Surge modelling in the eastern Irish Sea: present and future storm impact

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Abstract It is believed that, in the future, the intensity and frequency of extreme coastal flooding events may increase as a result of climate change. The Natural Environment Research Council (NERC) Flood Risk from Extreme Events (FREE) project, Coastal Flooding by Extreme Events and EU FP7 Morphological Impacts and Coastal Risks Induced by Extreme Storm Events project are investigating the flood risks in the eastern Irish Sea, an area that includes most of England's coastal types. Using a previously modelled and validated historical extreme surge event, in November 1977, we now investigate the changes in peak surge as a result of possible future climate conditions. In order to simulate the surge, we have set up a one-way nested approach, using the Proudman Oceano-graphic Laboratory Coastal Ocean Modelling System 3D baroclinic model, from a domain covering the whole NW European continental shelf, through to a 1.85 km Irish Sea model; both areas are forced by tides, atmospheric pressure and winds. We use this modelling system to investigate the impact of enhanced wind velocities and increased sea levels on the peak surge elevation and residual current pattern. The results show that sea level rise has greater potential to increase surge levels than increased wind speeds.

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1 Introduction

Future extreme coastal flooding events are expected to increase (in intensity and frequency) as a result of climate change. The NERC–FREE Coastal Flooding by Extreme Events (CoFEE) project and EU FP7 Morphological Impacts and COastal Risks induced by Extreme storm events (MICORE) project are investigating past, present and future storm events in Liverpool Bay and especially along the Sefton coastline (see Fig. 1), where the mobile dunes exposed to the prevailing SW winds and depressions moving across the UK from west to east are at risk of enhanced erosion. The present-day surge conditions due to extreme events are being investigated using wave and surge modelling over an 11-year period (1996–2007). This paper uses a hindcast simulation of the November 1977 surge event, which caused significant flooding on the Sefton coast. We then study the sensitivity of the system by considering changes in the peak surge elevation resulting from this storm under future climate conditions. The future scenarios include increasing the mean sea level (by 0.7 and 1.4 m) and the wind strength (by 5% and 10%) to look at the new surge levels that could arise in the future. The resulting surges are investigated at ports in the eastern Irish Sea. We present results for Hilbre, Heysham and Douglas (located in Fig. 3). Hilbre and Heysham represent shallow locations on either side of the Sefton coastline, and thus give insight to the surge conditions that may occur along this stretch of coast. The Liverpool tide gauge had timing errors in its data, which is why we have concentrated on the results at Hilbre and not Liverpool. The surge results at Douglas have also been presented to show how the surge
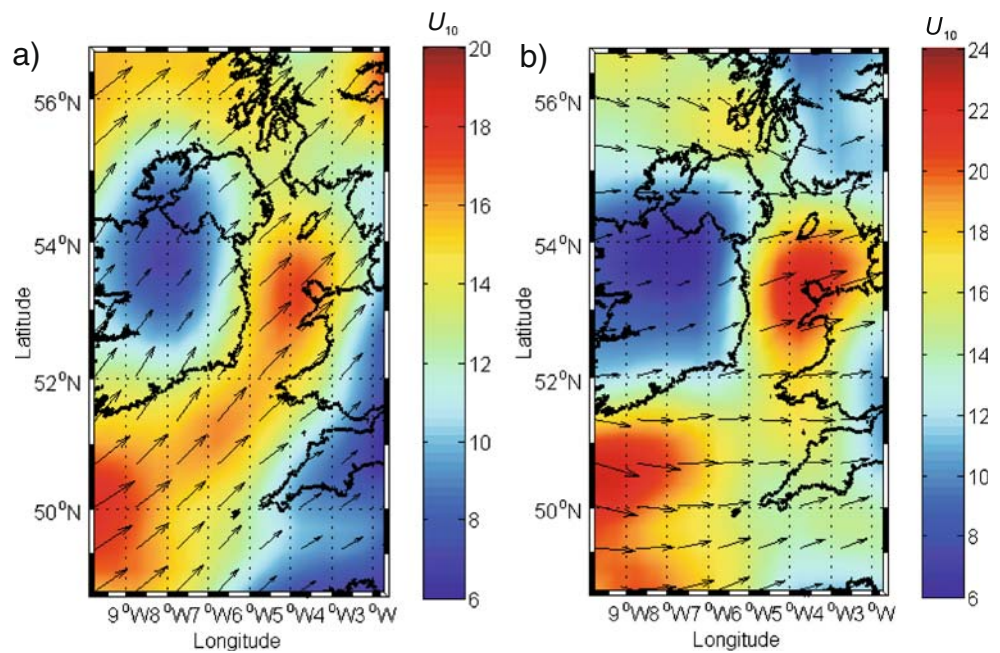
Fig. 1 The 10 m wind velocity (m/s) at **a** 12:00 11th November 1977 and **b** 00:00 12th November 1977

behaves at a deep location within the Liverpool Bay study area. To allow investigation of the full picture, results are presented for both elevation and velocity.

The tide–surge modelling has been improved by implementing the Charnock (1955) method in place of Smith and Banke (1975) to calculate the wind surface stress, following Brown and Wolf (2009). Wu (1982) has shown that using a constant Charnock parameter captures most of the variation in surface roughness without the need for including wave effects over a range of winds speeds (0–55 m/s), and thus sea states. Brown and Wolf (2009) have shown that within the eastern Irish Sea, where the waves are locally generated and shoaling, a constant spatially uniform Charnock parameter of 0.0185 is adequate for hindcasting surge events. This method therefore allows computations to be made without the need for a coupled wave–current model, thus limiting computational costs.

We use the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS), as described in Section 3, as a tide and surge modelling system in a one-way nested framework from ~12 to 1.85 km. A synoptic description of the storm event in November 1977 is given in Section 2 and the performance of the modelling system and results are presented in Section 4. Changes in sea level and wind forcing have been imposed, in Section 5, to investigate future scenarios and provide insight into how the impact of such a severe storm combined with high spring tides might be increased in the future. The research concentrates mainly on surge elevation, but the residual surge current patterns are also briefly investigated. We discuss the results in Section 6 followed by the conclusions in Section 7.

