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An 11-year validation of wave-surge modelling in the Irish Sea, using a nested POLCOMS–WAM modelling system

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A B S T R A C T

In the future it is believed that extreme coastal flooding events will increase (in frequency and intensity) as a result of climate change. We are investigating the flood risks in the eastern Irish Sea posed by extreme storm events. Here, an 11-year simulation (01/01/1996–01/01/2007) including wave–current interaction has been validated. These data can then be used to investigate the potential for coastal flooding in the study area.

To accurately model a storm event in the eastern Irish Sea both wave effects and the influence of the external surge need to be considered. To simulate the waves, we have set up a one-way nested approach from a 1° North Atlantic model, to a 1.85 km Irish Sea model, using the state-of-the-art 3rd-generation spectral WAve Model (WAM). This allows the influence of swell to be correctly represented. The Proudman Oceanographic Laboratory Coastal-Ocean Modelling System (POLCOMS) has been used to model the tide–surge interaction. To include the external surge we have set up a one-way nested approach from the 1/9° by 1/6° operational Continental Shelf surge model, to a 1.85 km Irish Sea model. For the high resolution Irish Sea model we use a POLCOMS–WAM coupled model, to allow for the effects of wave–current interaction on the prediction of surges at the coast.

Using two classification schemes the coupled model is shown to be good and often very good at predicting the surge, total water elevation and wave conditions. We also find the number of low level surge events has increased in the study area over the past decade. However, this time period is too short to determine any long-term trends in the wave and surge levels.

1. Introduction

Flood prone areas continue to become more densely populated. It is believed that increased coastal flooding in both intensity and frequency will occur in response to climate change (e.g. Houghton, 2005; IPCC, 2007). Sea level rise combined with human reclamation and development of wetlands has lead to increased damage by coastal flooding (IPCC, 2007). The increasing threat of coastal flooding is therefore a cause of great concern for individual citizens, businesses and those charged with management and protection of the coast (e.g. Lowe et al., 2001). The Coastal Flooding by Extreme Events (CoFEE) project and Morphological Impacts and COastal Risks induced by Extreme storm events (MICORE) project are assessing past, present and future flood risk for a range of coastal environments due to extreme events (Brown et al., 2009; Wolf et al., 2008). Survey data was available from 1996 to 2007 for the initial modelling stages of these projects. Through the use of advanced modelling techniques (described in Section 2) an 11-year wave-surge hindcast (01/01/1996–01/01/2007) has been performed for the Irish Sea (Fig. 1). Here, we examine the long-term model validation (Section 3) of both WAM and POLCOMS–WAM at different grid scales. An initial analysis of the modelling results and data has determined the extreme surge levels and wave heights that occur in Liverpool Bay at present. Further investigation will later be carried out to distinguish the different causes of extreme present day conditions in the eastern Irish Sea. The basic causes are discussed in Section 6. The most extreme events will be selected to investigate surges within Liverpool Bay (Fig. 1) using a higher resolution model. This area provides a range of different coastal environments, providing examples of most of England's coastal types, and also has the added benefit of a vast and available dataset (POL Coastal Observatory).

The occurrence of extreme high water levels and waves are considered more important than rising sea level with regard to changes in the dune morphology along the Sefton coast, just north of Liverpool (Pye and Blott, 2008). More frequent and longer lasting extreme tidal levels have occurred in Liverpool Bay since 1990. Mean high water spring tide level reaches 4.17 m above mean tidal level (MTL) at Liverpool and 4.53 m (MTL) at Heysham. In Liverpool Bay MTL is ∼22 cm above Ordnance Datum Newlyn (ODN). At these locations the mean spring tidal range is 8.22 m and 8.47 m,

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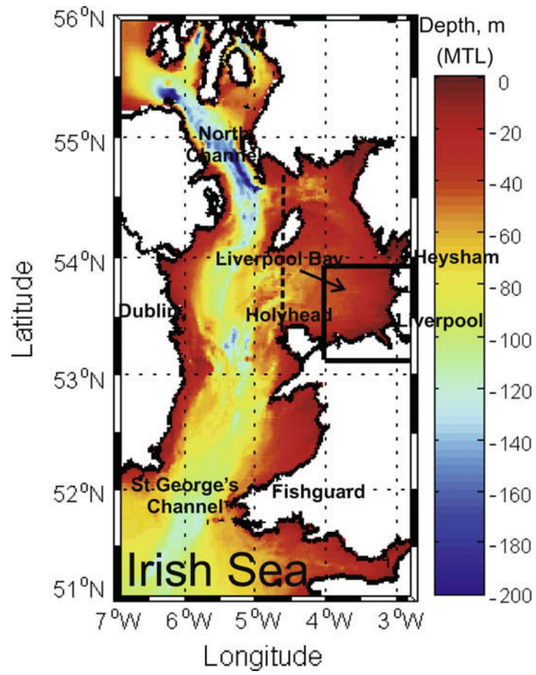

Fig. 1. The model area showing the Liverpool Bay model extent nested within the Irish Sea model. The vertical dashed line defines the boundary of the eastern Irish Sea.

respectively, and the highest astronomical tide is 5.14 m (MTL) and 5.62 m (MTL), respectively (Pye and Blott, 2008). The largest historical surge reached 2.47 m on the 26th February 1990. The five largest observed high water levels occurred in 1977, 1983, 1990 (two events) and 1997. The surge levels during these high waters were between 0.68 m and 1.43 m (Pye and Blott, 2008). A longer data set for Liverpool (Woodworth and Blackman, 2002) found the most extreme high water levels occurred in 1905. Other long-term records reveal that the worst storm to afflict Liverpool occurred at midnight on the 6th January 1839 resulting in significant localized loss. Severe damage due to coastal flooding throughout Lancaster and Merseyside also resulted from a surge driven by SSW winds on the 28th–29th October 1927 (Lamb, 1991). For surges in Liverpool Bay 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). A nested modelling system must therefore be adopted to provide the external surge forcing to the Irish Sea model. Wave conditions may also be critical to coastal flooding, through overtopping of sea defences and wave setup in low-lying areas. The prevailing winds at this site are south-westerly. The largest waves and surges in Liverpool Bay are generated by westerly and northwesterly winds which have the longest fetch up to 200 km (Wolf, 2008; Pye and Blott, 2008). Refraction focuses the waves onto Formby point (Pye and Blott, 2008). Liverpool Bay is sheltered from swell waves from the Atlantic and experiences locally wind-generated sea (Brown and Wolf, 2009). It is therefore less important to include external wave forcing with regard to this region, but this is important in central and southern parts of the Irish Sea, which are exposed to swell from the southwest. The wave height typically exceeds 3 m during 5–10 events per year and exceeds 4 m from 1–5 times per year. The extreme 1 in 50 year wave height is estimated to be 5.5 m (Wolf, 2008). Wind waves are the mechanism through which the wind-stress interacts with the sea surface and the surface roughness is related to wave age. Local conditions may mean that waves are not in equilibrium with the wind so it is of benefit to model surge and waves simultaneously in a coupled modelling system. We use the Proudman Oceanographic Laboratory Coastal Modelling System (POLCOMS) as the surge model and the 3rd-generation spectral Wave Model (WAM). The November 1977 and January 2007 storm surge events have been previously used to calibrate the surge prediction in the eastern Irish Sea using this coupled wave–tide–surge (POLCOMS–WAM) model (Brown and Wolf, 2009).

Within the study area there is a vast and available data set to validate the modelling systems. Met Office 12 km wind data are available to drive the models and tide gauge data around the UK are held at the British Oceanographic Data Centre (BODC) to validate the surge hindcast. Wave data have been recorded in Liverpool Bay since October 2002, and other wave buoy data around the UK are available for the decadal period of interest from the Irish Marine Institute and UK Met Office. The main focus of the modelling will be to assess the impacts of extreme events on the morphology of the Sefton coastline, north of Liverpool.

