a data base of events and clusters of events is also of interest for research purposes. For example, Dissanayake et al. (2015) uses the 5 December 2013 event and two other events that month to model storm impacts that occur between the bi-annual shoreline survey intervals. Such research furthers the information available to local managers about individual and cumulative storm impacts.

In the Sefton region, the water level alone of the largest event of 5 December 2013 was approx. 40 years return period, but when considering coincidental waves, the analysis indicates this water level and wave event was > 200 year return period (although a large extrapolation given the length of the input data sets). Erosional storm impacts were the most significant seen in living memory, the loss of dune land being greater than the last major event in February 1990 when the National Trust frontage lost 13.6 m (Smith, 2014). This event damaged (but did not breach) natural and manmade defences and some coastal flooding. The 3 January 2014 was an approx. 75 year joint water level-wave and also caused some damage (and also followed less than a month after the Xaver event). As our analysis indicates, the 2013/2014 winter contained more extreme events (defined by annual probability exceedance) than any other season, and this is a likely contributor to the coastal retreat of the 2013/2014 winter being greater than the cumulative erosion experience over the previous 5 years. Survey data (8 October 2014) shows that the system had not recovered by the summer 2014. At Sefton, previous studies showed that a moderate high water and large waves can damage defences, notably the dune systems are vulnerable when there is a lack of recovery time between erosion events (Esteves et al., 2012). However, given this previously unseen water level cluster and extreme return periods of 2013/2014, the defences stood up well. With the Crosby sea wall at Sefton nearing the end of its design life and a new scheme to be implemented in the next 10 years, our assessment indicates the return periods and storms that this defence design was already resilient to.

In Suffolk during the 5 December event, sections of defence failed to prevent flooding (e.g. at Lowestoft – see Sect. 2 of this paper) and there were breaches and structural failures. The 5 December 2013 HW at Lowestoft was an almost a 1 in 200 year occurrence, reduced by the joint sea level-wave assessment to 1 in 75 years. However, here it is especially important to differentiate between "open coast" and "tidal river/estuary" locations. There was overtopping at the coast due to the extreme sea level and waves superimposed, but most open coast defences held. Floods occurred in the Oulton Broad area of Lowestoft, a location sheltered from costal waves and where the River Waveney flows into Lake Lothing and the Inner Harbour. Furthermore, other reported breaches (e.g. including those which affected Waldringfield and Ipswich) were on the tidal Deben and Orwell rivers. It is important to note that we did not include river levels in our assessment, but these were exceptionally high due to heavy rainfall across this period (MetOffice, 2014). To properly assess the return period of the sea levels at these locations (in an equivalent way in which waves supplement the open coast return period assessments) we would also require river level data. Steers (1953) remarked that the 31 January 1953 flood would have been much worse in the Anglia regions if river levels had been high (which at the time they were not). Overall flooding in Suffolk during 2013 was much less than in 1953 – that event was larger on the open coast due to extreme onshore wind and waves (Wolf and Flather, 2005). The Lowestoft high waters of 1953 and 2013 were comparable in elevation and return period: HW

1953 was approx. 1 in 270 years by the 2008 return levels, and 1 in 400 years when offset for the 0.11 m SLR since then (based on the global 1.8 mm yr^{-1} rate). Furthermore, Suffolk County Council are currently working on a major flood defence program for the Lowestoft area, estimated at GBP 30 million, to be completed in several years from now. At Sizewell, extreme events are a threat to safety and energy supply: EDF Energy have proposed building an additional nuclear power station there (Sizewell C). The site was not flooded during 2013/2014, and although on 5 December 2013 the sea broke over the coastal dunes just south of the Dunwich cliff, it did not breach the nearby Minsmere dunes (as it did in 1953).

The defences and floodplain between the two regions are fundamentally different – more of the land immediately behind defences is lower lying in Suffolk hence even small defence failures can cause serious inundation of coastal communities. At Sefton, the natural and engineered defences are located just above mean spring HW. Since the tidal range controls the severity of water levels in this location and also the wave impact on the upper beach the damage was measured more in terms of erosion and overtopping, even with some overtopping defences provided adequate protection from the recent events.

