The Coastline Evolution Model 2D (CEM2D) V1.1

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Abstract. Coasts are among the most intensely used environments on the planet, but they also present dynamic and unique
10 hazards including flooding and erosion. Sea level rise and changing wave climates will alter patterns of erosion and deposition, but some existing coastline evolution models are unable to simulate these effects due to their one-dimensional representation of the systems, or of sediment transport processes. In this paper, the development and application of the Coastline Evolution Model 2D (CEM2D) is presented, that incorporates these influences. The model has been developed from the established CEM model and is capable of simulating fundamental cause-effect relationships in coastal systems. The
15 two-dimensional storage and transport of sediment in CEM2D, which is only done in one-dimension in CEM, means it is also capable of exploring the influence of a variable water level on sediment transport and the formation and evolution of morphological features and landforms at the meso-scale, from 10 to 100 years and over 10 to 100 kilometres. The model sits between one-dimensional and three-dimensional models, with the advantage of increased complexity and detail in model outputs compared to the former, but with more efficiency and less computational expense than the latter.

20 **1 Introduction**

Coastal systems are amongst the most dynamic environments on the planet, with their form and dynamics being highly sensitive to changes in environmental conditions, over a range of spatial and temporal scales (Wong et al., 2015). Under the context of rising global sea levels and considering the social and economic importance of many coastal locations, understanding the behaviour and potential future evolution of coastal environments is essential for the development of
25 suitable and sustainable management (Wong et al., 2015). Numerical models are increasingly being used for this purpose, providing powerful tools that can give an insight into the complex morphodynamics and sensitivities of coastal systems (e.g. Ashton, Murray and Arnault, 2001; Nam, Larson, Hanson and Hoan, 2009; Nicholls et al., 2012).

Simulating changes in coastal geomorphology over 10 to 100 years and over 10 to 100 km areas, herein referred to as the
30 mesoscale, is highly relevant for coastal management and also fits with our historic frame of observation for model validation and calibration (French et al., 2015; van Maanen et al., 2016). This scale sits between reduced complexity

reductionist studies and complex synthesist investigations, which have more traditionally been the focus of research into coastal behaviours (Fig. 1) (van Maanen et al., 2016).

35 Reductionist or 'bottom-up' models are designed to investigate small scale processes that act over relatively short timescales (Fig. 1) (van Maanen et al., 2016). They typically simulate complex behaviours by including a large range of processes that could influence the evolution of the system using more detailed calculations at higher resolutions (van Maanen et al., 2016). Using these types of models for mesoscale applications would be computationally expensive and inefficient, since there are a large number of processes that could be simulated over relatively long time scales (van Maanen et al., 2016). Decisions

40 would have to be made about which processes to include, since each process adds computational expense and additional uncertainty, which can propagate errors or inaccuracies over long simulated timescales (Hutton, 2012; Murray, 2007). Mesoscale models, like many types of model, should be parsimonious and include only fundamental processes that capture the main physical dynamics of a system, thus minimising model uncertainty (Wainwright and Mulligan, 2013).

45 Synthesist or 'top-down' models are designed to simulate large scale behaviours that act over longer time periods and often include only a few parameterised processes (Fig. 1) (Murray, 2007; van Maanen et al., 2016). They are intended to represent general behaviours and patterns in natural systems, rather than answer specific research questions (Murray, 2007). As such, synthesist models are relatively limited in their ability to provide a level of understanding and prediction of coastal behaviours that is required for mesoscale research (Murray, 2007).

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Examples of existing mesoscale coastline models are shown in Table 1, which is not comprehensive but includes a number of examples of models commonly cited in the literature and which are representative of the current methods used for simulating the behaviour of coastal environments. All of the approaches given in Table 1 are limited in their ability to simulate coastal morphodynamics and the effects of sea level change over mesoscales. Sediment transport in COVE, CEM

55 and GENESIS (Hanson and Kraus, 1989; Ashton et al., 2001; Hurst et al., 2014) are limited to one-dimension and represent the coastline simply as a line with little accommodation for the nearshore shape or bathymetry. This means the models are parsimonious and fast, but are limited in their application for example, to investigate the effects of sea level rise on costal geomorphology. Conversely, Delft3D (Lesser et al., 2004) can simulate coastal hydrodynamics and sediment transport processes in two- or three-dimensions, but its complexity and long model run times means investigating sea level rise

60 responses over meso timescales is presently impracticable. Therefore, there is a gap for a two-dimensional coastal model that can simulate features such as spits, bars and beach migration along with the nearshore bathymetry, but is parsimonious enough to enable short run times to answer research questions about coastal evolution at meso-spatiotemporal scales.

In this paper, the development and application of the Coastline Evolution Model 2D (CEM2D) is presented. This model is
65 based on the underlying assumptions of the CEM, but with sediment transport processes that are applied over the two-

dimensional grid which allows us to represent the morphology of coastlines in more detail and incorporate sea level rise. A key aim of the model development is to create a tool to improve our understanding of the mesoscale morphodynamic behaviour of coastal systems, their sensitivities and the influence that sea level rise may have on their evolution over centennial to millennial timescales. We describe in full the model's operation and parameterisation, and compare the model

70 outputs to the original CEM, illustrating some similarities in model outputs but also key differences that are due to the improved two-dimensional representation of the coastline and sediment transport processes.

2 The Coastline Evolution Model (CEM)

As CEM2D builds on many concepts developed in the original CEM, it is important to first understand how CEM operates. CEM is grid based, dividing a plan-view coastline into a grid of regular square cells, of a user-defined size (m). Each of

75 these cells contains a fractional proportion of sediment (Fi) that represent its horizontal fill across the domain. The Fi values are updated according to the longshore transport of sediment and the landward or seaward migration of the shore (Ashton et al., 2001). Cells can be defined as fast or slow eroding, to represent basic lithological characteristics of a coastline.

The one-line coastline can be drawn along shoreline cells, at the interface between land and sea cells. A shoreline search

80 technique is used to locate these shoreline cells, as illustrated in Fig. 2. The initial shoreline cell on the left side of the domain is located by iterating through the first column of cells from the top down, until a land cell is found. A clockwise search is then used around the first shoreline cell to locate the next cell. This is then repeated until all shoreline cells are found.

85 The sediment flux and net erosion or accretion of material in each cell determines the cross-shore movement of the shoreline and is controlled by wave-induced sediment transport calculated using the CERC formula in terms of breaking wave quantities following Eq. (1):

$$Q_s = KH_b^{\frac{5}{2}} sin(\phi_b - \theta) cos(\phi_b - \theta) \tag{1}$$

here, Qs is the sediment flux (m³/day), K is a calibration coefficient, Hb is the breaking wave height (m), ϕ_b is the breaking

90 wave angle (º) and θ is the local shoreline orientation (º).Breaking wave characteristics are calculated from an offshore wave climate that is transformed over assumed shore-parallel contours, using Linear Wave Theory (Ashton et al., 2001). An arbitrary offshore water depth is iteratively reduced and the offshore wave angle and height recalculated until the waves break. The wave climate characteristics at the point of breaking are then used to compute the sediment flux between each cell and the net erosion or deposition of sediment using Eq. (2) (Ashton et al., 2001):

95 $$\Delta Fi = Q_{s,net}\Delta t/(W^2 D_i) \tag{2}$$

where W is the cell width and Di the depth to which significant sediment transport occurs, known as the Depth of Closure (DoC). The DoC is defined as the location from the shore where the depth of water is greater than the depth of wave influence and therefore, the flow has a negligible impact on cross-shore sediment transport; this depth is often approximated as half the average wavelength (Hallermeier, 1978; Nicholls et al., 1997; Pinet, 2011). The assumed location of the DoC in
100   CEM is the point where the continental shelf and the linear shoreface slope intersect (Fig. 3) (Ashton et al., 2001). The slope of the shoreface is assumed constant and does not evolve morphologically throughout simulations or vary the beach profile. Sediment is not transported out of cells that are shadowed by protruding sections of coastline, since they are protected from incoming waves (Fig. 4).

Where a shoreline cell overfills with sediment (Fi > 1), the excess material is deposited in the surrounding empty cells. As
105   new cells become active land cells, the shoreline advances. This redistribution of material has no effect on the topographic profile of the coastline, but simply shifts the location of the shoreline to where cells have filled with sediment. If a greater volume of sediment is removed from a cell than it contains, the shoreline retreats. With this one-line approach, effectively the water level in the model is held constant and cannot be varied, which limits its application to studies interested in the influence of sea level change on coastal evolution.

110   **3 The Coastline Evolution Model 2D (CEM2D)**

CEM2D contains a significant number of modifications to enable it to model the evolution of coastal features including their topographic profiles and to study the influence of a variable water level. The model domain is divided into regular square cells of a user-defined size (m), as per CEM (Fig. 5(a)), however, each cell contains values for depth of sediment to the continental shelf, elevation of sediment above the water level or depth of water (Fig. 5(b)). Having these additional values
115   enables CEM2D to represent two-dimensional coastlines with greater topographic detail compared to the original CEM, as illustrated in Fig. 5. Importantly, the two-dimensional profile allows the morphology of the beach and shoreface to evolve according to the transport of sediment, across the entire model domain. It explicitly models the slope of the continental shelf and shoreface and the morphological profile of the beach and sea floor.

