Micore Project end users report:
Storm conditions causing morphological impact along the Sefton Coast.

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1. Introduction

The Sefton coast borders the eastern Irish Sea and extends 36km northwards from the Mersey estuary to the Ribble estuary (see inset Fig.1). Modelling studies have focused predominantly on a 16km-long stretch of coastline around Formby Point dominated by recreational beaches and one of the largest coastal dune systems of Great Britain, which extends 4km inland and has dune heights reaching 30m (Fig.1). These dunes have high recreational and conservation value and form an effective coastal flood defence for urban development, high-grade agricultural land and a significant number of conservation areas of national and international importance. Given its sedimentary nature it is vulnerable to erosion during storm events. In common with other coastal areas there is not always a clear boundary between those areas at risk from flooding and those at risk from coastal erosion. In a number of locations coastal erosion will lead to tidal flooding. Storm impact on the sand dune system can cause landward realignment. This will be most significant immediately after the storm event and will be reduced when the dunes have recovered through slumping and windblown sand accretion. The extent of erosion for an isolated storm event will depend on the initial state of the dunes system, e.g. whether a previous high tide has eroded or destabilised the dune face. Upon breaching of the sand dune system there are a number of areas that could be exposed to tidal flooding.

Together wind waves and elevated water levels can cause flooding and extensive erosion in low-lying coastal areas. The water level at the coast may be a combination of mean sea level, tides, surges and wave-setup. Often surges and waves are generated by the same storm event. In areas with a wide continental shelf a travelling external surge may combine with the locally generated surge and waves. Significant interaction between the propagation of the tide and surge can also occur. Wave height at the coast is controlled largely by water depth so the effect of tides and surges on waves must be also be considered, while waves contribute to the total water level by means of wave setup through radiation stress. These processes are well understood and accurately predicted by models, assuming good bathymetry and wind forcing is available. Other interactions between surges and waves include the processes of surface wind stress and bottom friction as well as depth and current refraction of waves by water levels and currents, some of the details of these processes are still not well understood.

A valid coupled wave-tide-surge model hindcast (See Brown et al. 2010a for details), in addition to observation, has been used to determine the characteristics of extreme offshore storm events along the Sefton coast. For selected periods of observed morphological impact this model has been used to provide wave-tide-surge conditions to drive a coastal impact model for sections of the coast with the aim to setup an operational morphological impact and flood inundation system in the form of an on-line early warning system.

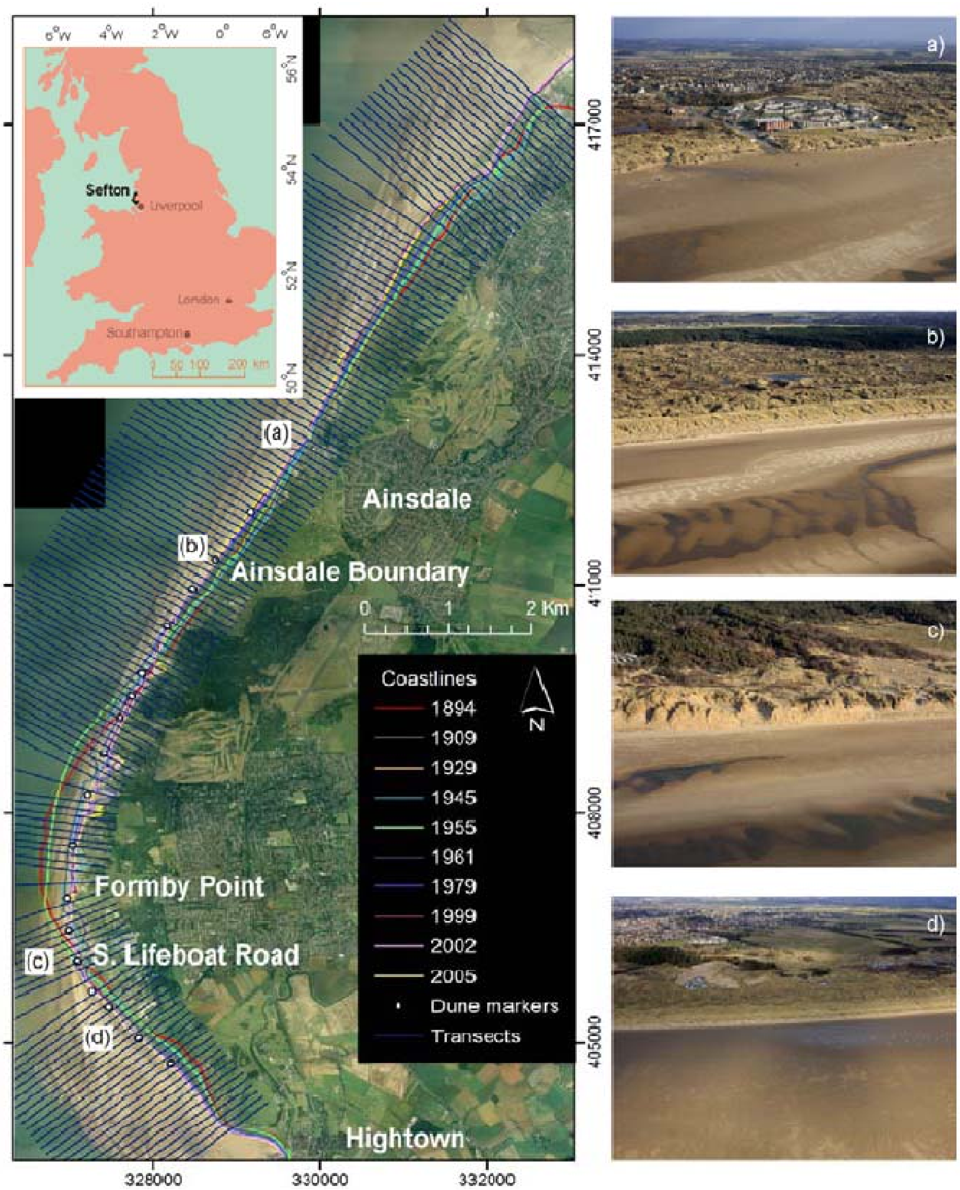

Figure 1: Sefton Coast is located in Northwest England (insert) and presents 16 km of undefended coastlines (aerial photograph taken in 2005). The lines indicate shoreline transects used to determine rates of dune and shoreline recession. Coordinates in British National Grid (m). The photographs show four different coastal locations.