The season as a whole saw the highest average high water level at both regions (Fig. 9). This was due to a combination of 2013/2014's frequent storms that crossed the UK (MetOffice, 2014; Matthews et al., 2014) during a high in both the 18.6 and 4.4 year inter-annual tidal cycles (Haigh et al., 2011; Wadey et al., 2014). Ongoing mean SLR is increasing the frequency of extreme sea levels and shown here it is important to consider the method of "offsetting" if attempting to assess the extremity of individual storm-tide, and determine meaningful storm-driven design thresholds to assess future defence performance (i.e. as defences are upgraded with SLR). For example at Liverpool mean sea level 1992–2014 (since the start of the data set, refer to Sect. 3 of this paper) is likely to have risen by over 0.03 m, which at present does not have a large impact on return periods in this record; but would be important for longer data sets and more extreme return periods (Haigh et al., 2010). As wave records become longer,

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offsetting in the joint water-wave level analysis will have a more distinct effect and the methods described here should be considered in return period analysis. With changing climate there is also the potential for a change in wave severity, again if trend in wave height become significant then an offset should also be considered in wave height.

6 Conclusions

In this paper we assessed the extremity of the 2013/2014 “storm season” from a perspective that could, for example, help to inform coastal managers who have to plan for defence upgrades. Our first objective was to use and generate return periods to catalogue extreme sea level and wave incidences of two case studies. This links to the second objective: to assess temporal clustering as determined by counting sea levels and waves (above an annual return period threshold) and how many of these fall within annual storm seasons across the data sets. At Liverpool (the central site to assess our first case study of Sefton, northwest England), 2013/2014 produced the largest sea level within the 22 year data set (approx. 40 year return period). At the other case study, Lowestoft (Suffolk, east England) it was the largest sea level in a 40 year data set (an approx. 200 year return period). We highlight that the magnitude of return periods (of water levels, waves and combined water-wave levels) change substantially from when they are considered independently to when they are considered together, in our example by including coincidence wave heights at the time of observed high waters. This change was different at each case study, indicating that the 5 December event at Sefton (upgraded from a 1 in 44 sea level to a 1 in 200 year joint high water and wave level) was actually more extreme than the event had been in Suffolk (downgraded from a 1 in 195 sea level to a 1 in 75 year high water and wave level). The number of extreme high waters was notable at both case studies: at Liverpool the 2013/2014 season is the biggest cluster of large high waters (using the 1 in 1 and 1 in 5 year thresholds) since the record began in November 1991, e.g. with 5 HWs above the annual threshold and 2 above the 1 in 5 threshold. At Lowestoft 2013/2014 was less distinctive as a “seasonal” sea level cluster but the 5–6 December 2013 storm caused consecutive extreme tidal high waters. The wave height data and joint probability assessment identified more extremes: at Liverpool there were 14 incidences above the annual level (increasing from only 5 when considering sea level alone); in Suffolk there were 9 incidences (only 2 of which were sea level alone) above an annual probability.

The third and fourth objectives were to compare the two case studies and discuss defence performance during 2013/2014. At Suffolk, only the 5 December event is notable as a coastal flood/erosion event during this season; whereas the 3 January 2014 also made an impact at Sefton. At Sefton in 2013/2014, from a sea level perspective, large high waters were more clustered and less extreme individually (than at Suffolk). Also at Sefton, the joint probability of high waters and wave suggests the season was both more extreme and clustered. However, the consequences of the rare and large storm-tides is a greater threat to life in Suffolk, and given slightly different storm conditions (e.g. as in 1953) the coastal flood event could have been more severe here. Also at Suffolk it appears that inland river levels during the 5–6 December 2013 would have played an important role in the defence responses (due to the high rainfall and breaches that occurred away from the open coast) – inclusion of this is in joint probability and clustering assessments is recommended for future work in this region. Whilst our ability to comment in detail on defence performance is limited by the length of the data sets and detail of defence failures, our analysis shows that the big event of the season, 5 December 2013, was a significant outlier in both case study regions (Fig. 5) (furthermore the tidal and meteorological conditions allowed for a national-scale impact at the coast).