120   In CEM2D the elevation of each cell relative to the water level is used to classify cells as either wet or dry on each model iteration. The boundary between wet and dry is used to locate the shoreline, using the same shoreline search technique as CEM (Fig. 2). As per CEM, Linear Wave Theory is used to transform the offshore wave climate and the CERC formula to calculate sediment flux between shoreline cells (Equation 1). Sediment transport is calculated using the same equation as CEM (Eq. 1) but because CEM2D represents sediment transport in two-dimensions, material eroded from a cell is
125   distributed to the surrounding cells based on the slope between cells and an angle of repose (Fig. 6). This method is based on the relationship between the properties of coastal material (e.g. sand, gravel) and slope angle as shown by McLean and Kirk (1969). We can assume that in general, coastal profiles will maintain an average slope angle consistent with the grain size of

beach material although there are a range of factors that can cause steepening or shallowing (McLean and Kirk, 1969). To
carry out this redistribution procedure an algorithm sweeps the entire model domain and identifies where a given angle of
130   repose has been reached between a cell and its neighbour. The material is redistributed, taking account of the elevation and
repose angles of the orthogonal surrounding cells (Fig. 6). The sediment metrics are then updated accordingly, including the
total volume of material and the cell's elevation above a reference point. The rules defining the sediment redistribution are
important parameters that can significantly alter the model outcomes and have therefore been thoroughly tested. The two
most critical components are (1) the threshold angle between cells that instigates transport and (2) the frequency that the
135   domain is analysed for these thresholds. These values should be calibrated to allow sediment to be distributed without
inducing sediment pilling or deep depressions forming in the domain. Similar techniques are widely implemented in
landscape evolution models, such as SIBERIA (Willgoose et al., 1991) and GOLEM (Tucker and Slingerland, 1994)
(Coulthard, 2001). The ability of the simulated coast in CEM2D to evolve dynamically in this way provides a more realistic
representation of the morphodynamic behaviour of these systems. How sediment is distributed can affect the longer-term
140   evolution of the system and record a morphological memory of landforms which can interact with other features as they
form and mature (Thomas et al., 2016).

CEM2D's two-dimensional structure allows the water level to be varied, but by default the water level is at 0 m elevation.
There are two dynamic water level modes within the model which can be run independently or in combination that can be
145   used to represent tidal fluctuations and long-term sea level change. The increased complexity of the model domain and of
sediment transport processes in CEM2D enable it to model complex two-dimensional coastal profiles and evolve their
morphology. The features allow more complex morphodynamic processes to be explored and to investigate not only the
evolution of the one-line shore, but the surrounding beach and shoreface. The sediment storage and handling technique allow
complex landforms and features to develop and leave a morphological memory in the bathymetry as they evolve. Sea level
150   change is an important addition to this model that could be used to explore the response of coastal systems to fluctuating
water levels and the influence of fundamental climate change effects such as sea level rise.

4 Methodology: Sensitivity Analysis and Model Evaluation

To evaluate how CEM2D simulates coastal change, CEM2D was compared to CEM model outputs as well as to the
behaviour and morphology of natural coastal environments. This provides both a check that the new model is able to
155   represent natural systems as the original, but also to indicate where the added features (namely 2D operation) might change
the model outputs. As the aim of this paper is to describe and highlight the technical developments CEM2D we do not offer
a full field-based comparison but the original CEM outputs (as described subsequently) have been evaluated against field
data.

4.1 Initial Conditions

160   CEM and CEM2D were initially set up with a uniform gridded domain measuring 200 (cross-shore) by 600 (longshore) cells, with a cell size of 100 m by 100 m (Fig. 7). A straight planform coastline was used, with uniform undulations along its length. The coastal profile is characterised by a fixed continental shelf slope of 0.1 with a minimum imposed depth of 10 m and an average shoreface slope of 0.01. Within CEM2D, these average slopes are imposed across the two-dimensional domain including the beach and bathymetric profiles which are built to replicate an average coastal profile slope of 0.01. The

165   left and right boundaries of both model domains are governed by periodic boundary conditions, to allow a constant flux of sediment from one end to the other and conserve the volume of material in the system. No-flow conditions were set at the seaward end of the domain to again, conserve sediment and prevent any gain or loss of material. A daily model time step is used for all simulations. The models were run over a simulated period of 3,000 years, to allow time for the model to spin-up, to reduce the potential influence of initial conditions and to allow sufficient time for the coastal systems to evolve.

170   ### 4.2 Wave Climate Conditions

An ensemble of wave climates was used to drive the model in order to explore the influence of wave conditions on the morphology and evolution of coastal systems. We use the four binned Probability Density Function (PDF) approach of Ashton and Murray (2006a) to define the proportional asymmetry (A) of waves and the proportion of high angle waves (U) approaching the coastline, according to the wave crest relative to the average shoreline orientation (Fig. 8). Twenty-five

175   simulations were completed, with A values varying between 0.5 and 0.9 in increments of 0.1 and U values that varied from 0.55 to 0.75 at 0.05 increments. The pseudo-random wave angle was generated on each iteration, according to these proportional values. The wave height and period are held constant, at 1.7 m and 8 s respectively.

4.3 Water Level

In this paper we do not examine the influence of a variable water level on coastal morphodynamics but explore the changes

180   that happen with a two-dimensional evolution of the coastal profile. A static water level was therefore used, which by default in CEM2D is set at 0 m elevation.

4.4 CEM2D Sensitivity Analysis

A sensitivity analysis (SA) technique designed by Morris (1991), and subsequently adapted by Campolongo et al., (2007), was used to identify the relationship between model inputs and outputs by performing multiple local SAs to approximate

185   model sensitivity across a global parameter space. The Morris Method's design of experiment uses a defined set of values for each input factor, which are discretised into equal intervals and constrained by upper and lower boundaries (Morris, 1991; Ziliani et al., 2013). Each value is altered incrementally per model sensitivity simulation and the elementary effect of each factor on model outputs is calculated according to the variance of performance indices, by Eq. (3):

$$d_{ij} = \left(\frac{y(x_1 x_2 \ldots, x_{i-1}, \ x_i + \Delta_i, \ x_{i+1}, \ldots, x_k) - y(x_1 x_2 \ldots, x_{i-1}, \ x_i, \ x_{i+1}, \ldots, x_k)}{\Delta_i} \right) \tag{3}$$

190 where d_{ij} denotes the value of the *j*-th elementary effect ($j = 1,\ldots,$r) of the *i*-th input factor (and where r is the number of repetitions), $y(x_1 x_2,\ldots,x_k)$ is the value of the performance measure, k is the number of factors investigated and Δ is the incremental step value. The main effect is then calculated according to the mean (μ) of multiple elementary effects computed randomly from the parameter space, which indicates the relative influence of each input factor on model outputs (Ziliani et al., 2013). The standard deviation (ϭ) is also used to determine which, if any, input factors have nonlinear effects or which

195 have an influence on model output but in combination with other unspecified inputs (Ziliani et al., 2013).

The number of input factors tests and the number of repeats using the Morris Method was constrained by resource availability and computational expense. Further, as demonstrated by Skinner et al., (2018) behavioural indices can be used in the place of performance indices where there is a lack of data to populate the performance indices to drive a more qualitative

200 assessment of model sensitivity. A total of eight key input factors were tested against four behavioural indices that represented fundamental processes in the model. The input factors were each ranked according to their relative influence on model outputs and to determine which, if any, input factors have nonlinear effects or which have an influence on model output but in combination with other unspecified inputs (Ziliani et al., 2013). The factors tested are given in Table 2 and the behavioural indices in Table 3.

205 **5 Results**

5.1 CEM2D Sensitivity Analysis

The mean and standard deviation of each input factor on each behavioural index is given in Fig. 9. The higher the mean, the greater the influence of that factor on model outputs and the higher the standard deviation, the greater the nonlinearity; nonlinearity refers to the nonsequential effects of the given factor on model sensitivity or that it influences model behaviour

210 through complex input-input interactions (Ziliani et al., 2013; Skinner et al., 2018). The results show the principle input factors which (1) have the greatest influence on model sensitivity (e.g. wave angle, wave height, sediment distribution factors), (2) those which have a negligible influence (e.g. wave period and domain characteristics) and (3) those which show nonlinear behaviours or interactions which can amplify variance in model outputs (those which also have the greatest influence on model behaviour, e.g. the wave angle). The results further highlight input factors that can have an influence on

215 model outputs, but only according to specific behavioural indices (e.g. water level and domain characteristics). It is important to note that the results of the SA can be influenced by the input factors used, the range of values and the behavioural indices that are chosen to assess sensitivity.

Aggregating the results from the four behavioural indices shows that the wave angle and height have the highest-ranking
220   influence on model behaviours, followed by sediment distribution factors and the domain set-up is considered the least
influential (Fig. 9). Factors which rank highly based on the mean, also tend to show greater nonlinearity and have complex
interactions with other inputs. It is also found, however, that the rankings of the various input factors differ according to the
behavioural indices used to assess model sensitivity, each of which describes a different behaviour in the model. For
instance, the water level shows a high influence on model behaviour when assessed against the ratio of wet to dry cells but
225   according to the sinuosity of the shoreline, is ranked just below average. The selection of model parameters, described in
methods, was driven by the results of the SA and particular attention was given to constraining optimum wave climate
conditions and sediment distribution parameters through a series of further behavioural sensitivity testing.