2 The November 1977 surge

We revisit the surge of November 1977, a storm event which caused damage on the Sefton coast in NW England. This period has previously been thoroughly studied, e.g. Jones and Davies (1998). The surge occurred on the 11th–12th November and was the result of an atmospheric depression crossing the region from west to east to the north of Scotland before moving on to northern Norway. This generated 16 m/s south-westerly winds in the eastern Irish Sea, which increased to 22 m/s and veered round to the west (Fig. 1; Jones and Davies 1998). The surge reached 1.5 m at Liverpool (Fig. 2), while wave heights were of the order 3.5 m with 6 s periods. The external surge was generated by winds blowing over the south-west Irish Sea (Fig. 1a), and the local surge was generated by winds blowing over the eastern Irish Sea (Fig. 1b). This severe storm coincided with high water spring tide (Fig. 2) leading to severe flooding as water overtopped coastal defences throughout Merseyside, Lancashire and Cumbria. We assume that the worst flooding will occur due to any amount of positive surge at high water elevation, especially during spring tides. This event is used to investigate how the surge component is modified under future scenarios.

3 Methods

In order to accurately simulate the external surge–tide effects generated outside of the Irish Sea, a one-way nested approach from a 1/9° latitude by 1/6° longitude (~12 km) model of the whole NW European continental shelf, over
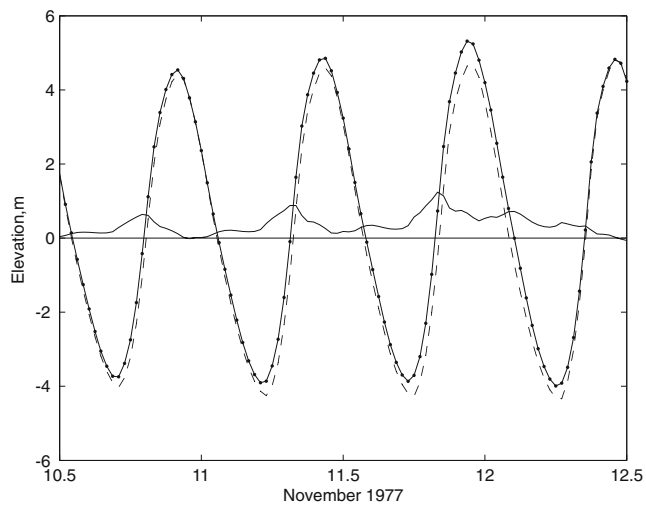
Fig. 2 The total (surge+tide) elevation (*dash dotted line*), tidal elevation (*dashed line*) and surge elevation (*solid line*) at Hilbre during the November 1977 event. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November

which surges impacting the UK are generated, to the 1.8 km Irish Sea model has been applied. For the 1977 surge event, the POLCOMS (Holt and James 2001) Atlantic margin model (Fig. 3) was used to provide the boundary forcing. In the Irish Sea, the standard Smith and Banke surface drag formulation for wind stress (1975), hereafter referred to as S&B, has been replaced by the Charnock (1955) method to better simulate the surge event following Brown and Wolf (2009). The surge is defined as the difference in the total simulated water level and the modelled tide, i.e. the residual water level due to meteorological forcing. Here, the modelled tide was simulated using the 15 tidal constituents (Q_1, O_1, P_1, S_1, K_1, $2N_2$, μ_2, N_2, ν_2, M_2, L_2, T_2, S_2, K_2 and M_4) available in POLCOMS. A minimum water depth of 5 m was applied to avoid treating wetting and drying conditions. Brown and Wolf (2009) discuss using the predicted tide combined with the surge simulation to assess the flood risk using the total water level and the 'skew surge' to remove inaccuracy in the modelled tide. The 'skew surge' is defined as the difference between the predicted high tide and the actual high water level due to the tide and surge.

The coarse grid models for POLCOMS were driven by 1° resolution European Centre for Medium-Range Weather Forecasts (ECMWF; ERA-40) atmospheric pressure and wind data provided every 6 h. For the medium resolution Irish Sea model, high resolution (both spatially, 1/2° by 1/3°, and temporally, three hourly) wind and pressure data (Jones and Davies 1998) were used to drive the model. The improved resolution of these data allows a more accurate simulation of the surge conditions in 1977. Surge elevation data obtained at five coastal tide gauges (Fig. 3) in the

eastern Irish Sea during this event have been used to validate the model.

3.1 Surface roughness

To accurately predict surge conditions in the eastern Irish Sea, different methods to predict the surface wind stress have been applied. Wind stress, τ, is dependent on the air density, ρ_a, and friction velocity, u_*, which is related to the wind speed at 10 m, U_{10}, where C_D=a drag coefficient (Janssen 2004):

$$\tau = \rho_a u_*^2 = \rho_a C_D U_{10}^2 \tag{1}$$

Charnock's (1955) method parameterises the roughness length, z_0, on dimensional grounds and has been found to be applicable from light to extreme (hurricane) wind conditions up to 60 m/s (Wu 1982). By assuming momentum, transfer from air to ocean is mainly through short surface gravity waves, then the roughness length is scaled by the acceleration of gravity, g, and u_*:

