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Quantification of uncertainties in shoreline response to the representation of offshore wave conditions

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ABSTRACT

This paper presents the results of a sensitivity study investigating beach/dune response to offshore wave boundary forcing. The modelling study was based on the convex-shape Sefton coast, UK which has a complex nearshore morphology and foreshore frontal dunes. Simulations were performed using a cascade of nested grids to transform offshore waves up to a high resolution nearshore XBeach model in which the beach/dune response was modelled. Two storm events representing low and high severity were simulated using uniform and varying offshore wave boundaries. The uniform boundary always resulted in higher storm waves in the XBeach domain. There were differences along the coast based on the coastline orientation and the local morphology, indicating different localised sensitivities to the wave boundary. Bed level change within the tidal regions indicated landward decrease of the wave boundary effect. Volume change in the sub-tidal area showed the highest sensitivity to the space varying wave boundary forcing. Applying a uniform wave boundary for the XBeach domain exacerbated the wave impacts in the model domain. Our study suggests that application of a spatially varying wave boundary condition for the XBeach domain was able to correctly capture sediment transport and hence the beach/dune response of the Sefton coast.

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1. Introduction

Coastal dune systems are rich with biodiversity accommodating local flora and fauna (Carter, 1988), and socio-economic value generating income for the local communities (Hanley et al., 2014), and provide safety against erosion and the hinterland flooding from the seaborn forcing (Harley and Ciavolo, 2013). All these functions are directly related to the existence of the dunes which are mainly threatened by the storm impacts (Tâtu et al., 2014). During storm events, the susceptibility to erosion of the beach/dune systems increases (Karunarathna et al., 2014) and thus strong erosion could lead to dune breaching and flooding. Therefore, the storm impacted dune erosion is of major concern for the coastal safety and the sustainable development of the local areas of which frontal dune systems are present (Dissanayake et al., 2015c).

Process-based coastal hydrodynamic and morphodynamic models have steadily advanced with improved physical processes over the last decades (e.g. Roelvink et al., 2009; Sauermann, 2001; Bosboom et al., 2000). Application of these models to investigate the beach/dune evolution is increased due to 1) predictability of storm impacts in high accuracy and 2) affordability of high computational power and storage capacity. XBeach is one of such process-based models and it was initially developed to simulate the hurricane impacts on the sandy coastal systems in USA (Roelvink et al., 2009). This model has since been applied to various beach/dune systems worldwide while continuously improving the embedded physical processes and in turn the predictive capacity. In the USA, Smallegan et al. (2016) simulated the morphological response of a barrier island fronted with a buried seawall during the impacts of Hurricane Sandy. The results indicated that the seawall decreased the wave impact and protected the nearby infrastructure and dune system. In the Netherlands, Winter et al. (2015) used XBeach to simulate the alongshore variability of the beach/dune response to storms at Egmond aan Zee. The results were able to reproduce the significant wave height with high accuracy (RMSE<0.086). Alongshore beach/dune response showed, XBeach overestimates erosion volume at the locations where dune-scarp occurs, while underestimating erosion volume at the locations of whole dune face collapsing. In Australia, Splinter and Palmsten (2012) simulated the dune toe retreat at Gold Coast using XBeach and two parameter models.
The results indicated, XBeach could reproduce the dune toe retreat and the dry beach volume change. However, the two parameter models were able to develop only dune retreat while underestimating the dry beach volume. These studies motivated us to use the XBeach model in the present study to investigate the beach/dune evolution on the Sefton coast, Liverpool Bay, UK.

The Sefton coast has been subjected to several process-based numerical model studies exploring the dune erosion processes. Williams et al. (2011) simulated storm impacted erosion and potential hinterland flooding at the local areas of the Sefton coast using XBeach in 1DH and 2DH modes. The wave boundary forcing was imposed as time-invariant (i.e. single wave) condition over tidal cycles. These conservative approaches showed overestimation of the storm impacts (e.g. excessive beach accretion during storms). Dissanayake et al. (2014) used the XBeach model (2DH) imposing spatial-uniform and temporal-varying wave boundary to simulate the erosion processes during

the March 2010 storm event at the Sefton coast. The model predicted erosion and sedimentation patterns along the susceptible areas due to the interaction of the nearshore ridge-runnel features with the approaching storm waves. However, the profile comparison showed that XBeach underestimates erosion for the profiles located north of Formby Point (i.e. the central point of the Sefton coast), which are attributed to the resolution of model domain and boundary forcing, and the limitations of profile measurements and model parameterisation. Impacts of the 2013/2014 catastrophic winter storm events on the Formby dune system (i.e. the centrally located dunes of the Sefton coast) were modelled by Dissanayake et al. (2015a,b) using XBeach. A 1DH approach was used in Dissanayake et al. (2015a) and three storm events of decreasing severity from the 2013/2014 winter were simulated to investigate the sensitivity of the beach/dune evolution to the wave chronology of a storm cluster. Results indicated that the occurrence of storm events in increasing severity causes the highest bed evolution. In Dissanayake et al. (2015b), a 2DH approach was employed to simulate the storm impacted beach/dune evolution during the entire storm cluster (i.e. 7 events) in the 2013/2014 winter period.
Each storm event was imposed using a spatial-uniform and temporal-varying wave boundary forcing type. Predicted erosion and sedimentation patterns along the coast showed the sensitivity to the severity of the imposed storm events. Furthermore, the clustering effect on the bed evolution increased as the number of events in the cluster increases. These modelling studies of the Sefton coast have only employed single wave conditions or spatial-uniform wave boundary forcing representing storm events. Other XBeach studies have also used so far spatially uniform wave boundary forcing which is mainly based on the data from an offshore located wave buoy (e.g. Smallegan et al., 2016; Winter et al., 2015; Vousdoukas et al., 2012). Furthermore, these exemplary studies have modelling areas with straight coastal segments and more or less uniform nearshore bathymetries therein. However, it should be noted that the Sefton coast has a convex-shape coastline with a complex nearshore ridge-runnel pattern (i.e. about 3 km seaward extension). Our hypothesis in this study is that, for more complex scenarios such as at Sefton, the representation of offshore wave conditions as being spatially uniform contributes to the errors in predicting beach/dune response. Therefore, the novelty of the present study is investigating the effect of the spatial-varying wave forcing on the Sefton beach/dune evolution.

The objective of this study is to investigate the sensitivity wave boundary conditions, which have on the storm driven beach/dune evolution by simulating spatially-uniform and spatially-varying (hereon referred to as uniform and varying respectively) wave boundary forcing. All wave boundary conditions are temporal-varying.

In the following, we first describe the study site in Section 2 and then the selected storm events in Section 3. The modelling approach is given Section 4. Section 5 provides the model results and the discussion. Conclusions are presented in Section 6.

2. Study site

Wave boundary impacts on the beach profile evolution were investigated by modelling the storm erosion of the Sefton coast, which is located in the Liverpool Bay, the northwest coast of the UK (Figure 1). The Sefton coast has a convex shape spanning about 36 km between the Mersey estuary (to the south) and the Ribble estuary (to the north). The Sefton dune system represents about 20% of the UK's entire dune systems and extends about 4 km landward and the maximum dune height reaches about 20 m (Souza et al., 2013). These dunes provide safety against storm impacts for the hinterland areas, which consist of high socio-economic and ecological interest (Edmondson, 2010).

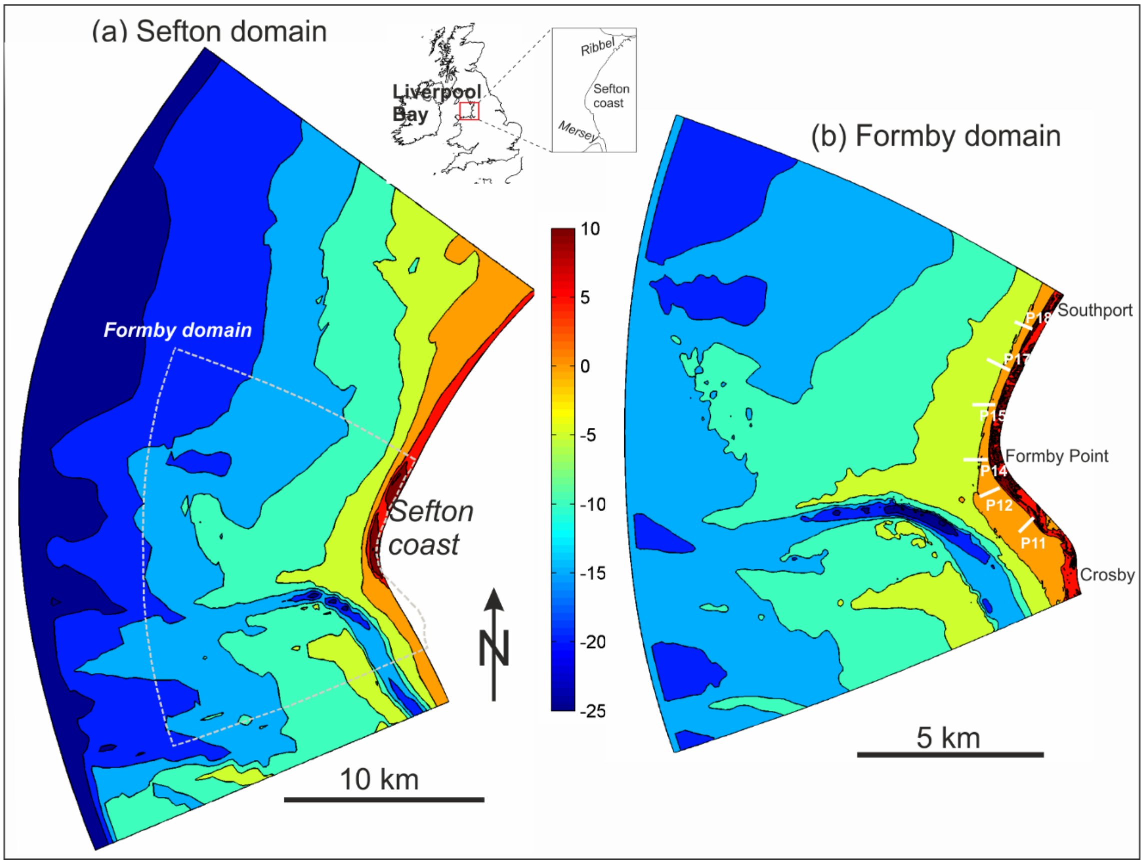

Figure 1 Location of Liverpool Bay and Sefton coast (bounded by Mersey and Ribble estuaries) with the two model domains: Sefton domain (dash-line indicates the outline of Formby domain) and Formby domain with the selected profile locations for the analysis: P11-P18