5.2 Simulating Fundamental Coastal Shapes

The ensemble plots in Fig. 10 and Fig. 11 show final coastal morphologies produced from CEM and CEM2D respectively
230   according to the twenty-five wave climate conditions. Both models demonstrate how different planform shoreline shapes
evolve according to the wave climate scenarios, as previously demonstrated by Ashton and Murray (2006a). The proportion
of high angle waves influences cross-shore sediment transport and the extent to which landforms accrete seaward, whilst the
wave asymmetry determines the balance of cross- to longshore transport and the planform skew of features. It is found that
there is some directional bias in the source code that drives a longshore current independent of the wave climate conditions.
235   This directional bias is more apparent in CEM2D and particularly where the wave climate is symmetrical. It also drives some
migration of the cuspate landforms downdrift, but a similar rate of movement is recorded in both CEM and CEM2D at 1.6 m
and 1.7 m per year respectively. The directional bias is induced by calculations in the model that process from the left to the
right of the domain. In future model versions, the routines will require updating which would also necessitate that sediment
transport methods be altered accordingly.

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Four principle shoreline shapes evolve under the driving wave conditions including cuspate forelands, alongshore sand
waves, reconnecting spits and flying spits. CEM2D shows a greater sensitivity to inputs variables compared to the CEM,
apparent in the development of these four feature types. In CEM2D a greater distinction is made between reconnecting and
flying spits due to the increased complexity of CEM2D's sediment handling and distribution methods. Each of these four
245   features types are compared to natural systems subsequently that are subject to comparable wave climate conditions.

5.2.1 Cuspate Forelands

Symmetrical wave climate conditions (A=0.5) are shown to form cuspate forelands in CEM and CEM2D, which compare to
those found along many shorelines globally. The Carolina Capes span parts of North and South Carolina's coast in the USA
and are used as a case site by Ashton and Murray (2006b) against results generated by CEM. The wave climate along this
250   stretch of coastline is characterised by high angle waves of relative symmetry, which broadly equate to PDF values of A =

0.55 and U = 0.6 (Ashton and Murray, 2006b). Placing the Carolina Capes into the context of the results shown in Fig. 11, CEM2D would model a cuspate coastline which is slightly skewed due to the 5% dominance of left-approaching waves. The wave direction plays a significant role in the formation of the features, with the slightly stronger southerly current skewing the tips of the landforms (Park and Wells, 2005). Considering that all site-specific conditions controlling the evolution of

255   capes are not represented in CEM2D, the model is able to predict a comparable shoreline type to that observed in this natural system.

5.2.2 Alongshore Sand Waves

A slight asymmetry in the wave climate (where A = 0.6) generates alongshore sand waves in both CEM (Figure 10) and CEM2D (Figure 11). However, CEM2D has a greater sensitivity to this parameter and the features show a greater skew

260   downdrift. For instance, under A=0.6 and U=0.75 cuspate sand waves form along the shoreline in CEM, but in CEM2D the features skew and hooks form at the distal points. Comparing these results to the planform morphology of sand waves found in natural systems, such as Benacre Ness in the UK which has PDF values of A=0.6 and U=0.8, demonstrates the ability of CEM2D to reflect the asymmetry of landforms formed under asymmetric wave climate conditions. However, it is noted that site-specific environmental and boundary conditions play a role in the formation and evolution of Benacre Ness which are

265   not modelled by either software and that the wave transformation equations used may not be wholly suited to this site.

5.2.3 Reconnecting and Flying Spits

Under high asymmetric wave climate conditions, dominated by high angle waves, spits forms along the shoreline in CEM (Ashton and Murray, 2001; Ashton et al., 2006b) and CEM2D. However, CEM2D again shows a greater sensitivity to the wave climate conditions, with more distinction made between reconnecting and flying spits due to the refinement of

270   sediment handling techniques in the model.

Ashton and Murray (2006b) compare results from CEM to the behaviour and development of the reconnecting Long Point Spit in Lake Erie, Canada, where the wave climate is characterised by high asymmetry (A = 0.8-0.9) and high angle wave dominance (U = 0.6-0.7) (Ashton and Murray, 2006b). Under all four potential wave climate conditions, reconnecting spit

275   features form in CEM (Fig. 10), whereas in CEM2D (Fig. 11) either sand waves or reconnecting spits form depending on the combination of A and U values within the given ranges. Ashton and Murray (2007) suggest that the wave climate is favoured towards an asymmetry (A) of 0.8 along the entire spit and under these conditions, reconnecting spits form in CEM2D (Fig. 11), as per the natural system.

280   Comparing model results to flying spits, Spurn Point in the UK extends off the southern end of the Holderness Coast and has a PDF wave climate of A = 0.75, U = 0.35. Following the pattern of results from CEM (Fig. 10) and CEM2D (Fig. 11), where there is proportional asymmetry (A) of between 0.7 and 0.8, net longshore sediment transport forms these types of

landforms. However, in CEM2D these features fluctuate between spits and sand waves owing to the strong longshore current generated by the low angle waves and high asymmetry. It is of note however that Spurn Point is a complex site which is
285 influenced by conditions that could be having a greater impact on coastal evolution, including estuarine processes and dredging activities.

5.3 CEM2D Dynamic Coastal Profile

The novel development of CEM2D is to simulate variations in the nearshore topography. Of particular interest are the dynamics of the upper nearshore which evolves under the influence of sediment exchange with the shoreline (Fig. 12(b)).
290 The lower nearshore profile tends to be influenced to a lesser degree (Fig. 12(c)) and consequently, is able to store remnants of morphological features as they evolve.

One-line models tend to assume that contours lie parallel to the shoreline, but the results in this study demonstrate that the bathymetric profile in particular is highly dynamic (Fig. 12). Whilst some of the results of CEM2D show a profile with
295 shore-parallel contours, the majority do not exhibit this behaviour, particularly where there is a strong asymmetry in the wave climate (Fig. 12). The shoreline and bathymetry is not solely influenced by current environmental conditions but previous states and morphological residuals. Omitting or smoothing the bathymetry in the representation of coastal systems could have implications for their long-term evolution. The effect of morphological inheritances have been previously suggested by authors including Wright and Short (1984), French et al., (2015) and Thomas et al., (2016). Many of the results
300 from CEM2D have noted the presence of remnant features or states in the coastal profile, particularly in the nearshore zone. The presence of these features is strongly attributed to the balance of cross- and long-shore sediment transport, and the rate of change. For instance, where sand waves form the rate of change is such that the longshore movement of landforms makes an impression in the profile that is significant enough to be sustained in the bathymetry as the features migrate (Fig. 13). However, where reconnecting spits form along the shoreline, the rapid rate of longshore and cross-shore sediment transport
305 act to smooth the profile and remove evidence of predeceasing morphologies (Fig. 13). These processes could prove important for understanding the nearshore dynamics of natural coastal environments, particularly under changing environmental conditions.

Relative rates of morphological change and coastal dynamics differs according to the driving wave conditions (Fig. 14). This
310 is illustrated in the volume stacks in Fig. 14 which present the change in volume of sediment across a transect (x = 30 km) every 30 simulated years, for four wave climate scenarios where (a) A = 0.5, U = 0.55, (b) A = 0.6, U = 0.6, (c) A = 0.7, U = 0.65 and (d) A = 0.8, U = 0.7. With increasing wave asymmetry and proportions of high angle waves, the active cross-shore zone exhibits greater dynamism and greater volumes of net longshore transport. However, the results also show that these systems have complex non-linear behaviours that emerge from the balance of longshore and cross-shore sediment transport.

6 Discussion

The purpose of this study was to provide an overview of the development and application of CEM2D and its ability to represent coastal systems better than other existing coastal evolution models of its kind. Adding two-dimensional functionality allows the model to generally reproduce the results of the original one-line CEM, simulating fundamental shoreline shapes according to the wave climate (Ashton and Murray, 2006a). Our results show the sensitivity of coastal systems to driving environmental conditions and in particular their response to changing wave climates which supports theories of high angle wave instability.

Importantly, restructuring and increasing the dimensionality of sediment transport in the model allows us to explore how the profile of the coastal systems changes with the shape of the shoreline. In many one-line models, the cross-shore profile of the coastline is kept constant and it is assumed that its core geometric properties are retained over meso-spatiotemporal scales. Whilst this is a well-used concept, there are advantages to modelling the topography and bathymetry of the coastline and it is necessary if we are to model the effect of a variable water level. For example, we can see that the nearshore evolves at a greater rate compared to the lower shoreface profile, supporting the theories of Stive and de Vriend (1995). The distribution of sediment across the profile is more transient towards the shore where the greatest volume of transport occurs. However, the geometry of the entire shoreface and the geometric demand for sediment distribution means that material is moved to the lower shoreface over time, but at a relatively slower rate (Stive and de Vriend, 1995). Further, the topographic profile of coastal landforms is indicative of their formation and evolution, highlighting patterns in sedimentation and drift processes. Using CEM2D to model how this profile changes over time can inform the stability and future behaviour of features.

Taken from the one-line CEM, CEM2D sediment transport calculations do not take into consideration the water depth, or how far from the shore the wave's break. These are both variables that can now be calculated with this 2D model and future developments of CEM2D focus on revision of the sediment transport equation and reviewing more suitable calculations that can take advantage of the increased complexity and added functionalities in CEM2D.

A key component of CEM2D is its variable water level. If we are to explore coastal evolution over the mesoscale, being able to model the effect of rising sea levels is essential. Whilst we have not exhausted the uses of this function here, we have demonstrated its development and how it is facilitated in the model. The power of this tool is vast and will be particularly useful for coastal managers who must plan for the dynamic evolution of these system over time periods that will be highly influenced by the effects of climate change.

