Author's Response to Reviewer Comments

Authors comments in bold.

We would like to thank both reviewers for their constructive comments on this manuscript. We would like to address each of your comments and the changes we have made to the paper in response to your feedback.

Due to the addition of text and subsections, some of the page and section numbers given by the reviewers may now have change. Page and section numbers in the responses given by the author are for the track changed document, whereby 'No Markup' is shown.

Comments from the editors and reviewers:

Reviewer 1: Minor Comments

1	L47 – "specific research questions" – Theoretical explorations can also derive from "specific" research questions. Do you mean questions that pertain to spatially explicit problems? (Simulating a particular reach of coastline?) Suggest rethinking this paraphrasing of Murray (2007).
	L47 changed to: ***"rather than pertaining to spatially explicit research questions"***

2	L323 – clarify sentence – (see "systems", plural?)
	L376 changed to: ***"profile of the coastal system changes"***

3	L335 – Confusing paragraph (and see punctuation of "waves") – I think the authors are trying to convey what was absent from CEM but is now present in CEM2D, but the paragraph doesn't read that way to me. Sounds like it's all still "to be calculated", as though these capacities don't yet exist in CEM2D. (But they do, correct?)
	The sediment transport equations in CEM2D do not currently take into consideration the water depth, or how far from the shore the waves break. The equations used are inherited from the original CEM and these have not been updated in this version of the model. Subsequent versions of the model will include revisions of the sediment transport equations so that these variables are taken into account, but this is a significant change that will require a substantial amount of work and so has been reserved for the next iteration of the model. **L386 has been changed to make this point clearer:** ***"The longshore sediment transport equations in CEM2D are inherited from the CEM and currently do not take into consideration the water depth, or how far from the shore the waves break. Since the water depth can now be calculated within this 2D model, future developments of CEM2D will focus on a revision of the sediment transport equation and include a more suitable calculation that can take advantage of the increased complexity and added functionalities in CEM2D."***

4	Fig. 2 – more labels? alongshore/crossshore, etc., to match Fig. 4?
	Figure 2 has been updated to include more labels and to show the shoreline search technique more clearly.

5	Fig. 9a, d – x axes? It's not clear to me what's plotted here.
	Figure 9 has been updated to make the axis labels clearer.

6	Fig. 10 – Labels for land versus sea? Strange visual inversion when sideways (Fig 11 clearer)
	Figure 10 has been updated to include 'land' and 'water' labels.

7	Fig. 12 – White band? I'm missing it, I think?
	Figure 12's caption has been updated to: ***"Cross-shore profiles taken for each of the twenty-five simulations, with water level shown as a dashed line and the initial cross-shore profile as a solid red line. Labelled are the (a) beach surface, (b) dynamic shoreline and upper nearshore and (c) the lower nearshore."***

Reviewer 1: Major Comments

8	I ended up confused about how the "variable water level" advance gets presented here. This manuscript seems like exactly the opportunity to showcase everything that the inclusion of a variable water level now allows – instead of a conservative assurance that there's been no loss of benefits from CEM.
	Both of these points highlight that we do not explore the variable water level function to a great depth in this paper. The aim of this paper was to outline the technical developments of CEM2D and the advantages of these (e.g. dynamic bathymetry and variable water level), whilst retaining the original model's ability to simulate fundamental cause-effect relationships which has received much credibility. **We have carried out significant novel research using the variable water level function to look at sea level rise impacts and as such, we felt it was better placed in the follow up results paper which is currently being finalsed. We do however recognise that it could be beneficial to add some additional detail into this paper about the variable water level function, given that it is one of the major developments. In light of this, the following changes have been made:** **A significant additional section (5.5 Variable Water Level) has been added to the results section:** ***"5.5 Variable Water Level*** ***Changing the water level against the dynamic topography allows CEM2D to explore how a rising water level might affect how coastal systems behave. The results demonstrate that a rising sea level causes landward recession of the shoreline and uplift of the profile (Figure 15), as is commonly held (Dickson et al., 2007; Bird, 2011). The rate of recession is broadly within two orders of magnitude the rate of sea level rise, prescribed at 2 m / 100 years in the simulations, which is in agreement with Bruun Rule estimations (Bruun, 1962). Variations in the rate of recession and morphology of the cross-shore profile are, however, observed with***

different wave climate conditions that differ in the balance of cross-shore and longshore flows (Figure 15).

As in Figure 14, Figure 16 shows the change in volume of sediment across a transect (x = 30 km) every 30 simulated years, for four wave climate scenarios where (a-b) A = 0.5, U = 0.55, (c-d) A = 0.6, U = 0.6, (e-f) A = 0.7, U = 0.65 and (g-h) A = 0.8, U = 0.7. The figure shows a comparison of the results with a static water level (top) and with a rate of sea level rise of 2 m / 100 years (bottom). The spatial extend of morphological change is more diverse and widespread when the systems are subject to sea level rise. The principal active zone also tracks backwards as the water level rises and the shoreline recedes.

A rising sea level influences the evolution of shoreline features that evolve in the model, including cusps (a), sand waves (b), reconnecting spits (c) and flying spits (d) (Figure 17). As also shown in Figure 17, recession of the shoreline is observed in all four coastal systems as the water level rises regardless of the wave climate conditions (also shown in Figure 15). Where the wave climate is symmetrical, cuspate features form under a static water level but have a slight asymmetry under sea level rise conditions, where the direction bias in the model is exaggerated. The cusps extend further offshore where the bays between the headlands are eroded, increasing wave shadowing and hence, exaggerating the effects of the directional bias. A slight asymmetry in the wave climate forms sand waves along the shoreline (Figure 17b), but submergence of these features under a rising sea level leads to the formation of a lagoon in the low-lying centre of the landform. Where the wave climate is defined by A = 0.7, U =0.65 (Figure 17c), reconnecting spits form when the water level is static, but as the water level rises the pathways that reconnect the spit to the mainland are submerged. In Figure 17d, flying spits are shown to evolve with and without sea level rise, where the wave climate is highly symmetric. The difference between these two simulations is that under a rising water level, the flying spits cycle through submergence and reformation, as they are drowned by the rising water, but new features are able to form due to the high rate of longshore sediment transport. Remnants of the submerged spits remain in the nearshore and promote the development of spits in these areas due to the shallower water and also influence the unique plan-form morphology of the features.”