2. The sequence of extreme offshore conditions

Sand dunes not only react to storm events but also react to a wide range of high tidal levels (>9.5m CD). Here the offshore conditions are presented, which could lead to a significant shoreline response. Extreme storm events have previously been identified from an 11-year data set (1996 – 2007) of model hindcast and observation (see Brown et al, 2010b). The storm event occurring on the 27th October 2002 is presented here to demonstrate the sequence of events that lead to extreme conditions along the Sefton coast. This event generated some of the most extreme storm conditions in recent years. A surge level of 2.26m occurred at Liverpool and offshore wave heights reached 4.09m within Liverpool Bay.

2.1. Wave conditions

In Liverpool Bay the waves are locally generate as a result of the winds blowing over the sea surface within the eastern Irish Sea (Fig. 2). The most extreme wave heights offshore in Liverpool Bay are in the range of 4.0 – 5.6m. Waves of this severity are typically generated when the winds blow from the west through to northwest. These directions provide the longest fetches (~200km) to the Sefton coast (Pye & Neal, 1994). The eastern Irish Sea is sheltered from external swell due to the surrounding coastline and the shallow depths throughout the Irish Sea.

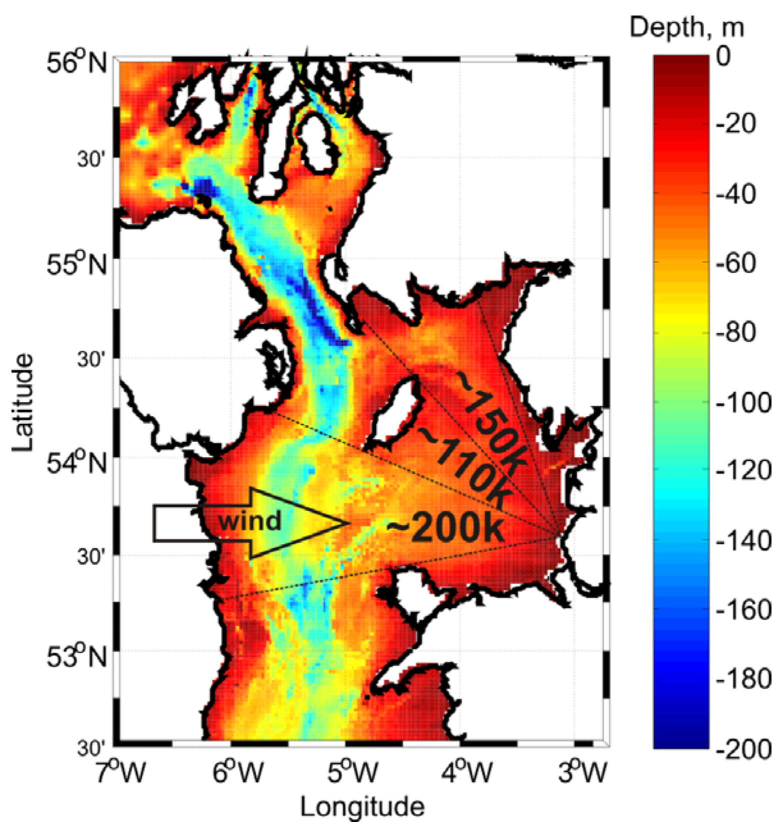

Figure 2: Fetch regions for local wave generation along the Sefton coast, the region for extreme waves is marked with an arrow.

2.2. Surge conditions

The surge generated externally to the eastern Irish Sea is at least as important as the locally generated surge within the eastern Irish Sea (Olbert & Hartnett, 2010). The external surge depends on both wind and pressure forcing, while the wind contribution becomes increasingly important within Liverpool Bay. The most extreme surge conditions result from winds blowing over the longest (south-westerly) fetches, to the offshore boundary of the eastern Irish Sea (Fig. 3). This wind direction results in an extreme external surge condition and moderate local surge generation. However, if the wind veers to the west from southwest an extreme local surge is generated, which contributes to and interacts with the extreme external surge creating the most severe surge elevations for the Sefton coast and Liverpool Bay. Within Liverpool Bay the most extreme surge conditions range between 1 – 2.5m.

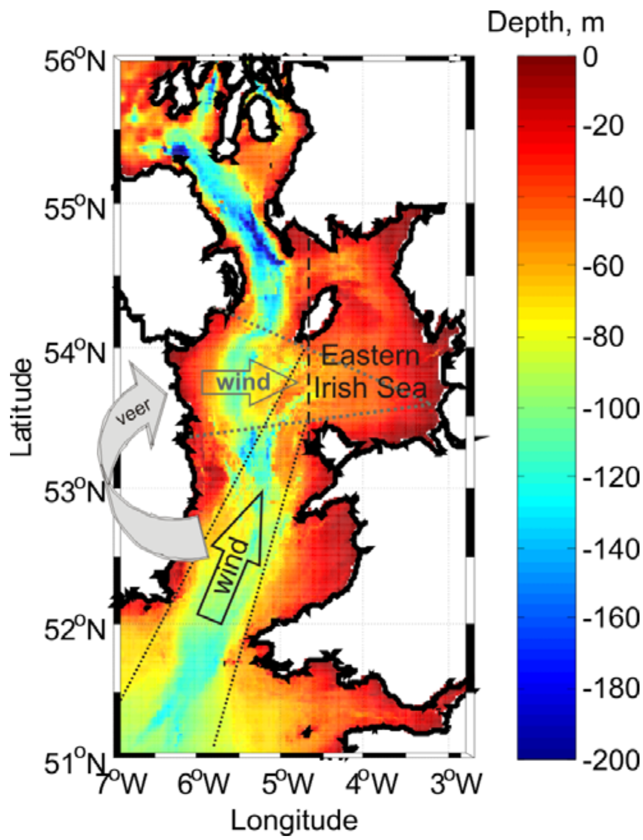

Figure 3: Fetches for extreme external (black region) and local (grey region) surge generation leading to extreme surge levels along the Sefton coast.