The aim of this paper is to validate the 11-year hindcast of wave and hydrodynamic conditions around the UK. The modelling methods are presented in Section 2, followed in Section 3 by validation of the coarse and medium resolution model results. An assessment of the wind forcing is also presented in Section 3. The results are presented in Section 4, followed in Section 5 by an estimate of the return period of extreme events along the Sefton coastline. A discussion of the results and methods to assess the model validity is made in Section 6. The conclusions are finally drawn on the validity of the hindcast modelling results in Section 7.

2. Method

The coupled POLCOMS–WAM system has been under development at the Proudman Oceanographic Laboratory for the last 6 years. We apply it here, using a parallel computer system (Ashworth et al., 2004), to the 1.85 km Irish Sea model (Fig. 1).

In order to accurately simulate the waves in the study area, we use the state-of-the-art 3rd-generation spectral Wave Model (WAM, Komen et al., 1994). In the coupled Irish Sea model, a modified version of WAM for shallow water (Monbaliu et al., 2000) has been applied. Following Osuna et al. (2007) WAM simulates the 2D wave spectral evolution considering the energy input by wind, energy dissipation by whitecapping and bottom friction, and non-linear wave–wave interactions. Depth-limited wave-breaking has not been included in this simulation, but will later be included in the Liverpool Bay model application in which drying areas are included. Externally generated waves propagating into the Irish Sea are included by adopting a one-way nested model approach. A 1° northeast Atlantic model provides hourly boundary forcing for the 1.85 km Irish Sea model (Fig. 2). This coarse grid model was driven by six-hourly, ~1° resolution ECMWF (ERA-40, see Uppala et al., 2005) wind data. In the coupled Irish Sea model (detailed in Osuna and Wolf, 2005), WAM uses wind forcing provided via the surge model (see below).

To simulate the tides and surge within the Irish Sea we use the hydrodynamic model POLCOMS (Proudman Oceanographic Laboratory Coastal-Ocean Modelling System), a three dimensional primitive equation numerical model. The model is formulated in spherical polar coordinates on a B-grid with a terrain following (sigma) coordinate system in the vertical (Holt and James 2001). POLCOMS can simulate both the barotropic and baroclinic processes, which arise from the tides, meteorological and riverine forcing (although density effects have not been included here). The turbulence closure scheme (Mellor and Yamada, 1982) has been modified to account for surface wave breaking (Craig and Banner, 1994). For the 11-year hindcast hourly wind and pressure data were provided by the UK Met Office northeast Atlantic

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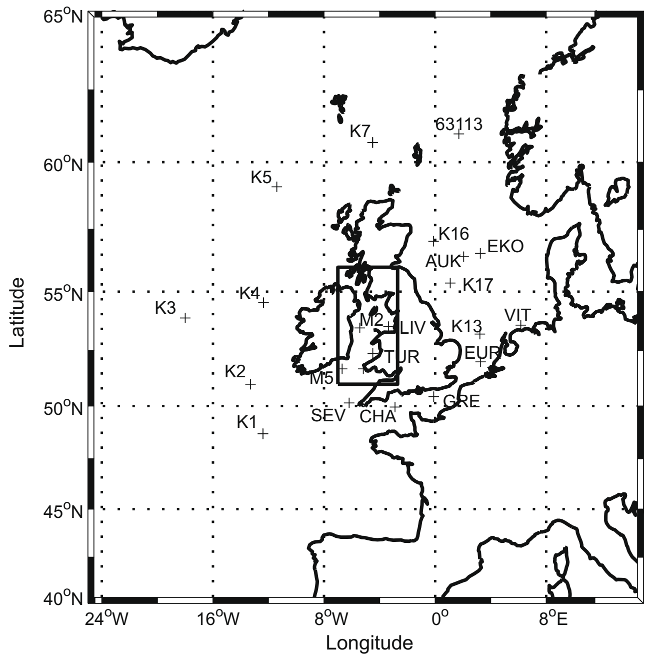

Fig. 2. The nested WAM model domains and the locations of the wave buoys and offshore platforms used for validation. The outer boundary of the figure represents the northeast Atlantic model and the inner rectangular box represents the Irish Sea model boundary.

(mesoscale) model, with a resolution of 0.11° (~12 km). Such a three dimensional model is required to represent the vertical structure of the wind-induced currents (Jones and Davies, 1998) when modelling surge events. To capture the external surge generated outside of the Irish Sea a one-way nested approach (Fig. 3) from the 1/9° by 1/6° (~12 km) operational surge model (run at Proudman) to the 1.8 km POLCOMS Irish Sea model, has been applied. The operational surge model (details of which can be found in Flather, 1994) provided total (tide plus surge) hourly elevation and velocity boundary forcing.

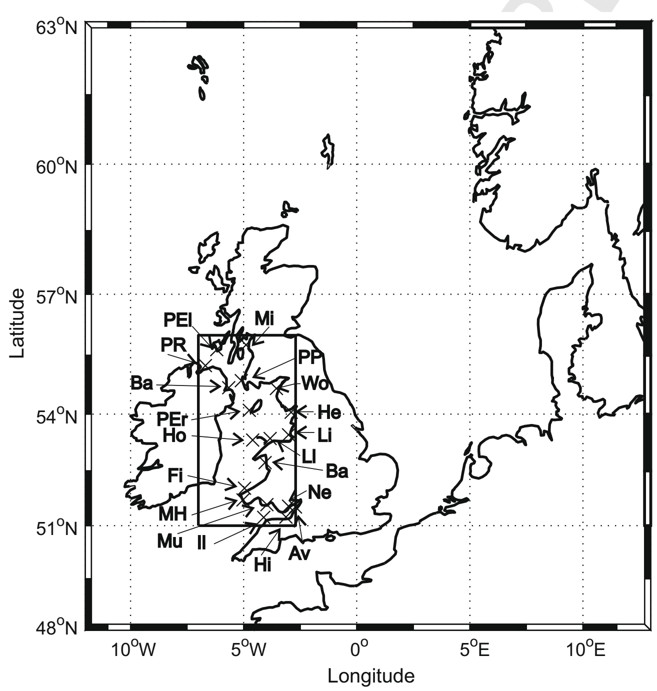

Fig. 3. The Irish Sea POLCOMS model domain (the inner box) nested within the operational surge model domain (the outer figure boundary). The locations of the tide gauge stations are also represented.

For the Irish Sea model wave–tide–surge interaction has been taken into account by two-way coupling of POLCOMS and WAM (Osuna and Wolf, 2005). The coupling is achieved through the surface and bottom stress and wave refraction due to the presence of time varying current and elevation fields (Wolf et al., 2002). Presently, radiation stress is not included within the coupled model, but is under development. The surface stress formulation allows waves to influence the surface roughness in the surge simulation using the method of Charnock (1955), with a wave dependent Charnock parameter (Janssen, 2004). The effect of waves on bottom friction is estimated using the method of Madsen (1994). In the standard POLCOMS–WAM model, the minimum water depth was set to 10 m, but for this research, in which we are focusing on Liverpool Bay, an improved bathymetric data (NOOS data set: Zijderveld and Verlaan, 2004) in the eastern Irish Sea has allowed a 5 m minimum water depth to be applied to this region only. This minimum depth allows resolution of the coastal bathymetric features, but prevents numerical instability due to drying areas occurring in the model domain as a consequence of the tidal variation. This gave improved surge prediction locally within the eastern Irish Sea (Brown and Wolf, 2009). The next step in the model study is planned using a Liverpool Bay model with a 'wetting and drying' scheme, which will eliminate the need to fix a minimum depth.

