JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, C05018, doi:10.1029/2009JC005662, 2010

An investigation of recent decadal-scale storm events in the eastern Irish Sea

Jennifer M. Brown,[1] Alejandro J. Souza,[1] and Judith Wolf[1]

Received 24 July 2009; revised 8 December 2009; accepted 17 December 2009; published 20 May 2010.

[1] The Proudman Oceanographic Laboratory Coastal Modelling System coupled to the WAve Model (POLCOMS-WAM) modeling system has been used to model combined tides, surges, waves, and wave-current interaction in the Irish Sea on a 1.85 km grid. A method for data analysis is presented to determine what factors and interactions contribute to extreme conditions in a region of interest. An 11 year hindcast (1996–2006) has been performed to investigate the meteorological conditions that cause extreme surge and/or wave conditions in Liverpool Bay. A one-way nested model approach was used. For waves, a 1° North Atlantic WAM model forces the boundary of the Irish Sea model, driven by ERA-40 wind (~1° resolution every 6 h). To capture the external surge generated outside of the Irish Sea, the (1/9° × 1/6°) Proudman Operational surge model extending to the continental shelf edge was run for tide and surge and was forced by Met Office mesoscale winds (~12 km resolution every hour). The data implied that the largest surges at Liverpool are generally driven by winds from the south to the west while the largest waves are forced by winds from the west to the northwest. The worst storm conditions in Liverpool Bay result under southwesterly wind conditions that veer to the west. The large tidal range in the region acts to enhance the impact of the surge through tide-surge interaction. Moreover, the highest water levels in Liverpool Bay are in response to southwesterly winds combined with high-water spring tide. Even though no significant surge occurs at this time, the flood threat is at its greatest.

Citation: Brown, J. M., A. J. Souza, and J. Wolf (2010), An investigation of recent decadal-scale storm events in the eastern Irish Sea, *J. Geophys. Res.*, *115*, C05018, doi:10.1029/2009JC005662.

1. Introduction

[2] Coastal flooding is caused by high water levels that are generated by the combined effect of tides and storm surges. Often the overtopping of coastal defenses by waves accompanies such conditions [*Wolf*, 2008]. The risk of coastal flooding in low-lying areas is likely to increase in the future in response to global warming and climate change [e.g., *Houghton*, 2005; *Lowe and Gregory*, 2005; *Lowe et al.*, 2001], as a result of future sea level rise combined with an increase in the intensity and frequency of storms. Storm winds over England and Wales have the following directional dependencies: 29% SW, 30% W, 21% NW, and 12% S, where the directions represent from where the wind has come [*Lamb*, 1991]. The shallow eastern Irish Sea is susceptible to large storm surges [*Wolf*, 2008], which at Liverpool can reach up to 2.5 m [*Pye and Blott*, 2008] as a result of storm winds and low-pressure systems. A major surge at Liverpool is likely to occur if a secondary depression with a speed of ~40 knots approaches such that its rear-right quadrant (defined in Figure 2) can act over a long fetch [*Lennon*, 1963]. Other factors which also contribute to a major surge are whether the depression can be represented as an independent, concentric system with a radius of ~150–200 nautical miles and if a pressure gradient of 30 mb over 250 nautical miles is present in the rear-right quadrant [*Lennon*, 1963]. For surges in the eastern Irish Sea the flow into the Irish Sea through the North Channel and Celtic Sea (the external surge) is about equally as important as the locally generated surge [*Jones and Davies*, 1998]. The large tidal range in Liverpool Bay (~10 m on spring tides) causes a significant tide-surge interaction. This large tidal range reduces the risk of the peak surge occurring at high water [*Horsburgh and Wilson*, 2007]. Details on tide-surge interaction are given by *Prandle and Wolf* [1978] and *Wolf* [2009]. The largest waves and surges in Liverpool Bay are generated by westerly and northwesterly winds which have the longest fetch (Figure 1). Liverpool Bay is sheltered from swell waves from the Atlantic and experiences locally wind-generated sea. The Coastal Flooding by Extreme Events (CoFEE) project and European Union (EU) FP7 Morphological Impacts and Coastal Risks induced by Extreme storm events (MICORE) project are investigating the flood risks in the eastern Irish Sea/Liverpool Bay. This study area includes many of England's coastal types and the project focuses on the management of the Sefton coast (between the

---

[1] Proudman Oceanographic Laboratory, Liverpool, UK.

0148-0227/10/2009JC005662

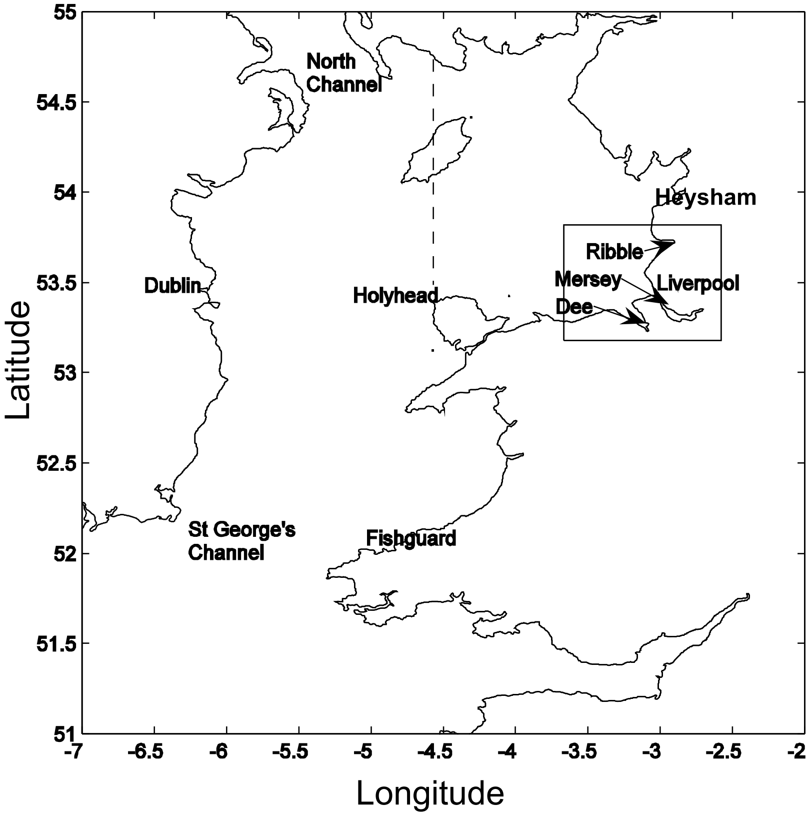

Figure 1. The Irish Sea model domain. Liverpool Bay is the region defined by the box, and the offshore extent of the eastern Irish Sea is determined by the dashed line. The Sefton coastline extends from Liverpool to the Ribble Estuary.

Ribble and Mersey estuaries) with its mobile dunes. The past, present, and future flood risk posed by extreme events is being investigated using surge and wave models [*Wolf et al.*, 2008; *Brown et al.*, 2009a]. Previously, an extreme event in November 1977, which coincided with tidal high-water overtopping coastal defenses throughout Lancashire and Cumbria, has been hindcast to represent a past extreme surge event [*Brown and Wolf*, 2009]. This event and a severe event in January 2007, for which both wave and surge data were available, have been used to initially validate and tune the coupled Proudman Oceanographic Laboratory Coastal Modelling System-WAve Model (POLCOMS-WAM) set up for the eastern Irish Sea [*Brown and Wolf*, 2009], prior to a long-term (11 year) hindcast [*Brown et al.*, 2010b]. It is known that the largest recorded surge at Liverpool at total high water was 1.98 m in January 1976. This resulted in a high water level of 5.56 m above the mean tidal level (MTL). However, the largest surges generally occur during lower water levels. The largest recorded surge achieved 2.47 m in February 1990. At Heysham, larger surges and tidal levels occur. The largest surge recorded was 2.6 m in February 1990 and the highest-observed tide exceeded 6.46 m (MTL) in February 1983; unfortunately the tide gauge failed during the peak tidal level. Since the 1990s the frequency and magnitude of extreme high water levels for the eastern Irish Sea has increased [*Pye and Blott*, 2008]. Waves have only been recorded continuously since October 2002, and the data show that waves exceed 3 m during 5–10 events per year and 4 m during 1–5 events per year. The 1 in 50 year wave height is about 5.5 m [*Wolf*, 2008]. Over the last 25 years the maximum wave height across the North Atlantic is thought to have increased [*Carter*, 1999]. The changes in extreme surges and waves could be linked to the North Atlantic Oscillation (NAO), and in particular the strength of the prevailing westerly winds [*Woodworth et al.*, 2007; *Wolf and Woolf*, 2006]. The foot of the Sefton dunes lies just above the mean spring high water level. Consequently, during the largest tides and mean spring tides combined with a storm surge, waves can break directly onto the dune frontage [*Pye and Neal*, 1994]. Significant dune erosion along the Sefton coastline has resulted from individual extreme storms, some of which lasted for more than a single high water, that occurred in 1961, 1965, 1967, 1968, 1975, 1976, 1983, 1990, 1997, 2002, and 2004 [*Pye and Blott*, 2008]. The most damaging storms occurred in November 1977, January 1983, and February 1990 [*Pye and Neal*, 1994]. During the 1977 [*Jones and Davies*, 1998] and 1990 [*Pye*, 1991] events the damage was due to winds veering west from the southwest generating extreme surge and wave conditions. To project the future risk of erosion and flooding, extreme value theory [*Coles and Tawn*, 2005] and joint probability of waves and water level [*Hawkes et al.*, 2002] need to be considered. The return periods for both waves and water level and the joint probability of occurrence of extreme conditions for Liverpool and Heysham have been determined by *Brown et al.* [2010b].