2.3. Tidal conditions

Liverpool Bay is a macro tidal region. According to data held by the National Tidal and Sea Level Facility (NTSLF, http://www.pol.ac.uk/ntslf/), at Liverpool the mean spring tidal range is 8.22m and the mean neap tidal range is 4.28m. The highest mean high water spring is 9.32m CD, while the highest astronomical tide is 10.29m CD. Significant impact on the dune system and flood risk due to storm events are most likely to occur during high tidal levels. Extreme tidal levels are mainly associated with spring tides combined with surge and wave set-up. Due to tide-surge interaction in Liverpool Bay the peak of the surge event often occurs on the rising tide and not at high water (Woodworth and Blackman, 2002). Consequently, it is the increase in observed high water compared with the predicted tidal high water level that is more important than the peak surge level (Fig. 4). This additional water level is known as the skew surge (de Vries et al., 1995). For Liverpool Bay the most extreme skew surge levels are 0.8 – 1.8m, in response to winds from the southwest through to west.

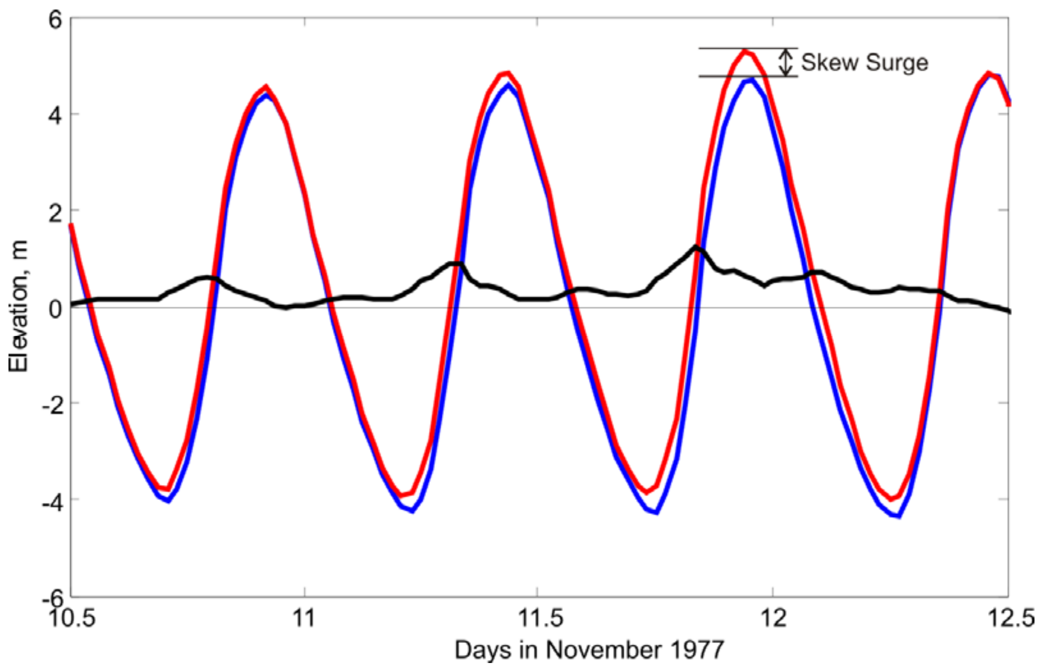

Figure 4: The November 1977 storm event shows the peaks in the surge (black line) occurring on the rising tide (blue line) and the resultant water level (red line). The peak in the skew surge occurs on the 12th November as a result of tide-surge interaction.

2.4. Storm conditions

The worst storm conditions occur as a result of a depression generating south-westerly winds veering west with wind speeds, at 10m above the surface, in the range 17 – 30m/s across the Irish Sea. This facilitates the generation of a large external surge, which propagates into the eastern Irish Sea. As the wind turns towards the west the locally generated wave and surge conditions become extreme. The overall effect is large waves on elevated tidal water levels. At the peak of the tide hard defences are at risk from wave overtopping and breaching from extreme water levels, while the dunes are at threat of erosion (Fig. 5). During spring tide conditions the potential for coastal flooding in response to such a storm is at its greatest.

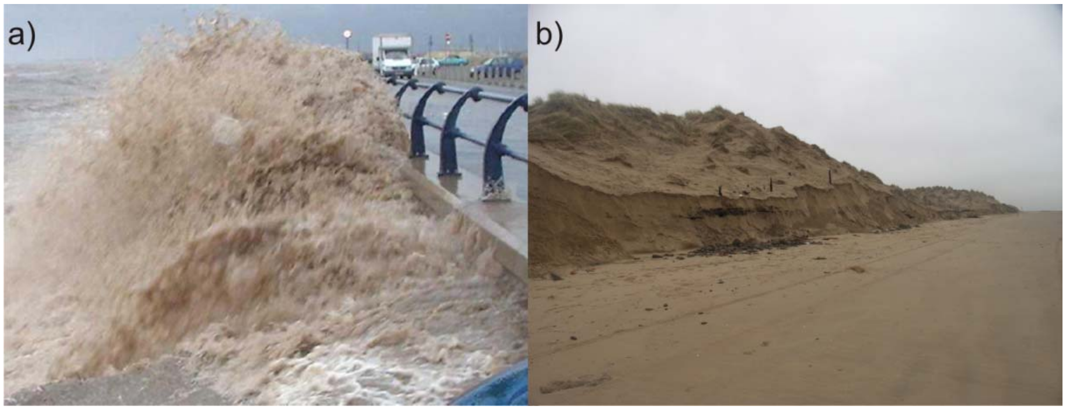

Figure 5: a) Waves impacting the sea wall constructed in 2002 at Southport and b) sand dune undercutting due to high tidal levels in February 2010.

Extreme storm conditions are likely to occur when a low pressure system travels from the west towards the northwest across the Irish Sea and just north of Liverpool Bay. For extreme wave and surge conditions the centre of the low pressure system needs to follow a track which lies in the region shown in Fig. 6. Such a track allows the required wind and pressure conditions to generate extreme storm conditions along the Sefton coast.