2.1. Surge definitions

We define the filtered surge as the residual obtained by filtering out periodic signals from the (modelled and observed) total water elevation. To do this the Matlab function 'filtfilt' is used. The M_4 (~6 h) and O_1 (~24 h) tidal periods are used to set the range of cyclic signals that are to be removed in the filtering process. This filtered surge is mostly the result of the meteorological event alone, the tide and any tide–surge interaction or wind periodicity with tidal frequency is removed. However, in the eastern Irish Sea tide–surge interaction significantly modifies the surge (Brown and Wolf, 2009), causing the largest peaks in surge to avoid tidal high water (Woodworth and Blackman, 2002). This modification has significant effect on both the timing and size of the peak surge (Horsburgh and Wilson, 2007) and is not accounted for in the filtered surge. Thus, in addition to the filtered surge, we also look at the additional water elevation on top of the predicted tidal elevation, commonly known as the surge residual. We apply the Proudman Oceanographic Laboratory Coastal Observatory tidal analysis program (Titan) to the total elevation to 'de-tide' the modelled prediction. The program is based on the Task 2000 package from the National Tide and Sea Level Facility (see http://www.pol.ac.uk/ntslf/software.html). This extracts surge residuals that may be compared with those provided as part of the tide gauge data set. Using tidal analysis is also less computationally expensive than generating an 11-year hindcast of the modelled tide. Tide–surge interaction modifies both the tidal and surge components of the total water level (Horsburgh and Wilson, 2007). The total elevation is therefore not just the addition of the surge due to the meteorological event and the tide. We cannot therefore subtract the filtered surge from the total water level to obtain the modelled tide as the resultant would leave the modelled tide, perturbed by the presence of the surge, plus the tidally modulated surge component.

2.2. Error metrics

Our data consists of total water elevation, surge and wave parameters with differing ranges. We aim to systematically assess the accuracy of the model variables. We do not use the typical

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root-mean-square error, since it does not provide a fair comparison between variables. Metrics that compare the size of the error with the range/variability in the data allow a universal comparison to be made. Allen et al. (2007) and Holt et al. (2005) present a set of error statistics to use for complex 3D modelling systems. We use two of these measures of accuracy to validate the 11-year model predictions compared to the data. In the following equations, M represents the model prediction, D represents the measured data and N is the number of data points in the 11-year hindcast period. The first measure is the *Percentage Model Bias* (*Pbias*). This provides a measure of whether the model is systematically under- or over-estimating the measured data. This is achieved by normalizing the sum of the model error by the data:

$$Pbias = 100\frac{\sum_{n=1}^{N}(D_n - M_n)}{\sum_{n=1}^{N}D_n} \quad (1)$$

The better the model the closer the value is to zero. The level of accuracy is quantified as follows $|Pbias| < 10\%$ excellent, 10–20% very good, 20–40% good, >40% poor. Although Eq. (1) works well for parameters that always maintain a positive value (e.g. H_s and T_p), it can be problematic for parameters which oscillate around zero (e.g. tides and surge). For the validations made here we modify Eq. (1) to be:

$$Pbias = 100\frac{\sum_{n=1}^{N}(D_n - M_n)}{\sum_{n=1}^{N}|D_n|} \quad (2)$$

Otherwise, the summation of the data can tend towards zero creating a large *Pbias*, even when the model is performing well. The true systematic under- or over-prediction of the model is still correctly calculated.

The second metric is the *Cost Function* (*CF*). This non-dimensional measure quantifies the 'goodness of fit' between the model and the observations. It is the ratio of model mismatch to the variance (standard deviation of the data, σ_D) in the data:

$$CF = \sqrt{\frac{1}{N\sigma_D^2}\sum_{n=1}^{N}(M_n - D_n)^2} \quad (3)$$

The model performance is classified as follows: $CF < 1.0$ the model has a change of predicting skill and <0.4 implies variables are well modelled.

3. Model validations

In this section, we present the validation of the 11-year nested model hindcast. The POL operational surge model is known to give accurate surge predictions (Flather, 2000), and is regularly validated (monthly) with data from the UK national tide gauge network (see http://www.pol.ac.uk/ntslf/surgemonthlyplots) for operational use. We therefore concentrate on validation of the coarse WAM model of the northeast Atlantic and the medium resolution POLCOMS–WAM coupled model of the Irish Sea. The data selected to validate WAM are given in Table 1 and the wave buoy and platform locations are shown in Fig. 2. The wave parameters are defined as follows: H_s is the significant wave height, T_z is the zero-crossing period and T_p is the peak period. H_s ($H_{m0} = 4\sqrt{m_0}$) and T_z ($T_{m02} = \sqrt{m_0}/\sqrt{m_2}$) are both derived from spectral moments (m_k, Krogstad et al., 1999). T_p is a rather unstable parameter compared with T_z, because the peak can irregularly change frequency for multi-modal spectra (Krogstad et al., 1999). Unfortunately, T_p is often the only available observed wave period parameter (Table 1) and therefore model validation can show the model to be less accurate than if T_z was used. This is highlighted in Table 3 by $CF < 1$ for locations at which T_z was available and $CF > 1$ for locations at which T_p was available.

Table 1
Available wave data used to validate the 11-year wave hindcast.

Location	Data available	Data used
K2	1991–2007	H_s, T_p
K5	1994–2007	H_s, T_p
63113	1998–2007	H_s, T_p
K17	1995–2005	H_s, T_p
Seven Stones LV (SEV)	1995–2004	H_s, T_p
M5	2004–2007	H_s, T_p
Channel LV (CHA)	1996–2005	H_s, T_p
Greenwich (GRE)	1994–2005	H_s, T_p
K1	2000–2004	H_s, T_p
K3	2000–2004	H_s, T_p
K16	1995–2003	H_s, T_p
Turbot Bank (TUR)	1998–2005	H_s, T_p
Ekofisk (EKO)	2003–2004	H_s, T_z
K13	1996–2001	H_s, T_z
Euro (EUR)	1996–2001	H_s, T_z
VTN SON (VTN)	1996–2001	H_s, T_z
AUK	2000–2003	H_s, T_p
K4	2000–2004	H_s, T_p
K7	2000–2004	H_s, T_p
M2	2001–2007	H_s, T_p
Aberporth (ABE)	1994–2005	H_s, T_p
Liverpool Bay (LIV)	2002–2007	H_s, T_p

Coastal tide gauges around the UK were used to validate POLCOMS; the positions of the chosen stations are shown in Fig. 3. The periods for which data were available at each tide gauge location are given in Table 2. For POLCOMS we validate not only the total water elevation (MTL) but also the different surge components defined in Section 2.1.

3.1. Northeast Atlantic (NEA) WAM validation

The 11-year (1996–2006) northeast Atlantic WAM model hindcast is compared with wave data collected around the UK. Not all of the locations within the Irish Sea are used in the validation since the model is too coarse to resolve the details of the Irish Sea. Table 3 gives the performance metrics for the model.

The *Pbias* results (Table 3) show the model simulation is good and even very good at a few locations, which are often comparatively close to the coast. We find the model is better at simulating T than H_s (for this metric) at most locations. Excellence is also achieved more frequently in T than H_s. For H_s the model generally under-predicts the measured data, while for T the model often over

Table 2
Available total water elevation data used to validate the 11-year hydrodynamic hindcast.

Location	Data available
Port Rush (PR)	1996–2007
Port Ellen (PEl)	1996–2007
Millport (Mi)	1996–2007
Bangor (Ban)	1996–2007
Port Patrick (PP)	1996–2007
Workington (Wo)	1996–2007
Port Erin (PEr)	1998–2007
Heysham (He)	1996–2007
Liverpool (Li)	1996–2007
Llandudno (Ll)	1996–2007
Holyhead (Ho)	1996–2007
Barmouth (Bar)	1996–2007
Fishguard (Fi)	1996–2007
Milford Haven (MH)	1996–2007
Mumbles (Mu)	1997–2007
Newport (Ne)	1996–2007
Avonmouth (Av)	1996–2007
Hinkley Point (Hi)	1996–2007
Ilfracombe (Il)	1996–2007

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Table 3
Performance metrics for the NEA WAM model 11-year hindcast. The locations are given in Fig. 2, H_s = significant wave height and T = wave period either the peak (T_p) or zero up crossing period (T_z) depending on the data available, given in Table 1.