7 Conclusion

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Here we have presented the development of CEM2D from its one-line origins. We have described the structure of the model, outlined the governing mathematical equations that drive the model, presented outputs from the sensitivity testing and assessed CEM2D's ability to simulate the behaviour and evolution of coastal systems. The results demonstrate the validity of the model by its ability to simulate fundamental coastal shapes as per CEM and in comparison to natural coastal systems.

350 Using the added functionalities, we have also shown how CEM2D can be used to explore the two-dimensional behaviour and morphodynamic evolution of coastlines and depositional features, over meso-spatiotemporal scales. From the results shown here, it is apparent that the model will enable us to conduct interesting and insightful investigations to answer research questions including how coastal systems behave under changing environmental conditions and how sea level change might influence their morphodynamic behaviour.

8 Code Availability

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The current version of the Coastline Evolution Model 2D (CEM2D) is available from the project website: https://sourceforge.net/projects/coastline-evolution-model-2d/ and on Zenodo (DOI: 10.5281/zenodo.3341888) distributed under the terms of the GNU General Public License.

9 Author Contributions

360 All Authors contributed to writing and editing this manuscript. The research and software development was led by CL, with extensive support from TC and AB.

10 Competing Interests

The authors declare that they have no conflict of interest.

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12 References

Ashton, A., Murray, B., and Littlewood, R.: The response of spit shapes to wave-angle climates, in: Coastal Sediments' 07, edited by: Kraus, N., and Rosati, N., American Society of Civil Engineers, New Orleans, LA., 2007.

370   Ashton, A., and Murray, B.: High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes, Journal of Geophysical Research, 111(F4), F04011, doi: 10.1029/2005JF000422, 2006a.

Ashton, A., and Murray, B.: High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature, Journal of Geophysical Research: Earth Surface, 111(F4), F04012, doi: 10.1029/2005JF000423, 2006b.

375   Ashton, A., Murray, B., and Arnault, O.: Formation of coastline features by large-scale instabilities induced by high-angle waves, Nature, 414(6861), 296–300, doi: 10.1038/35104541, 2001.

Campolongo, F., Cariboni, J., and Saltelli, A.: An effective screening design for sensitivity analysis of large models, Environmental Modelling & Software, 22(10), 1509–1518, doi: 10.1016/J.ENVSOFT.2006.10.004, 2007.

Coulthard, T.: Landscape evolution models: a software review, Hydrological Processes, 15(1), 165–173. doi:
380   10.1002/hyp.426, 2001.

French, J., Payo, A., Murray, B., Orford, J., Eliot, M., and Cowell, P.: Appropriate complexity for the prediction of coastal and estuarine geomorphic behaviour at decadal to centennial scales, Geomorphology, 256, 3-16, doi: 10.1016/j.geomorph.2015.10.005, 2015.

Gelfenbaum, G., and Kaminsky, G.: Large-scale coastal change in the Columbia River littoral cell: An overview, Marine
385   Geology, 273(1–4), 1–10. doi: 10.1016/j.margeo.2010.02.007, 2010.

Hallermeier, R.: Uses for a Calculated Limit Depth to Beach Erosion, Coastal Engineering, 1493–1512. doi: http://dx.doi.org/10.1061/9780872621909.090, 1978.

Hanson, H.: GENESIS: a generalized shoreline change numerical model, Journal of Coastal Research, 1–27, 1989.

Hanson, H., and Kraus, N. (1989) GENESIS: Generalized Model for Simulating Shoreline Change. Report 1. Technical
390   Reference, No. CERC-TR-89-19-1. Coastal Engineering Research Center Vicksburg Ms.

Hurst, M., Barkwith, A., Thomas, C., and Ellis, M.: Vector-based one-line model for shoreline evolution: application to explore wave-climate control on bay morphology, in In AGU Fall Meeting Abstracts, 2014.

Leach, C.: CEM2D Source Code, Zenodo, https://doi.org/10.5281/zenodo.3341888, 2019.

Lesser, G., Roelvink, J., van Kester, J., and Stelling, G.: Development and validation of a three-dimensional morphological
395   model, Coastal Engineering, 51(8), 883–915. doi: 10.1016/j.coastaleng.2004.07.014, 2004.

van Maanen, B., Barkwith, A., Bonaldo, D., Burningham, H., Murray, B., Payo, A., Sutherland, J., Thornhill, G., Townend, I., van der Wegen, M., and Walkden, M.: Simulating mesoscale coastal evolution for decadal coastal management: A new framework integrating multiple, complementary modelling approaches, Geomorphology, 256, 68–80. doi: 10.1016/j.geomorph.2015.10.026, 2016.

400   McLean, R., and Kirk, R.: Relationships between grain size, size-sorting, and foreshore slope on mixed sand - shingle beaches, New Zealand Journal of Geology and Geophysics, 12(1), 138–155, doi: 10.1080/00288306.1969.10420231, 1969.

Morris, M.: Factorial sampling plans for preliminary computational experiments, Technometrics, 33(2), 161–174, doi: 10.1080/00401706.1991.10484804, 1991.

Murray, B.: Reducing model complexity for explanation and prediction, Geomorphology, 90(3–4), 178–191, doi: 10.1016/j.geomorph.2006.10.020, 2007.

Nam, P., Larson, M., Hanson, H., and Hoan, Le X.: A numerical model of nearshore waves, currents, and sediment transport, Coastal Engineering, 56(11), 1084–1096, doi: 10.1016/j.coastaleng.2009.06.007, 2009.

Nicholls, R., Bradbury, A., Burningham, H., Dix, J., Ellis, M., French, J., Hall, J., Karunarathna, H., Lawn, J., Pan, S., Reeve, D., Rogers, B., Souza, A., Stansby, P., Sutherland, J., Tarrant, O., Walkden, M., and Whitehouse, R.: iCOASST – Integrating Coastal Sediment Systems, Coastal Engineering Proceedings, 1(33), 100, https://doi.org/10.9753/icce.v33.sediment.100, 2012

Nicholls, R., Birkemeier, W., and Hallermeier, R.: Application of the depth of closure concept, Proceedings of the Coastal Engineering Conference, 4, 3874–3887, doi: 10.9753/icce.v25, 1997.

Park, J.-Y., and Wells, J.: Longshore Transport at Cape Lookout, North Carolina: Shoal Evolution and the Regional Sediment Budget, Journal of Coastal Research, 211, 1–17, doi: 10.2112/02051.1, 2005.

Pinet, P.: Invitation to Oceanography, Jones & Bartlett Publishers, 2011.

Skinner, C., Coulthard, T., Schwanghart, W., Van De Wiel, M., and Hancock, G.: Global Sensitivity Analysis of Parameter Uncertainty in Landscape Evolution Models, Geoscientific Model Development, 11(12), 4873-4888, https://doi.org/10.5194/gmd-11-4873-2018, 2018.

Stive, M., and de Vriend, H.: Modelling shoreface profile evolution, Marine Geology, 126(1–4), 235–248, doi: 10.1016/0025-3227(95)00080-I, 1995.

Thomas, C., Murray, B., Ashton, A., Hurst, M., Barkwith, A., and Ellis, M.: Complex coastlines responding to climate change: do shoreline shapes reflect present forcing or remember the distant past?, Earth Surface Dynamics, 4(4), 871-884, https://doi.org/10.5194/esurf-4-871-2016, 2016.

Tucker, G., and Slingerland, R.: Erosional dynamics, flexural isostasy, and long-lived escarpments: A numerical modeling study, Journal of Geophysical Research: Solid Earth, 99(B6), 12229–12243, doi: 10.1029/94JB00320, 1994.

Wainwright, J., and Mulligan, M.: Environmental Modelling: Finding Simplicity in Complexity, Wiley-Blackwell, 2002.

Warren, I., and Bach, H.: MIKE 21: A Modelling System for Estuaries, Coastal Waters and Seas, Environmental Software, 7(4), 229–240, doi: 10.1016/0266-9838(92)90006-P, 1992.

Willgoose, G., Bras, R., and Rodriguez-Iturbe, I.: Results from a new model of river basin evolution', Earth Surface Processes and Landforms, 16(3), 237–254, doi: 10.1002/esp.3290160305, 1991.

Wong, P., Losada, I., Gattuso, J., Hinkel, J., Khattabi, A., McInnes, K., Saito, Y., Sallenger, A., Nicholls, R., Santos, F., and Amez, S.: Coastal systems and low-lying areas, in: Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United

Kingdom and New York, NY, USA, 361-409.

Wright, L., and Short, A.: Morphodynamic variability of surf zones and beaches: A synthesis, Marine Geology, 56(1–4), 93–

440   118, doi: 10.1016/0025-3227(84)90008-2, 1984.

Ziliani, L., Surian, N., Coulthard, T., and Tarantola, S.: Reduced-complexity modeling of braided rivers: Assessing model performance by sensitivity analysis, calibration, and validation, Journal of Geophysical Research: Earth Surface, 118(4), 2243–2262. doi: 10.1002/jgrf.20154, 2013.