Environmental forcing from tides and waves continuously shape this beach/dune system. Liverpool Bay has an alongshore propagating semi-diurnal tide with a mean spring tidal range increasing up to about 8.2 m (Palmer, 2010). Long-term wave characteristics show that the mean annual significant wave height is about 0.5 m while the extremes reach about 6 m (Brown et al., 2010b). Extreme surges exceed 2 m in the Liverpool Bay (Dissanayake et al., 2015a). Large surges generally occur during the rising tide and the maximum surge recorded at high water in the Liverpool Bay is 1.5 m on the 12th November 1977 (Brown and Wolf, 2009). Wolf et al. (2011) note that the largest wave conditions are associated with the west to north-west winds where the longest fetch exists. The nearshore area of the Sefton coast is characterised by a shore-parallel ridge- runnel system extending about 3 km seaward with a very mild slope of about 1:100 (Plater and Grenville, 2008). The sediment properties of this coast are determined by the tide dominated net onshore transport and the inflow of the adjacent estuaries. Sediment composition has the median grain size (D_{50}) in the range of 0.1 to 0.3 mm (Pye and Blott, 2008).

Susceptibility to erosion changes in response to the initial state of the beach profile, which has a seasonal cycle in beach elevation and short-term response to storm events influencing the ridge-runnel system (Pye and Blott, 2008). The Sefton dune foot (+4.8 m ODN) is located just above the mean spring high water level and the upper dune profile shows steep gradients particularly around Formby Point (Dissanayake et al., 2015c).
Therefore, the primary processes of dune erosion are the soaking of dune toe and the wave undercutting which can lead to slump of the dune face and then dune retreat. These processes are enhanced when extreme storm surge and wave event coincide with the spring high-tide. A recent example is found during the 2013/2014 winter storm cluster.
Peak storm wave (~4.5 m) conditions during the first storm event (D1) coincided with a water level > 6 m (Dissanayake et al., 2015a). However, there is a potential of significant erosion during storm surges with high wave energy (Halcrow, 2009). Smaller storms erode only a part of the Sefton coast while erosion of the entire dune frontage is possible during the most severe storms (e.g. D1). The convex-shape of the coast leads to different morphological changes along the coastline due to variations of the shoreline orientation to the wave climate. The apex, Formby Point, experiences erosion while the southern and the northern coastlines show seaward progradation (Pye and Neal, 1994). Therefore, Formby Point presently sits at the point of divergence within the onshore sediment pathway and provides a local sediment source delivered southward and northward.
Esteves et al. (2009) found that the annual dune retreat at north of Formby Point is about 5 m during the period from 2001 to 2008 and the morphological changes at Formby Point influence the evolution of the entire Sefton coastal system.

3. Selection of storm events

A storm event is defined based on a storm threshold wave height, which is 2.5 m for the Sefton coast (Dissanayake et al., 2015c), and there were seven storm events occurred within a cluster during the 2013/2014 winter period (Dissanayake et al., 2015b). Two of these events, D1 the first storm event occurred from 03:30 hr on the 5th to 04:00 hr on the 6th December 2013 and J2 the second storm event occurred from 10:30 hr to 18:30 hr on the 23rd January 2014, were selected to model the storm impacted erosion at the Sefton coast, applying uniform and varying wave boundary forcing. Storm power indicates the severity of a storm event and it is calculated based on the variation of wave height and the storm duration (Dissanayake et al., 2015b). D1 spanned 24.5 hrs and had a storm power value of 266 m^2hr, and J2 spanned 8.0 hrs and had a power of 52 m^2hr (Dissanayake et al., 2015b). Therefore, we selected these two events so that the storm power value is approximately five times large in D1 compared with J2, representing a high severity and a low severity event respectively. Water level (i.e. Astronomical tide + storm surge) and wave height variations during D1 and J2 with the storm threshold wave height (i.e. $H_{s,threshold}$: wave height is 2.5 m) are shown in Figure 2 based on the measured data at the UK Centre for Environment, Fisheries and Aquaculture Science (CEFAS) WaveNet buoy (see Figure 4). The peak storm wave height of D1 was higher than 4.5 m and coincided with the spring high-water (> 6 m ODN). The J2 event coincided with an intermediate tidal range between spring and neap conditions while reaching the maximum wave height of approximately 2.9 m. Therefore, each event also indicates a reduction in tidal range to assess the influence of uniform and varying forcing over a range of wave-water level conditions.

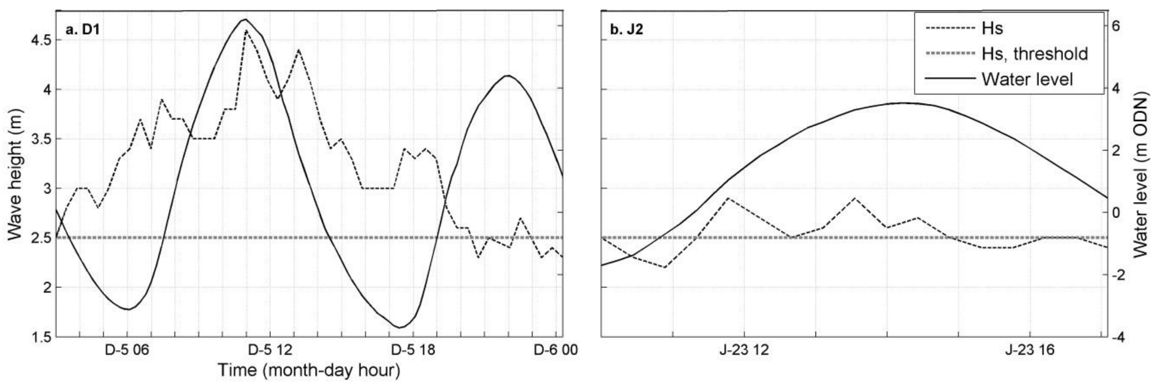

Figure 2 Wave height and water level during the selected two storm events D1 and J2 from the 2013/2014 winter period as defined in Dissanayake et al. (2015b).

Variation of wind speed during D1 and J2 with wind and wave directions is shown in Figure 3. In D1 (a), the wind speed was higher than 20 m/s during the occurrence of the peak storm wave height. Furthermore, both wave and wind approached the Sefton coast from the westerly directions during higher waves. Analysis on the previous events has shown that wind approaching from W-SW and W-NW sectors causes major events on the Sefton coast (Brown et al., 2010a). In the rest of the storm period, the wind speed decreased down to about 15 m/s, while wave and wind directions remained in the W-N quadrant. In J2 (b), both wind and wave had landfall in a quite similar direction between W and NW. It should be noted that the approach direction is fairly constant throughout the event. The maximum wind speed during this event was 16 m/s and the minimum was 12 m/s.

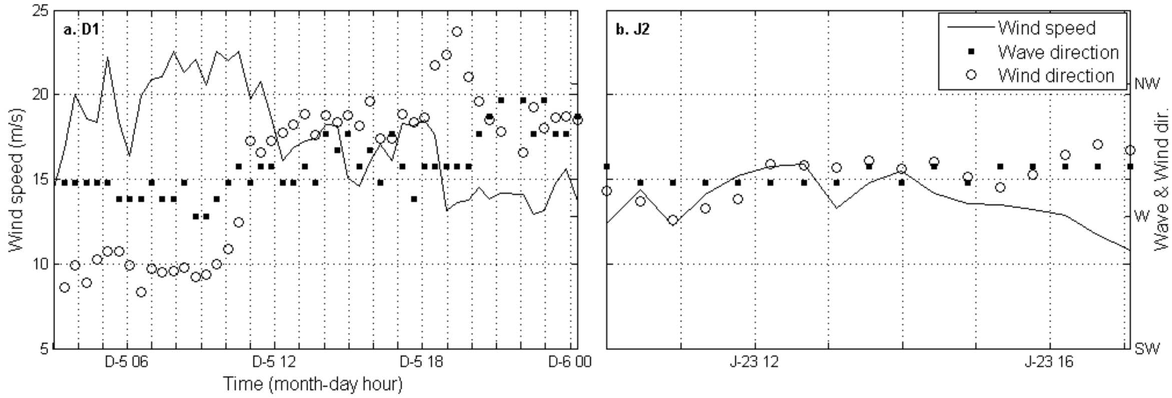

Figure 3 Variation of wind speed with wind and wave directions during storm events D1 (a) and J2 (b).

4. Modelling approach

We adopted the same nested model setup as in Dissanayake et al. (2015b), a large coarse-grid domain is used to transform offshore hydrodynamics to the boundary of a high-resolution coastal domain of which beach/dune evolution is simulated under different wave boundary forcing scenarios using D1 and J2. This approach optimised the computational time while accurately representing the nearshore topography of the beach/dune system. Calibration of this model setup was carried out using water level and wave height variations, and morphodynamic evolution (Dissanayake et al., 2014; 2015b).

Models

Three numerical models, Delft3D, SWAN and XBeach, were used in this study. The first two models were employed to simulate hydrodynamics only. XBeach was used to simulate both hydrodynamics and morphodynamics. The Delft3D modelling suite is based on the nonlinear shallow water equations and has different modules (Lesser et al., 2004). The basic module is Delft3D-FLOW in which hydrodynamics are calculated and used as input for the other modules (e.g. Delft3D-WAVE: Short wave propagation, Delft3D-SED: Sediment transport). SWAN is a spectral wave model which simulates shortwave-generation, -propagation and -dissipation, and based on the discrete spectral action balance equation (Booij et al., 1999).