Accordingly, the text has also been edited in Section 6 Discussion from L402:

“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. The results presented show that a rising sea level can significantly influence the evolution of coastal systems through recession and uplift of the cross-shore profile (Bruun, 1962), the types of shoreline features that form and the way in which these features evolve. Also found was the clear role of the wave climate conditions on the morphology of the shoreline and landform features behaviour, as the water level rises.”

Furthermore, we have added the following text to Section 4.3, clarifying the scope of the paper:

“The primary purpose of this paper is to highlight the technical development of CEM2D and demonstrate its additional functionalities. The simulations shown focus on how the coastal

	systems evolve with an unchanging water level at 0 m elevation, but results are also given for how an increasing water level at a rate of 2 m / 100 years influences the evolution of four shoreline types: cuspate, sand wave, reconnecting spit and flying spit. This rate of rise is in line with the UK Climate Projections 2009 (UKCP09) (Jenkins et al., 2009) H++ scenario of 0.93-1.9 m sea level rise by 2100 (Jenkins et al., 2009; Lowe et al., 2009).”

9	I would encourage the authors to show, as explicitly as they can, the difference in results yielded by CEM vs CEM2D. I see Figs. 10 & 11 – I mean some kind of quantitative demonstration of the differences in output? Here's what the old model did; and here's the amazing thing this one does. I wanted a clearer demonstration of the latter.
	There are two primary differences between CEM and CEM2D. This first is in the representation of the coastal domain, with CEM2D having a dynamic topography and bathymetry that evolves through the exchange of sediment between cells. The second development is in the ability of CEM2D to impose a variable water level in the coastal system. We have added some additional results to explore these functions more explicitly, as detailed below. **A significant additional section has been added to show some quantitative results regarding the differences in spatial scale of the features: 5.3 Spatial Scale of Shoreline Features. Within this section, it is highlighted that the differences in spatial scale of features between CEM and CEM2D are likely to occur due to the different way in which the domain is representation and sediment is distributed; as stated above, this is one of the primary developments of CEM2D. The text below is taken from this additional subsection:** ***“5.3 Spatial Scale of Shoreline Features*** ***The spatial scale of shoreline features differs between results from CEM and CEM2D. Metrics from the end of each run, as shown in Figures 10 and 11, show larger features evolve in CEM2D in six of the simulations. The larger features evolve under wave climate conditions where A = 0.6, U = 0.55-0.65 (sand waves), where A = 0.7-0.8, U = 0.7 (flying spit) and where A = 0.9, U = 0.75 (flying spit) and smaller features evolve in the remaining nineteen simulations. However, each run terminates at a different timestep and a comparison of results at the earliest termination for each pair of simulations shows that in all but one of the runs (A = 0.6, U = 0.55), the features are smaller and less developed in CEM2D than the CEM (Figure 18).*** ***The evolution of landforms is more gradual in CEM2D, likely as a result of differences in the representation of the domain and in the distribution of sediment. Rather than sediment being distributed evenly across the nearshore to the depth of closure, as in CEM, CEM2D uses the sediment distribution method to route sediment along lines of steepest descent and spreads available material across the nearshore profile. This leads to both the formation of shoreline features but also to the formation of a shallow nearshore shelf (see Section 5.4).*** ***Highlighted above are differences in results between CEM and CEM2D and in particular, the complexity of results generated in CEM2D due to the addition of a dynamically evolving profile. In nature, the features discussed evolve at different rates and to different spatial scales depending and in order to use CEM2D to investigate such systems, parameters in the model***

including the threshold and frequency of sediment distribution should be adjusted to suit the specific environment studied and the rates at which these features form."

A significant additional section has been added to show some quantitative results regarding the influence that a rising water level has on the coastal systems: 5.5 Variable Water Level. The principal results are as follows (see response number 8 for full text):

L358 *"The results demonstrate that a rising sea level causes landward recession of the shoreline and uplift of the profile (Figure 15), as is commonly held (Dickson et al., 2007; Bird, 2011). The rate of recession is broadly within two orders of magnitude the rate of sea level rise, prescribed at 2 m / 100 years in the simulations"*

L361 *"Variations in the rate of recession and morphology of the cross-shore profile are, however, observed with different wave climate conditions"*

L368 *"The spatial extend of morphological change is more diverse and widespread when the systems are subject to sea level rise. The principal active zone also tracks backwards as the water level rises and the shoreline recedes."*

L371 *"A rising sea level influences the evolution of shoreline features that evolve in the model, including cusps (a), sand waves (b), reconnecting spits (c) and flying spits (d) (Figure 17)."*

The text has also been edited accordingly in Section 6 Discussion from L402, as detailed in response number 8.

10	In CEM, is it possible to impose a linear erosion rate to simulate sea-level rise? And then, in CEM2D, could the authors show the equivalent experiment with the addition of an actual landscape gradient? … we need clearer and more specific supporting evidence than Fig. 14 provides.

We're trying to move away from the idea of imposing a linear erosion rate to simulate sea level rise, but rather in CEM2D we can increase the water level and investigate how it affects the existing erosion rate – thereby just changing sea level – rather than having to adjust the erosion rate.