445 **Table 1: A summary of popular mesoscale coastline evolution models that currently exist within published literature. The list is not exhaustive but highlights a number of commonly cited, relevant models.**

Model Name	Description	Domain Structure	Spatial Scale	Temporal Scale	Reference
COVE	The Coastal One-line Vector Evolution (COVE) model is designed to investigate the geomorphic evolution of coastal features, over decadal to centennial	Vector (Links and nodes)	$10^1 - 10^2$ kms	Decades to millennia	(Hurst et al., 2014)
CEM	The Coastline Evolution Model (CEM) is a one-contour line sediment transport model that is designed to simulate the plan-view evolution of coastal systems.	Cellular	$10^1 - 10^2$ kms	Years to millennia	(Ashton et al., 2001)
GENESIS	The GENEralized Model for SImulating Shoreline Change (GENESIS) is a one-line, grid-based model designed to simulate wave-induced shoreline change.	Cellular	$10^1 - 10^2$ kms	Monthly to yearly	(Hanson, 1989; Hanson and Kraus, 1989)
MIKE 21	MIKE 21 is a modular two-dimensional coastal modelling tool that can simulate complex hydrodynamic and sediment transport processes, amongst others, in	Cellular	Multiple	Multiple	(Warren and Bach, 1992)
Delft3D	The Delft3D package integrates various modules that are designed to simulate hydrodynamic flow and sediment transport, amongst other processes.	Cellular	Multiple	Days to centuries	(Lesser et al., 2004)

Table 2: A table listing the eight input factors from CEM2D used in the sensitivity analysis of Morris Method.

Code	Factor	Intervals	Minimum	Maximum	Justification
1	Wave Angle (°)	5	1	5	The wave climate is fundamental to driving sediment transport processes in CEM2D.
2	Wave Height (m)	5	1	6	
3	Wave Period (s)	5	1	14	
4	Sediment Redistribution Frequency (iterations)	5	10	50	The sediment redistribution method is a new scheme in CEM2D, governed principally by factors which defined the frequency and threshold for sediment redistribution.
5	Sediment Redistribution Threshold (%)	5	1 (%)	100 (%)	
6	Water Level Change (m)	5	0	2	The ability to induce sea level rise in the model is a new scheme that requires testing for its influence on model outputs.
7	Initial Shoreline Shape	3	1	3	The original CEM claimed to be relatively insensitive to these initial conditions. Increasing the dimensionality and complexity of sediment transport in the model warrants that their influence on CEM2D outputs be evaluated.
8	Domain Width (km)	3	1	3	

450 **Table 3: A table showing the 4 behavioural indices used in the Morris Method and the frequency that data is recorded in each simulation.**

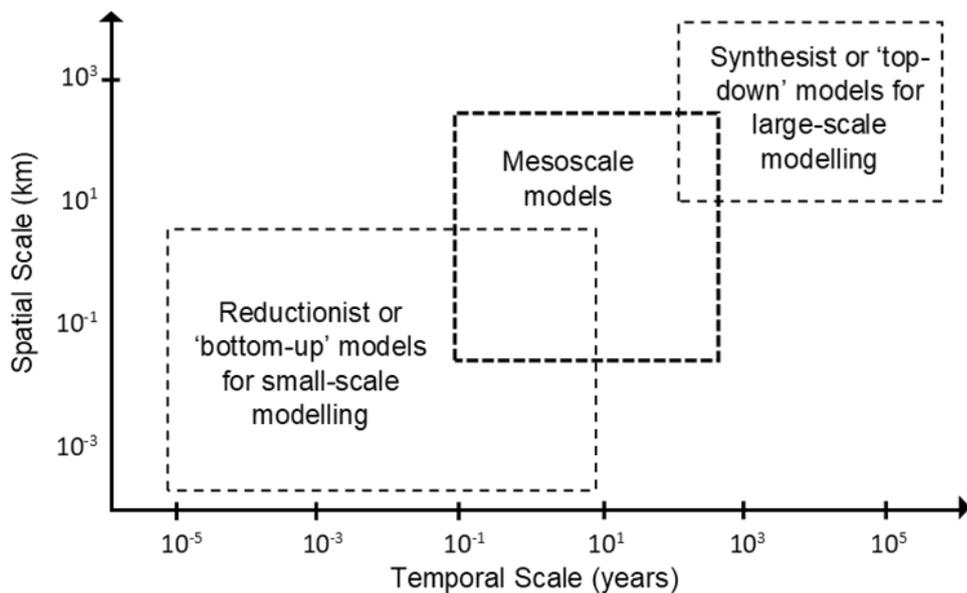
Number	Behavioural Index	Recording Frequency
1	Longshore sediment transport rate (m^3 / 10 years)	3650 model iterations (10 simulated years)
2	Coastal sinuosity	3650 model iterations (10 simulated years)
3	The ratio of wet-dry areas	300 model iterations (300 simulated days, to align with each diffusion frequency tested)
4	Run duration (simulated years)	1095000 model iterations (3,000 simulated years)

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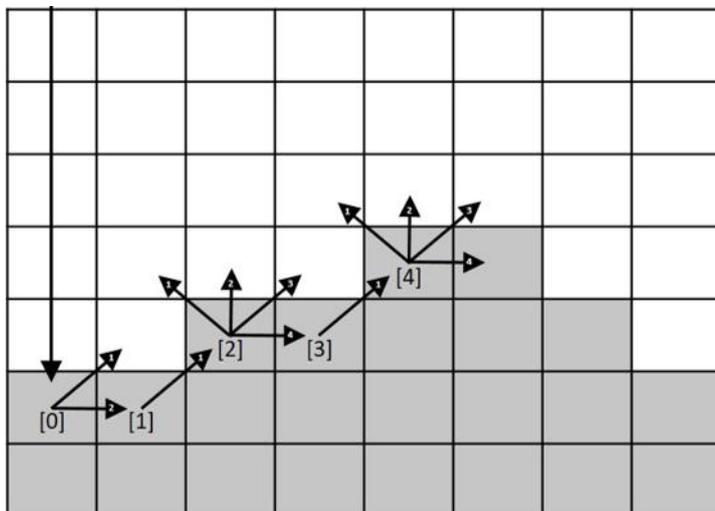
Figure 1: Spatial and temporal ranges for traditionally reductionist and synthesist models, with mesoscale models highlighted in grey within the scale appropriate for coastal management (adapted from Gelfenbaum and Kaminsky, 2010; van Maanen et al., 2016).

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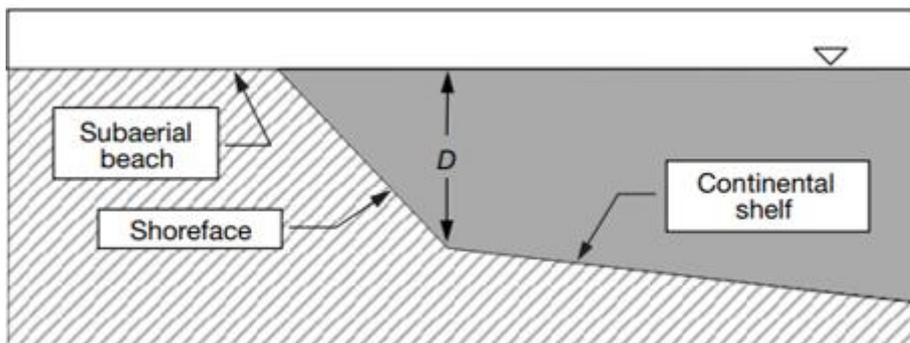
Figure 2: A schematic of the shoreline search technique used in CEM (and CEM2D) to map the X and Y location of the shoreline cells. The number in square brackets denotes the shoreline cell number that is associated with a particular X and Y value and the number on each arrow is the iteration of the clockwise search from the shoreline cell where it originates.

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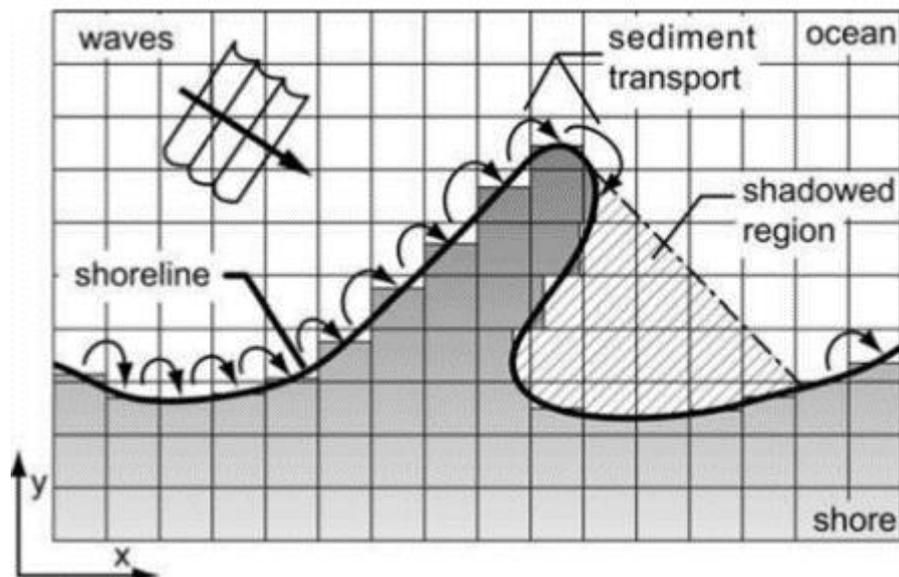
Figure 3: Cross-sectional profile of CEM showing the location of the depth of closure, where the shoreface slope intersects the continental shelf slope (after Ashton et al., 2001).