XBeach is a 2DH coastal morphodynamic model developed to simulate dune erosion due to hurricane impacts (Roelvink et al., 2009). XBeach is also based on the nonlinear shallow water equations. Sediment transport is computed as the total load transport according to the Soulsby-Van Rijn formulations (Soulsby, 1997). This study used an average sediment size of 0.2 mm (D_{50}) according to Pye and Blott (2008). XBeach simulates morphological changes using the *morfac* approach (Roelvink, 2006). Real-time morphodynamic evolution during storm impact was simulated applying a *morfac* of 1.
XBeach estimates dune erosion within four regimes: swash, collision, overwash and inundation as described by Sallenger (2000). In the swash-regime, the nearshore hydrodynamics are resolved by employing a 2DH description of wave groups and

infragravity motions (Roelvink et al., 2009). Wave group forcing, which drives the infragravity motion and longshore and cross-shore currents, is derived from a time varying wave action balance equation. In the collision regime, sediment transport from the dry dune to the wet swash is estimated with an avalanching model using a critical dry slope and a critical wet slope. During swash and collision regimes, XBeach calculates offshore sediment transport by return flow or rip-current. This facilitates progressive erosion due to removing sediment from the slumped dune face. In the overwash regime, XBeach calculates the landward sediment transport due to onshore flux of water driven by the wave group forcing. This results in depositing dune sand landward as overwash fans. In the inundation regime, dune breaching occurs due to formation of a new channel cutting through the dunes. XBeach calculates the dune breaching based on the sediment transport induced by the dynamic channel flow and the avalanching triggered bank erosion.

Model domains and grid setup

The two model domains are Sefton and Formby (Figure 4a and b) which were used to simulate the wave boundary impacts on the beach/dune evolution. The coarse-grid Sefton domain was employed to simulate offshore hydrodynamics up to the nearshore area using Delft3D (Lesser et al., 2004) and SWAN (Booij et al., 1999). Delft3D was first used to simulate spatial and temporal varying sea surface elevations and velocity fields, which were then used in SWAN to simulate the storm wave parameters (Hs, Tp, Wave direction and Wave spreading) up to the offshore boundary of the high-resolution Formby domain. These wave parameters and water levels of the Sefton domain, in turn, were used to define the boundary conditions to simulate morphological changes within the Formby domain using XBeach (Roelvink et al., 2009).

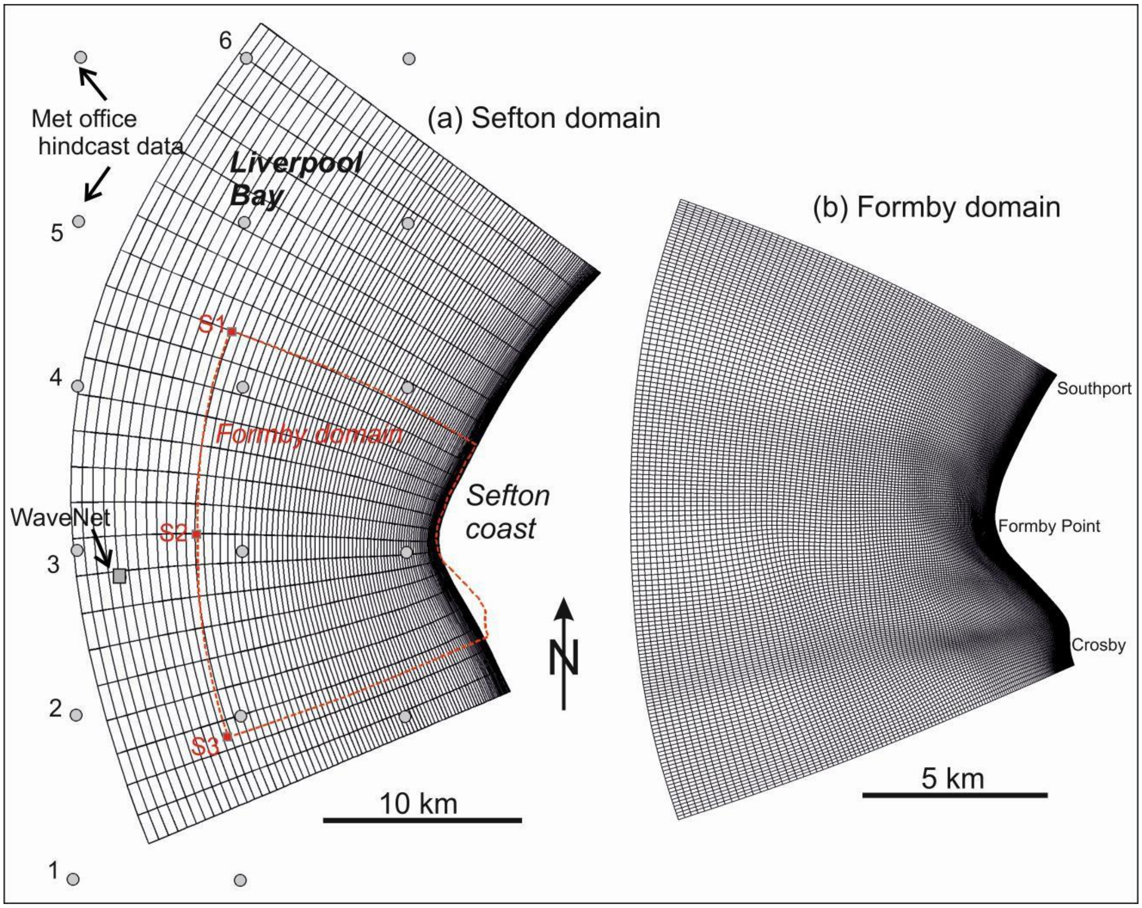

Figure 4 Grid setup for Sefton (a) and Formby (b) domains. Grey-circles: Met office hindcast wave data, grey-square: WaveNet buoy, red-dash-line: the outline of Formby domain, and S1, S2 and S3 are locations used for boundary wave condition. Every other second grid point is shown in both grids

Both domains consist of curvilinear grids which follow the convex-shape of the Sefton coastline and the dune topography. The Sefton domain extends over a 26 km length coastal stretch from the south of Crosby to the north of Southport representing the entire dune system. The offshore boundary was selected close to the WaveNet buoy (Figure 4a), of which the wave data was used for the wave boundary forcing. Lateral extension of this model is about 23 km offshore and the length of the offshore boundary is about 45 km.

Fairly coarse grids were applied in both *x* (cross-shore) and *y* (alongshore) directions (minimum grid at the beach/dune system ~25 m × 650 m and maximum grid at the offshore boundary ~300 m × 800 m). The Formby model domain encloses the highly dynamic Formby Point area and extends about 12 km alongshore from Crosby to Southport (Figure 4b). The offshore boundary was established following the concept of closure depth (Hallermeier, 1983). The estimated closure depth of the Liverpool Bay is about 15 m depth (i.e. $d_{doc,outer}$) using the empirical relation of Hallermeier (1983). This results in a lateral extension of about 15 km offshore from the Formby domain. High resolution grid cells (~ 2 m × 25 m in *x* and *y*) were applied in the beach/dune area in order to resolve the dune shape accurately and coarser grid cells (~ 150 m × 110 m) were used at the offshore.

Model bathymetry

Model bathymetry (i.e. sea bed and beach/dune topography, Figure 1a and b) was established by combining the bathymetry used in the National Oceanography Centre POLCOMS model (Bricheno et al., 2014; Brown et al., 2010a) and the LiDAR data (i.e. observed at the 11th October 2013, personal communication with Sefton Council). The POLCOMS bathymetry has a horizontal resolution of 90 m and extends from the Sefton dunes (+5 m ODN) to an offshore depth about -50 m ODN in the Liverpool Bay (Williams et al., 2011). The high-resolution LiDAR data (at 1 m horizontal resolution) covers the entire dune system down to about +2 m ODN depth. Therefore, the LiDAR data was used to construct the model bathymetries from the dune crest down to +2 m ODN while the bathymetry of the rest of the model domain (depth < +2 m ODN) was implemented using the POLCOMS bathymetry. The offshore boundary of the Sefton domain was located at -25 m ODN (i.e. close to the WaveNet buoy, see Figure 4a), and that of the Formby domain was set at -15 m ODN which is beyond the closure depth (i.e. $d_{doc,outer} < -15$ m).

Boundary forcing

Simulations in both domains were carried out by imposing tide, wind and wave boundary forcing. Tidal boundary was applied as alongshore propagating tide. Wind was applied as a spatial-uniform and temporal-varying wind field. Wave boundary was always temporal-varying with spatial-uniform and spatial-varying combinations (Table 1). Time series of these forcing for the Sefton domain were first established using the measured and the hindcast data for the durations of the selected D1 and J2 storm events from the 2013/2014 winter period. Thereafter, the boundary forcing for the Formby domain was set up using the simulated hydrodynamics of the Sefton domain. An alongshore (south to north) propagating tidal series were constructed using the data from the tidal gauges in Liverpool Bay following the approach of Dissanayake et al. (2014). Initially, the phase difference of the tidal wave between the north- and south-offshore points of the Sefton domain was estimated using the gauge data and the POLCOMS model predictions (Bricheno et al., 2014). Next, using the estimated phase difference and the observed tide data at the WaveNet location (Figure 4a), the time series of tide at the north- and south- points were established. Wind time series, which were uniformly applied on the model domains, were developed using the observed wind data at the nearby Hilbre Island (Dissanayake et al., 2015b). Hilbre Island is located close to River Dee to the south of the Sefton coast. Therefore, the wind data represents nearshore information rather than offshore. However, previous modelling studies have used this data to reproduce hydrodynamics and morphodynamics of the Sefton coast (Brown, 2010; Williams et al., 2011; Dissanayake et al., 2014). Uniform and varying wave boundary forcing for the Sefton domain was established using the UK Met office hindcast wave data (grey-dots in Figure 4a) in the Liverpool Bay (Leonard-Williams and Saulter, 2013). The hindcast data has 1 hour temporal resolution and approximately 8 km $\times$ 8 km spatial resolution. The uniform wave forcing for the durations of the D1 and J2 events was set up using the wave

data at the point 3 (i.e. the neighbouring hindcast point to the WaveNet buoy, see Figure 4a). The varying wave forcing used the wave data from the points 1 to 6, which are located adjacent to the offshore boundary of the Sefton domain. Six segments were defined along the offshore boundary, based on the spatial distribution of these six hindcast wave data points. Thereafter, the wave data for the storm durations from the respective points was directly applied for the corresponding segments to establish the varying forcing. Wave boundary forcing for the Formby domain during D1 and J2 was set up using the simulated SWAN wave-spectrum at S1, S2 and S3, which are located along the offshore boundary (Figure 4a). It should be noted that applying uniform or varying wave boundary for a coarse-grid model (e.g. Sefton) depends on the data availability. However, after simulating such a large model provides enough information to set up a varying boundary for a high resolution sub-domain (e.g. Formby). Therefore, we developed varying boundary for the Formby domain using the simulated wave spectrum at S1, S2 and S3 in both wave boundary scenarios of the Sefton domain.
Additionally, two uniform boundaries for D1 and J2 were also set up using the wave spectrum at S2 only to further investigate the sensitivity on the beach profile evolution.