We acknowledge that we need more evidence to show the variable water level function and have added results from this research into subsection 5.5 Variable Water Level. The full text from this additional section is given in response number 8 and the key findings are given below (also given in response number 9):

L358 *"The results demonstrate that a rising sea level causes landward recession of the shoreline and uplift of the profile (Figure 15), as is commonly held (Dickson et al., 2007; Bird, 2011). The rate of recession is broadly within two orders of magnitude the rate of sea level rise, prescribed at 2 m / 100 years in the simulations"*

L361 *"Variations in the rate of recession and morphology of the cross-shore profile are, however, observed with different wave climate conditions"*

	L368 ***"The spatial extend of morphological change is more diverse and widespread when the systems are subject to sea level rise. The principal active zone also tracks backwards as the water level rises and the shoreline recedes."*** **L371** ***"A rising sea level influences the evolution of shoreline features that evolve in the model, including cusps (a), sand waves (b), reconnecting spits (c) and flying spits (d) (Figure 17)."*** **The text has also been edited accordingly in Section 6 Discussion from L402, as detailed in response number 8.**

Reviewer 2: Major Comments

11	The improvements that this numerical redistribution of sediments introduces in landscape evolution over the previous model are not clear.
	We are sorry if this is not clear. In CEM the horizontal filling and emptying of cells can allow too much sediment to be added or removed from cells which then translates into the simplistic landward or seaward movement of the shoreline. This method is rather opaque in existing descriptions of the original CEM model and only really clear when analyzing the code. In CEM2D and in this description we have been very clear about the need to refine this process, especially in light of the model moving towards being two dimensional and the storage of sediment in cells being vertical as opposed to horizontal. **Importantly, the CEM2D sediment distribution method enables the model to simulate the dynamic topography of the coastal system not just the shore edge. Sediment transport is first calculated for the one-line shoreline, like the CEM, but rather than the material assumed to be distributed evenly across the nearshore profile, the sediment distribution method allows the profile to dynamically evolve. The method is based broadly on the sand pile theory and steepest descent method, which are used in other numerical models.** **To make this clearer in the manuscript, the following text has been added to L140 in Section 3:** ***"The implementation of this method in CEM2D allows the nearshore profile to evolve dynamically, rather than assuming an even distribution across the nearshore profile and forming shore-parallel contours, as is the case in CEM and other one-line models."*** **The differences observed between the CEM2D and CEM due to the implementation of this method are highlighted in Section 5.3 Spatial Scale of Shoreline Features, which has been added to the manuscript. An extract from L302 is shown below (see full text in response number 9):** **"The evolution of landforms is more gradual in CEM2D, likely as a result of differences in the representation of the domain and in the distribution of sediment. Rather than sediment being distributed evenly across the nearshore to the depth of closure, as in CEM, CEM2D uses the sediment distribution method to route sediment along lines of steepest descent and spreads available material across the nearshore profile. This leads to both the formation of shoreline features but also to the formation of a shallow nearshore shelf (see Section 5.4)."**

12	The response to changes in sea level is even not explored through the paper.
	This feedback was also given by reviewer 1 and changes have been made accordingly, through the addition of Section 5.5 Variable Water Level and additional text in Section 6 Discussion, as detailed in response number 8 above.

13	I have also got the impression comparing Figure 10 and Figure 11 that this redistribution changes the spatial scale of the features developed due to probably a reduction on the effective alongshore flux due to this sediment redistribution scheme.
	The spatial scale of features is different between CEM and CEM2D, due to the way in which sediment is distributed in both models. This has now been addressed in the manuscript, with the addition of Section 5.3 Spatial Scale of Shoreline Features (see response number 9 for full text).

14	The CEM2D model produces very different results for example for A=0.5 with any U and what seems to be a numerical instability for U=0.75, A=0.6. The authors should have examined these big differences in model behavior.
	Having spent considerable time testing the model we are confident this is not numerical instability. Where A = 0.5, directional bias is observed in the model results due to directional bias found in some of the model routines. The effect is more apparent in CEM2D due to the more complex representation of the domain and sediment distribution in two directions but can also be seen in CEM. This has been highlighted in the manuscript, at L239. **For U=0.75 and A=0.6 the instabilities the reviewer may be referring to are ponds/pooling in the CEM2D outputs. This is a reflection and good example of how the 2D representation of a coast in CEM2D allows more complex topography (that evolves over time) to be simulated, rather than the ‘single line’ of the 1D CEM model that just identifies a shoreline. In our simulations this is not reflective of instability but the cumulative development of the coastline over time.**

15	In general, it is important to highlight what new features are better represented in the new version and what are the implications for coastline shape simulation, and a simple comparison with the old model results is not enough.
	In our revised manuscript, we identify in several places the new features of CEM2D and what they allow the model to do as progress from CEM. These have been listed below: **a. L113 *“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.”*** **b. L115: *“However, as opposed to each cell containing a fractional horizontal fill of sediment, 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 enables CEM2D to represent two-dimensional coastlines with greater topographic detail compared to the original CEM, as illustrated in Fig. 5.”***

c. L116: ***"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."***

d. L126 ***"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 distributed to the surrounding cells based on the slope between cells and an angle of repose (Fig. 6)."***
…L146 ***"The implementation of this method in CEM2D allows the nearshore profile to evolve dynamically, rather than assuming an even distribution across the nearshore profile and forming shore-parallel contours, as is the case in CEM and other one-line models. The ability of the simulated coast 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 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)."***

e. L148 ***"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 used to represent tidal fluctuations and long-term sea level change."***

f. L150 ***"The increased complexity of the model domain and of sediment transport processes in CEM2D compared to CEM, 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."***

g. L153 ***"The sediment storage and handling technique allows complex landforms and features to develop and leave a morphological memory in the bathymetry as they evolve, which is not possible in the equilibrium profile of the CEM."***

h. L155 "Sea level change is an important addition to this model from the original CEM, 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."