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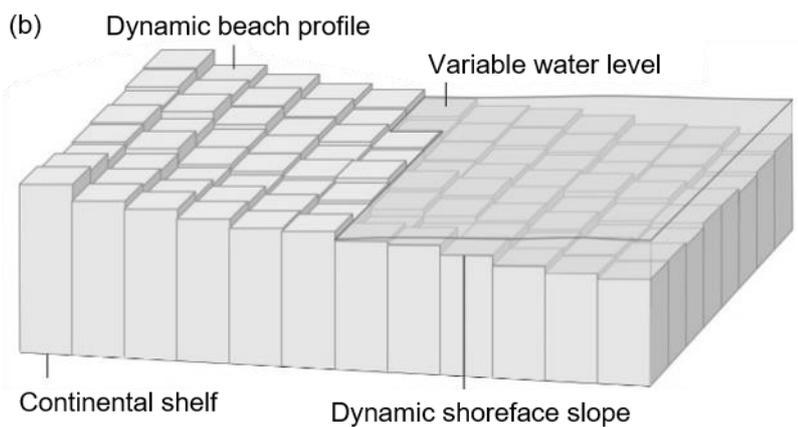
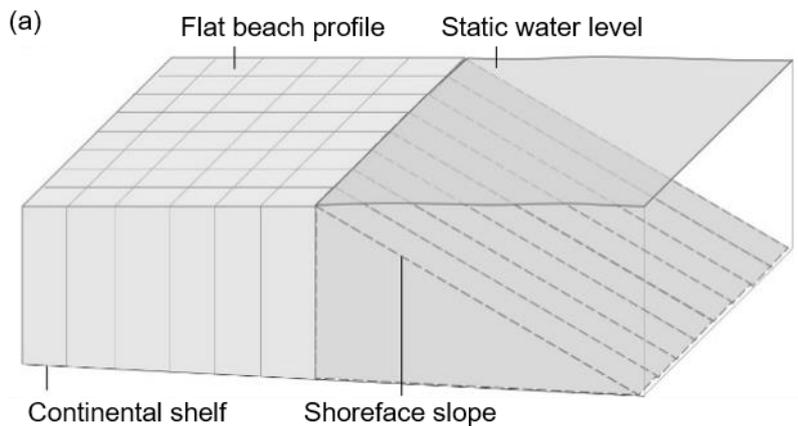
Figure 4: Plan-view schematic of CEM2D showing the shadow zone that is formed when protruding sections of coastline prevent waves from approaching the shoreline (after Ashton and Murray, 2006a).

475 **Figure 5: Schematics of CEM (a) and CEM2D's (b) profiles, illustrating the difference in structure and dimensionality of the two models.**

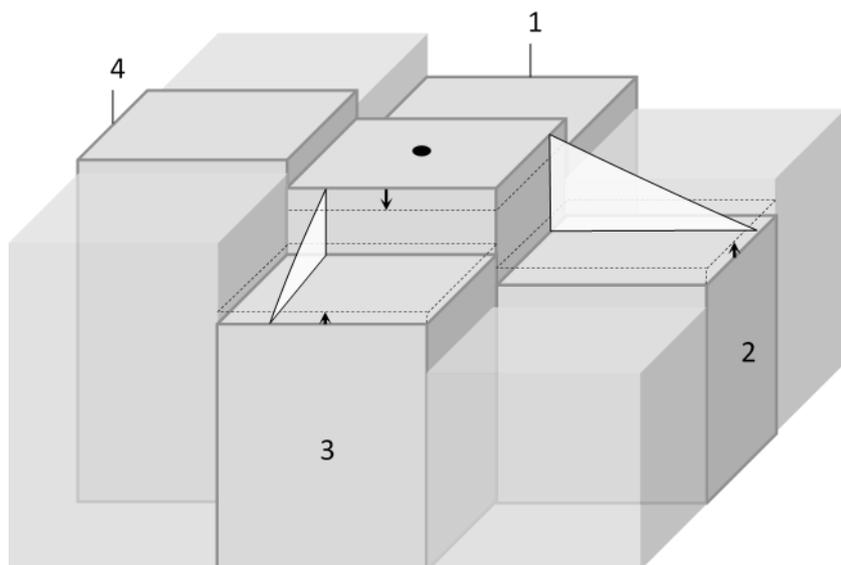



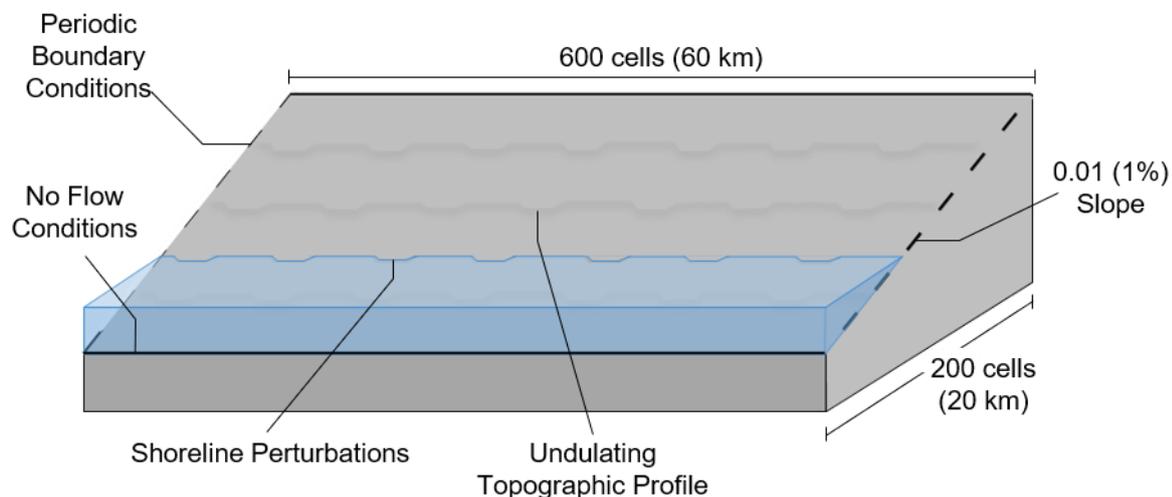
Figure 6: Schematic of the sediment distribution technique used to distribute sediment to cells with lower elevations. In the example, the angle between the central cell and cells [2] and [3] exceeds the threshold for diffusion. Sediment is removed from the central cell and redistributed to these cells. Cells [1] and [4] are not readjusted in this iteration but may be in subsequent sweeps of the coastline.

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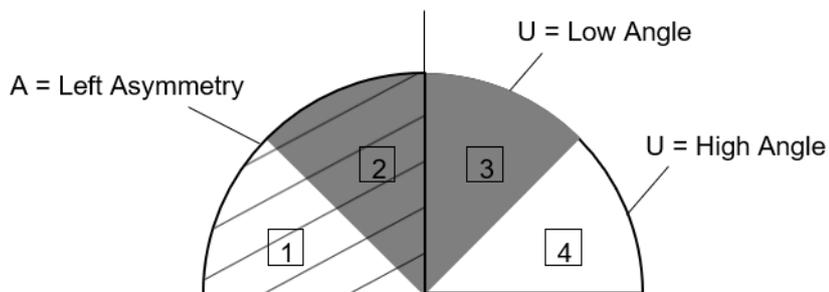
Figure 7: A schematic of CEM2D's model set-up and initial conditions used for simulations presented in this paper.

490 **Figure 8: Schematic showing the wave angle direction, defined by the wave climate asymmetry (A) and the proportion of high to low angle waves (U) with the numbers denoting the four bins.**

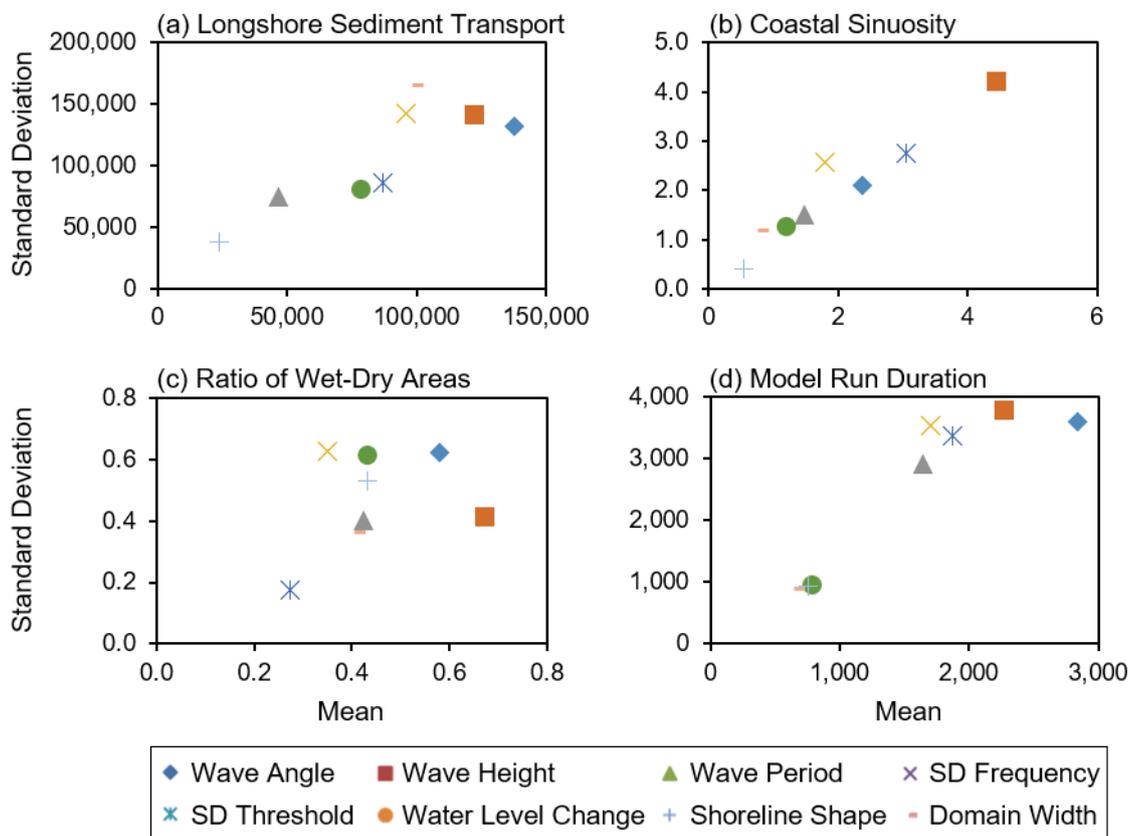



Figure 9: The mean and standard deviation of results from the input factors, according to the four behavioural indices labelled a-d.