Location	*Pbias* H_s (%)	*Pbias T* (%)	*CF* H_s	*CF T*
K2	−28.7737	11.7117	0.6856	1.1017
K5	−28.2662	13.7498	0.6454	1.1793
63113	−18.4596	23.0821	0.4907	1.5174
K17	−28.1119	11.4587	0.6557	1.2439
Seven Stones LV (SEV)	−11.5019	−8.8817	0.5720	1.3492
M5	−30.8981	21.1849	0.6515	1.5994
Channel LV (CHA)	−9.3614	−15.0275	0.4967	1.4378
Greenwich (GRE)	11.7389	−8.5982	0.5623	1.4518
K1	−28.4246	10.2943	0.6783	1.1039
K3	−28.5078	6.8208	0.7826	1.0467
K16	−28.0855	10.6327	0.6293	1.1952
Turbot Bank (TUR)	−27.6989	4.9711	0.5980	1.4722
Ekofisk (EKO)	−11.8922	−8.3807	0.4038	0.6190
K13	−13.5950	−10.7338	0.4481	0.8697
Euro (EUR)	−12.9723	−6.2893	0.5136	0.9678
VTN SON (VTN)	33.8081	−1.4307	0.8893	0.8446
AUK	−17.4478	22.6791	0.4630	1.4738
K4	−28.1923	11.1235	0.6618	1.0807
K7	−21.7120	14.5545	0.8966	1.3760

predicts the measured data (a result of the inverse relation between the two parameters). This is likely to be due to the low resolution (in space and time) of the wind forcing. The *CF* metric confirms the model performance to have acceptable predictive capability for H_s and T_z, but not T_p. The problem with using T_p was discussed earlier in Section 3. The best model performance based on this metric occurs within the English Channel and at certain locations across the North Sea.

3.2. Irish Sea (IRS) POLCOMS–WAM validation

The Irish Sea POLCOMS–WAM model has been validated at 19 tide gauges (Table 4) and five wave buoys (Table 5). The metrics used to assess the model's performance show the model to be very good to good across this region.

We find POLCOMS does not consistently under- or over-estimate the water level across the domain, unlike WAM that constantly under-predicts H_s across the region. This under-prediction could be related to the boundary forcing (negative *Pbias* values for K1, K5, M5, Turbot Bank (TUR) and Seven Stones LV (SEV) in

Table 5
Performance metrics for the IRS WAM model 11-year hindcast. The locations are given in Fig. 2, H_s = significant wave height and T_p = peak wave period.

Location	*Pbias* H_s	*Pbias* T_p	*CF* H_s	*CF* T_p
Aberporth	−23.4989	42.4145	0.6043	2.2750
Liverpool Bay	−37.9187	44.1666	0.6892	4.0571
M2	−22.9647	19.2718	0.7314	2.8791
M5	−14.3261	23.4532	0.4782	1.5315
Turbot Bank	−29.6608	12.2911	0.5641	1.4488

Table 3) or due to errors in the wind forcing. The POLCOMS model performs with a lower error than WAM when comparing the metrics for total elevation and wave height, with the exception of Port Ellen. At this location the tidal range is noticeably over-predicted with much higher high water elevation being predicted. Removing the tidal component from the total water level to obtain the surge improves the validity at this location. This is likely to be due to poor resolution of the coastal bathymetry at this position, especially within the operational model forcing the boundary, which is close to this position. The surge predictions are less accurate than the total water elevation. This comes about due to model inaccuracy (a limited number of tidal constituents) in the tidal forcing. Generally, for POLCOMS $|Pbias| < 30\%$ and often $|Pbias| < 10\%$ occurs with $CF < 0.6$, making this a very good model hindcast. Again WAM provides a good model hindcast in general with $|Pbias| < 38\%$ with $CF < 0.7$ when using H_s alone represent the model. Section 3 discusses why T_p can be unreliable for model validation.

3.3. Wind validation in the Irish Sea (IRS)

The accuracy of any model is dependent on the quality of the input data. We validate the mesoscale wind forcing for the IRS model using data from the Hilbre met station, situated at the mouth of the Dee Estuary (53°22.94′N, 3°13.60′W). The data are available from 16th April 2004 so only data between this date and 1st January 2007 are validated. The mesoscale winds (~12 km) are interpolated by POLCOMS onto the Irish Sea model grid (~1.8 km). For the wind speed the $Pbias = -38.5044\%$ and $CF = 0.9385$ and for the wind direction $Pbias = -21.7814\%$ and $CF = 1.9721$. The model wind speed is classified by the *CF* metric to be simulated, while the direction is questionable. The *Pbias* metric shows the winds are lower than that observed. This may explain why the (locally

Table 4
Performance metrics for the IRS POLCOMS model 11-year hindcast. The locations are given in Fig. 1, T = total water elevation (MTL), TS = tide–surge residual and FS = filtered surge residual.

Location	*Pbias* T	*Pbias* TS	*Pbias* FS	*CF* T	*CF* TS	*CF* FS
Port Rush (PR)	−25.7953	−3.9721	−58.4782	0.6475	0.5160	0.7014
Port Ellen (PEl)	66.5815	−17.5542	83.9508	1.3284	0.5328	0.9063
Millport (Mi)	6.4545	−8.2903	30.6919	0.3201	0.5372	0.4517
Port Patrick (PP)	−9.3815	−21.3442	−51.2732	0.2545	0.5454	0.5925
Bangor (Ban)	5.0557	−13.3765	28.9313	0.3008	0.5245	0.4648
Port Erin (PEr)	−10.4704	17.6140	−75.4464	0.1812	0.6026	0.7886
Workington (Wo)	1.4315	−39.7164	15.6042	0.1312	0.7230	0.3988
Heysham (He)	−6.5620	−30.5616	−71.2734	0.3062	0.8533	0.7581
Liverpool (Li)	−2.2495	−10.7752	−26.7623	0.0900	0.6153	0.5179
Llandudno (Ll)	3.6964	6.7715	42.5507	0.1139	0.6086	0.5608
Holyhead (Ho)	−6.7683	−17.7237	−60.6046	0.1380	0.5577	0.06307
Barmouth (Bar)	−3.6900	−20.5419	−23.8174	0.1645	0.6034	0.4356
Fishguard (Fi)	−14.9663	−52.3491	−89.4927	0.2095	0.7569	0.9917
Milford Haven (MH)	−6.1786	−39.6882	−64.1926	0.1815	0.7408	0.6850
Mumbles (Mu)	−8.4916	18.1895	−91.6339	0.1642	0.6838	1.0459
Newport (Ne)	−2.0904	−9.2842	−33.2298	0.1279	0.8226	0.5252
Avonmouth (Av)	−1.0135	−11.8201	−17.3332	0.1872	0.8666	0.5841
Hinkley Point (Hi)	−8.7223	−7.4704	−95.5093	0.1253	0.7630	1.3735
Ilfracombe (Il)	3.9622	−22.8961	5.0495	0.1588	0.7397	0.4189

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generated) wave heights are generally under-predicted in the Irish Sea. However, the surges seem well predicted. Further investigation of the strength and duration of the wind on wave and surge generation is therefore required.

4. Results

Here, we present the statistics of the occurrence of extreme wave and surge events. The 11-year hindcast and available data sets have been used to determine the most extreme peak surge elevations, high water (HW) levels and wave heights in Liverpool Bay. Patterns in the extreme event over this 11-year period are also investigated, but the length of the studied period prevents any significant long-term trends being determined. We investigate the observed surge levels, the filtered surge residual and HW levels at two tide gauge locations, namely Heysham and Liverpool. These adjacent gauges encompass the full extent of the Sefton coastline, which is the focus of interest of the research programme. The surge residual allows analysis of the additional water level on top of the predicted tide due to a storm event interacting with the tide, whereas the filtered surge allows analysis of the impact of meteorological forcing at the two locations. The waves are analysed at the wave buoy location within Liverpool Bay.