[3] In order to investigate the present-day flood risk posed by extreme events, we use an 11 year period (1996–2006) of model hindcast data combined with long-term data sets collected across the Irish Sea [*Brown et al.*, 2010b], as presented in section 2. A methodology is presented to analyze the data to investigate what causes the most extreme tide-surge residuals, filtered surge residuals, and wave heights. These factors can be used to determine regional flood risk and coastal erosion. The most significant surge and wave events are selected in section 3. The meteorological conditions driving these events are then discussed in section 4, followed in section 5 by a conclusion on the factors generating severe flood risk conditions in Liverpool Bay.

2. Method

[4] To determine the most extreme flood risk conditions in the eastern Irish Sea we use observed and modeled data from an 11 year period (1 January 1996–1 January 2007). To simulate the waves, we use the state-of-the-art third-generation spectral wave model [WAM, *Komen et al.*, 1994], modified for shallow water [*Monbaliu et al.*, 2000]. In order to accurately simulate the waves and the surge in the study area, a one-way nested modeling approach has been set up. For waves, a 1° North Atlantic model forces the boundary of a 1.85 km Irish Sea model, using WAM. Any influence that swell might have in the study area will therefore be correctly represented. The tide and surge is simulated using the POLCOMS [*Holt and James*, 2001]. To capture the external surge effects generated outside of the Irish Sea the 1/9° by 1/6° Operational Continental Shelf surge model [CS3, *Williams and Flather*, 2000]) provides boundary forcing to the 1.85 km Irish Sea POLCOMS model. The coarse WAM model was driven by 1° resolution ERA-40 data provided every 6 h. The other models were forced by ~12 km resolution wind and pressure data provided hourly by the UK Met Office mesoscale atmospheric model. The models were validated using data collected from wave buoys and coastal tide gauges around the United Kingdom [*Brown et al.*, 2010b]. For the Irish Sea a coupled POLCOMS-WAM model was used to capture the wave-tide-surge interaction. This allows the waves to be refracted by time varying current and depth fields, while the surface stress and bottom friction in the tide-surge simulation are modified by the presence of waves. Tidally varying water elevation also has a significant impact on the surge residual. Prior to the 11 year hindcast, the coupled model was set up by *Brown and Wolf* [2009] to simulate valid model hindcast results in the eastern Irish Sea using two extreme storm events in November 1977 and January 2007.

[5] Analysis of the 11 year wave-tide-surge model hindcast and observed data provide us with insight into what causes the most severe conditions in Liverpool Bay (defined in Figure 1), and in particular along the Sefton coastline. Tide gauge data collected at Liverpool and Heysham, which are ports at either end of the Sefton coastline, have been used to isolate the most extreme surge events that have occurred in the last decade. Extreme wave conditions are also investigated at the Liverpool Bay wave buoy location (53°31′89N, 3°22′28W). Owing to limited wave data (from October 2002 onward) model hindcast data has mainly been used to determine the most severe wave conditions in Liverpool Bay. The model results were validated by *Brown et al.* [2010b] to show good agreement with observation. To determine the wind conditions that generate extreme wave and storm surge conditions in the eastern Irish Sea we look at the peak wind velocity, from the mesoscale model data, at an offshore location (53°45′N, 4°54′W). This provides us with an idea of the wind conditions blowing over the adjacent sea generating the local wave and surge conditions.

[6] We use the tide-surge residual (meaning the additional water level on top of the predicted tide level) to examine the potential for coastal flooding at high water. This residual is the result of surge-tide interaction as well as meteorological forcing, the tidal interaction modifying both the timing and size of the peak surge. This quantity provides information about the increase or decrease in the actual water level at all states of the tide compared with the predicted astronomical tidal level due to the surge and tide-surge interaction. This residual is useful in dune management, since the period over which the water level exceeds the dune toe is important. We also use the filtered surge, defined as the residual water level after all periodic signals (tidal influence and storm periodicity within a tidal period) are removed. This residual is due to the meteorological event only. Filtering is achieved by passing the total water elevation through the MATLAB filtering routine "filtfilt." This performs zero-phase digital filtering removing the tidal signal between the M_4 (~6 h) and O_1 (~24 h) tidal periods. Comparison of the magnitude and timing of these surge residuals during extreme events provides insight into how important the tide-surge interaction is within a region. The "skew surge" [see *de Vries et al.*, 1995] is also briefly investigated. This quantifies the amount by which the maximum water level exceeds the predicted tidal high water, a quantity that is important in coastal flood management. Finally the most extreme high water event at Liverpool and Heysham is investigated in order to determine what conditions (tidal range, filtered surge, tide-surge) generated the worst flood risk conditions in the last decade within this study area. Wave setup has not been included here, but can reach 0.3 m locally [*Wolf*, 2008]. This will be investigated in further research for this location.

3. Extreme Events in the Eastern Irish Sea

[7] This section presents the most extreme events that have occurred in the eastern Irish Sea over the past 11 years (1996–2006, inclusive). For each event the wind conditions are analyzed to determine what conditions (wind directions) are most likely to pose a flood risk in the future. The five largest wave events and five largest surge events are studied further in section 3.3. The events are named in Tables 1 and 2 as T1–T10 depending on when they occurred in time; in most, but not all cases, the names occur in both tables since the extreme wave and surge events occurred simultaneously.

3.1. Extreme Surge Events

[8] We define a major surge event along the Sefton coastline as a tide-surge residual elevation greater than 1.5 m at either Heysham or Liverpool. This elevation is chosen

Table 1. Extreme Tide-Surge Residual Elevation, $\eta > 1.5$ m, Observed at Liverpool and/or Heysham Over the Past 11 Years[a]

Date	Time	η_{LIV} (m)	Time	η_{HEY} (m)	H_s (m)	T_p (s)	U_{veer}	U_{10} (m/s)	U_θ (deg)
6 Nov 1996 (T1)	*02.45*	*1.48*	*03.45*	*1.54*	*4.50*	*9.23*	*NW–SW–W*	*23.75*	*216.61*
19 Feb 1997 (T2)	18.00	1.84	18.00	1.86	3.73	8.39	S–W	24.75	216.18
24 Dec 1997 (T3)	*21.30*	*2.19*	*21.30*	-	*5.63*	*10.15*	*SE–W*	*28.81*	*255.78*
24 Oct 1998	21.00	1.50	-	-	2.97	7.63	SW–NW	17.42	290.54
26 Dec 1998 (T4)	*22.45*	*2.02*	*22.45*	*2.43*	*5.39*	*10.15*	*S–SW*	*30.39*	*249.81*
3 Dec 1999	*09.15*	*1.78*	*08.45*	*1.48*	*4.02*	*8.39*	*SW–W*	*20.95*	*238.96*
24 Dec 1999 (T5)	21.00	1.53	21.15	1.63	3.40	8.39	SW–WSW	18.54	211.98
10 Feb 2000	07.30	1.53	06.45	1.43	2.88	6.93	SW–W	22.31	192.33
13 Dec 2000 (T6)	*03.45*	*1.74*	*04.00*	*2.12*	*4.09*	*8.39*	*W*	*23.81*	*274.11*
26 Feb 2002 (T7)	06.00	1.98	-	-	2.53	5.73	SW–W	17.73	254.05
27 Oct 2002 (T8)	*10.00*	*2.26*	*10.00*	*1.54*	*4.09*	*7.63*	*SW–W*	*19.80*	*264.70*
19 Mar 2004	10.00	1.11	10.00	1.57	2.98 (3.16)	6.93 (5.41)	S–W	19.69	190.75
20 Mar 2004	18.00	1.50	16.00	1.62	3.49 (3.27)	7.63 (5.87)	SW–WSW	18.49	254.90
8 Jan 2005 (T10)	*05.15*	*1.75*	*07.00*	*2.08*	*5.40 (4.46)*	*9.23 (7.14)*	*SW–W*	*25.93*	*251.39*
3 Dec 2006	05.15	1.61	05.03	1.50	1.31	4.31	S–SW	23.71	180.29
3 Dec 2006	15.15	0.96	15.30	1.56	3.56	7.63	SW	23.97	223.53