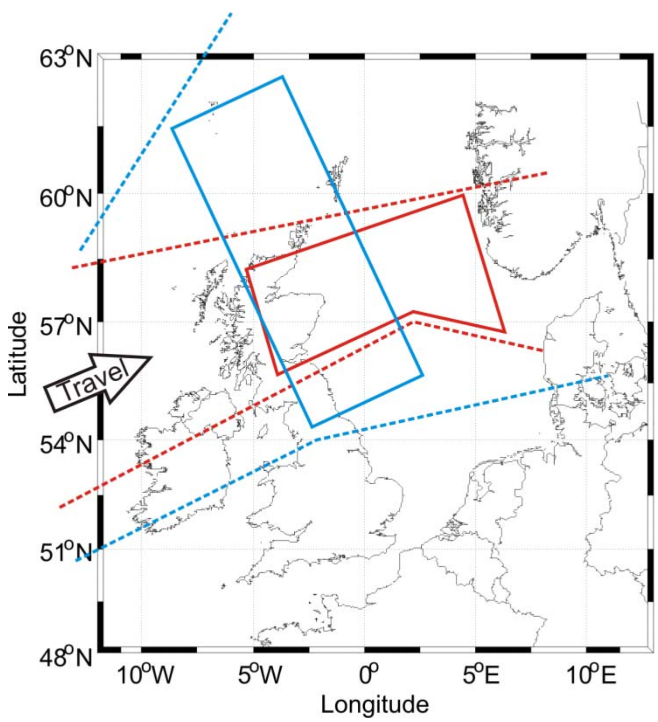

Figure 6: Storm track regions generating extreme surge (blue) and waves (red) along the Sefton coast. The boxes indicate the location of the depressions centre at the time of peak surge (blue) or peak wave (red) conditions. The arrow represents the general direction of travel of the storm across the region.

The time of peak waves and peak surge may or may not coincide. This will depend on the sequence of wind veering and the tide surge interaction. Extreme surge generation depends on a strong south-westerly wind component, but tide surge-interaction will affect when the peak in surge occurs, by which time the wind may have turned. The waves are dependent on a strong westerly wind component. This can coincide with the time of peak surge or at a different time when the storm track has moved to a location generating a strong westerly wind component. Often the location of the pressure system at the time of the peak in the wave conditions occurs after that for peak surge conditions, as the pressure system moves from the blue region into the red region in Fig. 6. This is due to the local generation of the waves requiring westerly wind conditions, and the surge requiring veering wind conditions dominated by an initial southwest direction. On 27th October 2002 the peak in waves occurred an hour after the peak in surge as the low pressure system moved further northeast and the winds veered from a south-westerly to a westerly direction. The storm tracks across the Irish Sea of the two dispersions, which occurred in the period 25th – 29th October 2002, are shown in Fig. 7. The first (blue track, Fig. 7) had a central low pressure of 968 – 976mb and the second (red track, Fig. 7) had a central low pressure of 972 – 980mb. Each storm generated a peak in the storm conditions. The sequence of events at Formby point is presented in Fig. 8. As the depressions tracked over the UK and into the North Sea, veering south-westerly to westerly winds, reaching speeds of 16-18m/s locally, were generated in the eastern Irish Sea (Fig. 8a). The time series of the modelled wind speed, wind direction, significant wave height, surge elevation, tidal elevation and total elevation are given at Formby point in Fig. 8.

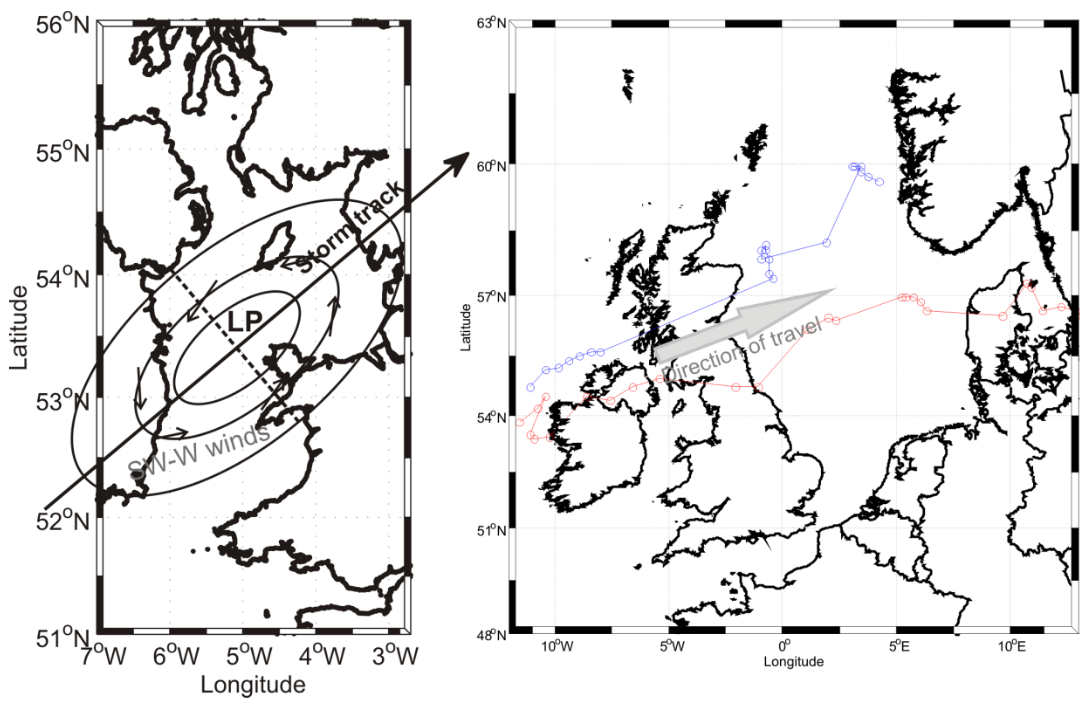

Figure 7: The storm tracks of the centre of the low pressure system generating storm conditions on the 26th October 2002 (blue track) and 27th October 2002 (red track). A schematic of a low pressure system and its corresponding winds is also given.