$$z_0 = \frac{\alpha u_*^2}{g} \tag{2}$$
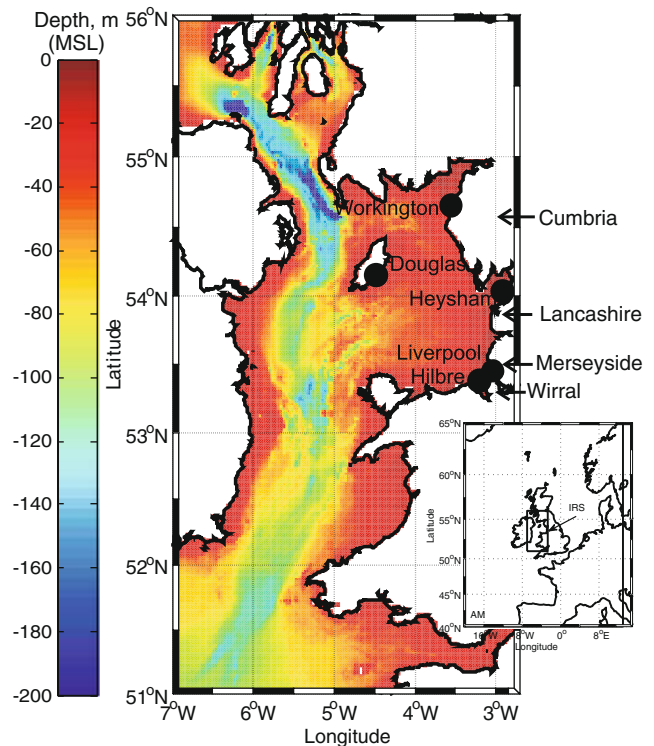
Fig. 3 The Irish Sea model domain and the coastal tide gauges used to validate the surge elevation predicted by the modelling system, during November 1977 (*filled dot*). The nested model domains for the Atlantic Margin model (*AM*) and the Irish Sea model (*IRS*) are shown in the *bottom right corner*

The Charnock parameter, α, is often treated as constant in models with values between 0.0112 and 0.035 (Wu 1980). Although $\alpha=0.0185$ seems to provide accurate representation of the surface stress for all sea states (Wu 1982), a larger constant value (0.0275) has also been found to be appropriate for surge modelling and is applied in the UK operational surge model (Williams and Flather 2000). To model the surface drag to accurately predict the surge events, both the methods of Smith and Banke (1975) (S&B) and Charnock (1955) were previously investigated. Three constant Charnock parameters have been used. The first ($\alpha=0.0275$) was found to give good surge prediction in the operational surge model over the whole UK shelf (Williams and Flather 2000). The second ($\alpha=0.0144$) was that used by Janssen (1989) to model the impacts of waves on the surface roughness. The third ($\alpha=0.0185$) was found by Wu (1982) to give good surface stress prediction for all sea states (wind conditions). Brown and Wolf (2009) found the optimum constant and spatially uniform value for the eastern Irish Sea to be 0.0185, although this might be dependent on model resolution. Local modulation by wave age effects may provide some further improvement but this is not very significant in the eastern Irish Sea. We therefore use this Charnock constant to simulate the future scenario surge conditions investigated here.

4 Results

4.1 Hindcast surge elevation

In the following results, observed data at Heysham and Hilbre stop just after peak surge due to the tide gauges being damaged during the following tidal high water combined with the weakening but still significant surge levels.

Comparison of the surge elevation at coastal tide gauges across the eastern Irish Sea (located in Fig. 3) has shown that there is significant tidal modulation in the surge (Fig. 2). The times of high water compared to the peaks in surge are shown in Figs. 2 and 4, where it may be seen that the peak surge residual occurs on the rising tide (i.e. ~3 h before high water). The large (10 m) tidal range in the eastern Irish Sea has a significant effect on the depth-averaged surge generated by the wind stress in shallow coastal locations. The locally generated peaks in surge occur at low water levels when the water depths are shallowest, but tide–surge interaction due to tide and surge propagation means the peak surge occurs on rising tide (Horsburgh and Wilson (2007); Wolf 1981). The data (Fig. 4) also shows that the surge is much greater (~1 m) along the Sefton coast (Heysham and Hilbre) compared with that occurring on the Isle of Man (Douglas). The

higher constant value ($\alpha=0.0275$) was found to be more accurate at capturing the peak surge at the deep tide gauge locations compared to the lower value ($\alpha=0.0144$) and vice versa for the shallow tide gauge locations (Fig. 4). On average, across the eastern Irish Sea, the intermediate constant ($\alpha=0.0185$) was found to most accurately model the peaks in tide–surge conditions (Fig. 4). Figure 5 shows how the surge predicted using a Charnock method, with $\alpha=0.0144$, is very similar to that predicted by S&B. For this model, resolution S&B slightly under-predicts the surge peaks but still gives a reasonable prediction, unlike the predictions when using a coarse resolution model (Williams and Flather 2000). Figures 4 and 5 show that a Charnock method with constant value of 0.0185 is the most appropriate method over time to simulate the surface roughness in a tide–surge model of the eastern Irish Sea, instead of the S&B methods.

4.2 Simulated flow patterns

Although it is the water elevation that controls the extent of coastal flooding, future changes in the magnitude and extent of the current field in relation to the coast will modify natural defences and the beach profile along a coastline. In particular, the Sefton coastline has a vast extent of sand dunes and salt marsh providing a significant amount of protection at present. We therefore investigate the possible future changes in depth-averaged current at the coastal tide gauge locations.