We find that along the Sefton coast the extreme surge elevations due to meteorological forcing (filtered surge) can reach 1.2 m at Liverpool and 1.4 m at Heysham (Fig. 4). When tide–surge interaction is accounted for the peak surge increases and the extremes can reach 2.3 m at Liverpool and 2.4 m at Heysham (Fig. 5). The most extreme high water levels are not significantly greater than a typical spring tide HW of ~5 m (MTL) at Liverpool, since the surge peak avoids HW due to tide–surge interaction. During this 11-year period an extreme HW can reach 5.6 m (MTL) at Liverpool, while at Heysham, where the tidal range is larger with typical spring HW levels of 5.4 m (MTL), extremes can reach 6.2 m (MTL) (Fig. 6). In addition to the increased water levels during a storm event, extreme waves of up to 5.6 m (MTL) were generated in Liverpool Bay (Fig. 7).

Fig. 8 shows periods when extreme high water levels (>5 m) at the ports coincided with extreme offshore waves (>2 m) at the wave buoy location. The symbols for wave height (H_s) and HW vertically align for each joint event. There are more cases for Heysham since the tidal range is larger than at Liverpool, so high water more frequently exceeds 5 m. If major wave conditions and water levels occur simultaneously at Liverpool the same is often true for Heysham (8 out of 13 events). Whether both ports simultaneously experience major events for a given storm depends on the storm

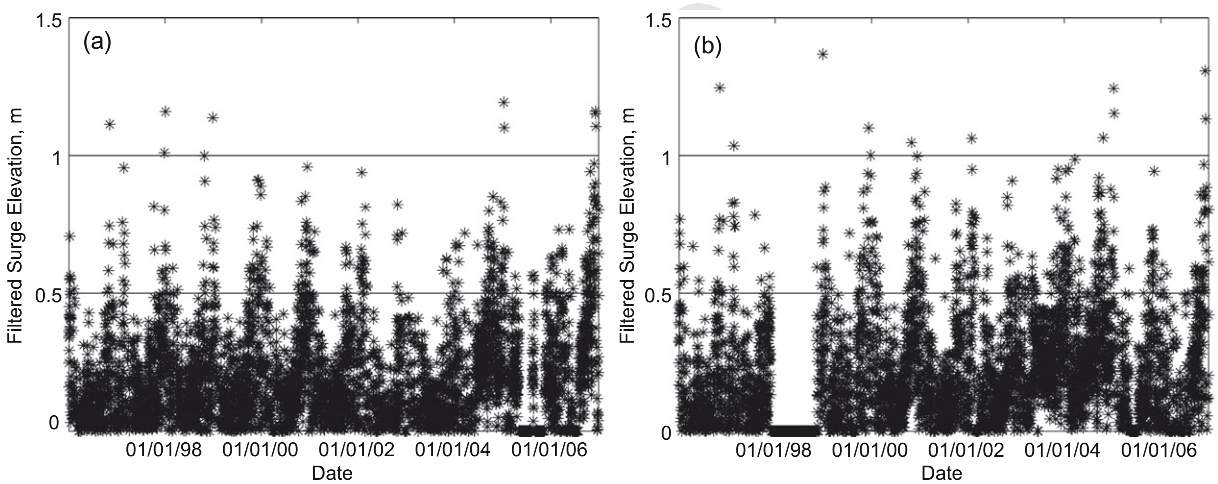

Fig. 4. The (positive) peak filtered surge residuals, due to the meteorological forcing alone, over the past 11 years, obtained from tide gauge data at (a) Liverpool and (b) Heysham.

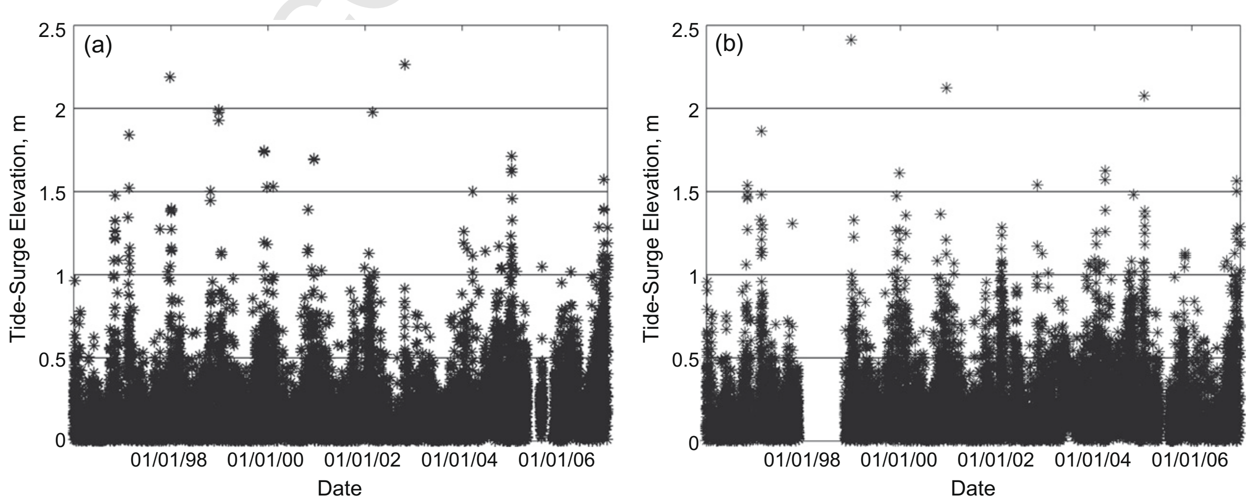

Fig. 5. The (positive) peak surge residuals, due to tide–surge interaction, over the past 11 years, obtained from tide gauge data at (a) Liverpool and (b) Heysham.

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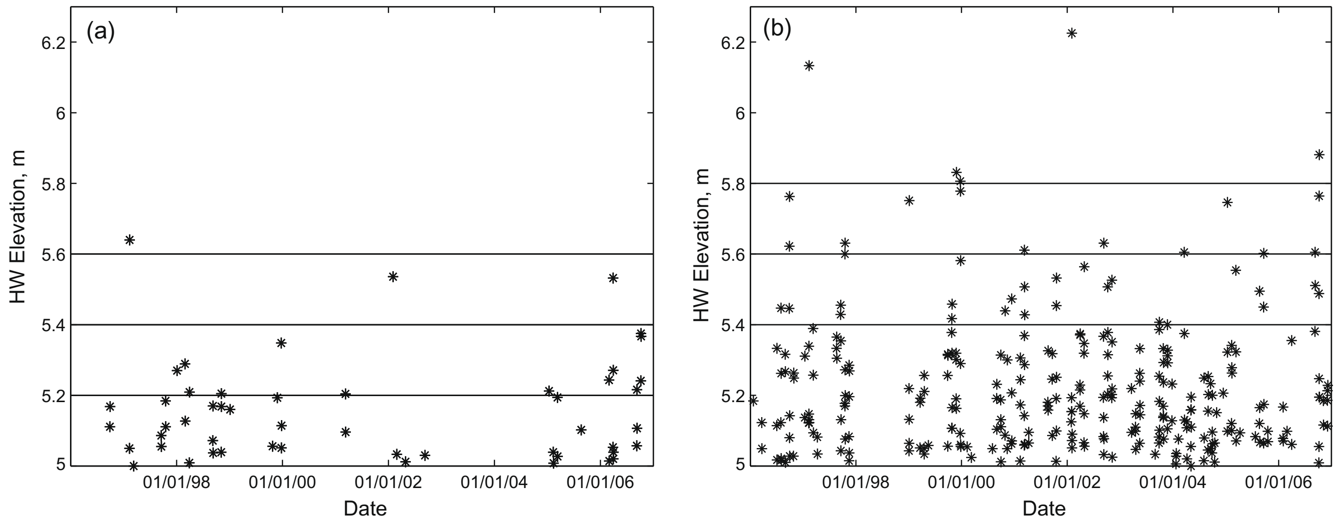

Fig. 6. High water elevations (above MTL) greater than 5 m over the past 11 years, obtained from tide gauge data at (a) Liverpool and (b) Heysham.