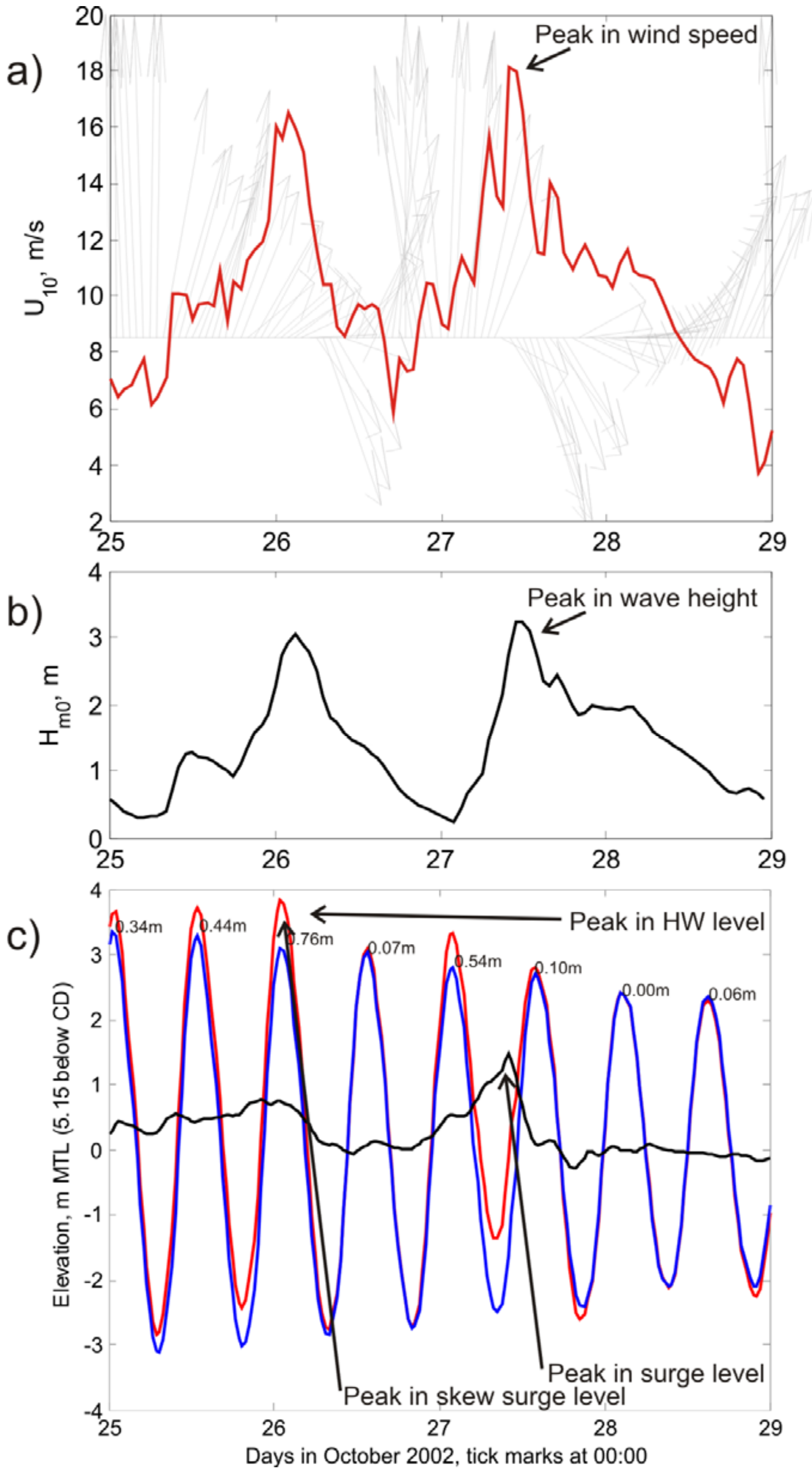

Figure 8: The modelled wind speed with direction at 10m (a), the significant wave height (b) and the surge elevation with tidal elevation and total (tide + surge) elevation (c) at for Formby point. The numbers in (c) indicate the skew surge value during each tide.

The time series in events for the storm in October 2002 shows how the tidal range in relation to the peak in the storm is important. At Formby point there are two peaks in the wind speeds and both peaks consist of winds veering from south west to west leading to extreme hydrodynamic and wave conditions. The most extreme winds occurred on the 27th generating the most extreme waves and surge during this period. However, on the 26th a larger tidal range causes a greater flood risk due to the skew surge. Although the surge is not extreme (<1m) during the 26th the skew surge (additional water level at HW) is slightly larger than that during the 27th. Combined with the larger tidal range on the 26th the skew surge leads to the highest total water level generating an extreme storm tide. The slightly weaker wind speeds at this time produce slightly reduced but still extreme wave heights (>3m) on top of the raised water levels. This combined effect leads to the greatest risk of coastal erosion and flooding on the 26th, while the wind wave and surge conditions are most extreme on the 27th. The failure of the hard defences will depend on the instantaneous wave conditions; conversely, the dune stability is much more complex. An initial set of high tidal levels or storm tides with or without waves may destabilised the due system, but not lead to (significant) breaching or realignment. While a second set of less extreme tides combined with waves or in isolation may cause a significant impact on the system in response to a weakened dune toe.

3. Morphological Impact

The critical storm parameter thresholds to determine dune erosion are not simple (Esteves, et al., 2011a). Important factors leading to erosion include the duration the dune toe is soaked by the tide and whether wave activity occurs at this time. If conditions (e.g. high tides, water table level) destabilised the dunes they become susceptible to erosion during weaker storm conditions than when they are stable. Recovery time between high tides and extreme events is also important to consider along with other factors, such as wind erosion, ground water effects and human activity.

Storms are thought to be the main drivers for coastal evolution and therefore greater understanding of how the coast responds to different offshore storm conditions is important to sustain long-term coastal management. Past trends in storminess for the Sefton coast show little change (Esteves, et al., 2011b). However, understanding the response to a range of present conditions should give good insight into future impact, when considering sea level rise and changes in storm track position. To investigate the response of the shoreline to storm conditions the XBeach model has been setup for a 16km section of the Sefton coast (Fig. 10). This model is specifically designed to simulate dune beach profile response to offshore conditions as they propagate across the nearshore zone and flood inundation over low lying land. An extreme storm, 31st March 2010, was the first storm to hit Sefton since the winter of 2008 and occurred at the end of a period of field surveys. The storm was generated as a low pressure system (980mb) tracked from west to east across the UK during 29 March 2010 to 1 April 2010. At the peak of the storm average wind speeds in the Irish Sea reached ~20m/s with gusts exceeding 25m/s. The northwesterly wind direction generated maximum offshore wave heights of ~3.9m, sustained above

3.5m for ~12 hours, with 8.2s peak period. Historically, storms with these characteristics are not unusual, typically occurring once or twice a year. However, it is more unusual that such events are also coincident with peak spring tide. High tide at Liverpool reached 10m CD and was coincidental with the time of maximum wave conditions. The tidal elevations were sufficient to soak the dune toe, while exposing them and upper beach to wave action. These conditions are often associated with significant morphological impact and have been modelled using offshore hindcast time series from the tide-surge-wave modelling system. The results are encouraging giving confidence in this system to be used as an operational tool (Fig. 11).