Variation of wave characteristics at the WaveNet buoy and the Met office hindcast data along the offshore boundary of the Sefton domain (see numbers from 1 to 6 in Figure 4a) is shown in Figure 5 for the durations of D1 and J2. All points tend to represent the storm wave signature as observed at the WaveNet buoy. However, the hindcast data does not consist of small variations as found with the buoy data. In the D1 event, the highest peak storm wave height is found at the most northward point (6) and then the peak wave height decreases from north (6) to south (1). It is further noted a phase lag of peak storm wave height which increased towards south. Peak wave periods at all locations of the hindcast data are fairly similar whereas they appear to be smaller than the WaveNet buoy values during the peak storm wave heights. Hindcast wave directions show generally a better agreement with the buoy data except at the most southerly location (1). In the J2 event, the hindcast wave heights at all locations are lower than the WaveNet data. However, wave periods are almost same at these locations and it has a better agreement with that of the buoy data. Wave directions at the locations from 2 to 6 better agree with the buoy directions, and they are close to west. The direction at the southern location (1) is nearly from northwest. In both storm events, the point 1 shows the highest deviation with the other hindcast locations as well as with the buoy data. This comparison indicated that the wave characteristics (particularly wave height and direction) vary based on the spatial locations. Therefore, a varying wave boundary will be able to represent the most realistic spatial variability of the wave forcing along the offshore boundary of the Sefton domain. Furthermore, the hindcast data had some difference compared with the WaveNet data. In this sensitivity analysis, we are not comparing the measured beach/dune profiles after storm events with the simulated results, and therefore such difference will not affect on the impacts of wave boundary types.

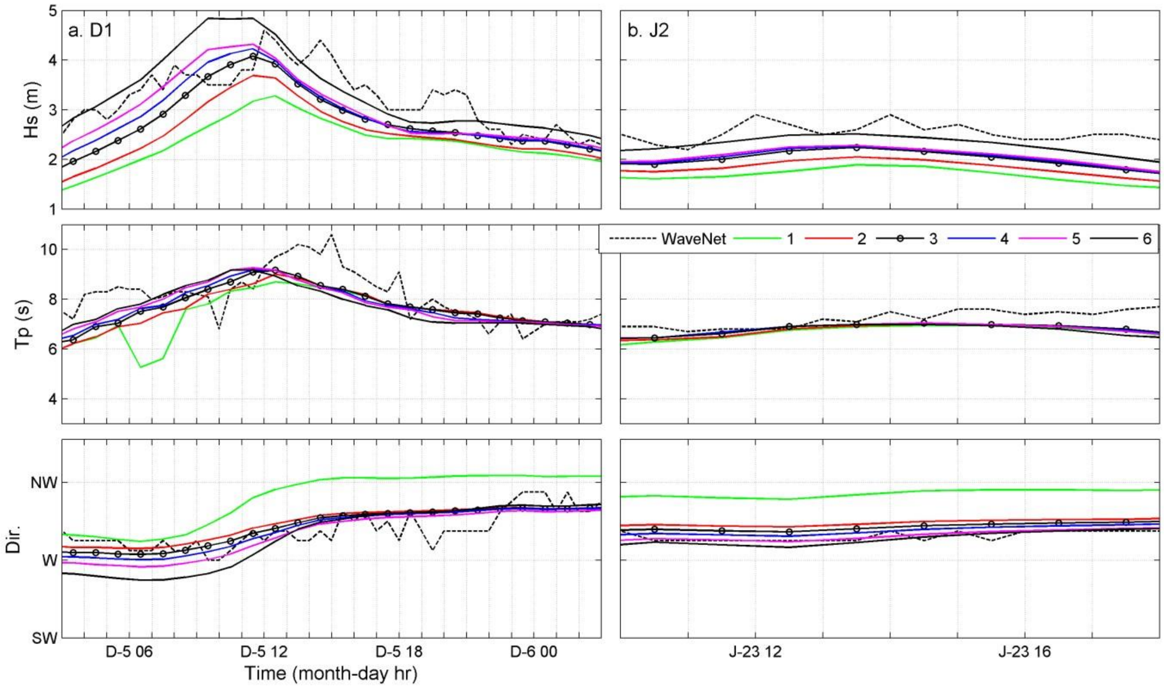

Figure 5 Significant wave height (Hs, m), Peak wave period (Tp, s) and Wave direction of the WaveNet data and the Met Office hindcast data points along the model boundary (from 1 to 6, see Figure 4a) during storm events D1 and J2

Model simulations

We carried out two series of model simulations (H: Hydrodynamics and M: Morphodynamics) using the Sefton and Formby domains within the periods of the two storm events D1 and J2, and they are summarised in Table 1. It should be noted that the model setup with the Sefton and Formby domains has already been calibrated for the 2013/2014 winter storm events by Dissanayake et al. (2015c). Their settings were therefore adopted for each simulation of the present study. In the first series (H), the simulations of the Sefton domain were carried out taking into account coupled wave- current interactions using Delft3D and SWAN to transform the offshore storm hydrodynamics up to the boundary of the Formby domain. For each storm event (D1 and J2), this simulation was carried out applying both uniform (H1 and H2) and varying (H3 and H4) wave boundary types. In the second series (M), XBeach was used to simulate storm-induced morphodynamic change in the Formby domain. This series of simulations was systematically carried out by applying the varying wave boundary conditions based on the wave characteristics at S1, S2 and S3 as described earlier in boundary forcing. M1 used the simulated wave data from H1, M2 from H2 and so on. Application of the varying wave boundary conditions for the Formby domain is able to represent the spatial variability of the storm waves along the computational domain. Two additional simulations for D1 (M11) and J2 (M21) were carried out using the uniform boundaries developed from the wave data at S2 only from H1 and H2 respectively. The hydrodynamic models within the Sefton domain were simulated from 00:00 hr on the 05th December 2013 to 00:00 hr on the 31st January 2014 (Note. D1 event begins at 03:30 hr on the 5th December). The morphodynamics with the Formby domain were simulated applying a spin-up period of 0.5 hr in addition to the storm event duration.

Model simulation	Storm event	Wave boundary		Model	Domain
H1	D1				
H2	J2				
H3	D1				
H4	J2				
M1	D1		S1, S2 and S3 (Figure 4a) from H1		
M2	J2		S1, S2 and S3 from H2		
M3	D1		S1, S2 and S3 from H3		
M4	J2		S1, S2 and S3 from H4		
M11	D1		S2 only from H1		
M21	J2		S2 only from H2		

Table 1 Model simulations applying Sefton domain (Hydrodynamics: H) and Formby domain (Morphodynamics: M) within two storm events (D1 and J2) using Uniform and Varying boundary conditions

The morphological simulations (XBeach) were carried in the Swansea University 'Blue Ice' HPC Linux Cluster which has 600 CPU-core and 1.2TB RAM processing capacity. The required computational time for D1 is about 25 hours and it is about 1.5 hours for J2. It should be noted that the Formby domain has more than 88000 grid cells.

5. Model results and discussion

Simulated storm waves using uniform (H1 and H2) and varying (H3 and H4) boundary of the Sefton domain was first compared at the three offshore boundary locations of the Formby domain (S1, S2 and S3) (Figure 4). Thereafter, the simulated morphodynamics of the beach/dune system under each boundary condition type were compared with each other to investigate the sensitivity on the bed level changes along the Sefton coast to the wave boundary types. The comparison was carried out considering the beach/dune evolution during the two storm events (D1 and J2) at the dune toe and of the cross-shore profiles along the entire beach/dune area.

Simulated wave boundary

Simulated wave characteristics at S1, S2 and S3 of the Sefton domain are shown in Figure 6 for the durations of the two storm events (D1 and J2), and these results were used to set up the wave boundary forcing for the Formby domain. In the D1 event, the uniform boundary resulted in higher wave heights (Hs) at all three locations compared with that of the varying boundary. However, both boundary types present a spatial variability of the storm wave. Applying the uniform boundary, S1 tends to have the highest wave heights, while S3 has the lowest. Wave height variation at S2 is found between those of the other two points. After the peak storm wave height, S2 exceeds S1 for about 6 hours. Furthermore, the occurrence of the peak storm wave height shows a time lag among these locations (~ 1 hour). Therefore, the storm reached S1 first and then S2 and finally S3. Similar trends but lower wave heights were found at the three locations when the space-varying wave boundary was applied. Furthermore, the occurrence of the peak wave height at S1 and S2 coincided in the varying boundary, but not with the uniform boundary. Peak periods (Tp) also show generally higher values at all three locations with the uniform boundary than that of the varying boundary. However, the differences between the values at the three locations and also between the boundary types is lower compared with that of the wave heights. In the case of wave directions (Dir), both boundary types show more or less similar variations. The spatial variation at S1, S2 an S3 is still found in both boundary types. In the lower wave height J2 event, these three parameters show smooth variations compared with that of D1. The spatial variability at S1, S2 and S3 is also noticeable. Wave heights are higher with the uniform boundary than the varying type. However, the maximum difference between S1 and S3 is about 0.7 m in both wave boundary types. Peak periods also have higher values applying the uniform boundary compared with the varying type. They present a noticeable spatial variability between S3 and the other two, than between S1 and S2, similar to that in D1. Wave directions show slight veering from W to NW particularly at S1 and S2 in both boundary types. At S3, they are nearly constant during the storm event J2. It should be noted that the difference between the boundary types is lower than the difference among the spatial locations as found in D1.