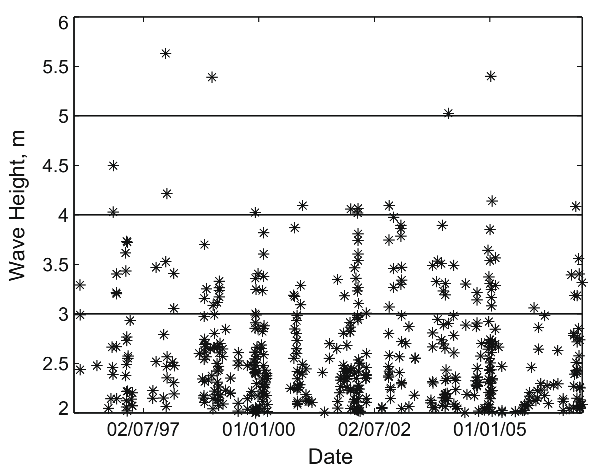

Fig. 7. Wave height greater than 2 m over the past 11 years, obtained from model hindcast data due to limited observations (02/10/02 onwards).

track. This is being investigated further following Lennon (1963). When extreme coincidental HW and waves occur for both ports these cases cause the slightly larger '■' to be covered by a '□' in Fig. 8, creating a thicker outline, '□'. For Liverpool 13 major joint events occur and at Heysham 23 major joint events occur over the 11-year period investigated. Although Heysham experiences higher water levels the offshore waves during these high water conditions are within the same range as those when Liverpool experiences major water levels. These joint major conditions only occur between October and March. Over the 11-year period a 'V'-shaped pattern is evident (with peaks at the start and end of the study period and a trough early in 2003) in the data, more so for water levels than wave heights. The years 2001 and 2003 are the only years when no simultaneous major events happen. This pattern is not a consequence of the 18 year nodal tide. The tidal maximum occurred in 1997 and will occur again in 2015 and the tidal minimum occurred in 2006 (Pugh, 2004). The trend could be linked to decadal trends in storm track position and the North Atlantic Oscillation (see Woodworth et al., 2007), but requires further study and a longer model hindcast.

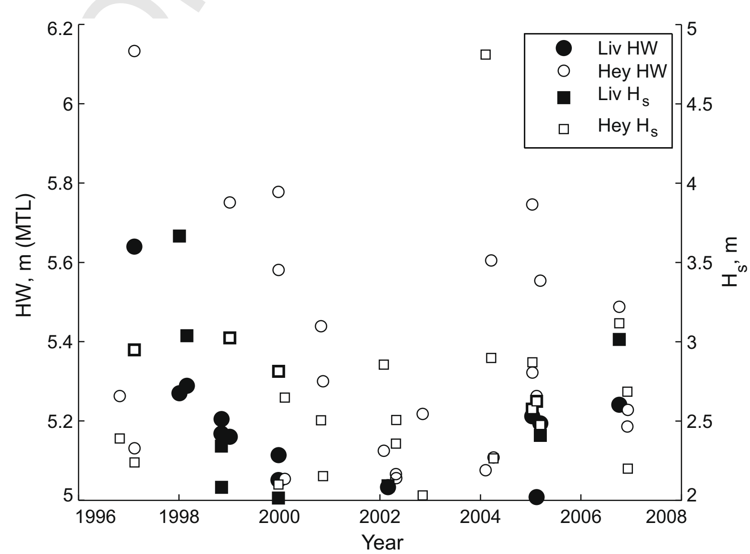

Fig. 8. Periods of coincidental extreme water levels and wave events. Observed high water (HW) levels exceeding 5 m at Liverpool (Liv) and Heysham (Hey), with modelled offshore wave heights (H_s) exceeding 2 m at the wave buoy location, coincidental with HW at one of the ports.

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Next we investigate the frequency of extreme events over the past decade. For each year the peak surge level and number of occurrences the peak of a surge event exceeds 0.5 m is given in Table 6. No obvious pattern exists over the past decade (Table 6, Figs. 4–6). However, the greatest occurrence of large surges (>0.5 m) occurred in the second half of the decade. The largest peaks are more evenly distributed across the years. Neither end of this coastline is consistently experiencing larger tide–surge residuals than the other end, although there is a slight bias for surge residuals greater than 0.5 m to occur more frequently at the Heysham (northern) end of the coastline. This location has also experienced the largest surges over the last decade. At Heysham the filtered surge residual is often greater and more frequently above 0.5 m compared with Liverpool; this suggests extreme wind events have a more significant impact on the water level at Heysham.

Over the last 11 years the occurrence of surges and HW greater than specified levels is given in the following Tables 7–9. Table 7 shows surges > 1 m, while Table 8 shows surges < 1 m and Table 9 shows total water level (MTL). Often the frequency of separate surge events above an extreme specified value is less at Heysham than at Liverpool (Table 7). Table 8 shows that the frequency of smaller filtered surges is greater at Heysham than Liverpool. Heysham has a greater tidal range than Liverpool so achieves higher HW levels (Table 9). The three most extreme HW levels for Liverpool (>5.2, >5.4 and >5.6) and Heysham (>5.6, >5.8 and >6.0) are generally achieved with a similar number of occurrences, a consequence of the locations not experiencing independent events.

Table 10 shows how frequently the modelled peak of separate wave events in Liverpool Bay exceeds 3 m and the peak wave height achieved each year. The most extreme annual wave event often exceeds 4.0 m and is often (6–18 times per year) greater than 3.0 m. In 2002 the greatest number of extreme events occurred, while in 1997 the largest wave height was reached. The data implies that there is some inter-annual variability in wave intensity (Fig. 7 and Table 10) with peak conditions exceeding 5 m for two consecutive years twice over the study period. A longer time series of data is required to determine any pattern. In Table 11 we show that waves greater than 4 m have been fairly infrequent over the past decade, whereas 3.0–4.0 m waves are quite common.

5. Return periods

We use the General Extreme Value (GEV) method (see Coles, 2001) to determine the return periods of extreme events in Liverpool Bay. Table 12 shows the estimated high water levels and wave heights that are likely to be exceeded once for the given return period in Liverpool Bay. We analyse observed high water levels to obtain an idea of the most extreme total water level along the Sefton coast and the wave height in Liverpool Bay as this will

Table 7
The number of times the observed peak surge residual exceeds the levels specified in the table at Liverpool and Heysham.

Surge level	Liverpool	Heysham
>1.0 m	100	99
>1.5 m	19	11
>1.7 m	10	4
>1.9 m	6	3
>2.1 m	2	3

Table 8
The number of times the observed peak filtered surge residual exceeds levels specified in the table at Liverpool and Heysham.

Filtered-surge level (m)	Liverpool	Heysham
>0.5	313	425
>0.7	73	117
>1.0	9	12

Table 9
The number of times the observed high water level (MTL) exceeds levels specified in the table at Liverpool and Heysham.

HW level (m)	Liverpool	Heysham
>5.0	50	289
>5.2	16	125
>5.4	3	40
>5.6	1	17
>5.8	0	5
>6.0	0	2

Table 10
The peak annual significant wave height and the number of events the wave height exceeds 3.0 m from model hindcast at the Liverpool wave buoy location.