i. L252 ***"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."***

j. L278 ***"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 sediment handling techniques in the model."***

k. L282 ***"…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 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."

l. L306 ***"The evolution of landforms is more gradual in CEM2D, likely as a result of differences in the representation of the domain and in the distribution of sediment. Rather than sediment being distributed evenly across the nearshore to the depth of closure, as in CEM, CEM2D uses the sediment distribution method to route sediment along lines of steepest descent and spreads available material across the nearshore profile"***

m. L312 ***"Highlighted here are differences in results between CEM and CEM2D and the added complexity in the evolution of the coastal systems with the addition of a dynamically evolution profile in the latter model."***

n. L318 ***"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)). 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."***

o. L346 ***"Changing the water level against the dynamic topography allows CEM2D to explore how a rising water level might affect how coastal systems behave."***

p. L360 ***"A rising sea level influences the evolution of shoreline features that evolve in the model, including cusps (a), sand waves (b), reconnecting spits (c) and flying spits (d) (Fig. 17)."***

q. L377 ***"Adding two-dimensional functionality allows the model to generally reproduce the results of the original one-line CEM (Ashton and Murray, 2006a) by simulating fundamental shoreline shapes according to the wave climate but advances the models ability to analyse how the two-dimensional profile of the systems evolve and the influence of a variable water level."***

r. L384 ***"Importantly, restructuring and increasing the dimensionality of sediment transport in the model allows us to explore how the profile of the coastal system changes with the shape of the shoreline. In many one-line models, such as the CEM, 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."

s. L402 ***"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."***

t. L415 ***"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"***

16	Antolinez et al. (2018) use CEM for hindcasting 150 of shoreline evolution in the Carolinas capes, but they don't account for changes in sea level, this new CEM2D model brings a great opportunity to account for this process adequately and to show what CEM is missing.
	Yes, this would be a great opportunity. Though as in answer 8 to reviewer 1, our purpose with this paper was to outline the technical developments of CEM2D. A paper detailing results from simulations investigating the influence of a variable water level on coastal evolution is currently in preparation, but we do agree that some results that showcase the variable water level function would benefit the manuscript. **An additional section (5.5 Variable Water Level) has been added, detailing some results with a variable water level. The text has also been edited accordingly in section 6 Discussion from L402, as detailed in response number 8.**

17	The authors claim this new model is a 2D model, however the model is still a single process model, alongshore sediment transport, with numerical diffusion in 2D using a stability slope condition. The model would not work in waves perpendicular to the coast. In my opinion, it is not consistent to claim a 2D model that is only solving alongshore sediment transport with an integrated semi-empirical formula, why the authors don't solve sediment transport at cell level? How is this integrated transport redistributed in the cross-shore? Or is it all taken from the adjacent cell to the shoreline position? If the last, I have the impression that the model would create spurious shoreline change behavior as it has the possibility to remove a lot of sand from the adjacent cell to the shoreline in alongshore direction and later on the need to redistribute sediment in the cross-shore direction due to the slope criteria, when in nature sediment would have been taken gradually from several cells in cross-shore direction; your slope condition is changing the cross-shore profile shape in the upper-shoreface in time, could you validate this?
	As authors, we discussed the use of the term 2D and concluded that it was suitable for this model since it distributes sediment longshore and cross-shore and also allows the elevation of cells to change according to the volume of sediment they contain. We can change this to quasi-2D or part 2D if the editor thinks this is appropriate.

For the second point, as described in Section 3 of the paper, sediment transport is calculated for each shoreline cells and is moved alongshore accordingly, as in CEM. At a defined frequency, calculated according to when a sufficient amount of sediment has built up in these shoreline cells, the sediment will get redistributed. The frequency and threshold for the sediment distribution method is calculated so that enough sediment is moved to be within the threshold of a given slope angle, but not so much that large volumes of sediment are moved and make the system unstable. As a result, sediment is gradually redistributed from as many cells as meet the threshold criteria on each timestep that the method is employed.

We appreciate this may not be completely clear in the manuscript so have modified Section 3 from L123, to make this clearer:

"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). Longshore sediment transport is calculated using the same equation as CEM (Eq. 1) but is then redistributed from the shoreline cells across the model domain using a sediment distribution method which is induced when the slope angle between cells reaches a critical threshold (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 the sediment redistribution procedure, at user-defined time-step intervals an algorithm sweeps the entire model domain and identifies where a given threshold angle has been reached between a cell and its neighbour. The material is redistributed, taking account of the elevation 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 the redistribution method and (2) the frequency that the domain is analysed for these thresholds. Whilst the longshore sediment transport method is carried out along the shoreline on every timestep, activating the sediment distribution method at this frequency causes instability in the model and it is therefore activated less frequently. The threshold and frequency parameter 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)."

We agree that validation of the cross-shore distribution of sediment across the nearshore profile would be advantageous. However, for this we would need field data and field examples of which we do not have.

18	I also miss a lot of discussion and review of recent existing models accounting for alongshore and cross-shore responses and accounting for changes in sea level, for example, Larson et al. (2016), Vitousek et al. (2017), Robinet et al. (2018), and Antolinez et al. (2019).

Thank you for your suggestions and for the list of references at the end of your response. We have edited the text in Section 1 starting at L51 that details some of the existing models and added these authors to the review. We recognize that this list is not exhaustive but contains some of the key models and texts relevant to the paper.