[a] The peak wave height, H_s, with corresponding peak wave period, T_p, peak offshore wind speed, U_{10}, direction, U_θ, and an indication of the direction of wind change, U_{veer}, during an event are also given. Values in italics indicate events when both the tide-surge residual and wave heights are considered extreme. Observed wave data are provided in parentheses when available.

since it is exceeded approximately 20 times in 11 years [*Brown et al.*, 2010b]. An extreme surge is considered to have an elevation of 2.1 m or greater, since such events only occur twice in 11 years [*Brown et al.*, 2010b]. Using tide gauge data at these two locations, we find 16 major surge events that occurred in the last 11 years of which 4 are classed as extreme (Table 1). Out of these 16 events only 14 have data at both locations.

[9] From the long-term observations (Table 1) we find that the largest tide-surge residuals along the Sefton coastline can reach 2.43 m and occur due to winds from the south to the west. Wave heights accompanying these surge events are in the range 2.5–5.6 m. Often the waves are not considered extreme (defined in section 3.2) during extreme surge events at these locations (i.e., there are few underlined values in Table 1).

3.2. Extreme Wave Events

[10] Major wave events are defined as significant wave heights greater than 4 m. *Brown et al.* [2010b] found such events to occur 15 times in 11 years. Extreme events are considered to have heights above 5.4 m, as these conditions are only achieved twice in 11 years [*Brown et al.*, 2010b]. These major events occur due to winds between the directions of west–southwest and west–northwest (Table 2). Waves in the area are mainly the result of local wave generation. Waves propagating into the Irish Sea from the Southwest Approach very rarely penetrate into Liverpool Bay. Wave propagation through the North Channel is restricted and sheltering from Wales may prevent significant external wave propagation into the eastern Irish Sea. Thus local wave generation is limited by the short fetches to Liverpool Bay across the northern Irish Sea. Extreme wave events combined with extreme tide-surge residual events (Table 2, italic values) are less common than extreme wave events alone. The tide-surge residual levels due to extreme wave generating conditions can be from 0.2 m up to 2.43 m.

[11] Very rarely (twice in the last 11 years) extremely severe west–southwest winds ($U_{10} > 28$ m/s), which occurred after the wind has veered from a more southerly

Table 2. Extreme Wave Heights, $H_s > 4$ m, Hindcast in Liverpool Bay Over the Past 11 Years[a]

Date	Time	H_s (m)	T_p (s)	η_{LIV} (m)	η_{HEY} (m)	U_{veer}	U_{10} (m/s)	U_θ (deg)
5 Nov 1996	06.00	4.03	8.39	0.61	0.79	WNW	20.31	296.10
6 Nov 1996 (T1)	*10.00*	*4.50*	*9.23*	*1.48*	*1.54*	*NW–SW–W*	*23.75*	*216.61*
24 Dec 1997 (T3)	*22.00*	*5.63*	*10.15*	*2.19*	-	*SE–W*	*28.81*	*255.78*
3 Jan 1998	18.00	4.22	9.23	1.42	1.61	SW–WSW	23.47	255.56
26 Dec 1998 (T4)	*21.00*	*5.39*	*10.15*	*2.02*	*2.43*	*S–WSW*	*30.39*	*249.81*
3 Dec 1999	*12.00*	*4.02*	*8.39*	*1.78*	*1.48*	*SW–W*	*20.95*	*238.96*
13 Dec 2000	*04.00*	*4.09*	*8.39*	*1.74*	*2.12*	*W*	*23.81*	*274.11*
28 Dec 2001	10.00	4.06	8.39	1.04	0.89	SW–NW	11.05	286.39
20 Feb 2002	12.00	4.02	8.39	-	0.47	W–NW	20.43	277.78
23 Feb 2002	05.00	4.07	8.39	-	0.78	W	18.68	274.19
27 Oct 2002	*11.00*	*4.09*	*7.63*	*2.26*	*1.54*	*SW–W*	*19.80*	*264.70*
20 Dec 2003	23.31	3.89 (4.07)	8.39 (6.9)	0.71	0.60	WNW	17.31	288.65
8 Feb 2004 (T9)	03.36	5.03 (5.37)	9.23 (7.84)	1.16	1.05	NW–W	20.60	288.65
8 Jan 2005 (T10)	*10.00*	*5.40 (4.46)*	*9.23 (7.14)*	*1.75*	*2.08*	*SW–W*	*25.93*	*251.39*
18 Jan 2005	18.58	4.14 (4.42)	8.39 (6.9)	0.79	0.65	W–NW	18.91	260.53
13 Feb 2005	11.31	3.56 (4.18)	7.56 (5.97)	0.66	0.21	NW–W	17.12	298.71
11 Nov 2006	17:00	4.09 (3.68)	8.39 (8.33)	0.70	0.41	W–NW	18.39	283.89

[a] Observed wave data are provided in parentheses when available. The corresponding peak wave period T_p, peak tide-surge residual elevation η, and peak offshore wind speed U_{10}, direction U_θ, and an indication of the direction of wind change U_{veer}, during an event are also given. Values in italics indicate events when both the tide-surge residual and wave heights are considered extreme.

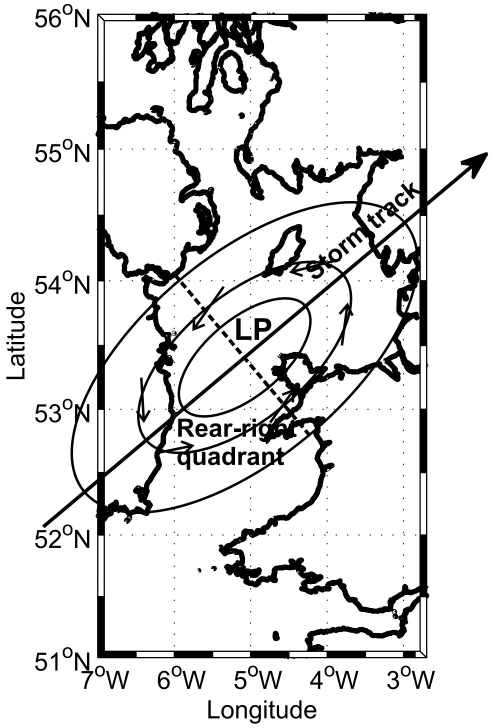

Figure 2. An example low-pressure system tracking across the Irish Sea showing the location of the rear-right quadrant and the track of the central low pressure defining the storm track. The arrows on the pressure system represent the wind direction.

direction, have generated waves up to 5.63 m. This is larger than the more frequently generated waves (4–5 m) in the last decade due to weaker west–southwesterly through to northwesterly wind conditions. These waves have the longest periods, but are still locally generated according to coastal engineering formulae [see *Hurdle and Stive*, 1989]. Assuming waves in Liverpool Bay have a maximum fetch of 200 km in a depth of 20 m (approximate depth at wave buoy), then a wind of 29 m/s can generate waves between 5.47–5.67 m with periods between 9.67–11.57 s. The largest waves are generated by the strongest winds (Table 2), but the wind duration and wind speed over fetches between the southwest to northwest will determine the peak wave conditions. For example, the waves on 26 December 1998 are smaller than on 24 December 1997. Even though the peak wind from west–southwest was stronger on 26 December 1998 it veered more westerly during the peak wind conditions on the 24 December 1997. The winds are often stronger when blowing from a southwest to west–southwest direction, generating larger wave heights (Table 2). Such conditions lead to extreme waves combined with extreme surge, since this is when the most significant surge is also generated (see section 3.1).