In the eastern Irish Sea, the tide is asymmetric. The depth-averaged flow vectors are shown every 2 h for Douglas, Heysham and Hilbre in Fig. 6. At Douglas, the deepest location, the tide is rectilinear with the flood tide directed in a (positive) northeast direction and ebb tide in a (negative) southwest direction. This rectilinear velocity pattern is a result of the coastline configuration in relation to the tide in the eastern Irish Sea. Interestingly, although the flood tide is of shorter duration, the peak ebb tide is a few centimetres per second faster. At Heysham, a shallow location away from the influence of an estuary mouth, the tide is nearly rectilinear with the flood tide and ebb tide in the same direction as Douglas. Here, the flood tide is faster than the ebb as in typical flood tide asymmetry (short, fast flood and long slow ebb), but both are of similar strength to the currents at Douglas. At Hilbre, a shallow location in the mouth of the Dee Estuary, the tide is less rectilinear and floods towards the south (negative) and ebbs towards the north (positive). In this location, the typical (for shallow water) flood tide asymmetry occurs, comprising of a significantly faster, shorter flood tide compared with the ebb. The flood tide at Hilbre is slightly weaker than that at Douglas and Heysham, while the ebb is much faster.
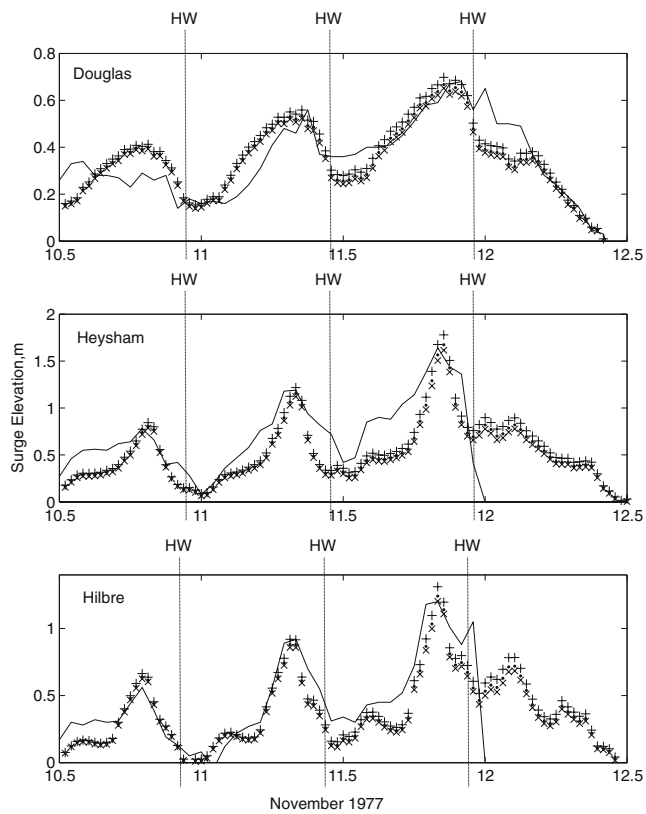
Fig. 4 Surge prediction using Charnock parameters of 0.0275 (*plus symbol*s), 0.0185 (*filled dots*) and 0.0144 (*multiplication symbols*), using POLCOMS with a minimum depth of 5 m, compared to tide gauge data (*solid line*). Douglas represents a deep location, while Heysham and Hilbre represent shallow locations along the Sefton coast. The times of high water (*HW*, *vertical lines*) are after the peaks in surge, which occur on the rising tide. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November

5 Future scenarios

We used the November 1977 storm as our base storm to simulate future scenarios using combinations of (1) increased winds (by 5% and 10%) and (2) increased sea level (by 0.7 and 1.4 m). To simulate the effects of increased sea level, the mean tidal level in the model was raised. Any non-linear effects due to tide–surge interaction in the deepened water are therefore captured. Since the surge is defined as the additional water on top of the tidal level, we remove the present-day tidal level from the future total water levels to compare the surge directly with present-day tidal conditions. The rise in sea level at Liverpool is currently 1.4 mm/year (Woodworth et al. 1999); if rates remain constant, these increased sea levels are unlikely to be achieved in the next 100 years. It is thought sea level rise will be of the order of metres over the next 15–100 years due to thermal expansion alone (IPCC 2007); we therefore investigate multiples of 1.4 mm/year to represent a sea level rise of this magnitude. These future
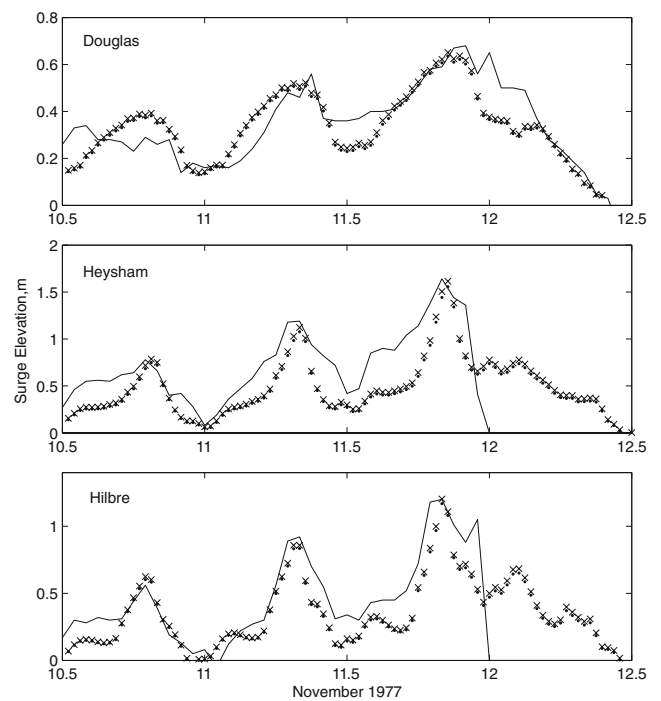
Fig. 5 Surge prediction using S&B (*filled dots*) and a Charnock parameter of 0.0144 (*multiplication symbols*), using POLCOMS with a minimum depth of 5 m, compared to tide gauge data (*solid line*). Douglas represents a deep location, while Heysham and Hilbre represent shallow locations along the Sefton coast. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November
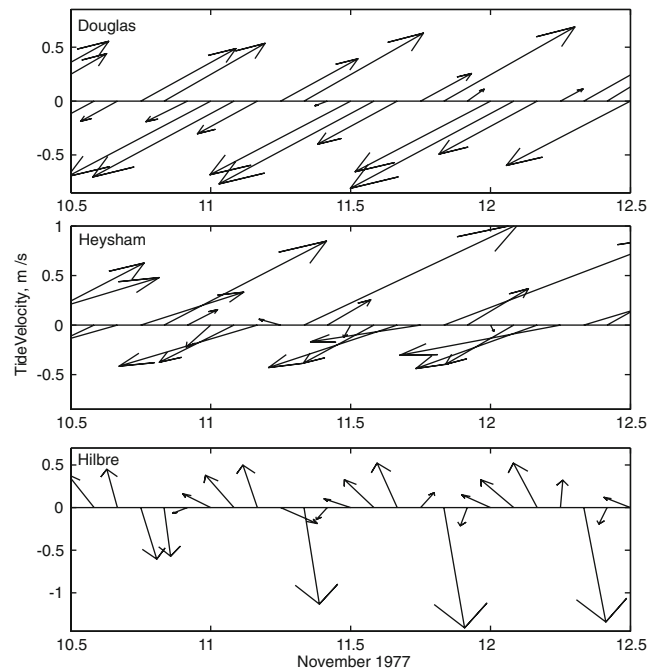
Fig. 6 Tide only depth-averaged current vectors every 2 h at Douglas, Heysham and Hilbre, located in Fig. 3, during the period 10th November (12:00) to 12th November (12:00) 1977. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November