L51: ***"In the field of coastal modelling, there is a gap for a two-dimensional coastal model that can simulate features such as spits, bars and beach migration along with a dynamic nearshore bathymetry and a variable water level but is parsimonious enough to enable short run times allowing us to answer research questions about coastal evolution at meso-spatiotemporal scales. Existing models with such scope, such as CEM, COVE and GENESIS (Hanson and Kraus, 1989; Ashton et al., 2001; Hurst et al., 2014), are limited to transporting sediment in 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. Hybrid shoreline change models such as COCOONED (Antolínez et al., 2019) and CoSMoS-COAST (Vitousek et al., 2017) calculate sediment transport in cross-shore and long-shore directions and can varying the water level in model but are transect based and do not include a dynamically evolving bathymetry. The LX-Shore model (Robinet et al., 2018) is cellular-based with longshore and cross-shore sediment transport calculations but has an equilibrium beach profile as in models such as CEM and COVE. In contrast to these longer-term models, finer scale models such as Delft3D (Lesser et al., 2004) can simulate coastal hydrodynamics and sediment transport processes in two- or three-dimensions, but their complexity and long model run times means investigating sea level rise responses over meso-timescales is presently impracticable."***

19	In the abstract the authors explain the model is suitable for evolving morphological features in time scales from 10 to 100 years, but any analysis is performed in these timescales.

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, to allow sufficient time for the coastal systems to evolve to a state of relative stability and to generate a sufficient amount of data to analyse the behavior of the systems (see L172). Whilst this is the case, the results are applicable to timescales of 10 to 100 years and we agree that this should be better expressed in the paper. The following text has been edited at L176:

"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, to allow sufficient time for the coastal systems to evolve and to generate sufficient data from which quantitative and qualitative analysis could be completed. Whilst this is the case, the results are applicable to timescales of 10 to 100 years."

20	I support the idea of changing the bathymetry, but what is the added value if wave transformations are still assuming parallel contours to the shoreline as in CEM? other models such as Robinet et al., 2018 already account for a scheme propagating waves in complex bathymetry and studies such as the one presented in Limber et al. (2017) proofs its importance.

	This is a great point. With CEM2D we have made the topography 2D but retained a 1D approach to waves. This really comes down to the scope and parsimony of the model. Adding in wave transformations according to the changing bathymetry/topography would be a great addition and something we have thought about. However, the complexity and associated numerical overhead associated with this then restricts the spatial and temporal scope over which the model can be applied. Simply, we have chosen or line of simplification to be with a simple wave approach. CEM2D is not, nor intended to be a complete solution but by including a dynamically evolving topography and bathymetry, the model can be used to analyse how the profile of the coastal system evolves over time, the morphology of shoreline features and the existence of remnant features that are stored in the bathymetry. It was also necessary in order to account for a variable water level. **The advantage of having a dynamically evolving bathymetry also means that we can continue to increase the complexity of the model through the additional of processes that use metrics of the bathymetry, such as wave transformations.**

21	I can read several times through the text the authors acknowledge certain model limitations and they propose to incorporate improvements in coming versions, why do not incorporate them now? (for example, lines 238-240)
	We acknowledge that there are several limitations of the model highlighted in the manuscript. These have been included, as it is important to understand how the model works and what the limitations are. Model development is an ongoing process and we discuss these limitations, as areas we feel are important to focus on for future developments, that will require a significant amount of research to address.

22	Certain Figures are not properly presented, for example Figure 10 and Figure 11 cut the model domain and shoreline shapes are not complete, Figure 9 has different color markers in the legend than in the subplots.
	Figure 9 has been updated with the correct markers. **Figure 10 and 11 have been reduced along the x-axis so that the entire matrix of results can be viewed on a single page. They have been reduced by cropping the periodic boundaries from the model domain, which are repeats of the central portion of the domain (shown). Removing these Sections, therefore, do not impeded the results.**

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

Chloe Leach[1], Tom Coulthard[2], Andrew Barkwith[3], Daniel R. Parsons[2], Susan Manson[4]

[1]School of Geography, The University of Melbourne, Parkville, Melbourne, VIC 3010, Australia
[2]Department of Geography, Geology and Environmental Science, University of Hull, Hull, HU6 7RX, UK
[3]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK
[4]Environment Agency, Crosskill House, Mill Lane, Beverley, HU17 9JW, UK

Correspondence to: Chloe Leach (chloe.leach@unimelb.edu.au)

Abstract. Coasts are among the most intensely used environments on the planet, but they also present dynamic and unique 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 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.

1 Introduction

Coastal systems are amongst the most dynamic environments on the planet, with their form and evolution being highly sensitive to changes in environmental conditions, over a range of spatial and temporal scales (Wong et al., 2014). 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 suitable and sustainable management (Wong et al., 2014). 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 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).

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 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).

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~~pertaining to spatially explicit 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).

~~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 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 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 the field of coastal modelling, there is a gap for a two-dimensional coastal model that can simulate features such as spits, bars and beach migration along with a dynamic nearshore bathymetry and a variable water level but is parsimonious enough to enable short run times allowing us to answer research questions about coastal evolution at meso-spatiotemporal scales.

Existing models with such scope, such as CEM, COVE and GENESIS (Hanson and Kraus, 1989; Ashton et al., 2001; Hurst et al., 2014), are limited to transporting sediment in 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. Hybrid shoreline change models such as COCOONED (Antolínez et al., 2019) and CoSMoS-COAST (Vitousek et al., 2017) calculate sediment transport in cross-shore and long-shore directions and can varying the water level in model but are transect based and do not include a dynamically evolving bathymetry. The LX-Shore model (Robinet et al., 2018) is cellular-based with longshore and cross-shore sediment transport calculations but has an equilibrium beach profile as in models such as CEM and COVE. In contrast to these longer-term models, finer scale models such as Delft3D (Lesser et al., 2004) can simulate coastal hydrodynamics and sediment transport processes in two- or three-dimensions, but their complexity and long model run times means investigating sea level rise responses over meso-timescales is presently impracticable.