Year	Liverpool Bay wave height	
	Peak	Occurrence > 3.0 m
1996	4.50	6
1997	5.63	7
1998	5.39	7
1999	4.02	11
2000	4.09	10
2001	4.05	3
2002	4.09	18
2003	3.90	12
2004	5.03	9
2005	5.46	11
2006	4.09	7

Table 6
The peak annual surge and filtered surge residuals and the occurrence of surge events with peak greater than 0.5 m when observations are available at Liverpool and Heysham.

Year	Liverpool surge residual		Liverpool filtered-surge residual		Heysham surge residual		Hesysham filtered-surge residual	
	Peak	Occurrence > 0.5 m	Peak	Occurrence > 0.5 m	Peak	Occurrence > 0.5 m	Peak	Occurrence > 0.5 m
1996	1.48	52	1.11	13	1.54	52	1.25	23
1997	2.19	66	1.01	18	1.86	70	1.04	14
1998	1.99	91	1.16	20	2.41	14	1.37	5
1999	1.75	108	0.91	31	1.61	118	1.10	42
2000	1.70	107	0.96	34	2.12	137	1.05	47
2001	1.04	55	0.72	15	1.06	65	0.87	36
2002	2.26	83	0.94	27	1.54	140	1.06	47
2003	0.76	21	0.63	5	1.07	111	0.95	49
2004	1.50	161	0.85	50	1.62	256	1.06	86
2005	1.71	90	1.19	23	2.08	88	1.24	31
2006	1.57	224	1.16	77	1.56	135	1.31	45

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Table 11
The number of occurrences the modelled peak significant wave height (H_s) for an event exceeds certain levels in Liverpool Bay.

H_s (m)	Liverpool
>3.0	101
>3.5	40
>4.0	15
>5.0	4

lead to defence overtopping, especially if combined with extreme water levels. These estimated levels give an idea of the likelihood of extreme present day events causing coastal inundation due to surges increasing the total water level and wave overtopping. We see that the 100-year peak total water is 0.8–1 m above the typical extreme annual storm level. The 100-year extreme wave height is 7.3 m, 3.2 m greater than the typical extreme annual storm level. Over a long-term (100-year period) wave over topping due to extreme waves is more likely to cause coastal flooding compared with extreme total water levels, as significant increases in the extreme wave height occur with a relatively low return period. Large annually occurring events are considered to have total water levels above 5.2 m for Liverpool and of 5.7 m for Heysham and/or wave heights exceeding 4 m, i.e. a 1 year return period. Extreme events are defined by water levels and wave heights that exceed the 5 year return period, given in Table 12.

The joint probability of major water levels and corresponding wave conditions in Liverpool Bay is investigated, using the 11-year data sets. Over this period data were available for 6919 high waters at Liverpool and for 6306 high waters at Heysham. The modelled offshore wave heights at the time of every observed high water during the study period are plotted for water levels at Liverpool (Fig. 9) and Heysham (Fig. 10). The actual wave heights at the coast will be lower than those presented as the waves will shoal as they propagate towards the coast away from the wave buoy location. Using the JOIN-SEA software, freely available from HR Wallingford, the joint probability of waves and water levels was determined using the method described by Hawkes (2000). The contours of equal joint exceedance are shown in Figs. 9 and 10 for different return periods. The worst case water level – wave height pairs are data points that fall towards the top right corner in figures, i.e. the points with large wave heights (>4 m) combined with high water levels ($\geqslant$5 m). At Heysham the worst case pairs are (4.90, 5.40) and (5.07, 4.81) (Fig. 10). At Liverpool the worst case pairs are slightly lower, taking values of (4.82, 5.40) and (4.50, 4.81) (Fig. 9). For both locations these worst case pairs have a return period of over 50 years.

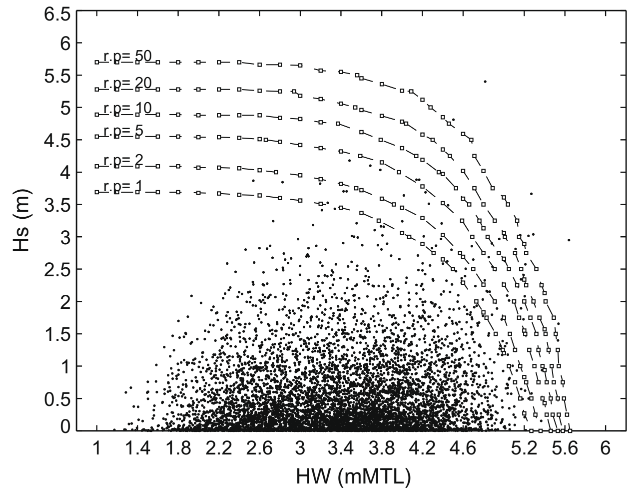

Fig. 9. Wave heights (H_s) during high water (HW) at Liverpool during 1996–2006. The contours show the equal joint exceedance probability for a range return periods (r. p.), predicted by the JOIN-SEA software.

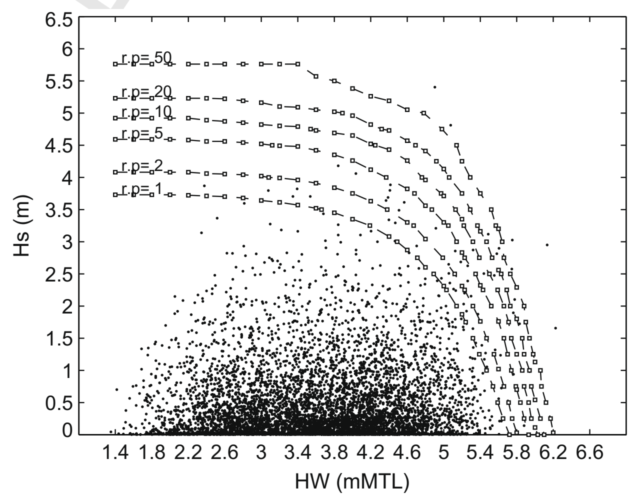

Fig. 10. Wave heights (H_s) during high water (HW) at Heysham during 1996–2006. The contours show the equal joint exceedance probability for a range return periods (r.p.), predicted by the JOIN-SEA software.

6. Discussion

A nested POLCOMS–WAM modelling system has been run for an 11-year period to allow long-term validation of the models and provide model data to investigate storm surge and wave events in the eastern Irish Sea.

Our results show that T_p is not a good parameter to use to validate a model. WAM provides good H_s and T_z simulations. It is therefore unlikely that T_p is invalid, but instability in this parameter creates significant discrepancy between model hindcast and

Table 12
The return periods for high water (HW) levels (MTL) at Liverpool and Heysham along the Sefton coast and for wave heights (H_s) at the wave buoy location in Liverpool Bay.

Return period (years)	Liverpool		Heysham		Wave buoy	
	HW level (m)	Standard error (m)	HW level (m)	Standard error (m)	H_s (m)	Standard error (m)
1	5.22	0.03	5.65	0.05	4.09	0.14
2	5.29	0.05	5.79	0.07	4.49	0.21
5	5.41	0.09	5.97	0.13	5.05	0.38
10	5.52	0.14	6.12	0.18	5.51	0.57
20	5.64	0.23	6.27	0.25	6.01	0.82
25	5.69	0.26	6.32	0.28	6.18	0.92
50	5.84	0.40	6.49	0.37	6.72	1.27
100	6.01	0.59	6.66	0.48	7.30	1.71
1000	6.79	1.77	7.28	1.00	9.56	3.89

observation. Due to the lack of T_z data we will base our assumptions about the accuracy of the wave model on H_s. Validation of the coarse northeast Atlantic (NEA) WAM model has shows that the model 'goodness of fit', quantified by *Pbias*, is 'very good' to 'good' around the UK, although, there is a systematic under-prediction of wave height. The models hindcast capability is good, as quantified by *CF*. Therefore we find this model to have adequate resolution to provide boundary forcing for the Irish Sea model. Improved wind forcing (in time and space) and bathymetry (taken as constant 600 m in the NEA model) would help to reduce the systematic under-prediction in H_s and over-prediction of T, shown in the *Pbias* metric.