scenarios have been simulated to give insight into what might occur in the future. The external surge important to the eastern Irish Sea is generated in the Celtic Sea and also enters from NW Approaches through the North Channel (Jones and Davies 1998). These regions are included within the Irish Sea model used here; we have therefore not modified the boundary conditions to this model but allowed the external surge to the eastern Irish Sea to be changed as a result of increased wind forcing and sea level rise across the Irish Sea model domain.

5.1 Future surge elevations

We focus on three tide gauge locations, namely Douglas, Hilbre and Heysham. These three locations show the main changes in the surge along the Sefton coast and also at a deep and shallow coastal position. The percentage change in the peak surge elevation for Douglas (0.668 m peak surge), Heysham (1.673 m peak surge) and Hilbre (1.242 m peak surge) are given in Tables 1 and 2, respectively. Under all future scenario conditions, the peaks in surge increase. The increase is much greater at the shallow locations compared to the deeper location. For the changes in sea level and wind speed, we have de-tided the total water elevation to obtain the surge using the present-day tide (sea levels). This allows us to see the total increase in surge elevation as a result of changes in the tide, surge and tide–surge interaction. The changes in sea level have more impact than the change in wind speed on the enhancement of the peak surge (Tables 1, 2 and 3). As expected, the combined effect of increasing the wind speed and sea level led to the worst increase in peak surge. For shallow coastal locations such as Hilbre, only a small increase in sea level (+0.7 m) causes a significant (15%) enhancement in the peak surge. Along the Sefton coast, stronger winds enhanced the surge by a more significant amount at Heysham (Table 2) compared with Hilbre (Table 3), while sea level rise has less impact at Heysham compared with Hilbre. For this area, Lowe et al. (2001) also concluded that sea level rise would have more significant impact on the peak surge than changes in meteorological forcing.

Figure 7 shows how increased sea level modifies the surge. At both the shallow (Hilbre and Heysham) and deep

Table 2 Percentage change in peak surge elevation at Heysham

Sea level rise	Increase in U_{10}		
	0%	5%	10%
0 m	–	6.83	13.99
0.7 m	12.13	18.41	24.99
1.4 m	22.73	28.43	34.42

The 1977 peak surge reached 1.673 m

(Douglas) locations, the amplitude of the surge peaks is increased due to higher peak surge elevations and lower minimum surge elevation. This can be attributed to changes in the tide and bottom friction affecting the tide–surge interaction, which controls the modulation of the surge. The total water level at high water determines the extent of coastal flooding. At high water levels, the surge may be reduced due to increased sea level (lower minimum surge elevations in Fig. 7), but the increase in total water levels due to sea level rise will still pose more frequent flood risk (Lowe et al. 2001). Surprisingly, there is also a phase shift in the surge at Douglas, the deeper location, such that it occurs later. The timing of the peak in total water level is consistent for varying sea levels at this location. The lag in surge peak is thought to be related to modified tide–surge interaction as a result of sea level rise also modifying the tides at this location.

Figure 8 shows how increase wind speed increases the peak surge at shallow (Heysham and Hilbre) and deep (Douglas) locations. The increased wind causes the surge to achieve higher elevations throughout the event, i.e. the curve is shifted to higher elevations in Fig. 8. This shift is greater the larger the surge elevation, i.e. the peaks in surge during low water levels undergo greater enhancement.

Figure 9 shows how the most extreme increase in sea level (+1.4 m) and wind speed (+10%) affects the surge. Again there is a phase shift at Douglas, the deeper location, such that the surge occurs later when sea levels are increased. At all locations, the increased water depth increases the peak surge and reduces the minimum surge levels. Enhanced winds combined with sea level rise increases the surge height throughout the simulation compared to that in which only the sea levels are increased.

Table 1 Percentage change in peak surge elevation at Douglas

Sea level rise	Increase in U_{10}		
	0%	5%	10%
0 m	–	1.92	4.01
0.7 m	4.29	6.26	8.40
1.4 m	9.295	11.27	13.41