In this paper, the development and application of the Coastline Evolution Model 2D (CEM2D) is presented. This model is 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 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 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 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.

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):

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

here, Qs is the sediment flux (m^3/day), K is a calibration coefficient, Hb is the breaking wave height (m), ϕ_b is the breaking wave angle (°) and θ is the local shoreline orientation (°).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):

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

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 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 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.

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 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.

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 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 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 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 implementation of this method in CEM2D allows the nearshore profile to evolve dynamically, rather than assuming an even distribution across the nearshore profile and forming shore-parallel contours, as is the case in CEM and other one-line models. In CEM2D, the ability of the simulated coast 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 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 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 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 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

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 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.

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 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 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.~~The primary purpose of this paper is to highlight the technical development of CEM2D and demonstrate its additional functionalities. The simulations shown focus on how the coastal systems evolve with an unchanging water level at 0 m elevation, but results are also given for how an increasing water level at a rate of 2 m / 100 years influences the evolution of four shoreline types: cuspate, sand wave, reconnecting spit and flying spit. This rate of rise is in line with the UK Climate Projections 2009 (UKCP09) (Jenkins et al., 2009) H++ scenario of 0.93-1.9 m sea level rise by 2100 (Jenkins et al., 2009; Lowe et al., 2009).

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 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):

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

where d_{ij} denotes the value of the *j*-th elementary effect (*j* = 1,…,r) of the *i*-th input factor (and where r is the number of repetitions), $y(x_1x_2,\ldots,x_k)$ 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 (б) is also used 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 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 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~~1 and the behavioural indices in Table ~~3~~2.

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 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 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 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 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~~ Shoreline ~~Shapes~~Features

The ensemble plots in Fig. 10 and Fig. 11 show final coastal morphologies produced from CEM and CEM2D respectively 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. This directional bias is more apparent in CEM2D and particularly where the wave climate is symmetrical (A = 0.5). 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.

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 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 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 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 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 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 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 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.

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 influenced by conditions that could be having a greater impact on coastal evolution, including estuarine processes and dredging activities.

5.3 Spatial Scale of Shoreline Features

The spatial scale of shoreline features differs between results from CEM and CEM2D. Metrics from the end of each run, as shown in Figures 10 and 11, show larger features evolve in CEM2D in six of the simulations. The larger features evolve under wave climate conditions where A = 0.6, U = 0.55-0.65 (sand waves), where A = 0.7-0.8, U = 0.7 (flying spit) and where A = 0.9, U = 0.75 (flying spit) and smaller features evolve in the remaining nineteen simulations. However, each run terminates at a different timestep and a comparison of results at the earliest termination for each pair of simulations shows that in all but one of the runs (A = 0.6, U = 0.55), the features are smaller and less developed in CEM2D than the CEM (Figure 18).

The evolution of landforms is more gradual in CEM2D, likely as a result of differences in the representation of the domain and in the distribution of sediment. Rather than sediment being distributed evenly across the nearshore to the depth of closure, as in CEM, CEM2D uses the sediment distribution method to route sediment along lines of steepest descent and spreads available material across the nearshore profile. This leads to both the formation of shoreline features but also to the formation of a shallow nearshore shelf (see Section 5.4).

Highlighted above are differences in results between CEM and CEM2D and in particular, the complexity of results generated in CEM2D due to the addition of a dynamically evolving profile. In nature, the features discussed evolve at different rates and to different spatial scales depending and in order to use CEM2D to investigate such systems, parameters in the model including the threshold and frequency of sediment distribution should be adjusted to suit the specific environment studied and the rates at which these features form.

5.4 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)). 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 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 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 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 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.

5.5 Variable Water Level

Changing the water level against the dynamic topography allows CEM2D to explore how a rising water level might affect how coastal systems behave. The results demonstrate that a rising sea level causes landward recession of the shoreline and uplift of the profile (Figure 15), as is commonly held (Dickson et al., 2007; Bird, 2011). The rate of recession is broadly within two orders of magnitude the rate of sea level rise, prescribed at 2 m / 100 years in the simulations, which is in agreement with Bruun Rule estimations (Bruun, 1962). Variations in the rate of recession and morphology of the cross-shore profile are, however, observed with different wave climate conditions that differ in the balance of cross-shore and longshore flows (Figure 15).

As in Figure 14, Figure 16 shows the change in volume of sediment across a transect (x = 30 km) every 30 simulated years, for four wave climate scenarios where (a-b) A = 0.5, U = 0.55, (c-d) A = 0.6, U = 0.6, (e-f) A = 0.7, U = 0.65 and (g-h) A = 0.8, U = 0.7. The figure shows a comparison of the results with a static water level (top) and with a rate of sea level rise of 2 m / 100 years (bottom). The spatial extend of morphological change is more diverse and widespread when the systems are subject to sea level rise. The principal active zone also tracks backwards as the water level rises and the shoreline recedes.