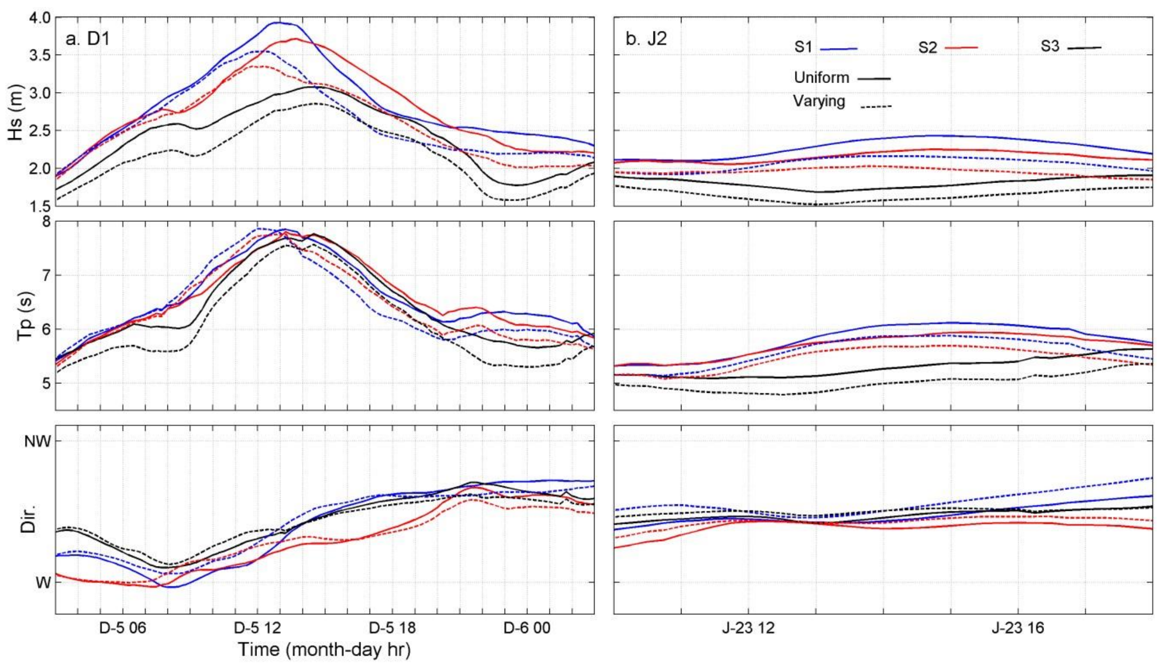

Figure 6 SWAN model predicted wave characteristics at S1, S2 and S3 (see Figure 4a) using Uniform (H1: D1 and H2: J2) and Varying (H3: D1 and H4: J2) boundary of the Sefton domain

These simulated wave characteristics show that applying the uniform boundary results in higher storm waves though they tend to develop spatial distributions similar to that of the varying boundary type. Therefore, applying an uniform wave boundary for the Formby domain could overestimate the characteristics of the storm wave events.

Dune toe level change

During D1, the water level raised up to more than 6 m ODN while the maximum water level in J2 was about 3.5 m ODN (Figure 2). Therefore, the dunes could be severely affected in D1 due to direct wave impacts and also due to the wave undercutting (Dissanayake et al., 2014). Evolution of the dune toe level during D1 when applied uniform (M1) and varying (M3) offshore wave boundaries was therefore estimated at the south part of the coast (P11, see Figure 1b), the apex of the Sefton coast (P14, Formby Point) and the north part of the coast (P17). Resulting change of the dune toe (Figure 7) was computed with respect to the initial bed topography at these locations. Positive change indicates accretion (i.e. slumping of the upper dune area) and negative implies erosion (i.e. removing of sand and lowering the bed) at the dune toe level. The dune toe change at Formby started during the rising tide while the south and the north locations have been impacted during the highest tide at 11:00 hrs (see with Figure 2). After reaching the mean water level (at 14:00 hrs), all three locations show no further changes to the dune toe. Both Formby and the south location show positive change. At Formby, M1 resulted in higher change than that of M3. Formby experienced a maximum change of about 0.011 m and the difference between wave boundaries is marginal (10^{-3} m).
Higher impacts in M1 than in M3 occurred due to the higher wave heights derived from H1 than the wave heights of H3 (see Figure 6). The highest dune toe change of these three locations resulted at the south (0.055 m) and both boundary types show more or less similar evolution. It appears that the wave boundary effects are minimal at the southern coast. This could be due to lower wave heights at S3 (Figure 6). Furthermore, the southern coast is fairly protected from the W-NW waves with the convex orientation of the Sefton coast. In contrast to Formby and the south, the north coast has experienced erosion because it is rather exposed to the approaching storm waves from the W-NW sector. The maximum erosion of -0.025 m is found in M3 and the erosion in M1 is slightly lower (-0.021 m). This location experienced higher wave impacts (i.e. S1 has the highest waves). However, the presence of the nearshore ridge-runnel could cause to dissipate the higher wave heights in M1 leading to lower impacts at dunes compared with that in M3.

Applying the uniform boundary for the Formby domain (M11) resulted in different morphodynamics at these locations. Both M11 and M3 showed the similar dune toe accretion (positive) at Formby. As previously found, the south coast experienced accretion while the north coast showed erosion. However, M11 resulted in marginal change than that of M3 at both locations (maximum change < 0.015 m), indicating fairly similar evolution at the dune toe if the high resolution domain (Formby) is applied with an uniform boundary.

These results indicated that the boundary wave heights at the offshore of the coarser domain (Sefton) alone do not determine the dune toe change. Based on the variations of the nearshore bathymetry and the coastline orientation, the approaching storm wave from offshore to the beach/dune system significantly differs leading to different morphodynamics along the coast. During the D1 event from W-NW, the increased erosion at the north coast provides increased sediment supply towards south leading to reduction of erosion at the southern coast.

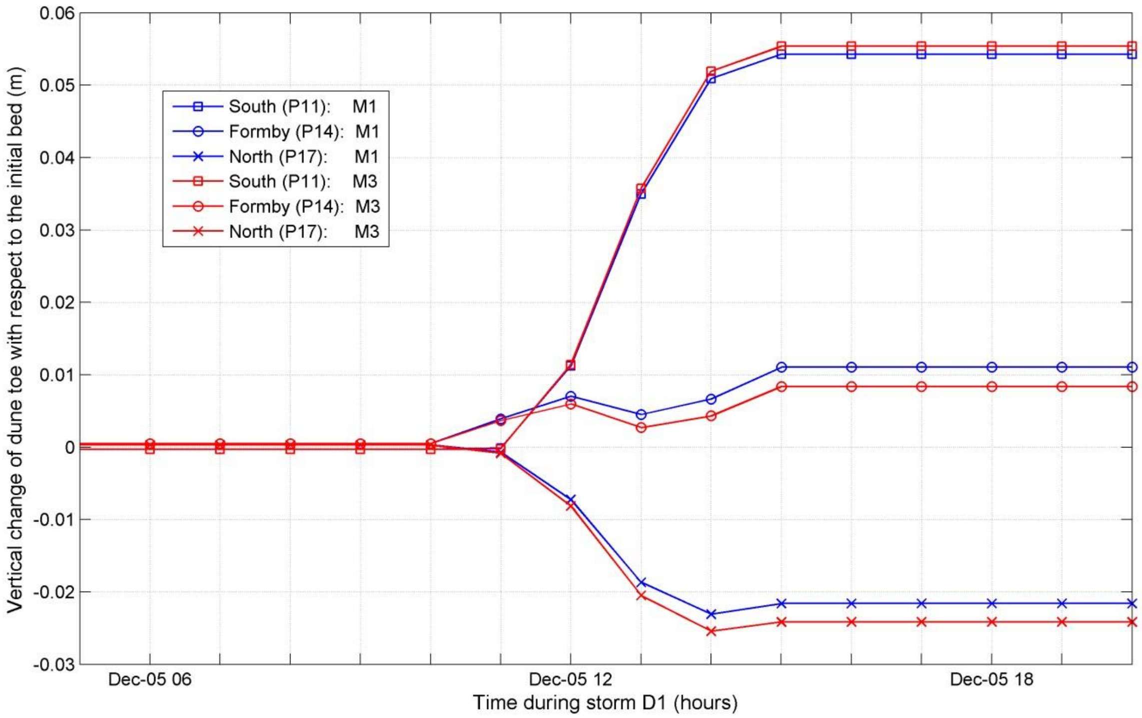

Figure 7 Vertical change of the dune toe level (+4.8 m ODN) within the storm event D1 at the south coast (P11), Formby Point (P14) and the north coast (P17) in M1 (blue lines) and M3 (red lines). Profile locations (P11, P14 and P17) are referred to Figure 1b.

It should be noted that the simulated dune toe change indicates lower values. The dune toe change was analysed based on the Formby domain which has the highest cross-shore resolution of about 2 m at the beach/dune. Therefore, the slope of the dune face of the model bathymetry could be milder than at the site, which leads lower erosion during wave impacts. However, these results indicate the relative sensitivity to the wave boundary forcing and to the spatial location along the coast.

Profile evolution

Selected six profile locations (P11, P12, P14, P15, P17 and P18, see Figure 1b) represent the entire beach/dune system. P11 and P12 are located in the southern part of the coast. P14 is at Formby Point (i.e. the apex of the Sefton coast) which shows a sediment diverging system with increased susceptibility to storm impacts due to the local geometry (Dissanayake et al., 2015b). Other three profiles P15, P17 and P18 represent the northern coast where the dune height reaches as high as 20 m ODN (see dark-red patches in Figure

1b). Profile evolution was analysed during the highest severity event D1 (M1: forcing from uniform wave in H1 and M3: forcing from varying wave in H3).