Future work should aim to monitor and catalogue extreme flood and erosion incidences alongside water level and wave analysis, so that event-driven and long term coastal response to storms at any given site can be understood. This would allow a better understanding of storm severity upon long-term repeat impact and inter-storm recovery, which influences the long-term geomorphology of a system (Plater and Grenville, 2010). As noted in Sect. 2, coastal processes in England and Wales are also considered within shoreline management, often on a regional basis. Storm impact can control regional sediment supply (e.g. via regional cliff erosion), influence geomorphology and structural integrity. If a change in state occurs due to storm impact it is important to identify whether this was a consequence of a temporal cluster in events or a single extreme event to understand how events could cause impact on similar natural systems (e.g. dunes at the Sefton are important features that respond to repeated loads; in other places state changes may be to other features such as rip channels). To catalogue extreme water level and wave instances (in response to storms and tides), this was enhanced by using all three methods (assessing sea levels and wave independently, and combined). This allows a comprehensive list of events for which loads can be associated with storm damages across multiple years; whilst maximising the full length of the respective observed data sets and where they overlap. For the UK, the joint probability of waves and other loads at the time of tidal high water is especially important to indicate high overtopping, floods and damage, for example it in some regions the biggest sea level alone are not always highly correlated with the worst flooding (Ruocco et al., 2011). A quantitative assessment of sea level and wave extremes associated with defence performance and natural system changes over time is complimentary to the development of new management approaches and schemes for coastal protection. Having a data base of observations that can be related to different event levels allows assessment of the defence systems; this is important because joint probabilities are widely used in flood planning, with science informed management a standpoint for government and coastal managers, when targeting improvements to long-term resilience in defence planning. There is uncertainty over mean sea level projections (Church et al., 2013) and storm patterns (Zappa et al., 2013). It is recommended that in further work, return periods, particularly waves, are regularly updated to incorporate new data. This, in combination with sea level can be used to systematically compare the extremity and duration of loads on defences between past events and winter seasons – and ideally would be accompanied by a time series which logs defence standards, upgrades, damage and repair.

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Table 1. Summary of return period data: the total water level return heights given are those from the EA study (McMillan et al., 2011), and the significant wave heights we calculated via a Weibull distribution.

Return level	Sefton (Liverpool tide gauge and Waverider) – return heights			Suffolk (Lowestoft tide gauge and Waverider) – return heights		
	Water level (m ODN)	Hs (m) Observed data	Hs (m) 30 year hindcast	Water level (m ODN)	Hs (m) Observed data	Hs (m) 30 year hindcast
1	5.51	3.36	4.21	2.00	3.13	3.68
2	5.62	3.57	4.37	2.14	3.28	3.80
5	5.77	3.79	4.55	2.33	3.44	3.94
10	5.90	3.93	4.68	2.48	3.54	4.03
50	6.25	4.19	4.93	2.88	3.73	4.21
100	6.42	4.29	5.03	3.07	3.80	4.28
1000	6.87	4.56	5.31	3.78	4.00	4.49

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Table 2. Time instance of extreme conditions > than the 1 in 1 year return period during the winter of 2013/2014 at Sefton – the italic font identifies independent or storms very close together (and whose effects would have combined to generate extreme conditions). Event groups 1–3, 5–8, 9–12 and 13 are from secondary storms that quickly followed the first – the earlier storm usually being the larger event. The bracketed values represent the values when HW is offset for mean sea level, relevant only to the (longer) sea level records.