A rising sea level influences the evolution of shoreline features that evolve in the model, including cusps (a), sand waves (b), reconnecting spits (c) and flying spits (d) (Figure 17). As also shown in Figure 17, recession of the shoreline is observed in all four coastal systems as the water level rises regardless of the wave climate conditions (also shown in Figure 15). Where the wave climate is symmetrical, cuspate features form under a static water level but have a slight asymmetry under sea level rise conditions, where the direction bias in the model is exaggerated. The cusps extend further offshore where the bays between the headlands are eroded, increasing wave shadowing and hence, exaggerating the effects of the directional bias. A slight asymmetry in the wave climate forms sand waves along the shoreline (Figure 17b), but submergence of these features under a rising sea level leads to the formation of a lagoon in the low-lying centre of the landform. Where the wave climate is defined by A = 0.7, U =0.65 (Figure 17c), reconnecting spits form when the water level is static, but as the water level rises the pathways that reconnect the spit to the mainland are submerged. In Figure 17d, flying spits are shown to evolve with and without sea level rise, where the wave climate is highly symmetric. The difference between these two simulations is that under a rising water level, the flying spits cycle through submergence and reformation, as they are drowned by the rising water, but new features are able to form due to the high rate of longshore sediment transport. Remnants of the submerged spits remain in the nearshore and promote the development of spits in these areas due to the shallower water and also influence the unique plan-form morphology of the features.

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 system~~s~~ 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.~~The longshore sediment transport equations in CEM2D are inherited from the CEM and currently do not take into consideration the water depth, or how far from the shore the waves break. Since the water depth can now be calculated within this 2D model, future developments of CEM2D will focus on a revision of the sediment transport equation and include a more suitable calculation 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

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. 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

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

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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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~~1: 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 (^{o})	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	

Table ~~3~~2: 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)

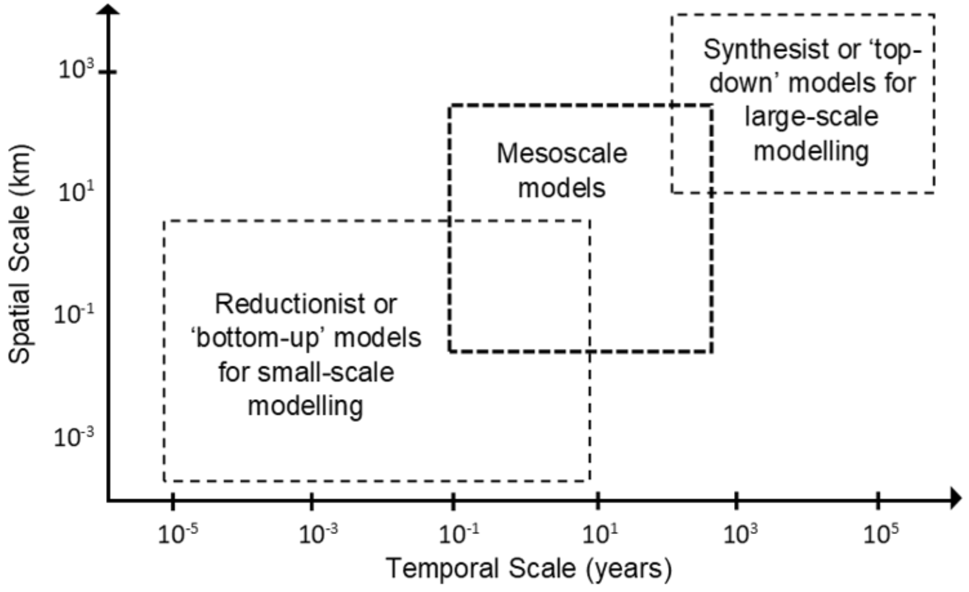


Figure 1: Spatial and temporal ranges for traditionally reductionist and synthesist models, with mesoscale models highlighted in grey within the scale appropriate for coastal management (adapted from Gelfenbaum and Kaminsky, 2010; van Maanen et al., 2016).

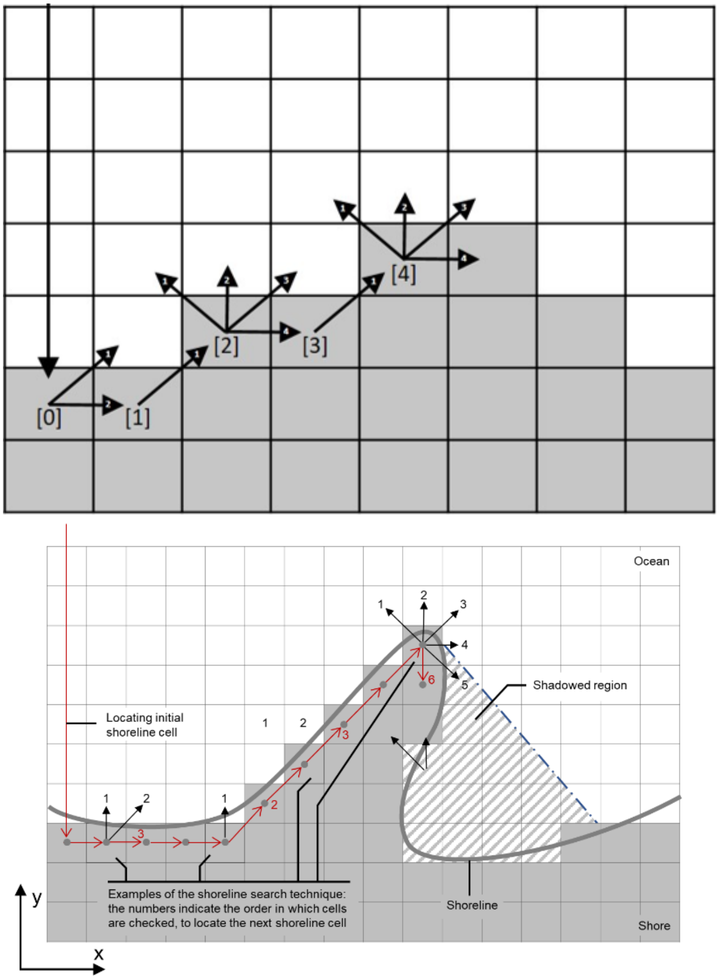
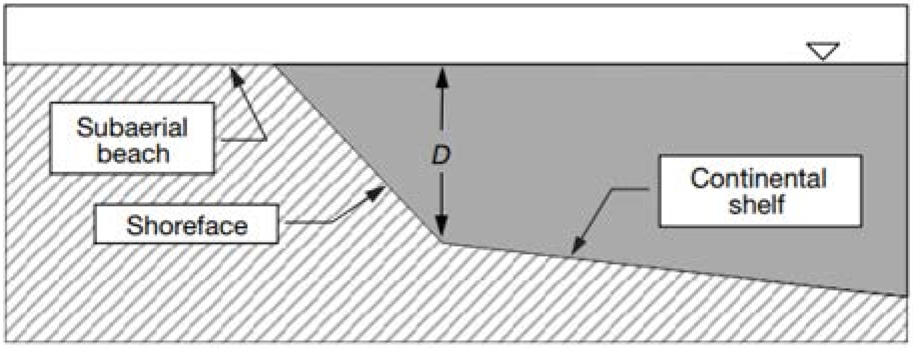