The 1977 peak surge reached 0.668 m

Table 3 Percentage change in peak surge elevation at Hilbre

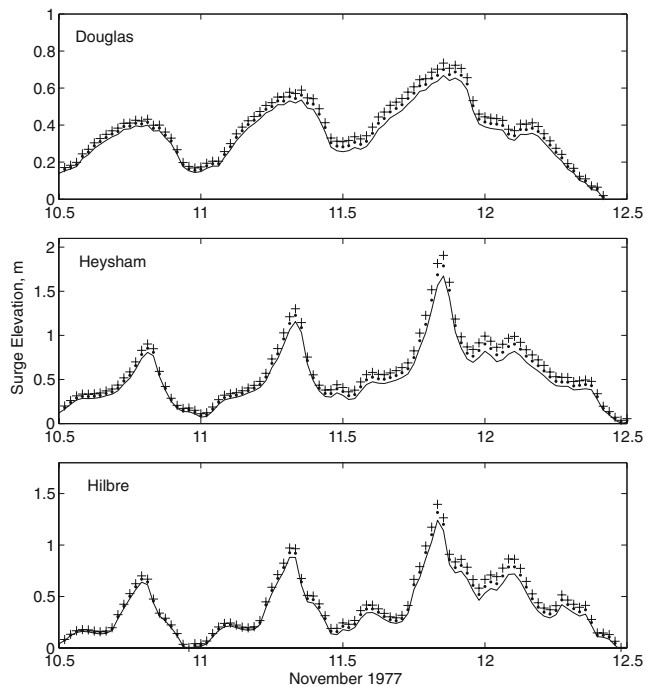| Sea level rise	Increase in U_{10}		
	0%	5%	10%
0 m	–	5.99	12.38
0.7 m	14.73	20.35	26.36
1.4 m	27.23	32.54	38.19

The 1977 peak surge reached 1.242 m
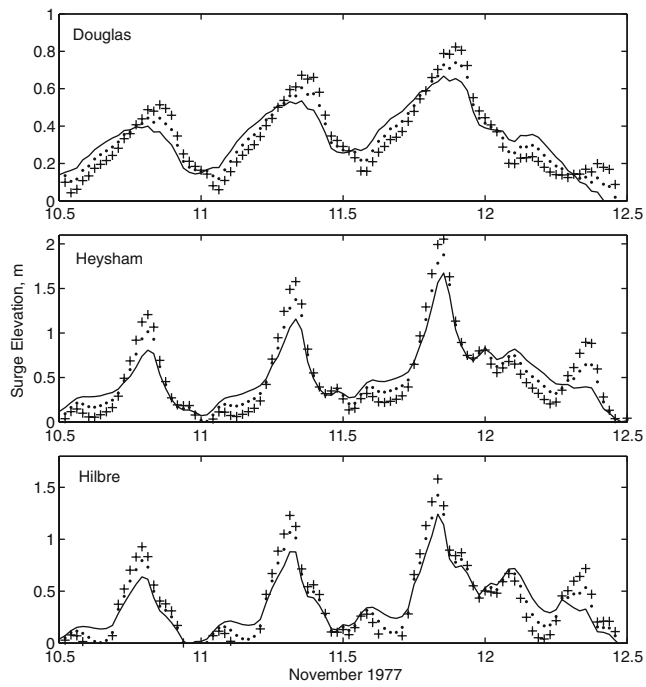
Fig. 7 The surge prediction at Douglas, Heysham and Hilbre for present-day conditions (*solid line*) and with sea level rises of 0.7 m (*filled dots*) and 1.4 m (*plus symbols*). The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November
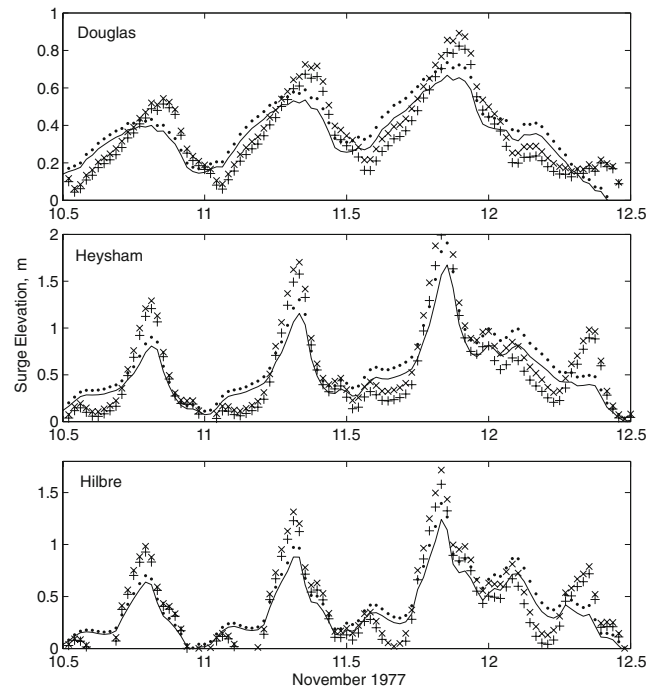
Fig. 9 The surge prediction at Hilbre and Douglas for present-day conditions (*solid line*), present-day conditions with enhanced wind speeds of 10% (*filled dots*) and 1.4 m sea level rise (*plus symbols*) and combined 1.4 m sea level rise and 10% wind enhancement (*multiplication symbols*). The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November

This shift is greater for the peaks in surge and is most significant at Hilbre, the shallowest estuarine location.

5.2 Future residual flow patterns

We now look at the effect of the surge on the residual depth-averaged velocities at the same three locations as in Section 5.1. We initially analyse the effects of future conditions at Douglas, the deeper coastal location. Figure 10 shows that the trend in magnitude (length) of the residual surge current vectors through time has three distinct peaks, like the residual surge elevation. At this deep location, the residual flow is generally in a northwest direction, i.e. in the flood tide direction. Since the wind direction is south westerly until mid-day on the 11th November when it veers west, the residual surge is driven by the winds across the Irish Sea. The residual magnitude is modulated by the tide, causing weaker velocities to occur at times of high water (Fig. 4) and greater velocities at low water. Although the magnitude of the residual increases with wind velocity, the direction remains constant in the direction of the wind during the initial stages of the surge. This demonstrates that the duration of the wind in a particular direction is important at this location; veering in the wind takes time to impact the residual surge currents. For this location, an increase in the wind velocity by 10% (bottom panel,
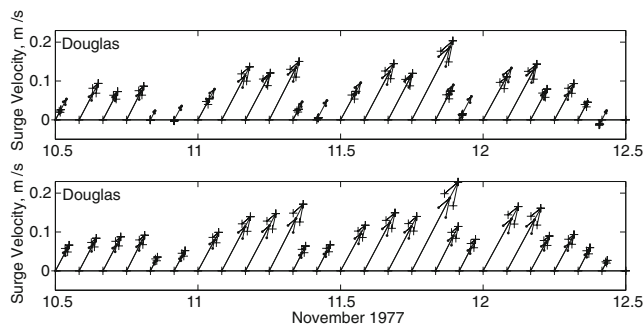