Instances of extreme high water and/or waves	Context in which the instance is extreme	Date-time	Sea level Return period value is 2008 (in brackets is offset value)				Waves			Sea level and Hs RP
			HW (mODN)	*Tide (mODN)	Skew surge (m)	RP	Hs (m)	Tz (s)	RP	
1–3	*JL*	*2 Nov 2013 22:00*	*5.20*	*4.37*	*0.83*	*< 1*	*3.80*	*6.20*	*< 1*	*35*
	WH	*3 Nov 2013 23:45* *(wave peak: 00:30)*	*4.80*	*4.62*	*0.19*	*< 1*	*4.39*	*7.60*	*2*	*< 1*
	JL	*5 Nov 2013 11:45*	*5.30*	*4.82*	*0.48*	< 1	1.81	4.10	< 1	*2*
4	WL, WH, JL	5 Dec 2013 12:30	6.22	5.13	1.09	44 (38)	4.55	6.90	5	> 200
5–8	*WL, JL*	*3 Jan 2014 12:00*	*5.86*	*5.49*	*0.37*	*8 (7)*	*2.23*	*5.00*	*< 1*	*75*
	JL	*4 Jan 2014 00:30*	*5.26*	*5.13*	*0.13*	*< 1*	*2.51*	*5.00*	*< 1*	*4*
	JL	*6 Jan 2014 14:30*	*5.36*	*4.90*	*0.46*	*< 1*	*1.97*	*4.60*	*< 1*	*4*
9–12	WL, JL	1 Feb 2014 11:45	5.66	5.52	0.14	3 (2)	2.14	4.50	< 1	15
	JL	2 Feb 2014 00:15	5.36	5.18	0.18	< 1	1.97	4.60	< 1	4
	WL, JL	2 Feb 2014 12:45	5.53	5.49	0.04	1 (1)	1.46	4.30	< 1	4
	WL, JL	3 Feb 2014 13:30	5.57	5.26	0.31	1 (1)	1.39	3.90	< 1	4
13	*WH, JL*	*12 Feb 2014 21:45*	*4.29*	*3.49*	*0.80*	*< 1*	*4.39*	*6.90*	*2*	*8*
	JL	*15 Feb 2014 11:30*	*4.87*	*4.32*	*0.55*	*< 1*	*2.71*	*5.50*	*< 1*	*2*
14	WL, JL	2 Mar 2014 11:30	5.60	5.40	0.20	2 (1)	0.52	2.90	< 1	2

Table 3. Time instance of extreme conditions > than the 1 in 1 year return period (RP) of 2013/2014 at Suffolk. The bracketed values in the RP column represent the values when HW is offset for mean sea level.

Instances of extreme high water and/or waves	Context in which the instance is extreme	Date-time	Sea level				Waves			Sea level and Hs RP
			HW (mODN)	*Tide (mODN)	Skew surge (m)	RP	Hs (m)	Tz (s)	RP	
1–3	JL	10 Oct 2013 12:30	1.78	1.13	0.65	< 1	1.66	4.00	< 1	4
	JL	11 Oct 2013 01:00	1.47	1.10	0.37	< 1	2.32	4.80	< 1	2
	JL	12 Oct 2013 01:15	1.11	1.04	0.07	< 1	3.16	5.70	< 1	2
4–5	SL, JL	05 Dec 2013 22:30	3.26	1.28	1.98	196 (189)	0.90	4.80	< 1	75
	SL, JL	06 Dec 2013 11:15	2.13	1.09	1.04	2 (2)	1.39	5.20	< 1	15
6	JL	19 Dec 2013 22:15	1.82	1.07	0.75	< 1	1.05	4.8	< 1	4
7	WH	24 Dec 2013 03:00 (time of wave peak, HW: 00:45)	0.33	0.88	−0.55	< 1	3.95	6.50	5	2
8	JL	01 Jan 2014 20:45	0.9	0.91	−0.01	< 1	3.40	6.90	< 1	2
9	WH	14 Feb 2014 22:30 (wave peak, HW: 20:15)	0.6	0.84	−0.24	< 1	3.94	5.50	5	< 1