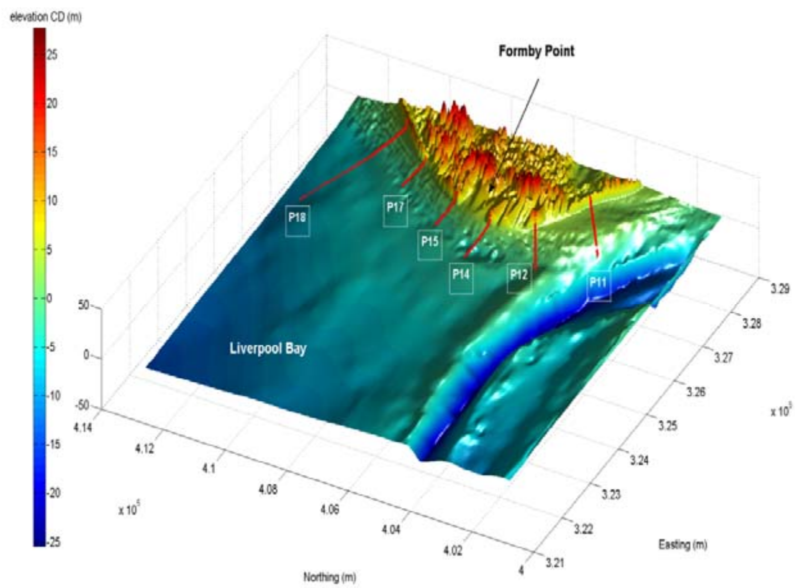

Figure 10: The modelled section of Formby point, with the cross-sections depicted that were used to validate the XBeach model performance.

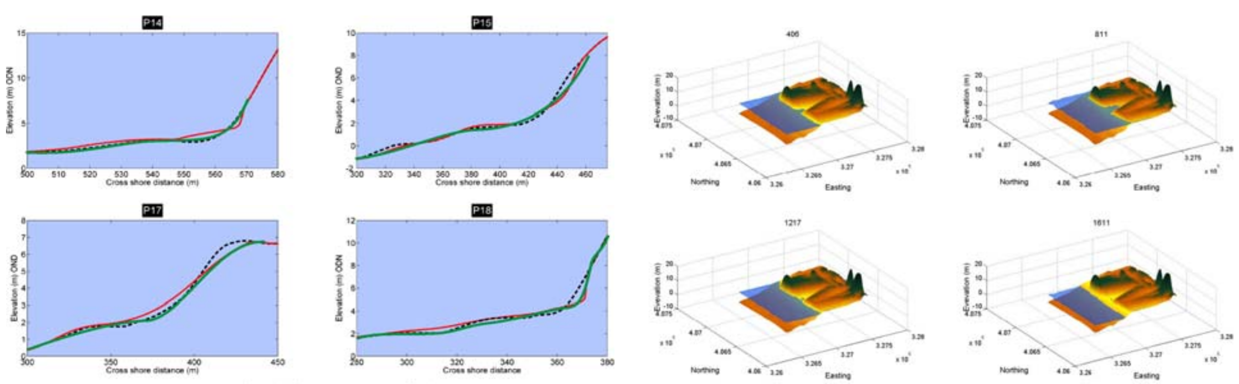

Figure 11: On the left: Observed and modelled 1D upper beach/ dune profiles along select cross-sections in Fig. 10 showing storm impact during the 31st March 2010 event. On the right: Modelled inundation of a dune blow out, cross-section P17 in Fig. 10, during the same storm.

4. Operational modelling

At Formby point storm impact results in erosion of the dune frontage and potential flooding. An early warning of storm impact has been developed to help end-users and stake holders target monitoring around a particular event and at specific locations, potentially vulnerable to erosion and flooding. Forewarning of storm conditions also enables the local authorities to secure (remove or repair) any lose materials on the beach, e.g. chestnut paling, which forms sand trap fencing, to avoid unnecessary damage and cost.

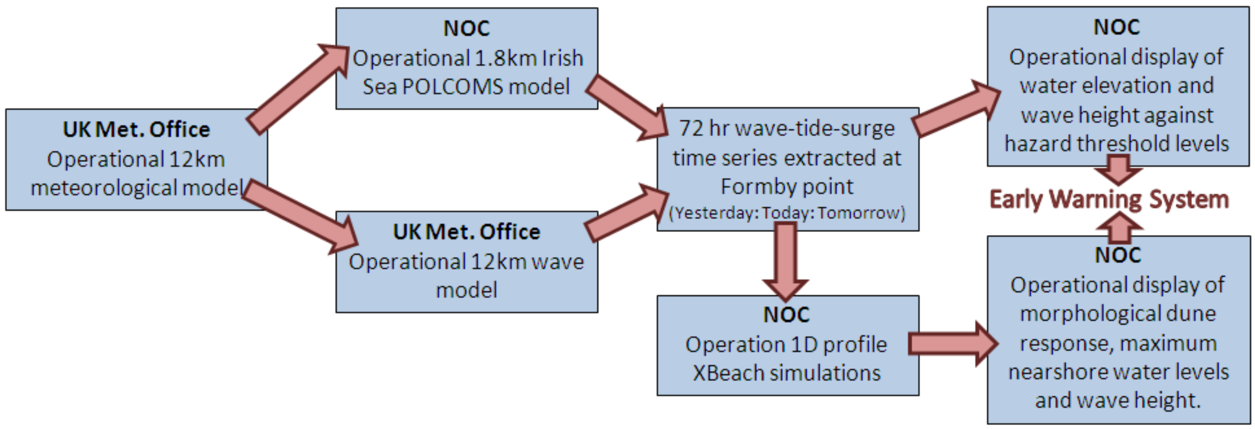

Figure 12: The operational early warning system model flow diagram.