Resulting profile evolution during D1 is shown in Figure 8 with the corresponding initial profiles. For clarity, only a segment from MSL to +3 m ODN is compared between M1 and M3. It should be noted that the *x*-axis has the same scale with different expansions based on the local bed topography along the coast. The zoom-out views present the evolution around the dune toe level. Along the profiles of each location, it is found that the ridges are severely affected and they appear to have landward shifted during the storm impacts. The highest ridge-change between MSL and +3 m ODN is found at the southern coast (P11) and it is about 0.06 m. At Formby Point (P14), the maximum profile change is about 0.03 m, and that in the northern coast is about 0.04 m. At all profile locations, the bed level change between the initial and the final profiles of M1 and M3 is always higher than between the final profiles. Therefore, M1 and M3 indicate more or less similar evolution along the coast. This is further evident by comparing the evolution at the dune toe levels (see zoom-out views). As discussed earlier, the southern coast (P11 and P12) experienced accretion at the dune toe. Formby Point (P14) also shows accretion whereas it is lower than that of the southern coast. Along the north coast, it appears that the erosion at the dune toe decreases from south to north (from P15 to P18). Both M1 and M3 still indicate more or less similar evolution. The maximum difference occurred between M1 and M3 is in the order of 10^{-3} m along the selected profile locations.

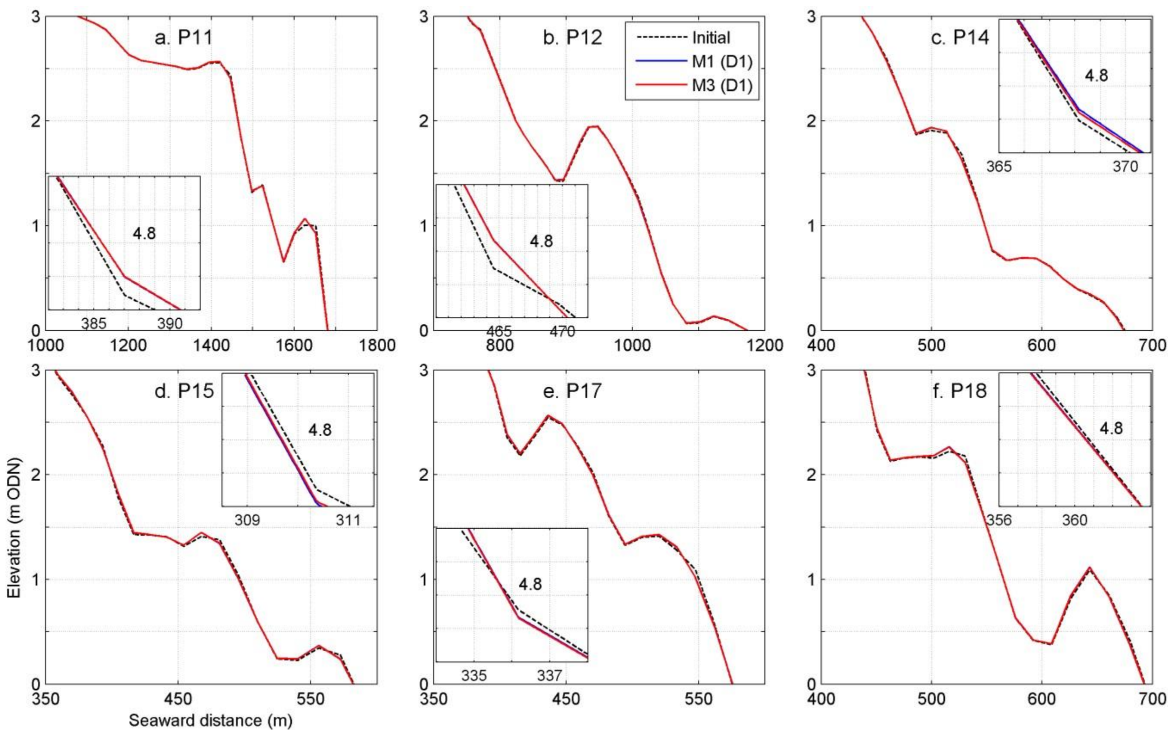

Figure 8 Comparison of model predicted final profiles from P11 to P18 (see locations in Figure 1b) during the D1 storm event in M1 (blue-lines) and M3 (red-lines). The initial profile is shown with the dash-line. Zoom-out view (vertical-scale: 0.1 m and horizontal-scale: 1 m) shows the evolution at the dune toe (4.8 m ODN)

In the application of the uniform boundary for the Formby domain (M11), the profile evolution had marginally increased compared with that in M1. At P11, the maximum ridge-change (accretion) is 0.067 m relative to the initial profile while it was 0.061 m in M1. There is no change at Formby Point, both M11 and M1 resulted in accretion of 0.027 m. However, at the north coast, the ridge-change has slightly decreased during the storm impacts of M11. For example at P18, M11 resulted in 0.030 m change relative to the initial profile and it was 0.042 m in M1.

Within the selected storm impacts (D1), the boundary forcing of M1 (starting from the uniform boundary in Sefton: H1) and M3 (starting from the varying boundary in Sefton: H3) showed only marginal changes (10^{-3} m) along the coast. According to the analysed profiles, these changes were slightly modified (increased, neutralized or decreased) if the Formby domain is forced by a Uniform boundary (M11). These results indicate that the profile evolution is a very localized process and that mainly depends upon the interaction of approaching storm wave with the nearshore bathymetry while propagating from the offshore boundary up to the dunes. Therefore, one could obtain nearly similar evolution of beach/dune forcing with a varying boundary which was set up based on the simulated waves either from uniform or from varying offshore boundary types. However, applying an uniform forcing for the Formby domain could lead to relatively over- or under- estimate the dune impacts compared to that of a varying forcing, depending on the spatial characteristics (e.g. orientation of the coastline, variation of the nearshore bathymetry). Furthermore, the profile evolution shows only one cross-shore segment of the 2DH domain with the bed level change along the grid points of the profiles. Therefore, it should be noted that even marginal changes along the profiles could lead to a noticeable difference of volume between the wave boundary types, when the bed level changes are computed with the alongshore extension of the 2DH domain.

Erosion/Sedimentation pattern

Erosion and sedimentation patterns were estimated with respect to the initial bed topography to qualitatively analyse the bed level change induced by the storm impacts. Simulated bed level change was compared with the two wave forcing types in D1 (M1 and M3) and J2 (M2 and M4). Results are shown in Figure 9 for the region between MSL and +5 m ODN around Formby Point. This region of the Sefton coast experienced relatively strong storm impacts (Dissanayake et al., 2015c) and thus was adopted in this comparison.

Storm impacted erosion presents in blue-colour while the sedimentation areas are shown in red-colour (Figure 9). It should be noted that the maximum bed level change at the dune front in D1 was higher than 0.5 m, however, the colour spectrum was set to lower values in order to visualise bed level change within the inter-tidal area, and to compare with the evolution in J2. Spatial variability of the erosion and sedimentation pattern indicates that the Sefton coast has different level of storm vulnerability along the coast. Furthermore, the area at Formby Point appears to have higher vulnerability to storm impacts in both storm events and also the wave boundary forcing types. Spatial extension and magnitude of the bed change vary based on the storm severity (wave height, tidal level and duration). During the storm impacts, the shore-parallel ridges have rolled over landward by eroding at ridges and accreting at the neighbouring landward runnels as found in the profile evolution. In the high severity event D1 (Figure 9a and b), occurrence of these processes is shown appearing the shore parallel erosion areas (blue) at the seaward side and accretion areas (red or yellow) at the landward side. The dune front has experienced strong bed change, particularly at Formby Point. Both wave boundary types (M1: Figure 9a and M3: Figure 9b) resulted in almost the same pattern of evolution during D1. However, one can still find minor differences in magnitude or spatial extension by comparing the individual locations along the coast. For example, there exist elevation differences of the spikes of accretion within the square-areas in Figure 9a and b. In the weak storm event J2, similar erosion and accretion trends are found in both wave forcing types (M2: Figure 9c and M4: Figure 9d). However, they are not as aligned as in D1 with the shoreline. The dune front was not vulnerable to storm impacts in J2 due to lower water levels. Spatial extensions of bed change appear to be broader in the beach area though they have lower magnitudes than in D1. The highest bed change occurred close to MSL at the north of Formby Point. Only marginal differences between M2 and M4 are noticeable along the coast indicating the impacts of wave boundary types. In the example circular-areas, the spikes of accretion in Figure 9c are stronger compared with those in Figure 9d.

Application of the uniform wave boundary for the Formby domain, both storm events (M11: D1 and M21: J2) resulted in similar pattern of bed change as in M1 and M2 respectively. However, some individual locations along the coast tend to show contrasting blue- and red-colour. These indicate that some areas of the coast experienced relatively increased erosion and sedimentation forcing with the uniform boundary than that of the varying forcing, and however the order of the difference is only a few centimetres.

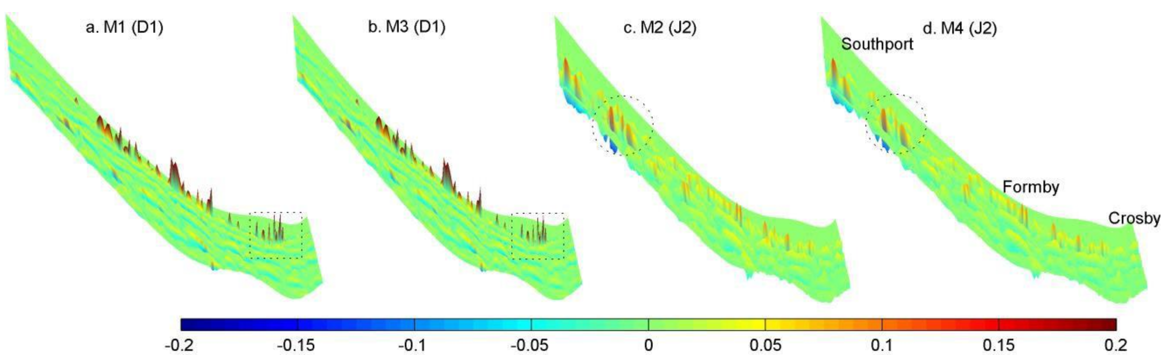

Figure 9 Erosion and sedimentation patterns around Formby Point during D1 (M1: forcing from Uniform boundary model H1, M3: forcing from Varying boundary model H3) and J2 (M2: forcing from Uniform boundary model H2, M4: forcing from Varying boundary model H4). For clarity, from MSL to +5 m ODN (upper dune) is shown.