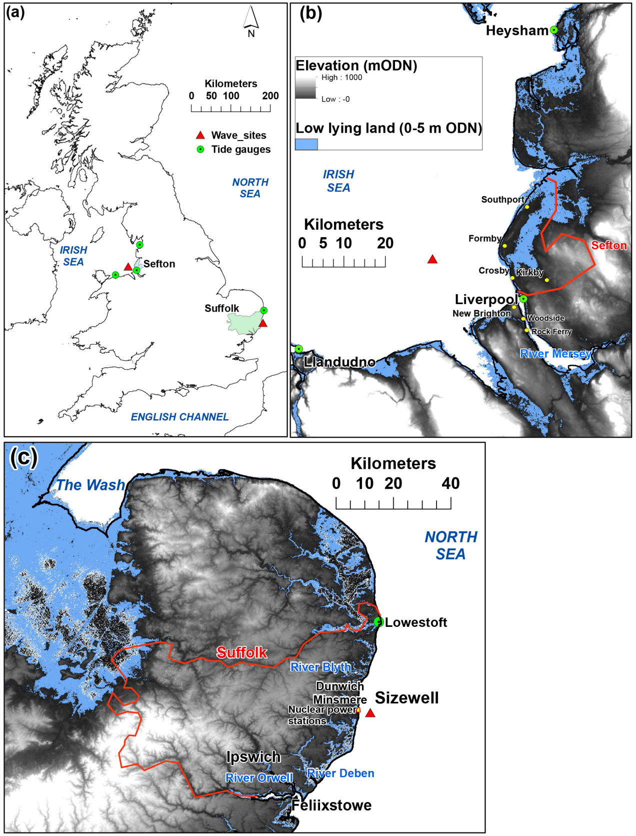

Figure 1. (a) Location of the case studies and data recorders, with a close up of the flood plains in **(b)** Sefton and **(c)** Suffolk

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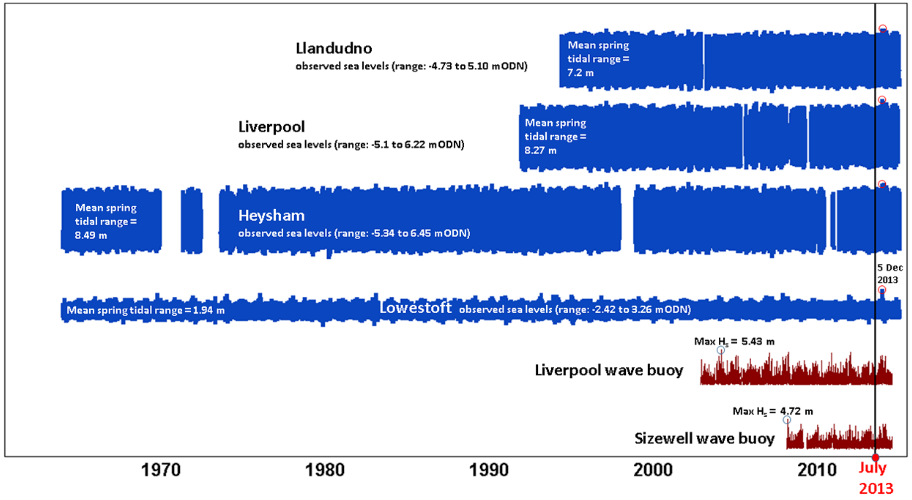

Figure 2. Observed tide gauge and wave data availability that was used to assess the 2013/2014 winter (BODC water level record and CEFAS wave records) – diagram is to scale.