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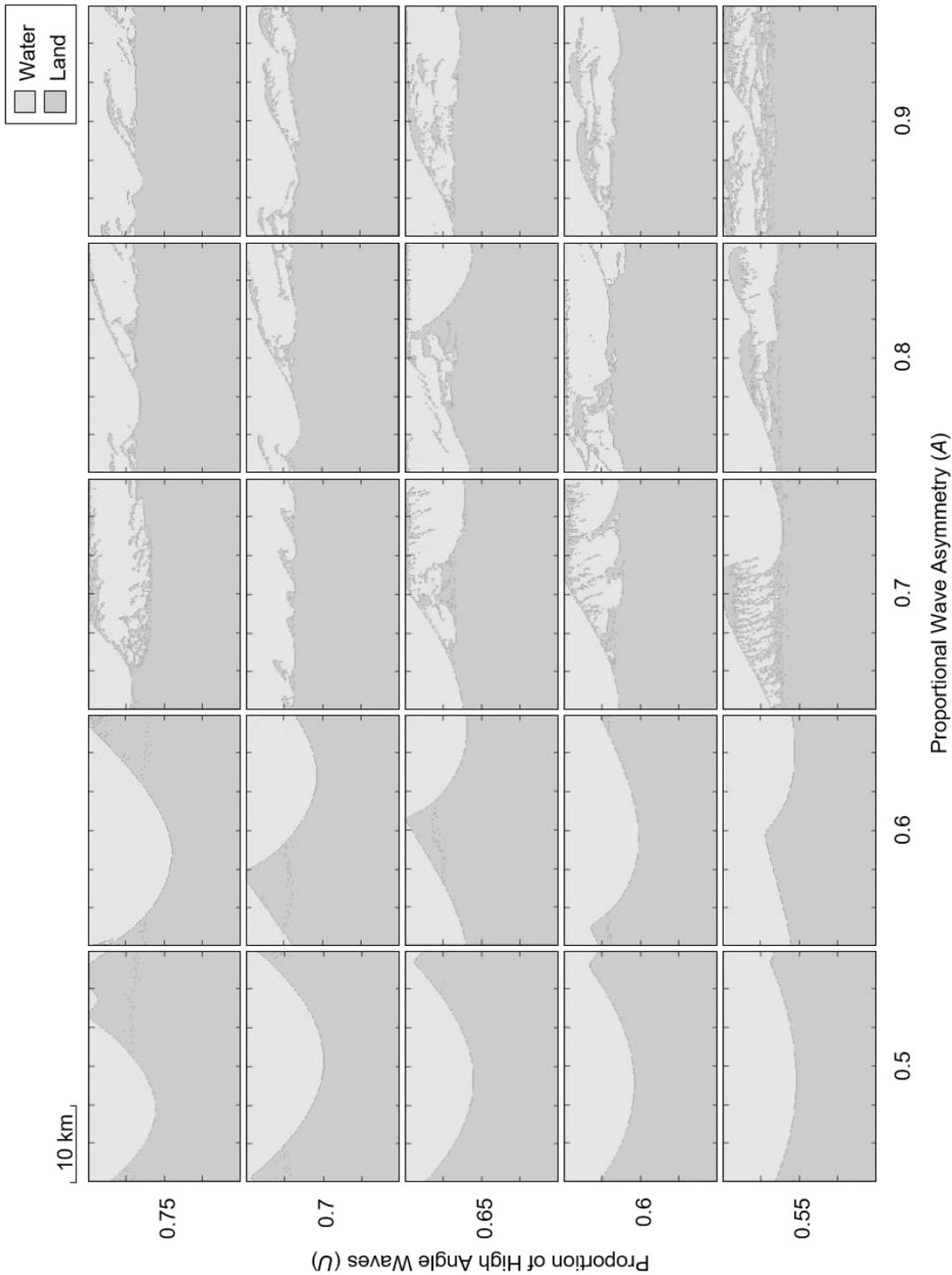


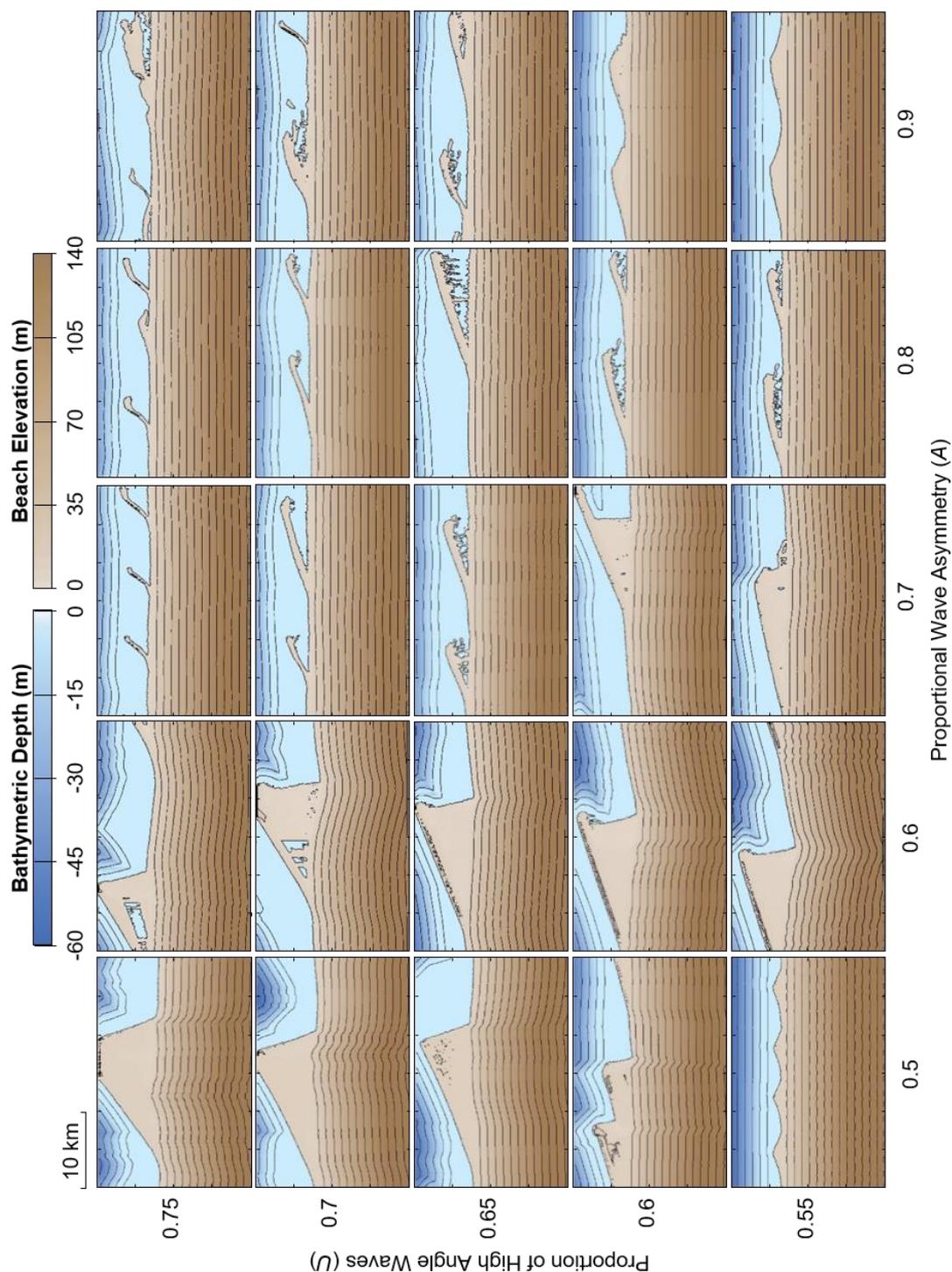
Figure 10: A matrix of results from CEM showing final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and are not inclusive of the periodic boundaries.