Fig. 8 The surge prediction at Douglas, Heysham and Hilbre for present-day conditions (*solid line*) and with enhanced wind speeds of 5% (*filled dots*) and 10% (*plus symbols*). The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November
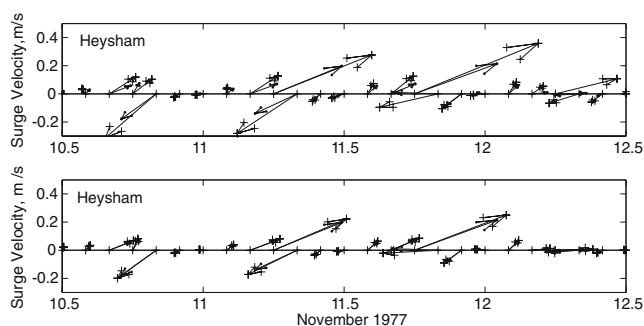
Fig. 10 Surge (residual) depth-averaged current vectors every 2 h at Douglas, located in Fig. 3, during the period 10th November (12:00) to 12th November (12:00) 1977. The *vector arrows depicted with dotted end points* represent the actual 1977 surge conditions, while the *arrows depicted by crossed end points* represent the 1977 surge under future scenario conditions as follows: In the top panel, a 1.4 m sea level rise is included and in the bottom panel a 10% increase in wind speed is included. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November

Fig. 10) had greater impact on the magnitude of the residual velocity than increasing the present-day sea level by 1.4 m (top panel, Fig. 10).

At Heysham (Fig. 11), a shallow location at the northern end of the Sefton coast, the residual surge velocity is often in the counter direction to the tidal flow and not determined by the wind direction as at Douglas (Fig. 10). The largest residuals occur around high water (Fig. 4) as the tide turns. Similarly to Hilbre (Fig. 12), the effect of a 1.4 m sea level rise has more impact (top panel, Fig. 12) on the enhancement of the residual velocities than a 10% increase in the wind velocity (bottom panel, Fig. 11). The increase in sea level also causes a slight change in the direction of the residual current at certain times of the tide.

The results for Hilbre (Fig. 12) are somewhat different to both other locations. At this shallow location in the mouth

Fig. 11 Surge (residual) depth-averaged current vectors every 2 h at Heysham, located in Fig. 3, during the period 10th November (12:00) to 12th November (12:00) 1977. The *vector arrows depicted with dotted end points* represent the actual 1977 surge conditions, while the *arrows depicted by crossed end points* represent the 1977 surge under future scenario conditions as follows: In the top panel, a 1.4 m sea level rise is included and in the bottom panel a 10% increase in wind speed is included. The time resolution is the day in November, e.g. 10=00:00 10th November and 10.5=12:00 10th November
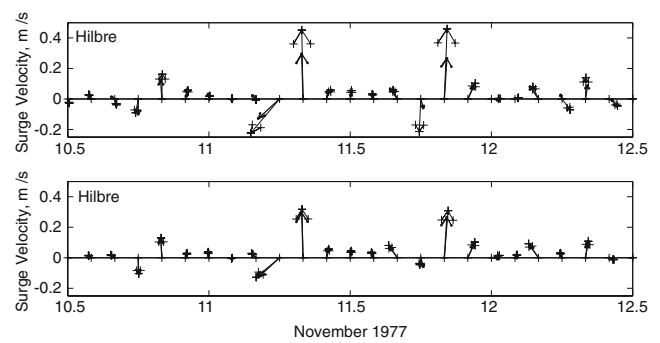
Fig. 12 Surge (residual) depth-averaged current vectors every 2 h at Hilbre, located in Fig. 3, during the period 10th November (12:00) to 12th November (12:00) 1977. The *vector arrows depicted with dotted end points* represent the actual 1977 surge conditions, while the *arrows depicted by crossed end points* represent the 1977 surge under future scenario conditions as follows: In the top panel, a 1.4 m sea level rise is included and in the bottom panel a 10% increase in wind speed is included. The time resolution is the day in November, e.g. 10 =00:00 10th November and 10.5=12:00 10th November

of the Dee Estuary, the residual surge velocity is generally out of the estuary (in a positive direction). The residual flow pattern does not follow the same trends as the surge. Contrary to the results for Douglas (Fig. 10), the largest residual occurs close to high water (Fig. 4) and is a factor of 2 greater than the peak residual velocity at Douglas. For Hilbre, this is also the time for peak flood flow. For all other states of the tide, the residual is weaker than at Douglas and Heysham. Again, the effect of a 1.4 m sea level rise (top panel, Fig. 12) leads to greater enhancement of the residual velocities and also causes a slight change in the direction of the residual current at certain times of the tide. The 10% increase in the wind velocity (bottom panel, Fig. 12) has less effect than the change in sea level.

6 Discussion

A good tide–surge simulation in the Irish Sea results from using a constant Charnock parameter of 0.0185. Interestingly, the POL operational surge model, with ~12 km resolution, requires a larger value of 0.0275. We also notice that the S&B prediction is quite valid in the Irish Sea (~1.8 km) model, although it under-predicts when applied in the POL operational model. It is thought that the model resolution plays an important role in the optimum value for the Charnock parameter and the validity of the S&B procedures. As the model grid becomes more highly resolved, the average depth within each coastal grid cell is more accurately resolved. In low resolution models, the average depth of the large grid cells may be greater in coastal zones compared with high resolution models. This greatly influences the effect of the surface stress on the water column. For low model resolution, the stress must therefore be enhanced for accurate surge

prediction at the coast. This enhancement is reduced with improved grid resolution and the S&B method becomes more accurate.