3.3. Storm Tracks

[12] Here the storm track is based on the central low-pressure location as a storm moves across the British Isles (Figure 2). The storm tracks for the five largest wave events and five largest tide-surge residuals at Heysham and Liverpool have been investigated (see Figures 3–5). These storms named T1–T10 are identified in Tables 1 and 2. This provides insight into which storms will cause the largest waves and additional water levels on top of the tide. We find similar results to *Lennon* [1963], as follows. The surge period is transitory with a period of 6–12 h. The largest surge conditions are generated by storms which track from west to northeast across the British Isles (Figures 3 and 4). In most cases large waves are also generated with these storm events (see Table 1) and even extreme wave events (e.g., T3, T4, and T10; Figure 5). The position of the storm along its track at peak wave and peak surge levels is different; since extreme wave generation depends on a westerly wind and extreme surge generation is dependant on a more southwesterly wind. Storms tracking from north to east along the eastern side of Britain (T9; Figure 5) or with a significant easterly component along the north coast of Scotland (T1; Figure 5) can generate extreme waves. The associated surge may or may not be considered extreme (see Table 2) depending on the track the storm takes. The position of the storm at the time of peak surge or waves is to the northeast of the British Isles.

[13] We find the storms that generate major surges at Heysham (Figure 3) have a more northerly position in their track compared with Liverpool (Figure 4). The tracks do not directly cross the Irish Sea, only the North Channel. Surge generation occurs at Liverpool (Figure 4) if the storm track crosses the northern or eastern Irish Sea. There are two exceptions to this (T2 and T4; Figure 4), when depressions west of Ireland move northeast past the same latitude as Liverpool generating a significant external surge component to the eastern Irish Sea. We cannot track the initial positions of these two tracks since they are outside the boundaries of the available data. As found by *Lennon* [1963] the position of the storm at peak surge is to the northeast of the British Isles. This is when the wind in the rear-right quadrant of the storm has local surge/wave generating capability due to its direction (Figure 2). The speed of the storm also seems to affect the size of the surge. Fast-moving storms, before the peak in the surge, continue to act on the (external) surge as both surge and storm propagate toward the coast, therefore the surge becomes more extreme. For example, T4, T6, T8, and T10 are fast traveling and cause the majority of the largest surges at Heysham and/or Liverpool.

[14] Extreme wave events in Liverpool Bay are often generated by the same storms that generate significant surges at both Liverpool and Heysham. Their tracks are north of Liverpool Bay passing across or to the north of the North Channel. But they are also generated by storms with a marked easterly component in their track moving north of the Irish Sea (T1; Figure 5) and by storms moving to the southeast (T9; Figure 5). During these storms the winds are mainly between the northwest and west. Surges due to northwesterly winds, e.g., the surge on the 13–15 November 1977, can reach ~1.5 m at Liverpool [*Jones and Davies*, 1998], but very rarely exceed this level. This is a consequence of the North Channel restricting the external surge propagating into the eastern Irish Sea. T1 in Table 1 is the only extreme surge (>1.5 m) observed (at Liverpool alone) over the 11 year period due to an initially northwesterly wind. In this case the wind backs to the southwest for a short duration at the time of peak surge, but rapidly veers to the

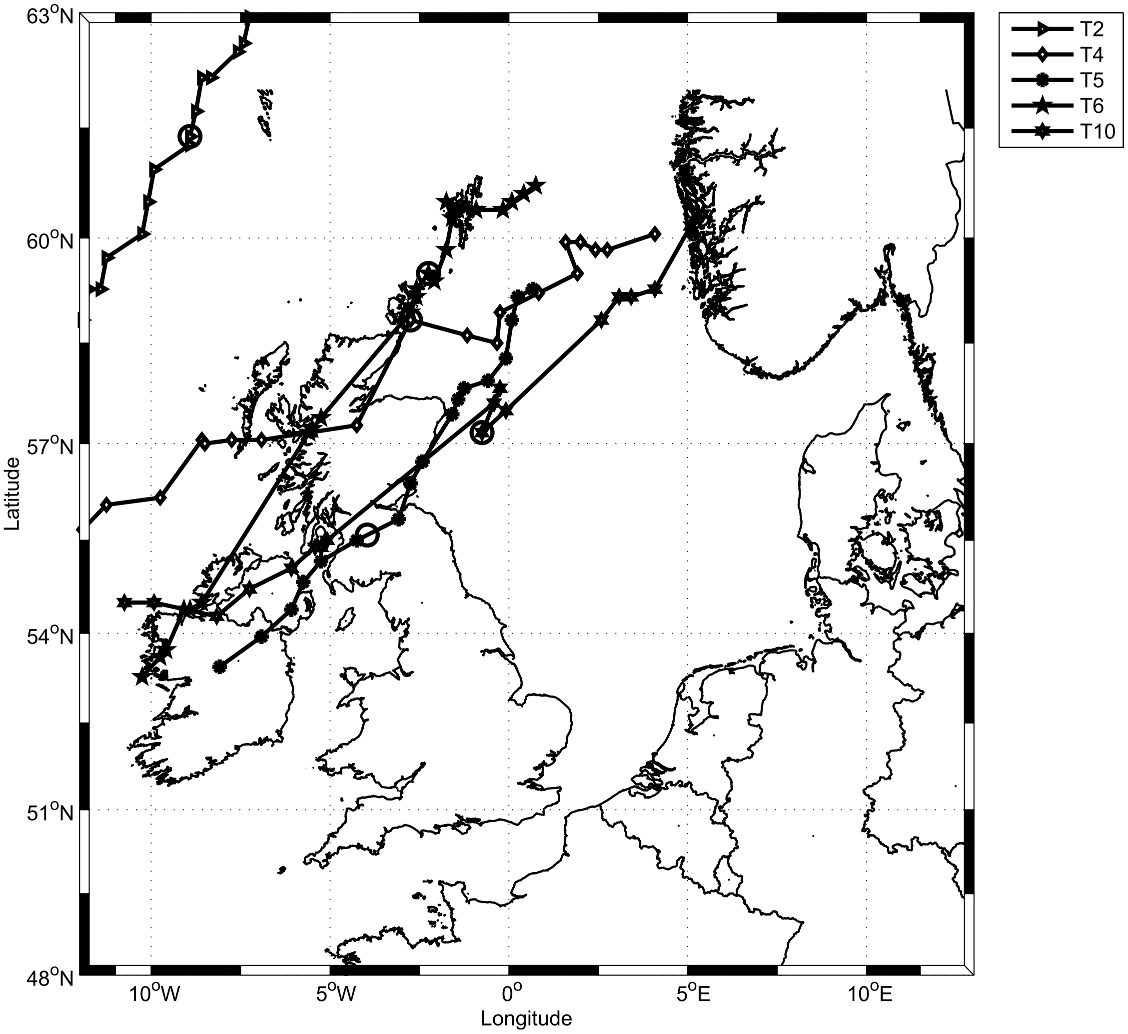

Figure 3. Storm tracks generating the five largest surge events at Heysham. The track number relating it to a surge event is given in Table 1. The storm position is plotted every hour, and the locations at peak surge are marked by open circles.

west generating the peak in wave height. In the case of storm T9, two storms track around the British Isles, which is why there is a break in the track as one storm diminishes and the second grows. Although the first storm generates westerly winds it is thought that the second storm has more impact on wave growth as it moves closer to the British Isles. For this storm only a low (locally generated) surge occurs since the storm was badly positioned for external surge generation into the eastern Irish Sea. The location of the storm at the time of peak wave activity is either close to the east coast of Scotland or further offshore in the North Sea. The speed of the storm has less affect on the wave conditions. T4 is the only fast moving storm before the peak in wave heights, but many storms, e.g., T3, T4, T9, and T10 generate extreme waves (>5 m).

4. Tidal Effects

[15] At Liverpool it is known that large surges generally avoid tidal high water (HW) and occur more frequently on the rising tide, especially under spring tide conditions, due to the tide-surge interaction. The annual maximum HW between 1768 and 1999 exceeded the average annual mean high water by 1.3–2.6 m. These extreme high waters occur on spring tides, with the largest high water occurring in 1905 [*Woodworth and Blackman*, 2002]. To investigate the importance of the tide, we compare the magnitude of the peak tide-surge residual to peak filtered surge residual for the five largest tide-surge residuals and five largest filtered surge residuals at Liverpool. The tidal and surge residual conditions are also analyzed to determine what caused the largest high water levels at Liverpool over the past 11 years.