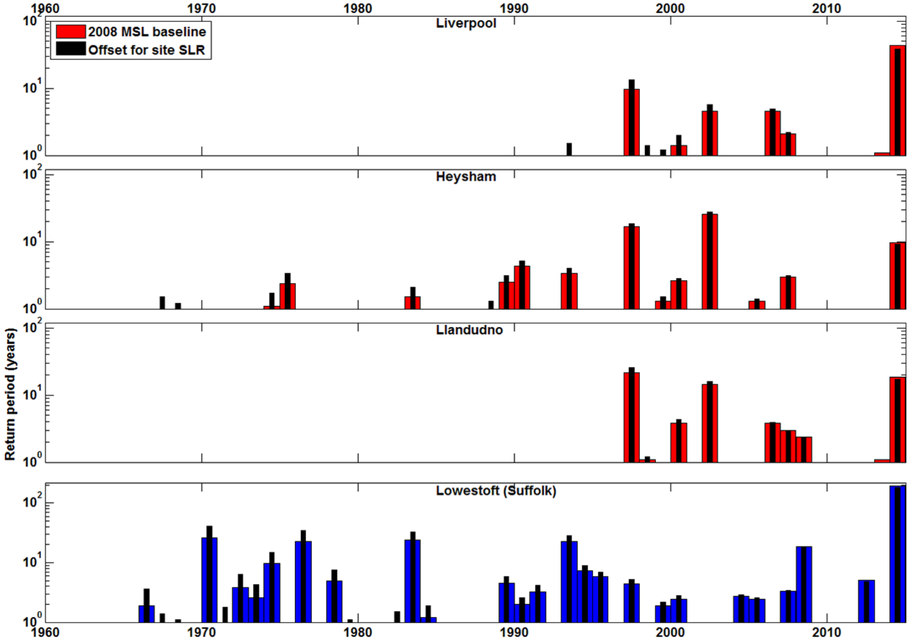

Figure 3. High water probabilities for the largest event in each annual winter "season" at the sites near Sefton, and Lowestoft in Suffolk. Liverpool is primarily relevant to Sefton, but Llandudno and Heysham are near and the latter has a longer data record. Note that the EA return sea level periods are relative to a baseline MSL for the year 2008, so in black we have offset for sea level rise (c.f. Haigh et al., 2010; Wadey et al., 2014).

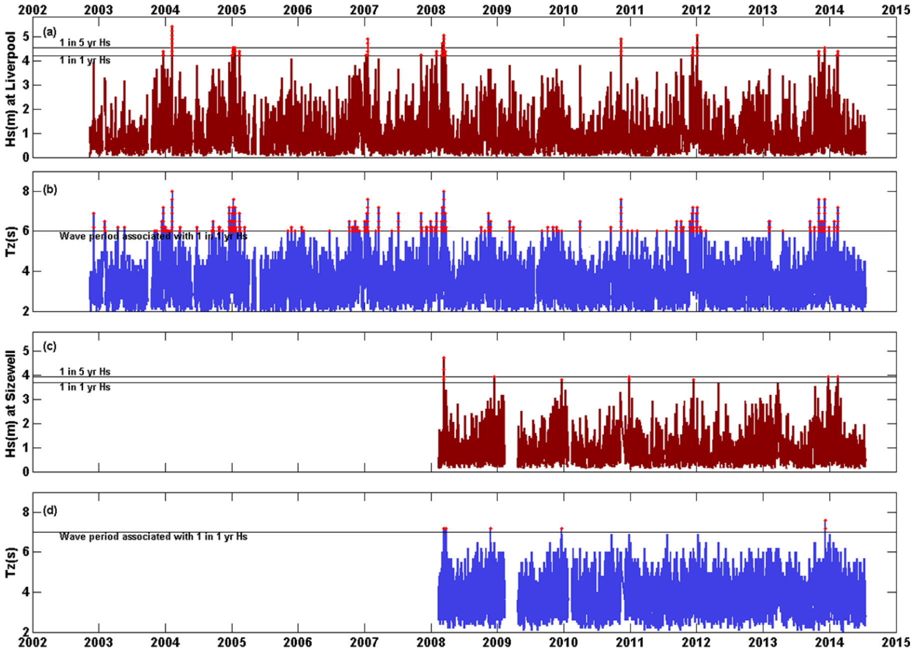

Figure 4. Wave time series and return period thresholds, **(a)** significant wave height (H_s) at Liverpool, **(b)** zero crossing over wave period (T_z) at Liverpool, the line is the approx. wave period most commonly associated with larger than a 1 in 1 year Hs, **(c)** (Hs) at Sizewell (Suffolk) and **(d)** T_z at Sizewell.

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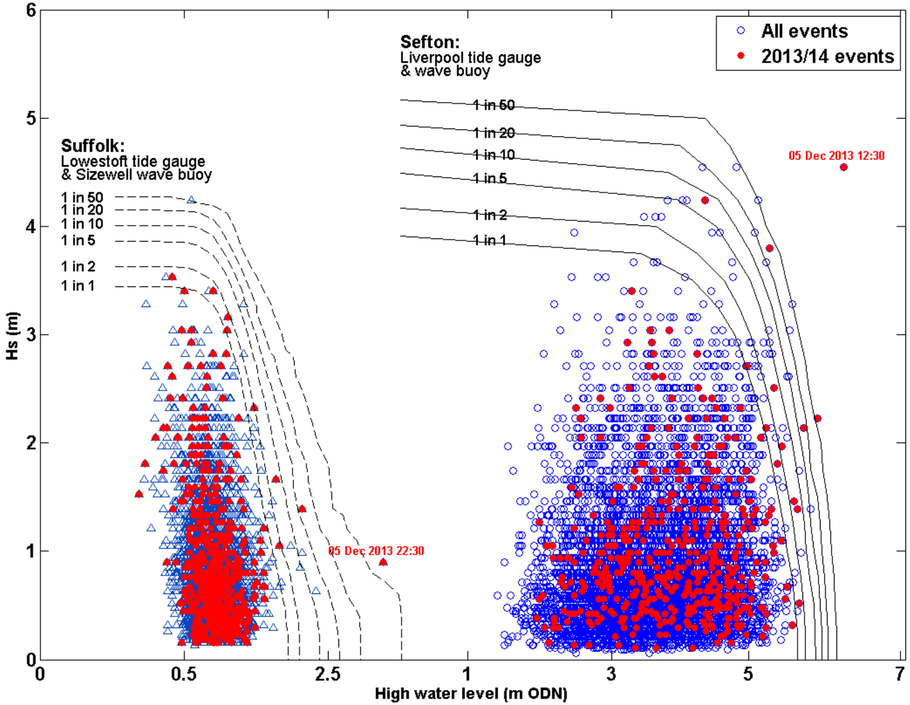