For the Irish Sea (IRS) the POLCOM-WAM model performs to a 'very good' to 'good' standard when forced by the NEA model and mesoscale wind. Improvements in the resolution of the meteorological forcing in both the IRS and NEA model would probably further improve the model's performance. Errors in the wind forcing account for some of the discrepancies between the model simulation and the observations, for example, the frequent under-prediction of the wave height. For POLCOMS, the *Pbias* suggests that the filtered surge is often poorly simulated. This is a result of the filtered surge taking low (often <1 m) elevation values. Any error in the modelled tide or meteorological forcing carried through into the filtered surge will therefore make the error in this variable look large in comparison to its size.

Surges >0.5 m in the eastern Irish Sea may have become more frequent over the last decade (Table 6), but the annual peak in surge does not seem to be getting more intense. Changes in the wind pattern will have a major influence on the filtered surge and wave events. The time of the wind event relative to the phase (spring-neap) and stage (HW–LW) of the tide will determine the size of the tide–surge residual. For Liverpool the risk of flooding occurs when the total water level exceeds 5.63 m. This is the level reached during the November 1977 surge, which caused significant damage to coastal defences along the Liverpool and Sefton coast. The water level gradient is proportional to the wind stress divided by the water depth. Consequently, during LW spring tides the largest local surge residual will be generated but the total water level compared to spring HW level will be insignificant, and thus not pose a flood risk. During HW spring tide the wind will have least effect locally and the tide–surge interaction can act to reduce the surge at the peak of the tide. Hence, the likelihood of water levels significantly exceeding the spring HW level is low. For example, at Liverpool a 2.26 m surge residual occurred on the 27/10/02 and a 2.12 m surge residual occurred on the 24/12/97. The peak HW levels during these events were 3–3.7 m (MTL), which does not pose a flood risk. The greatest HW level of 5.64 m (MTL) at Liverpool occurred on the 10/02/97. The surge level at this time was 0.61 m and the peak in the surge level was 0.76 m, 30 min after HW. Interestingly, the filtered surge at the time of HW was 0.755 m and at the time of the peak in tide–surge residual it was 0.758 m. This demonstrates the tide–surge interaction during the largest HW levels acts to reduce the magnitude of the wind driven (filtered-) surge on the total water level.

Heysham experiences more frequent smaller (<1 m) surges than Liverpool (Table 6–8, Fig. 5) and fewer extreme (>1 m) surges. However, when a large surge does occur it is often more intense than those experienced at Liverpool. Heysham is more exposed to surge-generating wind events (more frequent filtered surge events >0.5 m) than Liverpool, but the larger tidal range interacting with the surge seems to reduce the frequency of extreme surge events (>0.5 m) and extreme HW (>5.2 m, MTL) events. Although infrequent, when the peak surge occurs during lower water levels, the larger tidal range at Heysham is the cause of the more intense surge compared with Liverpool. Finally, the larger tidal range means the maximum HW levels are greater at Heysham than Liverpool.

By classifying extreme events as those with a 5 year return period, we find that for the Sefton coastline a 5.05 m offshore wave height with extreme high water levels of 5.98 m at Heysham and 5.41 at Liverpool is considered extreme (Table 12). Every year it is likely that a wave height of 2.6 m will coincide with a high water level of 4.4 m at Liverpool (Fig. 9) and 4.8 m at Heysham (Fig. 9). An example of the worst joint (5 year) extreme conditions is an offshore wave height of 3.0 m coinciding with high water of 4.7 m at Liverpool (Fig. 9) and an offshore wave height of 3.25 m coinciding with high water of 5.1 m at Heysham (Fig. 10).

This study shows that in the eastern Irish Sea (which has a macro-tidal range) the surge residual is a better measure for flood risk management compared with the filtered surge. Here, the tide can significantly enhance or reduce the surge due to the meteorological forcing alone. The surge residual represents the additional water level that will be experienced on top of the tidal level, hence allowing assessment of the flood risk posed at HW due to enhanced water levels.

The medium resolution Irish Sea model applied here has proven to be a valid modelling system for the long-term. The 11-year hindcast data will be used to investigate the meteorological conditions that have caused the most extreme surges and waves within the eastern Irish Sea over the past decade. The worst storm events in this region will be isolated and the model data used to provide boundary forcing for a high resolution (185 m) Liverpool Bay model. At this resolution additional physics will be included to investigate these isolated extreme events that pose flood risk along the Sefton coastline. For example, 'wetting and drying' of tidal flats, wave setup, effects of density stratification on the surge events and the resulting morphological change will be included.

Finally, we discuss the metrics used to validate the model. We find that there is discrepancy between which metric determines which variables are most accurately modelled. For example, the *CF* metric finds the wind speed to be more accurately simulated, while the |*Pbias*| metric finds the wind direction to be more valid. Confidence is gained when both metrics agree the model performance to be in similar categories, although the numerical value may disagree. The *CF* metric is more appropriate to determine the validity of a variable since it compares the error to the variation in the observation, confirming prediction of individual events. For tide, surges and waves the variation in the water and wave levels is important as extreme events pose flood risk. For an accurate model simulation the error is required to be small compared to this variation. The *Pbias* is a good indicator for systematic over- or under-prediction. The error is compared to the size of the data set, which is more appropriate for variables that have low variability in time.

7. Conclusion

An 11-year hindcast has been performed using the POLCOM-WAM nested modelling system for the Irish Sea. The model data have been validated across the Irish Sea using 19 tide gauges and 22 wave stations. We find that the model hindcast is valid in the long-term. Initial analysis of the data has shown that extreme surges in Liverpool Bay can reach 1.37 m as a result of the meteorological forcing alone. Surge levels due to tide–surge interaction can reach 2.41 m, demonstrating the importance of the tide in this region. The largest surge in the past 11 years reached 2.26 m at Liverpool on the 27th October 2002. Since the largest surges do not occur during high tidal levels the most extreme high water levels only exceed the spring tide high water level by less than a metre. The largest high water levels achieved in the past decade were 6.18 m (MTL) at Heysham and 5.64 m (MTL) at Liverpool. Over the 11-year hindcast period no obvious patterns in the intensity and frequency of extreme events is evident. However, future changes in climate during the 21st century are likely to be more significant and will be investigated in future work using longer time-series.

The largest surges are likely to occur during low water levels due to tide–surge interaction in this area, thus do not pose a significant flood risk. Heysham has less frequent but more intense surges, due to a larger tidal range compared with Liverpool. In Liverpool Bay the largest hindcast waves have reached 5.63 m in the last decade. The worst flood risk occurs when a significant wind event occurs close to high water, as any surge increases the high water levels and large waves are also generated. The tidal range at the time of the surge event will control the magnitude of the additional water level on top of the tide. The extreme high water level likely to be exceeded once every 5 years is 5.41 m (MTL) at Liverpool and 5.98 m (MTL) at Heysham, but will remain below 5.52 m (MTL) and 6.12 m (MTL), respectively. The extreme offshore wave height likely to be exceeded is 5.05 m, while remaining under 5.52 m. In the past 11 years such extreme wave and water levels have not been achieved simultaneously. The worst extreme conditions from the data presented here was a 5.1 m (MTL) high water at Heysham coinciding with 4.8 m waves offshore. From the modelling work presented and tide gauge observations there is no suggestion that extreme events (waves, surges, high water levels) are becoming larger or more frequent.

Following on from this validation and data analysis a further study into the trends and patterns of storm events that generate extreme water levels and wave heights is now underway.

Acknowledgments

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