4.1. Tide-Surge Interaction

[16] Tide-surge interaction is significant at Liverpool [*Brown et al.*, 2010b]. We look at the five most extreme tide-surge residuals (Table 3) and the 5 most extreme filtered surge residuals (Table 4) to determine how the tidal range modifies the magnitude of the peak in filtered surge (meteorological surge) to create the peak in tide-surge

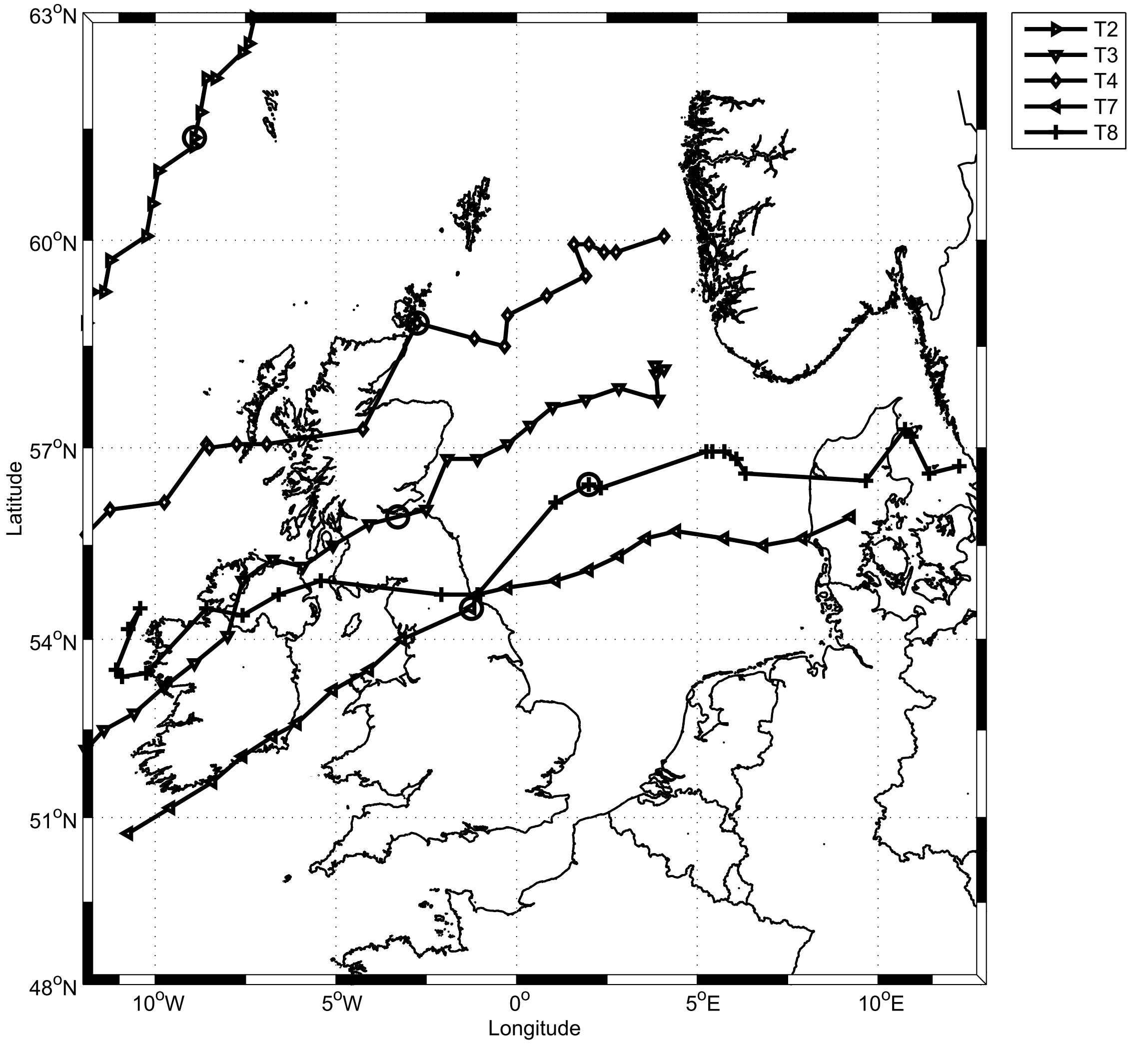

Figure 4. Same as Figure 3, but for Liverpool.

residual (overall surge). It is very infrequent that a storm event is classed as an extreme event by both surge definitions simultaneously.

[17] We find that the most extreme tide-surge residuals (Table 3) occur during low water levels (>1 m). Also the tidal range at the time of these surges implies that they occur during tides between neap (5 m) and mean (7.5 m) tidal ranges. The largest filtered surge residuals (Table 4) can occur at any water level, but only result in a significant tide-surge residual if the water level is low when it peaks (e.g., 26 December 1998). In all cases shown, the magnitude of the filtered surge residual (due to the wind) is enhanced due to tide-surge interaction. But it is possible for the surge to be reduced if it occurs close to spring high water levels (an example is discussed by *Brown et al.* [2010b]). Flood inundation in Liverpool Bay is therefore unlikely to result solely from an extreme surge event, but rather as a result of a smaller surge during (spring) tidal HW. On the rare occasion that a significant surge does occur on the falling tide, the surge can significantly contribute to the HW level leading to extreme flooding, e.g., 26 September 1905 and 11–12 November 1977 [*Woodworth and Blackman*, 2002].

[18] The skew surge is used to determine the flood risk at each location investigated. This value represents the additional water level on top of the predicted tidal high water [*de Vries et al.*, 1995]. Over the 11 year study period the maximum skew surge at both locations occurred on the 8 January 2005. At Liverpool it reached 1.80 m and for Heysham it reached 1.64 m. For this event the tide-surge residual was actually larger at Heysham (Table 1). So, although Heysham experiences the largest surges, the tide-surge interaction at this location can sometimes result in a lower skew surge than the coincidental skew surge at Liverpool, owing to the larger tidal range. The skew surge at Liverpool was 0.5 m or greater on 370 occasions in 11 years and was 1.0 m or greater 17 times in 11 years. At Heysham the skew surge was equal to or greater than 0.5 m and 1.0 m 470 times and 20 times, respectively. Since 1996 there seems to be a slowly increasing trend in the positive skew surge at both Liverpool (Figure 6, line 1) and Heysham (Figure 7, line 1). However, the trend in the extreme skew surge (≥0.6 m) is decreasing at both locations (line 2 in

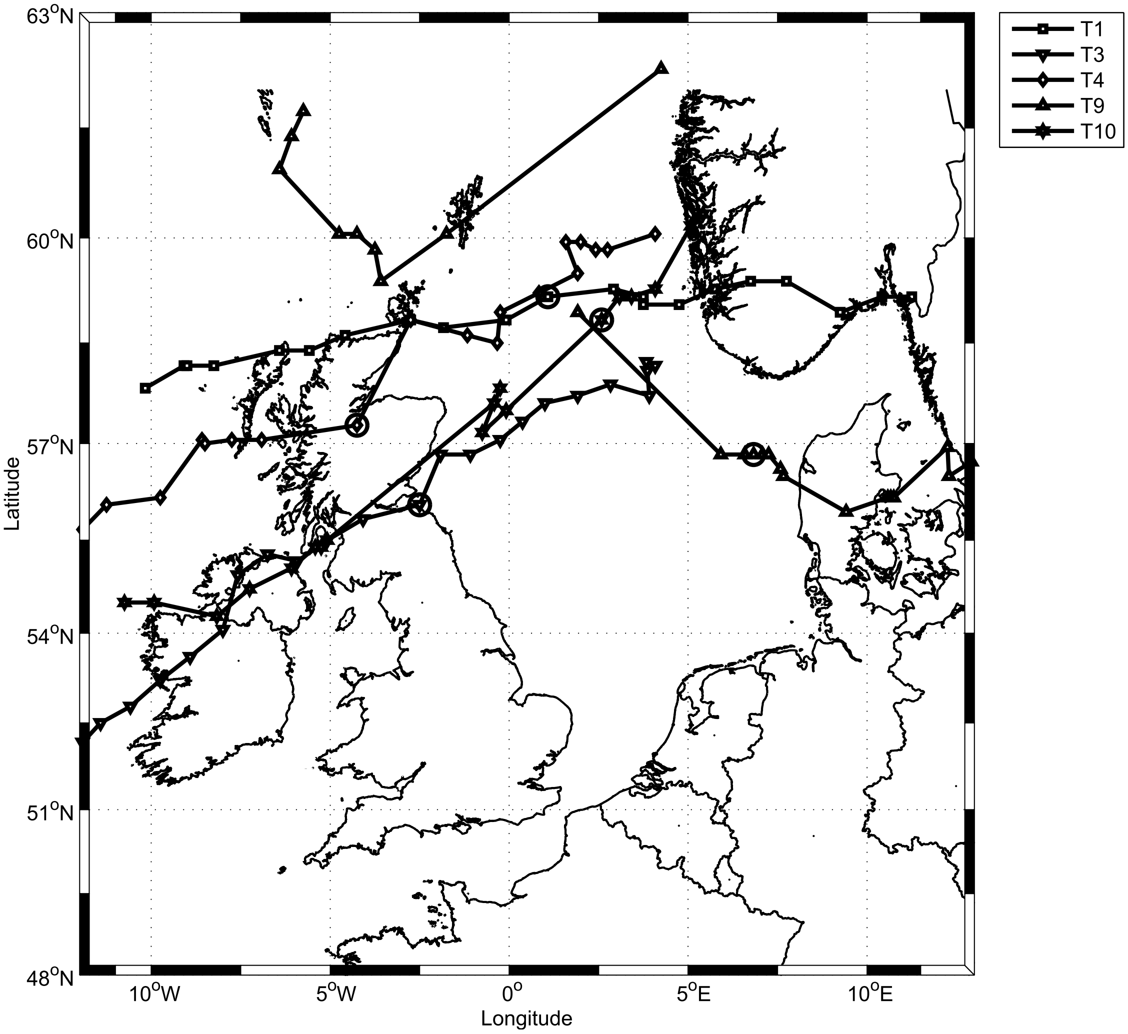

Figure 5. Storm tracks generating the five largest wave conditions in Liverpool Bay. The track number relating it to a wave event is given in Table 2. The storm position is plotted every hour, and the locations at the peak of the wave event are marked by open circles.