Figure 5. High water and significant wave height (H_s) joint-probability curves and events at Sefton and Suffolk. The length of the data limits the accuracy of the return period analysis so only up to 1 : 50 years is shown – in the text we note that the 5 December 2013 event may have exceeded the 1 in 200 year level.

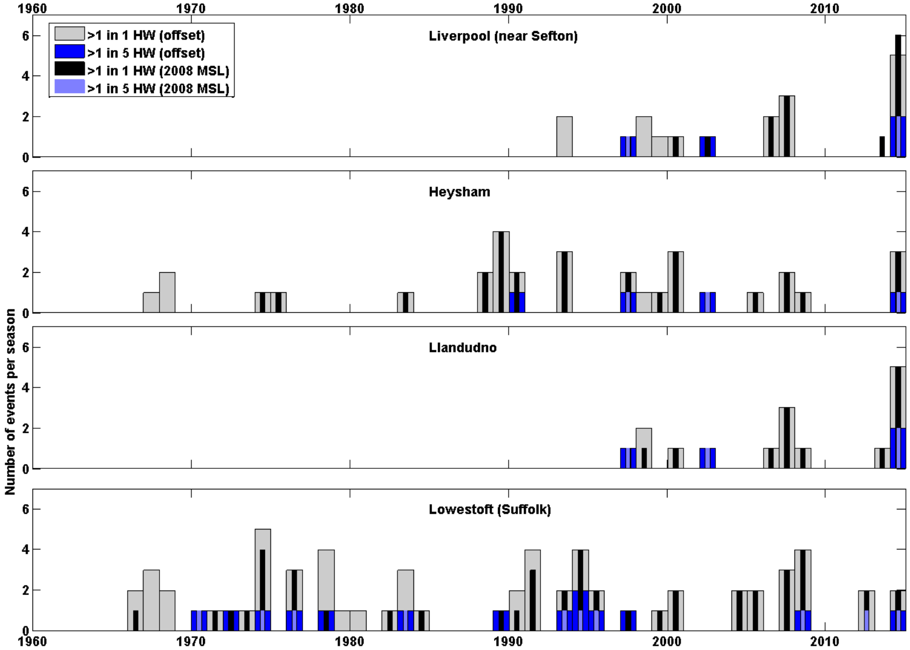

Figure 6. Seasonal high water counts above the annual return period event at Lowestoft relative to the 2008 baseline return period thresholds of McMillan et al. (2011) and to show how mean SLR has increased the occurrence of extremes in this longer record, the count of 1 in 1 year events offset for SLR is shown.