Interestingly, the residual surge velocity at Douglas occurs in the direction of the wind with longest duration across the Irish Sea. At Hilbre, the residual is often in the direction of the northerly wind component, but can be into the estuary as the tide turns from ebb to flood. This could be the result of the enhanced water levels during the rising tide (Fig. 4) changing the tidal forcing at the estuary mouth. Although open-ocean Ekman dynamics should lead to a residual flow at 90° to the right of the wind direction (Gill 1982), this is not observed in the eastern Irish Sea. The residuals seem to generally be in the wind direction due to the strong tidal currents and shallow (<50 m) depths in the eastern Irish Sea. For the peak wind velocity of 22 m/s, the Ekman depth is estimated to be 186 m. The strong tidal currents also create a large vertical eddy viscosity profile and turbulent mixing, preventing the formation of Ekman currents. Time-varying winds (in strength and direction) during a real surge event also prevent a residual depth-averaged Ekman current pattern forming in the period of the surge. This is why significant surges are generated by winds over greatest fetch towards the eastern Irish Sea rather than alongshore winds in the eastern Irish Sea.

The effect of waves on the surge events has also been investigated (Brown and Wolf 2009). They find that the inclusion of a wave-dependent Charnock parameter has minimal difference compared with that using a constant value of 0.0185. An 11-year simulation (1996–2007) following this model validation and that of Brown and Wolf (2009) is now underway to allow us to now investigate what storm conditions (wind and wave directions and strengths) pose the most significant threat to the Sefton coastline. This will enable a range of storm conditions to be tested under future scenario conditions and will provide a complete study of past, present and future extreme events for the Sefton coast.

We have found that, for the 1977 storm conditions, increased sea level has more impact on the increase in peak surge elevation than increased wind speeds. This result was also found by McInnes et al. (2009). The combined effect of these two changes can lead to a 20–40% increase in the peak surge relative to the present-day surge conditions on the coastal areas around Wirral, Merseyside and Sefton. The surge elevation along Sefton coast increases with distance to the north by about half a metre. Compared with Douglas (a deep location on the Isle of Man), the surge is much greater (nearly 1 m) at shallow location along the Wirral, Merseyside and Sefton coastline. When planning defences, the total (tide+surge) water level is of most interest. Table 4 shows the percentage change in the peak of

the total water level during the surge, which should be taken into account by managers. At Douglas, the rise in sea level has more impact than the increase in wind speed, but the opposite is true for Heysham and Hilbre. Sea level rise has most impact on the surge peaks (during low water levels; Fig. 7), while the winds influence the surge throughout the investigated time period (Fig. 8). Changes in the wind seem to have a greater effect at the shallower locations (Table 4). At all locations, the combined change is approximately the same as the linear addition of the percentage changes due to sea level and enhanced wind speeds. Although the surge at Hilbre is significantly large, the consequent flooding due to the total water level does not pose an extreme risk to the coastal population since there is an extensive volume of salt marsh, which will be flooded within the estuary before nearby towns become at risk. The size of the surge at high water along the Sefton coastline does pose a risk to the coastal population, as many towns are located on low lying land, e.g. Southport is built on reclaimed land. Along this coast, the defences are in the form of naturally developed sand dune, which under future climate may become eroded by both the sea and wind. Not only does the increased surge elevation allow the dunes to be eroded and breached but also the enhanced currents under future climate conditions will also scour the base of the dune system and alter the beach profile.

7 Conclusions

The November 1977 storm surge event has previously been used to tune and validate the POLCOMS model surge predictions in the eastern Irish Sea using this nested modelling system. We have shown that although the Smith and Banke formula under-predicts the peak surge, the Charnock method can be tuned to accurately predict a surge event at a given location. We find that the optimum Charnock value (0.0185) is lower than that found by Williams and Flather (2000) (0.0275). This may be due to the higher model resolution that is applied here to the Irish Sea.

Table 4 Percentage change in peak total water elevation at the study locations

Future change	Douglas	Heysham	Hilbre
+10% wind increase	1.35%	2.55%	2.20%
+1.4 m sea level rise	1.88%	0.45%	1.48%
Both the above	3.20%	3.04%	3.53%

The observed peak total water levels at Douglas, Heysham and Hilbre were 4.08, 5.49 and 5.13 m, respectively

Future scenarios in the eastern Irish Sea have shown sea level rise combined with stronger winds will both significantly enhance the peak surge, perhaps, up to 40%. This enhancement is greatest in shallow locations along the Sefton coastline, e.g. Hilbre and Heysham. We have shown that sea level rise has more impact than changing wind strength on the surge elevation, and thus greater potential for flood risk. Even if the wind speeds do not change significantly in the future, a 0.7 m increase in sea level, which is likely to occur in the next 100 years, will enhance the surge elevation by up to 15%. We can be certain that extreme storm conditions of today that cause large surge events along the Sefton coastline will have enhanced surge peaks in the future as further sea level rise is now inevitable (although the magnitude is uncertain, e.g. IPCC 2007). Defences along the Sefton coastline will therefore have to be carefully planned for future conditions involving storms combined with sea level rise.

For study, at Douglas the wind speed and duration has most influence on the surge velocities. The residual surge direction is controlled by the wind direction, while the strength is modulated by the tide. Future increases in wind velocity will have more potential to increase the current strength at Douglas than increase sea level. At Heysham, the residual surge velocity varies in direction due to interaction with the tide and coastline. We find that, for this location, sea level has greater effect on the increase in the surge currents than increased wind speeds. At Hilbre, the residual surge is generally out of the estuary due to the wind; increased sea levels rather than enhanced wind velocities pose greater risk with regard to faster surge currents.

From this study, we can conclude that future changes in wind strength and sea level will lead to increased surge elevations and velocities. The enhancement of the peak velocity and elevation residuals will be greatest at shallow coastal locations. This will pose a threat to the sand dunes along the Sefton coast that act as a natural defence against surge events.

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