Figures 6 and 7). This implies that the future flood risk could increase in frequency along the Sefton coastline but not in intensity. The rate of increase in the positive skew surge is greater for Heysham (~12 mm/yr) than Liverpool (~9 mm/yr). Compared with the overall variability in the data (0 to ~1.7 m) and the variability in the extreme values (~1.1 to ~1.7 m) over the 11 year period these trends have low significance.

4.2. Extreme High Water

[19] Over the past decade the most extreme high-water level reached 5.64 m at Liverpool on the 10 February 1997,

Table 3. The Five Most Extreme Tide-Surge Residuals Over the Past Decade at Liverpool[a]

Date	Peak Tide-Surge Residual (m)	Peak Filtered Surge Residual (m)	Tidal Elevation (m)	Tidal Range (m)
19 Feb 1997	1.841 (1800)	0.956 (2030)	−1.605	6.013
24 Dec 1997	2.189 (2130)	1.010 (2100)	0.973	4.477
26 Dec 1998	2.017 (2245)	1.138 (2130)	−2.729	5.595
26 Feb 2002	1.977 (0600)	0.713 (0800)	−2.545	7.419
27 Oct 2002	2.264 (1000)	0.822 (0930)	−1.669	5.423

[a] The corresponding peak in the filtered surge residual and the tidal elevation at the time of the peak in tide-surge residual are given with the tidal range during this event. The times of peak surge are given in parentheses. Times are in UT.

Table 4. The Five Most Extreme Filtered Surge Residuals Over the Past Decade at Liverpool[a]

Date	Peak Tide-Surge Residual (m)	Peak Filtered Surge Residual (m)	Tidal Elevation (m)	Tidal Range (m)
6 Nov 1996	1.221 (0130)	1.113 (0730)	2.262	4.198
3 Jan 1998	1.388 (1900)	1.160 (1430)	4.129	7.714
26 Dec 1998	1.990 (2300)	1.138 (2130)	−1.995	5.914
8 Jan 2005	1.753 (0515)	1.193 (0730)	2.546	6.134
3 Dec 2006	1.572 (0530)	1.162 (1130)	1.633	7.134

[a] The corresponding peak in the tide-surge residual and the tidal elevation at the time of the peak in filtered surge residual are given with the tidal range during this event. The times of peak surge are given in parentheses. Times are in UT.

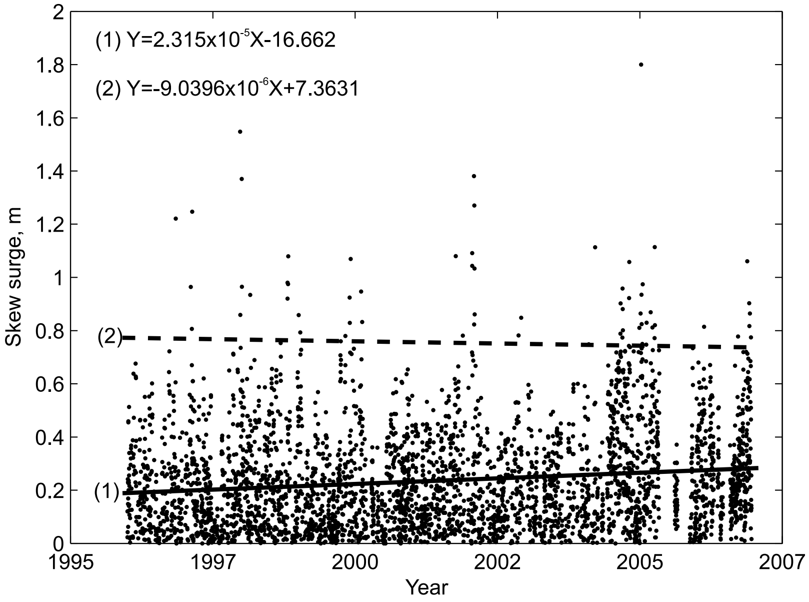

Figure 6. The positive skew surge at Liverpool between 1996 and 2006, with increasing trend line (solid line) and decreasing extreme (≥0.6 m) skew surge trend line (dashed line). The equations of the trend lines are given in the top left.

during spring tides (10.23 m range) (Figure 8). This event was the result of west–southwesterly winds (257.60°) with a maximum speed of 20.4 m/s. The filtered surge residual shows that the peak in the wind-driven surge occurred close to high water (Figure 8b). Spring tide-surge interaction prevented a significant tide-surge residual at this time (~0.6 m). The peak in the tide-surge residual followed during the lower water levels and reached 1.34 m, although large this is not considered to be an extreme surge. The tide-surge interaction enhanced the peak (filtered) surge by a factor of 1.77 as the water levels fell (i.e., the ratio of the peak tide-surge to peak filtered surge was 1.77). But the tide-surge residual was initially reduced during high water.

[20] At Heysham the highest water level achieved was 6.18 m on 1 February 2002, as a result of 22.0 m/s south–southwesterly winds (195.13°) (Figure 9). The tidal range was 10.49 m. Interestingly, the peak in the tide-surge residual nearly coincides with the time of the peak in the

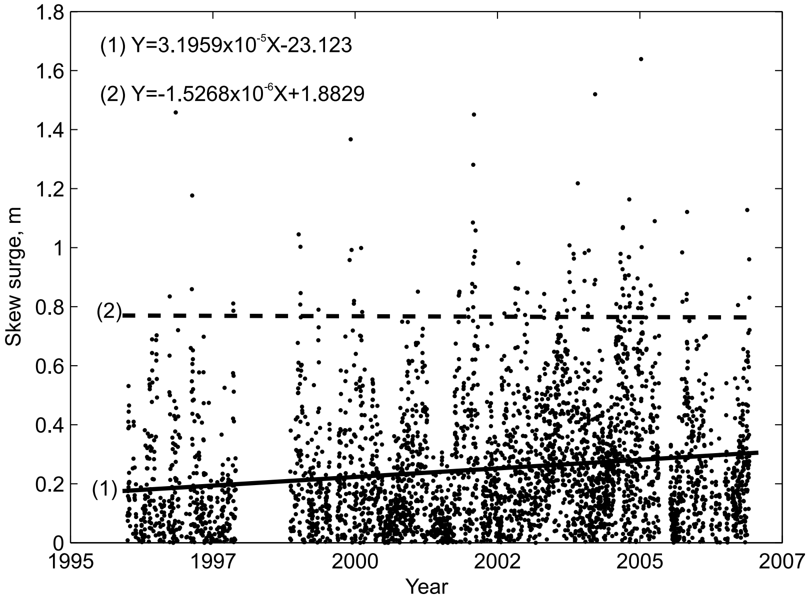

Figure 7. The positive skew surge at Heysham between 1996 and 2006, with increasing trend line (solid line) and decreasing extreme (≥0.6 m) skew surge trend line (dashed line). The equations of the trend lines are given in the top left. Between 26 November 1997 and 26 November 1998, the data are unreliable so has not been used in the trend fitting.