During the high severity storm event, the dune front of the Sefton coast was more vulnerable than the beach area. In contrast, the beach area experienced more bed change when the lower severity storm occurs. Wave boundary impacts were marginal and localized in both storm events. Erosion and sedimentation patterns provided only a qualitative impression of the spatial extent of bed level changes within the storm impacts.

Bed level change within tidal regimes

Bed level changes were quantitatively compared within three tidal regimes to investigate the storm impacted evolution between the two wave boundary types. The three tidal regimes were defined considering the average tidal excursion across the beach/dune system of the Sefton coast, 1) Sub-tidal (elevation < -5 m ODN), 2) Inter-tidal (-5 m ODN < elevation < 5 m ODN) and 3) Supra-tidal (elevation > 5 m ODN). Agreement of bed evolution between two wave boundaries was estimated using the coefficient of determination (R^2) as defined by Krause et al. (2005). R^2 explains the agreement of the variance in one data set with respect to another in the range from 0 to 1. In our analysis, we adopted the bed change of M1 and M2 (U) which used simulated waves from the uniform boundary in H1 and H2 respectively, and M3 and M4 (V) which used the varying boundary results in H3 and H4 respectively. Using *Eq.* 1, evolution of M1 was compared with M3 (D1), and M2 with M4 (J2) to explore the boundary forcing effects.

$$R^2 = \left(\frac{\sum_{i=1}^{n} (U_i - \bar{U})(V_i - \bar{V})}{\sqrt{\sum_{i=1}^{n} (U_i - \bar{U})^2} \sqrt{\sum_{i=1}^{n} (V_i - \bar{V})^2}} \right)^2 \quad (1)$$

A value of 0 indicates no correlation at all whereas a value of 1 has a perfect agreement between the variances of the bed level changes in both wave boundary types. The gradient and the intercept of the linear regression which are used to estimate R^2, provide additional information on the agreement. For a perfect comparison, the gradient should be close to 1 and the intercept should be close to 0.

Comparisons of bed level change during storm impacts D1 (M1 and M3) and J2 (M2 and M4) are shown in Figure 10 for the three tidal regimes. The dash-line is the line of linear regression, and both *x* and *y* axes have the same scale for a better interpretation. In the D1 event (i.e. highest storm severity), bed level changes in the two wave boundaries are highly correlated ($R^2 \sim 0.99$) and it further increases from the sub-tidal to the supra-tidal area. This indicates that storm impacts during a high severity event can be better simulated forcing with both boundaries. The supra-tidal area, which experienced the highest bed level change, shows the lowest effect of the forcing boundary types.
The lowest severity event (J2) has developed a relatively large difference with the forcing boundary than that of D1. Due to the low water levels, this event has impacted only sub- and inter-tidal regions. In these two regions, the agreements between wave boundaries are lower compared with those in D1. However, it is still noticed that the correlation increases from sub-tidal to inter-tidal and thus the boundary effect decreases towards landward. Therefore, both storm events resulted in a similar trend of wave boundary impacts across the beach/dune system.

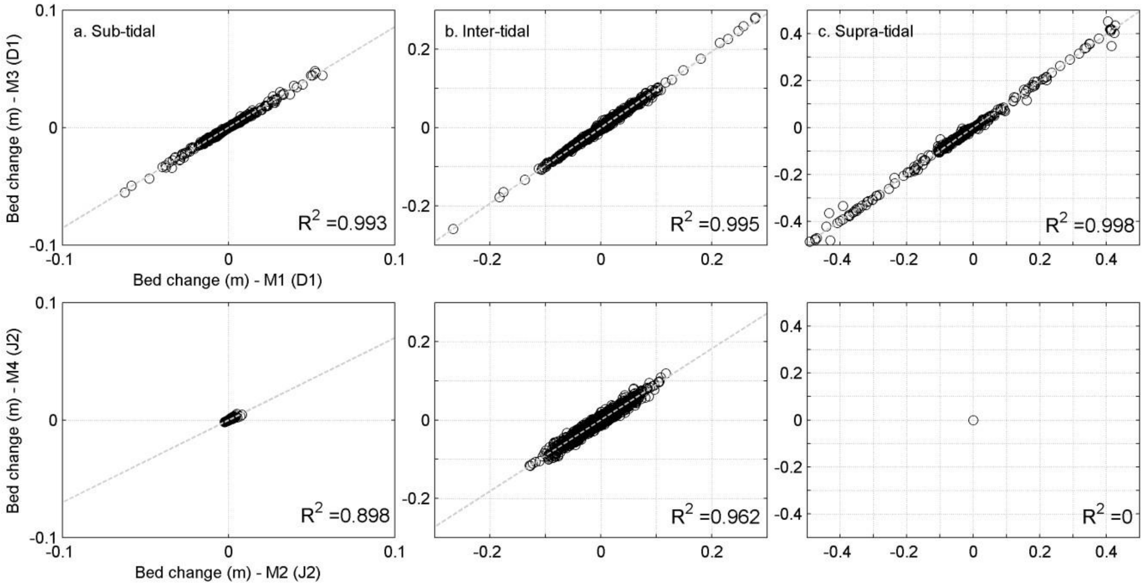

Figure 10 Comparison of bed level changes within three tidal regions, Sub-tidal (a), Inter-tidal (b) and Supra-tidal (c) during D1 (M1: forcing from uniform boundary model H1, M3: forcing from varying boundary model H3) and J2 (M2: forcing from uniform boundary model H2, M4: forcing from varying boundary model H4). The dash-line shows the line of linear regression. Note that the axes have different ranges.

The above agreements were then compared with those of the results from the simulations of which the Formby domain was forced with the uniform wave boundaries (M11 and M21). Results are summarised in Table 2. It is evident that applying the uniform wave boundary for the Sefton domain decreases the agreement with that of the varying boundary. In both storm events (D1 and J2), the highest decrease shows in the sub-tidal area. In D1, it is about 0.1 while it is about 0.2 in J2. Similar to the above agreements, the decrease of the wave boundary effect is still found from sub-tidal to supra-tidal in M11 and M21. This comparison implies that the wave boundary effect on the beach/dune evolution increases, while forcing with the uniform wave boundary, and it is further enhanced if the forcing storm event is weak.

Storm event	Simulation		Sub-tidal	Inter-tidal	Supra-tidal
	M1	M3	0.993	0.995	0.998
	M11	M3	0.888	0.948	0.995
	M2	M4	0.898	0.962	0
	M21	M4	0.732	0.955	0

Table 2 Agreements of bed level change (R^2) in different tidal regions across the beach/dune system by simulating the Formby domain in D1 and J2 forcing two wave boundary types. M1 and M2: varying using simulated waves applying uniform boundary (H1, H2), M11 and M21: uniform using simulated waves applying uniform boundary (H1, H2), and M3 and M3: varying using simulated waves applying varying boundary (H3, H4)

Total volume change

Total volume change of the beach/dune system was estimated to further explore the boundary forcing effects on the bed evolution within the D1 and J2 storm events. Similar to the previous analysis, the three tidal regions were adopted for the volume estimation and investigated the variations across the beach/dune system. Volume change at each grid cell was first estimated multiplying the cell area by the corresponding erosion or sedimentation height within each storm event. The evolution within the tidal regions was then derived by summation of the resulting volumes in the grid cells which are located in the respective tidal regions. Relevant grid cells for the respective tidal regions were identified using the levels -5 m ODN (mean tidal low water) and +5 m ODN (mean tidal high water) on the initial bed topography. It should be noted that the sub-tidal area herein considers the area from the elevation of -5 m ODN to the offshore boundary in order to estimate the sediment balance within the model domain. Boundary exchange of the sediment volume was also estimated to compare the sediment balance within the model domain. This was computed by multiplying the relevant sediment transport component (x or y) along the open boundary and the respective grid cell distance. Simulated hourly transport components were used to estimate the sediment exchange during the storm duration. It should be noted that the spatial model results of these simulations were stored with hourly intervals to avoid excessive storage capacity.

Estimated volume changes within the three tidal regions are shown in Figure 11, sub-tidal (a), inter-tidal (b) and supra-tidal (c). The sediment balance in the model domain (Figure 11d) was analysed by comparing the difference between the sum of volumes in the tidal regions (thin-bar) and the boundary exchange of sediment volume (thick-bar). Therefore, the lower the difference, the higher the sediment balance within the model domain. In all tidal regions and also in the sediment balance, the impacts of the high severity event (D1: M1 and M3) in volume change are significantly stronger than the low severity event (J2: M2 and M4) in the two boundary forcing types. In the sub-tidal area, the difference between M1 and M3 is about 0.38×10^4 m^3, while it is 0.12×10^4 m^3 and 0.13×10^4 m^3 in the inter-tidal and the supra-tidal areas respectively. Therefore, the high severity event tends to decrease the boundary impacts on the evolution towards landward. In contrast, M2 and M4 in the low severity event show the lowest difference in the sub-tidal area (0.05×10^4 m^3) and the highest in the inter-tidal area (0.16×10^4 m^3). As discussed earlier, there is no impact in the supra-tidal area during J2. This implies that the wave boundary effect in different regions of this coastal system depends on the severity of a storm event.