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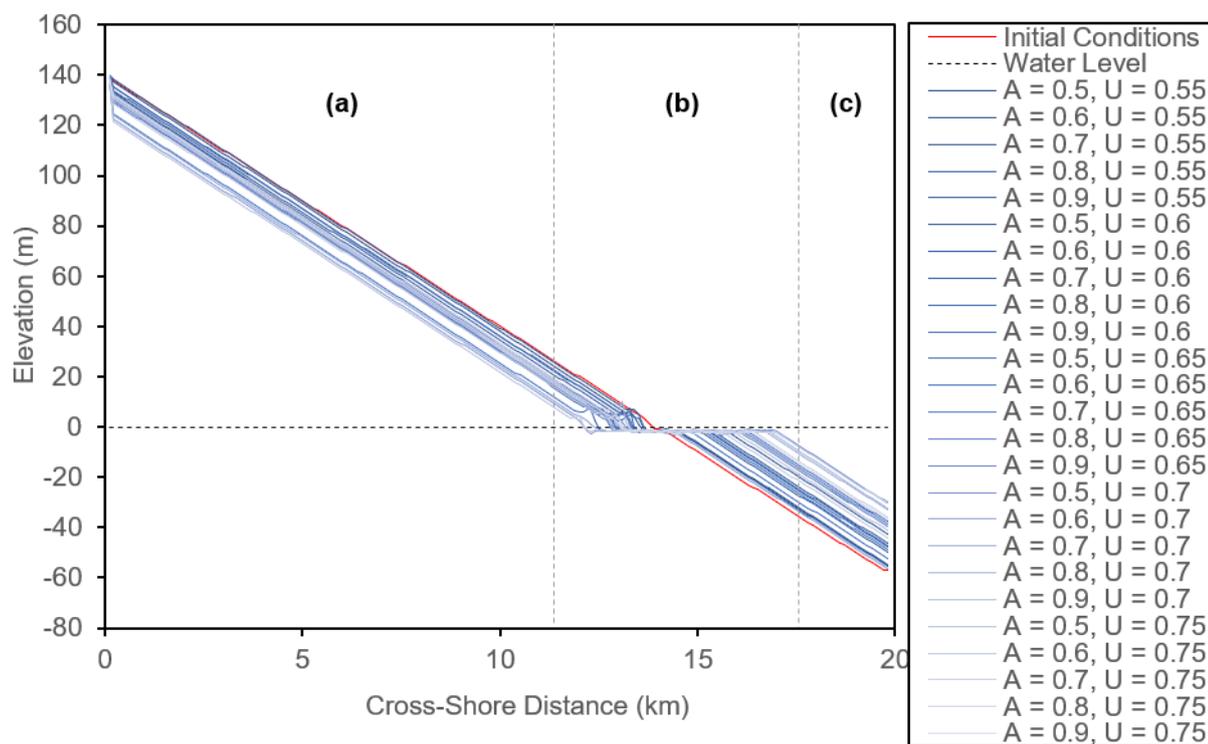
Figure 11: A matrix of results from CEM2D showing two-dimensional final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and are not inclusive of the periodic boundaries.

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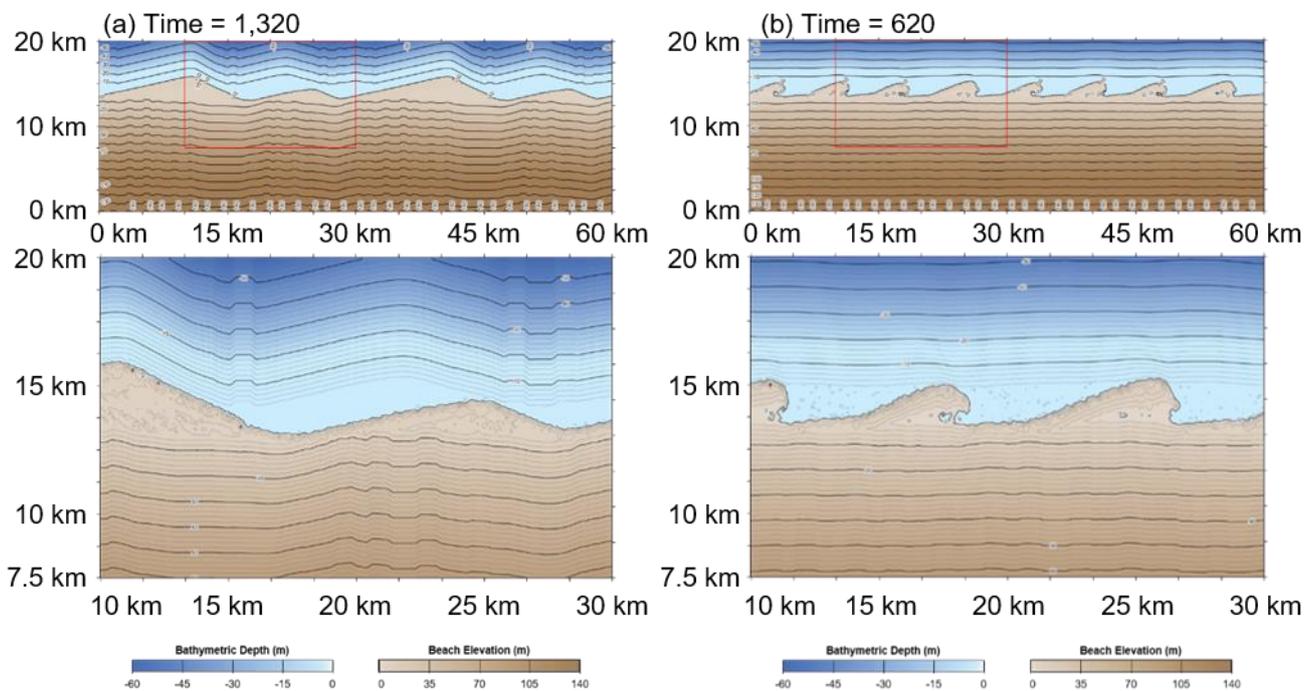
Figure 12: Cross-shore profiles taken for each of the twenty-five simulations shown as a 3D line graph, with water level shown as a white band across the transect. Labelled are the (a) beach surface, (b) dynamic shoreline and upper nearshore and (c) the lower nearshore.

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Figure 13: Morphology plots showing outputs of (a) A = 0.6, U = 0.6 at Time = 1,320 and (b) A = 0.7, U = 0.65 at Time = 620.
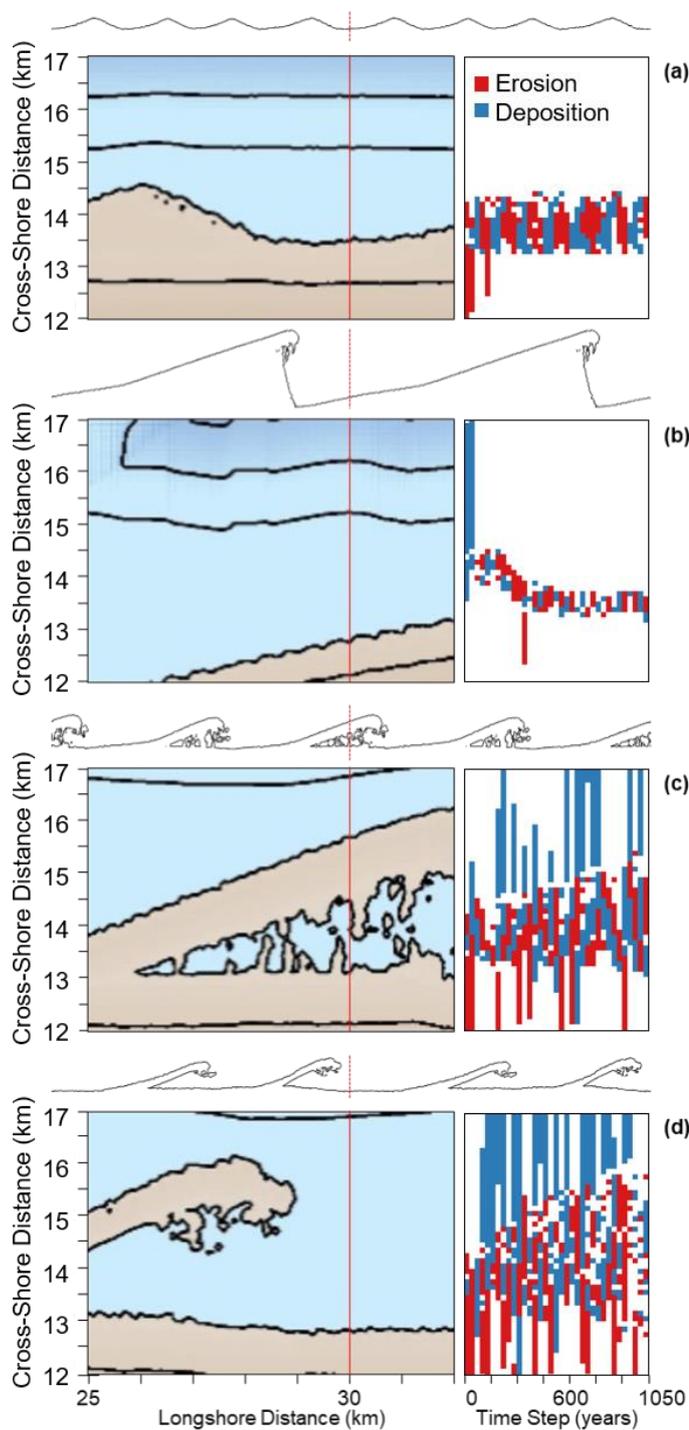
Figure 14: Shoreline Morphologies (left) and volume stacks (right) for four simulations where the wave climate is defined by (a) A = 0.5, U = 0.55, (b) A = 0.6, U = 0.6, (c) A = 0.7, U = 0.65 and (d) A = 0.8, U = 0.7. The red line marks the cross-shore transect where the change in volume at 30 year time intervals is recorded.