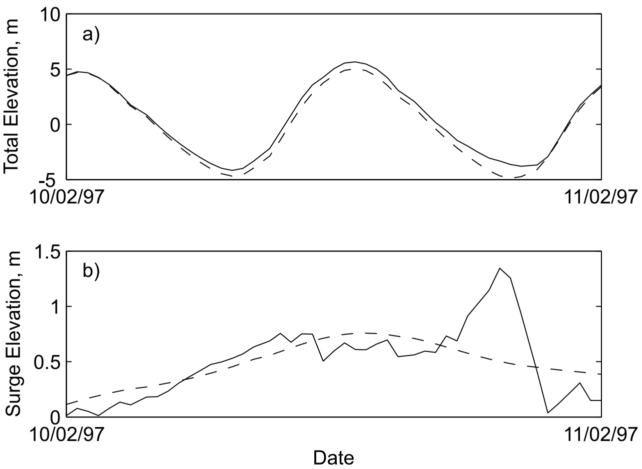

Figure 8. Observations from Liverpool tide gauge during the largest high water event. (a) The total water elevation (solid line) and predicted tide (dashed line) and (b) the tide-surge (solid line) and filtered (dashed line) surge residuals are shown.

filtered surge (Figure 9b) and is close to high water. The high water levels prevent a significant peak in the tide-surge residual (~1.28 m). In this case the peak (filtered) surge was enhanced by a (multiplication) factor of 1.43 due to tide-surge interaction giving the overall (tide-surge) residual. Although the filtered surge is of a similar magnitude to that in the Liverpool case, the modulation of the tide-surge residual is noticeably less than in the Liverpool case. This may be the result of slightly weaker wind-forcing at low water and/or the more southerly wind direction reducing the local surge contribution. The timing of the peak winds compared with the time of high water limited the tide-surge interaction preventing a significant enhancement in the tide-surge residual. Unlike the largest high water case at Liverpool, the tidal modulation of the surge is less significant.

[21] Neither of these events was associated with a significant tide-surge residual (i.e., <1.5 m) or filtered surge residual (i.e., <1 m). But the large tidal range combined with significant winds from the southwest can enhance high water levels leading to flood risk.

5. Discussion

[22] In the eastern Irish Sea extreme wave heights (>4 m) rarely coincide with the most extreme surge events (>1.5 m). West to northwesterly wind conditions leading to extreme wave conditions will generate surge events but not to extreme levels (i.e., <1.5 m). It is only under west–southwest and westerly wind conditions that extreme surge levels and wave heights can be generated simultaneously. When the wind veers from the southwest to the west, the largest waves and largest surge can coincide. Extreme west–southwesterly wind conditions therefore cause the worst flood risk along the Sefton coastline as a result of extreme surge levels (2–2.5 m) and large wave overtopping conditions (~5.6 m).

[23] Tide-surge interaction modulates the extent of the surge and the likelihood of coastal flooding in Liverpool Bay. We have found that the largest filtered surge residuals (i.e., the surge due to the wind alone) do not cause the largest tide-surge residual (i.e., due to the interaction of the tide and the wind driven surge). The tidal elevation at the time of the surge can either enhance or reduce the size of the resulting surge level (Figure 8b). The tide-surge residual gives an idea of the magnitude of the additional water level on top of the predicted tidal level. Hence, this is more important in a region of large tidal range, e.g., Liverpool Bay, when assessing flood risk. Often an extreme tide-surge residual peak will occur during low water levels in Liverpool Bay; hence the flood risk posed is minimal as the overall water level is still below that of spring high tide. Extreme tide-surge residual peaks and extreme filtered surge residual peaks very rarely coincide (Tables 3 and 4). A storm event classed as extreme by one residual classification may not be considered extreme by the other. The residual used to determine extreme events in regions of large tidal range must therefore be chosen carefully.

[24] The most extreme tide-surge residuals occur during tides with a range between neap and mean tides. Although the wind stress has most influence on the water column during spring low water, the duration and fetch of the wind also controls the size of the surge. Higher water elevations, above mean tidal level, during spring tide act to reduce the effect of the wind generating the local surge. This seems to have more of an effect than the lower water levels allowing the surge to be enhanced. Although smaller surges seem to occur during spring tides, the most extreme high water levels are still achieved during spring tides since the tide effect is dominant.

[25] Waves are locally generated in Liverpool Bay [*Brown and Wolf*, 2009]. Winds from the northwest and west have the longest fetches, thus generate the most severe wave conditions. If winds from these directions become more intense and frequent, so will the extreme wave conditions. Since the waves are locally generated the speed of the storm has little effect on the resultant wave conditions. The most severe surge conditions occurred when the winds were from the southwest. Since the external surge has a dominant contribution to the surge in the eastern Irish Sea this direction provides longest fetch for surge generation. A fast-moving storm can continue to act on the external surge as both surge and storm propagate along the fetches to Liverpool Bay enhancing the (total) surge conditions, while

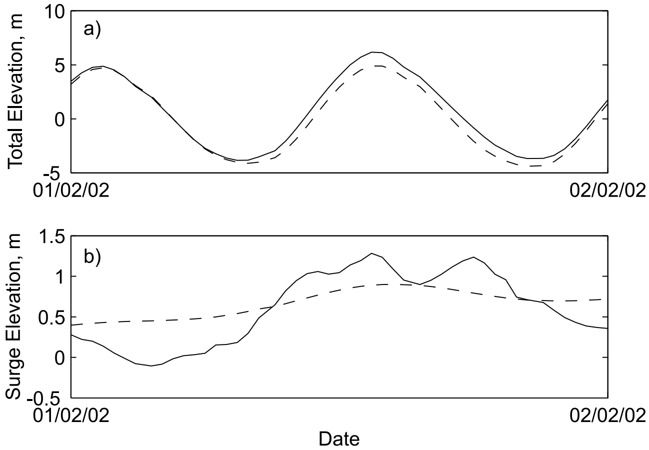

Figure 9. Same as Figure 8, but for Heysham.

having little influence on the (locally generated) wave conditions. The coast is at most risk from flooding when a southwesterly wind veers to the west during HW spring tide. Under these conditions substantial wave heights coincide with a low to moderate surge on top of extreme tidal levels. This leads to a high risk of defenses being overtopped and extreme dune erosion (e.g., November 1977) [*Jones and Davies*, 1998; *Pye and Neal*, 1994].

[26] The worst flood risk in Liverpool Bay, due to water levels alone, will be posed when strong southwesterly winds coincide with maximum spring high tide. During these conditions flooding could be worse if waves are present. In contrast, at times of highest water elevation the actual tide-surge residual is not classed as extreme due to the considerable water depth at the time of the peak in wind effect. A large tide-surge residual may occur during times of lower tidal levels, but will not pose a flood risk as a consequence of the much lower tidal levels at this time. Flood risk posed by wave overtopping is greatest during westerly or northwesterly wind conditions, especially if combined with maximum tidal water levels. The effect of wave setup will be assessed in further research using a higher resolution (185 m) model of Liverpool Bay.

[27] No long-term change in the level by which the average annual mean HW is exceeded by extreme high water levels is expected [*Woodworth and Blackman*, 2002]. However, an increase in future extreme water levels around the United Kingdom is expected due to sea level rise and an increase in wave height, up to 5% of present-day conditions by 2075 is projected around the United Kingdom by *Sutherland and Wolf* [2002], due to climate change. If coastal defenses remain unchanged then overtopping of seawalls could increase by 150%. This increased flood risk is mainly posed by sea level rise [*Sutherland and Wolf*, 2002]. At Liverpool the present rate of sea level rise is 1.4 mm/yr [*Woodworth et al.*, 1999]. Thus the change in water depth over the next decade will be small compared with the tidal range in the eastern Irish Sea. The major threat to Liverpool Bay will be an increase in the frequency and intensity of west–southwesterly wind events. These conditions generate the most extreme locally generated surge and wave events in response to storms. More rapid change in the morphology of the (Sefton) coastline could also result as a consequence of the increased frequency of extreme events. A change in the northeasterly storm tracks such that the maximum southwest winds cross over the eastern Irish Sea would also increase the flood risk within Liverpool Bay, whereas a shift further north would reduce the flood risk in Liverpool Bay.

6. Conclusions

[28] Using the presented methodology applied to model hindcast and observational data for the last 11 years (1996–2006, inclusive) we have found that the largest surge in the eastern Irish Sea during that period was 2.43 m and the largest significant wave height was 5.6 m. Extreme surge conditions in the eastern Irish Sea are generated by southwesterly to westerly winds. Extreme wave conditions are generated by westerly to northwesterly winds. The most extreme wave and surge conditions occur (simultaneously) when a southwesterly wind with significant strength (≥20 m/s) veers to the west. This often occurs when a storm tracks across or just north of the eastern Irish Sea and into the North Sea in a northeast direction. The peaks of the surge or waves occur at different times during the storm propagation, but both peaks occur between 6–12 h into the storm track.