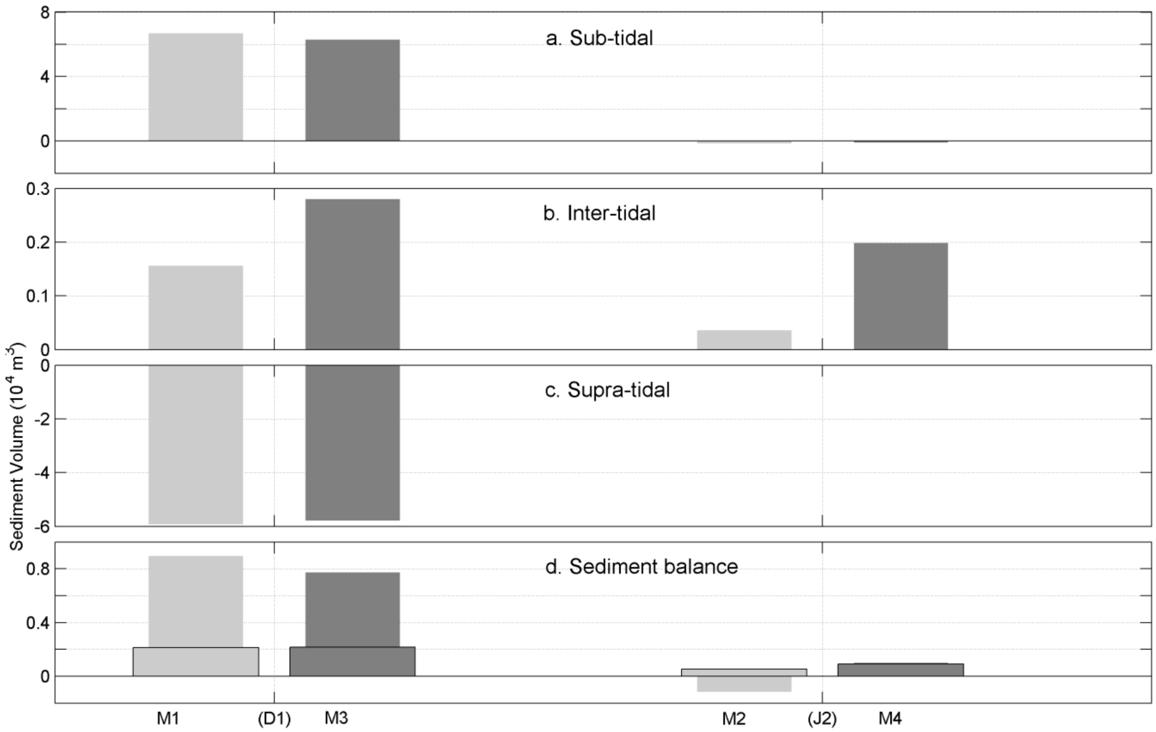

Figure 11 Total volume change in D1 and J2 storm events within the three tidal regions; Sub-tidal (a), Inter-tidal (b) and Supra-tidal (c), in M1 and M2 forcing by simulated waves using uniform wave boundaries in H1 and H2, and in M3 and M4 forcing by simulated waves using varying wave boundaries in H3 and H4. Estimated sediment balance is shown in (d). Thin-bar indicates the sum of volumes in the 3 tidal regions and thick-bar indicates open boundary sediment exchange.

Sediment balance (Figure 11d) in D1 indicates that M1 has a higher difference (0.66×10^4 m^3) between sum of volumes and boundary sediment exchange than that of M3 (0.55×10^4 m^3). However, it should be noted that the boundary sediment exchange is nearly same in M1 (0.21×10^4 m^3) and M3 (0.22×10^4 m^3). In contrast to D1, the sediment balance is significantly conserved during the low severity event. M2 has a difference of about 0.16×10^4 m^3, and the sum of volume agrees better with the boundary exchange in M4. However, the boundary sediment exchange in M2 (0.05×10^4 m^3) is twice lower than that of M4 (0.10×10^4 m^3). This indicates that during the low severity storm, the wave boundary effect influences the evolution of the beach/dune and also the boundary sediment exchange.

The above results are summarized in Table 3 with the corresponding values of the simulations of which the Formby domain was forced by the uniform wave boundaries in D1 (M11) and J2 (M21). M11 clearly indicates the overestimation of volume changes within the three tidal regions. However, it should be further noticed that the boundary sediment exchange (0.20×10^4 m^3) remains more or less similar to M1 (0.21×10^4 m^3) and M3 (0.20×10^4 m^3). This is further evident of lower wave boundary effects on the boundary sediment exchange during a high severity storm. M21 has influenced on the volume change depending on the tidal region. In the sub-tidal area, M21 (-0.12×10^4 m^3) better agrees with M4 (-0.10×10^4 m^3) than M2 (-0.15×10^4 m^3). However, it is significantly overestimated (-0.06×10^4 m^3) in the inter-tidal area than M2 and M4. The boundary sediment exchange of M21 has further decreased than M2. Therefore, applying the uniform wave boundary for the Sefton domain resulted in distinct evolution of the beach/dune system compared with that of a varying wave boundary.

Storm event	Simulation	Sub-tidal	Inter-tidal	Supra-tidal	Sediment balance	
					Sum of regions	Boundary sediment exchange
	M1	6.67	0.16	-5.93	0.87	0.21
	M11	6.68	-0.36	-6.36	-0.04	0.20
	M3	6.29	0.28	-5.80	0.77	0.22
	M2	-0.15	0.04	-	-0.11	0.05
	M21	-0.12	-0.06	-	-0.18	0.03
	M4	-0.10	0.20	-	0.10	0.10

Table 3 Sediment volume change (10^4 m^3) in different tidal regions across the beach/dune system by simulating the Formby domain in D1 and J2 forcing two wave boundary types. M1 and M2: varying using simulated waves applying uniform boundary (H1, H2), M11 and M21: uniform using simulated waves applying uniform boundary (H1, H2), and M3 and M4: varying using simulated waves applying varying boundary (H3, H4)

Simulating with the high severity event (D1), the bed level change (Table 2) and also the volume change (Table 3) within the tidal regions indicated that the wave boundary effects decrease towards landward. Moreover, the wave boundary forcing marginally influenced on the boundary sediment exchange. In the low severity event (J2), the bed level change further showed landward decrease of the wave boundary effect. However, the volume change increased from sub-tidal to inter-tidal between the wave boundary types (M2 and M4, M21 and M4). Also the relative influence on the boundary sediment exchange in J2 was considerable compared with that in D1. These differences could incur based on the analyses themselves. Bed level analysis used the change of each grid cell depth within the storm events. However, the volume change within the storm events was estimated by multiplying the depth change and the corresponding cell area of each grid. It should be noted that the model domain has been discretised with high resolution grid cells at the beach/dune system and coarser cells in the nearshore area. Therefore, the grid cell area varies from one tidal region to another and also within the same tidal region. As such, it can be expected to have lower volume change with the higher bed level changes when the grid cell areas are small, and higher volume change with the lower bed level changes when the grid cell areas are large. Accordingly, the discrepancies of the agreements are rational between the bed level and the volume change analyses within the three different tidal regions under the impacts of different wave boundary forcing types. Furthermore, the D1 event resulted in lower sediment balance compared with that in J2. Sediment exchange was estimated using the hourly transport components. If the transport has strong variations within an hour, this estimation decreases the accuracy. In D1, such transport pattern can be expected due to strong variation of the storm wave than in J2, and that could also contribute to the lower sediment balance.

6. Conclusions

Sensitivity of wave boundary effects on the beach/dune evolution was investigated by simulating two storm events of high and low severity on a complex beach/dune system, the Sefton coast in UK. Two model domains were used for the numerical simulations. Sefton domain was used to transform offshore storm wave up to the high-resolution Formby domain of which the wave boundary effects on the beach/dune evolution was investigated. Sefton domain was simulated using temporal wave data with spatial-uniform and spatial-varying boundary forcing. Resulting waves were then used to set up the varying wave boundaries for the Formby domain.

- The uniform wave boundary of the Sefton domain resulted in higher storm waves within the Formby domain compared with that of the varying boundary type.

- Forcing with uniform and varying wave boundaries in the Formby domain, the beach/dune evolution indicated the spatial variability along the coast due to the convex-shape of the coastline and the nearshore ridge-runnel pattern. The highest change was found at Formby Point (apex of the Sefton coast), and it was marginally higher by forcing with the simulated uniform waves than the varying waves from the Sefton domain.

- Cross-shore profile evolution in both events showed higher difference between the initial and the final profiles than the difference between the final profiles of two wave boundary types. The north coast of Formby experienced a relatively high change in the ridge erosion, and that increased if the Formby domain was forced with the uniform boundary from the simulated uniform waves of the Sefton domain.

- Both wave boundary forcing types resulted in fairly similar erosion and sedimentation patterns along the Sefton coast. However, a detailed comparison of individual locations showed some differences in magnitudes and the spatial extension of erosion and sedimentation areas.

- Comparison of the bed level changes within sub-tidal, inter-tidal and supra-tidal regions indicated that the wave boundary effect is higher in the sub-tidal area, and that decreases towards landward.

- In the high severity event, volume change within the tidal regions showed landward decrease of the wave boundary effect. Also, the boundary sediment exchange was less sensitive to the wave boundary forcing than the bed evolution of the beach/dune system. In the low severity event, the sediment exchange at the boundary showed higher sensitivity to the wave boundary forcing than in the high severity event.

Our sensitivity study suggests that the wave boundary effects on the bed evolution vary along the coast, within the tidal regions and also depends on the severity of storm events.

Applying the wave boundary (uniform or varying) on the Formby domain from the uniform simulated waves of the Sefton domain, the bed evolution was marginally different along the coast than that of the varying simulated waves from the Sefton domain. Applying the uniform wave forcing (Uniform-Sefton and Uniform-Formby) could particularly lead to inaccurate predictions of bed evolution (e.g. excessive steepening or misinterpretation of a nourishment scheme). This study was based on the offshore hindcast wave data. Further studies need to be carried out using measured wave data at several offshore locations to assess the corresponding beach/dune morphology by simulating the system response with a high resolution nearshore model domain. This analysis finally concludes that applying the uniform-varying combination in a model nesting has a lower sensitivity of the wave boundary effect to the beach/dune evolution than the uniform-uniform forcing. This is the case of the most coastal modelling studies, if the offshore data is limited to a single buoy.

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