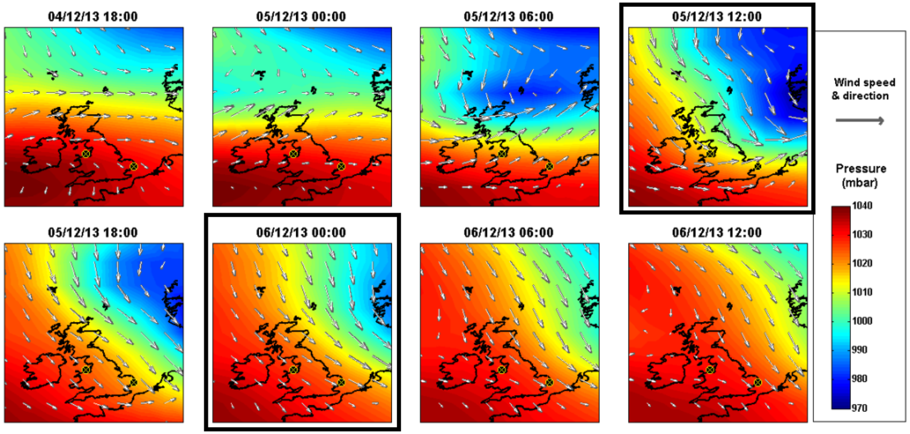

Figure 7. Time series of pressure and wind during 4–6 December 2013 – the locations of the Liverpool and Lowestoft tide gauges are shown. Plotted from gridded surface wind and pressure data from the NCEP/NCAR reanalysis (Kalnay et al., 1996).

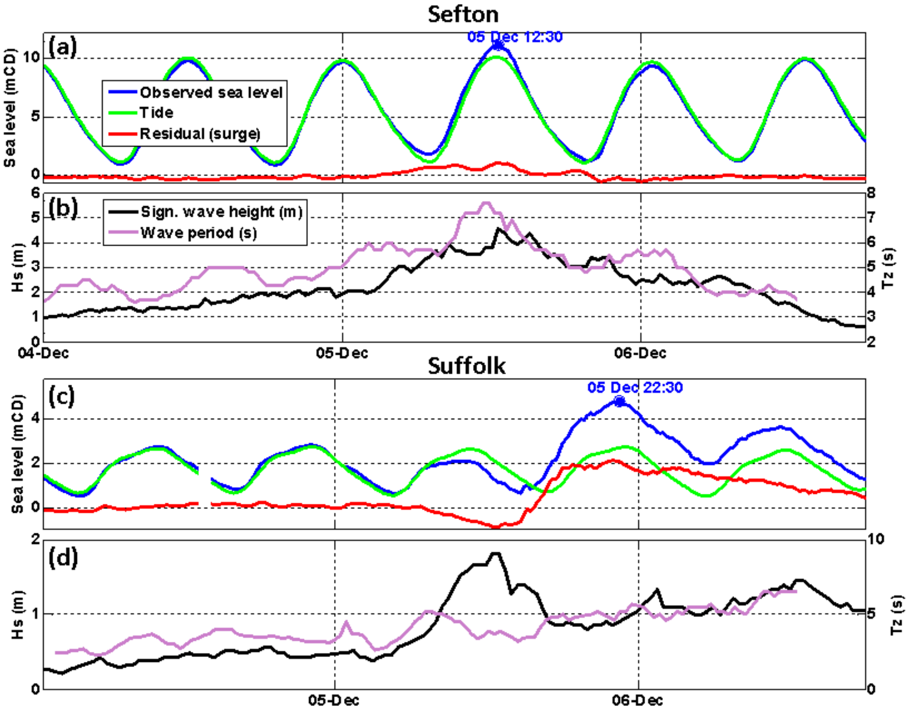

Figure 8. Time series of observed sea level and waves during the Xaver storm of 2013 **(a)** sea level (Liverpool), **(b)** wave height and periods (Liverpool), **(c)** sea level at Lowestoft (Suffolk) and **(d)** waves at Sizewell (Suffolk).

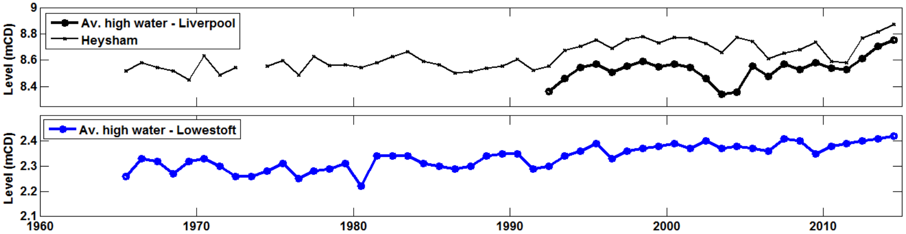

Figure 9. Seasonal averages of twice daily observed high water at Liverpool and Heysham (Sefton) and Lowestoft (Suffolk).