[29] When strong southwesterly winds occur close to spring high tide in Liverpool Bay the most extreme water levels result. When combined with the presence of waves, overtopping of coastal defenses along the Sefton coastline could lead to coastal flooding. Future flood risk will therefore increase with sea level rise and if more intense southwesterly wind conditions occur. Under these conditions the additional water level on top of spring high tide may be less than a meter, but the very high tidal range contributes significantly.

[30] The track of the storm determines the wind sequence experienced in the eastern Irish Sea. Storms traveling northeast passing to the north of Liverpool Bay cause the worst surge conditions in the bay. Often large waves are associated with these storm tracks. Storms moving southeast off the east coast of Britain or moving east just north of Scotland can generate significant waves within Liverpool Bay, with no simultaneous large surge event. From the results presented we can conclude that southwesterly wind conditions veering west pose the greatest flood risk as they generate the largest tide-surge residual and extreme wave conditions on top of the raised water levels.

[31] **Acknowledgments.** The CoFEE project is funded under the NERC Flood Risk in Extreme Environments (FREE) program (grant NE/E002471/1) and the MICORE project is funded by the EU FP7 program (grant 202798). Thanks to Jane Williams, the operational surge model output and Met data were provided over the 11 year period. Met data were also obtained from ECMWF to drive the coarse WAM model. Phil Knight is thanked for providing a tidal analysis program to validate the model data. Measured data for these validations were obtained from BODC, CEFAS, and both the U.K. and Irish Met Offices.

References

Brown, J. M., and J. Wolf (2009), Coupled wave and surge modelling for the eastern Irish Sea and implications for model wind-stress, *Cont. Shelf Res.*, *29*(10), 1329–1342, doi:10.1016/j.csr.2009.03.004.

Brown, J. M., A. J. Souza, and J. Wolf (2010a), Surge modelling in the eastern Irish Sea: Present and future storm impact, *Ocean Dyn.*, *60*, 227–236, doi:10.1007/s10236-009-0248-8.

Brown, J. M., A. J. Souza, and J. Wolf (2010b), An 11-year validation of wave-surge modelling in the Irish Sea, using a nested POLCOMS-WAM modelling system, *Ocean Modell.*, *33*(1–2), 118–128, doi:10.1016/j.ocemod.2009.12.006.

Carter, D. J. T. (1999), Variability and trends in the wave climate of the North Atlantic: A review, paper presented at 9th International Offshore and Polar Engineering Conference, ISOPE, Cupertino, Calif.

Coles, S., and J. Tawn (2005), Bayesian modelling of extreme surges on the UK east coast, *Philos. Tran. R. Soc. A*, *363*(1831), 1387–1406, doi:10.1098/rsta.2005.1574.

De Vries, H., M. Breton, T. De Mulder, Y. Krestenitis, J. Ozer, R. Proctor, K. Ruddick, J. C. Salomon, and A. Voorrips (1995), A comparison of 2-D storm surge models applied to three shallow European seas, *Environ. Softw.*, *10*(1), 23–42, doi:10.1016/0266-9838(95)00003-4.

Hawkes, P. J., B. P. Gouldby, J. A. Tawn, and M. W. Owen (2002), The joint probability of waves and water levels in coastal engineering design, *J. Hydraul. Res.*, *40*(3), 241–251.

Holt, J. T., and I. D. James (2001), An *s* coordinate density evolving model of the northwest European continental shelf: 1. Model description and density structure, *J. Geophys. Res.*, *106*(C7), 14,015–14,034, doi:10.1029/2000JC000304.

Horsburgh, K. J., and C. Wilson (2007), Tide-surge interaction and its role in the distribution of surge residuals in the North Sea, *J. Geophys. Res.*, *112*, C08003, doi:10.1029/2006JC004033.

Houghton, J. (2005), *Global warming, Rep. Prog. Phys.*, *68*(6), 1343–1403, doi:10.1088/0034-4885/68/6/R02.

Hurdle, D. P., and R. J. H. Stive (1989), Revision of SPM 1984 wave hindcast model to avoid inconsistencies in engineering applications, *Coastal Eng.*, *12*(4), 339–351, doi:10.1016/0378-3839(89)90011-2.

Jones, J. E., and A. M. Davies (1998), Storm surge computations for the Irish Sea using a three-dimensional numerical model including wave-current interaction, *Cont. Shelf Res.*, *18*(2), 201–251, doi:10.1016/S0278-4343(97)00062–9.

Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P. A. E. M. Janssen (1994), *Dynamics and Modelling of Ocean Waves*, 532 pp. Cambridge Univ. Press, Cambridge, U. K.

Lamb, H. (1991), *Historic Storms of the North Sea, British Isles and Northwest Europe*, 204 pp., Cambridge Univ. Press, Cambridge, U. K.

Lennon, G. W. (1963), The identification of weather conditions associated with the generation of major storm surges along the west coast of the British Isles, *Q. J. R. Meteorol. Soc.*, *89*, 381–394, doi:10.1002/qj.49708938110.

Lowe, J. A., and J. M. Gregory (2005), The effects of climate change on storm surges around the United Kingdom, *Philos. Trans. R. Soc. A*, *363*, 1313–1328, doi:10.1098/rsta.2005.1570.

Lowe, J. A., J. M. Gregory, and R. A. Flather (2001), Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by Hadley Centre climate models, *J. Clim.*, *18*(3–4), 179–188.

Monbaliu, J., R. Padilla-Hernández, J. C. Hargreaves, J. C. Carretero-Albiach, W. Luo, M. Sclavo, and H. Günther (2000), The spectral wave model WAM adapted for applications with high spatial resolution, *Coastal Eng.*, *41*(1–3), 41–62.

Prandle, D., and J. Wolf (1978), The interaction of surge and tide in the North Sea and River Thames, *Geophys. J. R. Astron. Soc.*, *55*, 203–216.

Pye, K. (1991), Beach deflation and backshore dune formation following erosion under storm surge conditions: An example from northwest England, in *Aeolian Grain Transport*, vol. 2, *The Erosional Environment*, *Acta Mech. Suppl.*, vol. 2, edited by O. E. Barndorff-Nielsen and B. B. Willetts, pp. 171–181, Springer, Berlin.

Pye, K., and S. J. Blott (2008), Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on Sefton coast, U.K., *Geomorphology*, *102*(3–4), 652–666.

Pye, K., and A. Neal (1994), Coastal dune erosion at Formby Point, north Merseyside, England: Causes and mechanisms, *Mar. Geol.*, *119*(1–2), 39–56, doi:10.1016/0025-3227(94)90139-2.

Sutherland, J., and J. Wolf (2002), *Coastal defence vulnerability* 2075, *Rep. 590*, HR Wallingford, 30 pp., HR Wallingford, Oxford, U. K.

Williams, J. A., and R. A. Flather (2000), Interfacing the operational storm surge model to a new mesoscale atmospheric model, *POL Internal Doc. 127*, 18 pp., Proudman Oceanogr. Lab., Liverpool, U. K.

Wolf, J. (2008), Coupled wave and surge modeling and implications for coastal flooding, *Adv. Geosci.*, *17*, 1–4.

Wolf, J. (2009), Coastal flooding: Impacts of coupled wave-surge-tide models, *Nat. Hazards*, *49*, 241–260, doi:10.1007/s11069-008-9316-5.

Wolf, J., and D. K. Woolf (2006), Waves and climate change in the north–east Atlantic, *Geophys. Res. Lett.*, *33*, L06604, doi:10.1029/2005GL025113.

Wolf, J., J. Brown, G. Lymbery, A. Souza, and J. Williams (2008), Coastal flooding in extreme events, paper presented at 9th International Conference, Littoral, Venice, Italy, 25–28 Nov.

Woodworth, P. L., and D. L. Blackman (2002), Changes in extreme high waters at Liverpool since 1768, *Int. J. Climatol.*, *22*(6), 697–714, doi:10.1002/joc.761.

Woodworth, P. L., M. N. Tsimplis, R. A. Flather, and I. Shennan (1999), A review of the trends observed in British Isles mean sea level data measured by tide gauges, *Geophys. J. Int.*, *136*(3), 651–670, doi:10.1046/j.1365-246x.1999.00751.x.

Woodworth, P. L., R. A. Flather, J. A. Williams, S. L. Wakelin, and S. Jevrejeva (2007), The dependence of the UK extreme sea levels and storm surges on the North Atlantic Oscillation, *Cont. Shelf Res.*, *27*(7), 935–946, doi:10.1016/j.csr.2006.12.007.

J. M. Brown, A. J. Souza, and J. Wolf, Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK. (jebro@pol.ac.uk)