An operational early warning system which updates at 12:00 each day is now available at http://cobsdev.pol.ac.uk/micore/ for Formby point indicating when coastal storm impact may occur along the dune frontage (Fig. 12). The system consists of a front page describing the geomorphology of the study area. This links to risk maps showing the return period water level contours for 1, 10 and 50 year return period storm conditions (Table 1). These water levels were developed using the 11-year model hindcast data set for Liverpool. From historical observation water level thresholds have been determined to define the hazard level of storm impact along the dune frontage (Table 2). Once water levels are high enough to cause a moderate risk wave action enhances the storm hazard. Thresholds for wave height hazard levels have therefore also been determined (Table 2) from historical data. The levels used are based on the storm impact indicators found by Esteves et al. (2011a). For water elevation they are as follows: (a) 9.0m CD, which is just above the water level required for starting dune erosion; (b) 9.4m CD, which is just above the water level suggested to cause 1-2 ma^{-1} of dune retreat and also is the mean high water springs at Liverpool; and (c) 10.2m CD, which is the water level suggested to cause severe erosion. For waves the thresholds are: (a) 2.0m, the typical wave conditions (Brown et al., 2010); (b) 2.6m, low waves conditions that lead to moderate erosion during moderately high water levels; and (c) 4.0m, extreme storm wave heights.

Return period	High water elevation, m CD	Wave height, m
1 year	10.42	4.09
10 year	10.72	5.51
50 year	11.04	6.72

Table 1: The return periods for high water levels at Liverpool and offshore wave heights in Liverpool Bay.

SII	Low risk threshold	Moderate risk threshold	High risk threshold
High water level, m CD	9.0	9.4	10.2
Wave height, m	2.0	2.6	4.0

Table 2: The storm impact indicator (SII) thresholds for water levels at Liverpool and offshore wave heights in Liverpool Bay.

The final part of the early warning system is the operational forecast. By providing a 72 hour (yesterday: today: tomorrow) model simulation facilitates model spin up and also assessment of the accuracy of the forecast period through assessment of the hindcast period. The operational forecast of offshore water level and wave height (Fig. 13) at Formby point is updated at about 12:00 each day and displayed on the website against hazard thresholds for storm impact. This enables local end-users to take required action when hazardous thresholds are crossed at targeted locations. The operational offshore wave-tide-surge forecast data (Appendix I) drives XBeach, enabling a nearshore simulation providing quantative indication of the extent of the expected dune erosion in response to the forecast conditions along specific 1D beach profiles around Formby point. By propagating the offshore conditions towards the beach the maximum water elevations due to wave-tide-surge interaction and wave heights are found for the 24 hour (tomorrow) forecast period over the 1D coastal profile.

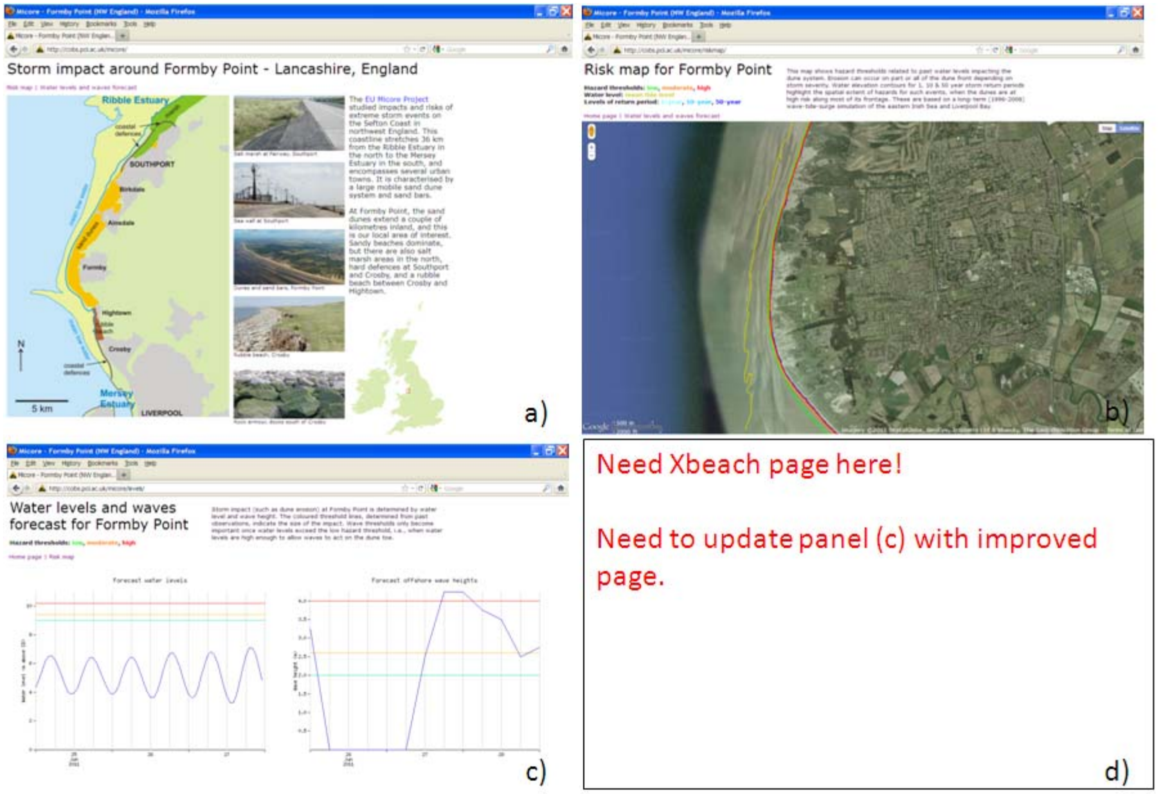

Figure 13: The on-line early warning system: a) the geomorphic map; b) the hazard map; c) the operational elevation and wave height forecast for Formby point. The hazard thresholds indicate the expected level of storm impact, flagging when emergency action may be required; and d) The morphological response to the forecast conditions and maximum nearshore conditions during the forecast period, which may result in impact.

5. Model limitations and future research recommendations

The tide-surge-wave modelling system applied has been previously validated (Brown et al, 2010a) and found to be a useful tool for the prediction of storm conditions across the Irish Sea. The model can therefore be used to give an idea of the extreme offshore storm conditions generated in the eastern Irish Sea as it includes important wave-tide-surge interaction as the storm propagates across the British Isles. For example, which storm track generates the most extreme conditions and an approximation of how large the extreme conditions could be are beneficially simulated by the model. However, caution should be exercised when determining actual values of storm parameters for an isolated storm event in the absence of local validation data. A further high resolution model (180m) of Liverpool Bay could be used for more localised studies of the Sefton coast and is currently being developed to include sediment transport and morphology. This model would enable more detailed investigation into the regional nearshore sediment transport pathways over varying time period such as a storm event, or over an annual or seasonal period.

Development of XBeach to simulate morphological beach and dune impact in response to a number of storms during 2002 to 2008, where field data is available to quantify the gross morphological impact, has allowed reasonable simulation of the morphological impact of isolated storm events or a period of high tidal levels on the Sefton dune system. The model reproduced with moderate skill the recession of the dune frontage and major changes in beach topography for 6 events when forced by the hydrodynamics and waves from model hindcast. Such modelling will enable the quantification of morphological response and flood inundation along sections of the coast, throughout a study region, over a specified period, of extreme or typical conditions, to be made. However XBeach does not consider ground water effects or sediment moisture content and its accuracy will depend on the details of the sediment properties implemented within the model.

The operational model gives a good indication of when a storm may impact the dune system. However limitations of the XBeach modelling system, e.g. starting from the same initial 2010 LIDAR bathymetry and not accounting for dune recovery, means the forecast erosion is only a quantative idea of what may occur. There may also be error in the hydrodynamic and wave forcing related to modelled meteorological forcing and limitations (limited physics) within these models. XBeach is run for select 1D profiles to allow efficient simulation times for operational use. This operational system could in future be extended and optimised for 2D forecasts of erosion and flood inundation within and behind the dune system.

6. Conclusions

Management of flood risk and sand dune realignment of the Sefton coast requires the best knowledge of storm conditions within Liverpool Bay. To determine extreme events in this region state-of-the-art model data has been combined with observation. It has been found that storm tracks generating a sequence of wind conditions, such that winds >17m/s veer from the southwest to west, generate the most extreme storm conditions characterised as follows: significant offshore wave heights >4m, surge elevations >1m and skew surge conditions >0.8m. When combined with extreme tidal levels >9.5m CD these conditions can have significant impact on both the natural and hard defences, posing a potential flood and erosion risk. Such a sequence of storm conditions can be related to recent events that caused morphological impact along the Sefton coast, e.g. 31st March 2010. By setting up a valid tide-surge-wave-impact modelling system for present conditions (events from 1996 – 2010) has allowed the development of a hazard map as part of an early warning system. The use available existing UK operational recourses has enabled a simple operational impact forecasting model for use by end users from the project to be set up. This system indicates when action may be required through the use of elevation and wave height indicators and suggests the amount of impact (erosion) that may occur.

Acknowledgments

This end user report is the consequence of the Morphological impact and coastal risk induced by extreme events (Micore) project, which was funded under the EU FP7 program (Grant 202798). The research to identify storm characteristics leading to potential impact along the Sefton coast for stake holders was the result of collaboration between Jon Williams (Abpmer) and Luciana Esteves (London Met), Alex Souza, Jenny Brown and Judith Wolf (National Oceanography Centre, Liverpool), Graham Lymbery, Michelle Newton and Paul Wisse (Sefton Metropolitan Borough Council) Annie Worsley and Vanessa Holden (Edge Hill University) and Andy Plater (University of Liverpool). The 11-year model data is now held and managed by Sean Gaffney (British Oceanographic Data Centre, BODC) and also by the Micore data dase. Data used to supplement and validate model output was obtained from the UK tide gauge network, (BODC), the Centre for Environment, Fisheries & Aquaculture Science (CEFAS) WaveNet data archive and beach profile measurements from the Sefton Metropolitan Borough Council. Metrological forcing was provided from the UK Met Office mesoscale model and external surge conditions were provided by the UK Operational surge model.

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Appendix I: Existing operational model details

I.2 Metrological Forecasts

The mesoscale UK continental shelf model is run at the UK Met Office four times a day, and gives a weather forecast for up to 3 days in the future. This model is used in the Irish Sea circulation model to calculate heat is exchanged between the ocean and the atmosphere, and drive the surge conditions. In the regional UK wave model the winds are used to simulate wave growth and propagation. The mesoscale model gives a forecast at every 3 hourly interval. It covers the area extending from 48°N to 63°N and 12°W to 13°E with a resolution of 0.11° (approximately 12km) in both directions.

I.2 Tide-surge Forecasts

POLCOMS is the Proudman Oceanographic Laboratory Coastal Ocean Modelling System. This baroclinic-barotropic 3D model runs operationally at the NOC, predicting mean currents, elevation, sea temperature, salinity, chlorophyll, oxygen, and nitrate. The Atlantic Margin Model covers a large area and runs initially to provide output to force the nested Irish Sea Model. The Irish Sea model runs daily covering an area from 7°W to 2.7°W and 51°N to 56°N. The resolution is 1/60° latitude and 1/40° longitude. Most output variables are mean daily values, however the hourly elevation and currents are available for select points of interest (e.g. Formby point as a consequence of this project).

I.3 Wave Forecasts

The UK met office run an operational nested modelling system from a global model to European model to the UK waters wave model. The model used is Wave Watch III, a 3rd generation spectral wave model. The UK model covers the north-west European continental shelf from 12°W, between 48°N and 63°N at a resolution of 1/9° longitude by 1/6° latitude (approximately 12 km). It includes the effect of time-varying currents on the waves, using currents forecast by the operational UK Met Office storm-surge model. The model runs four times daily to give a 48-hour forecast.

I.4 Nearshore forecast [Last facts need completing]

The NOC run XBeach operationally forced by offshore wave-tide-surge conditions once each day to give a 24 hr morphological and maximum nearshore conditions forecast. The model runs for ?? 1D profiles around Formby point with ?? resolution. The model runs at 12:00 each day when the tide-surge-wave operational data becomes available. Each 1D profile is forced by offshore conditions at the nearest sea point to Formby in the existing operational models, these comprise: elevation, depth-average currents, wave height, peak wave period and wave direction.