Figure 2: A schematic of the shoreline search technique used in CEM (and CEM2D) to map the X and Y location of the shoreline cells. The number in square brackets denotes the shoreline cell number that is associated with a particular X and Y value and the number on each arrow is the iteration of the clockwise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



560 **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).**

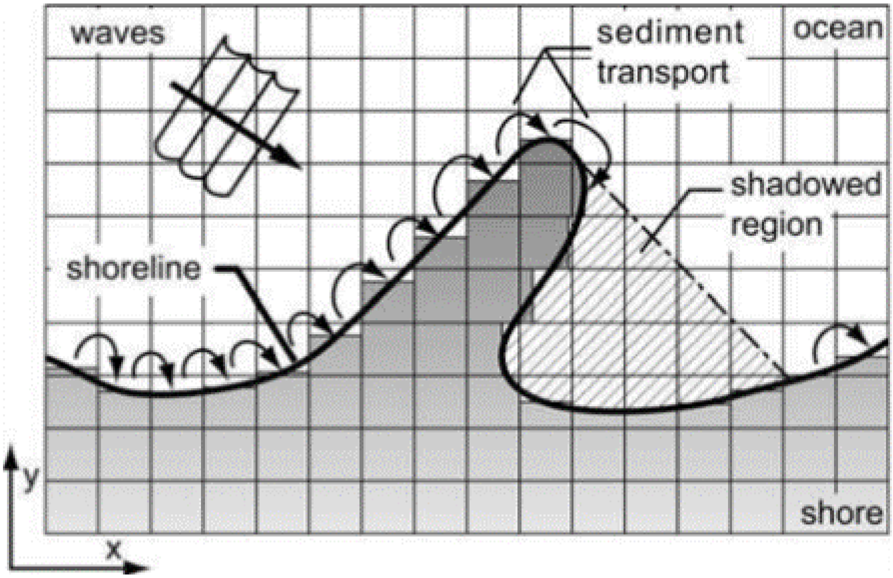


Figure 4: Plan-view schematic of CEM2D showing the shadow zone that is formed when protruding sections of coastline prevent waves from approaching the shoreline (after Ashton and Murray, 2006a).

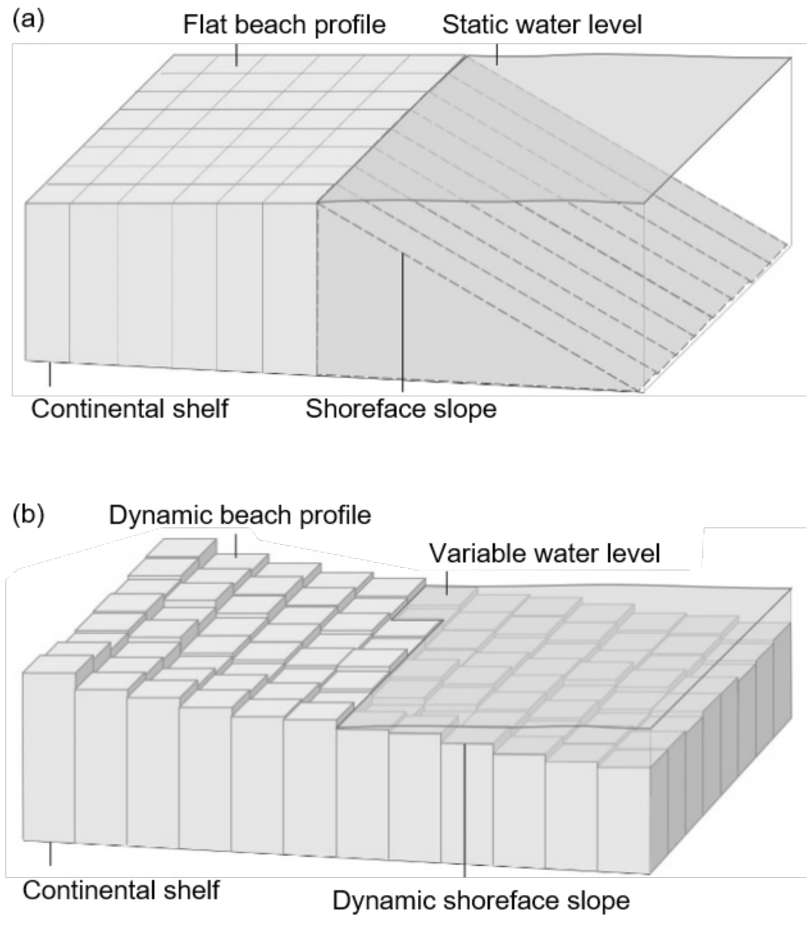


Figure 5: Schematics of CEM (a) and CEM2D's (b) profiles, illustrating the difference in structure and dimensionality of the two models.

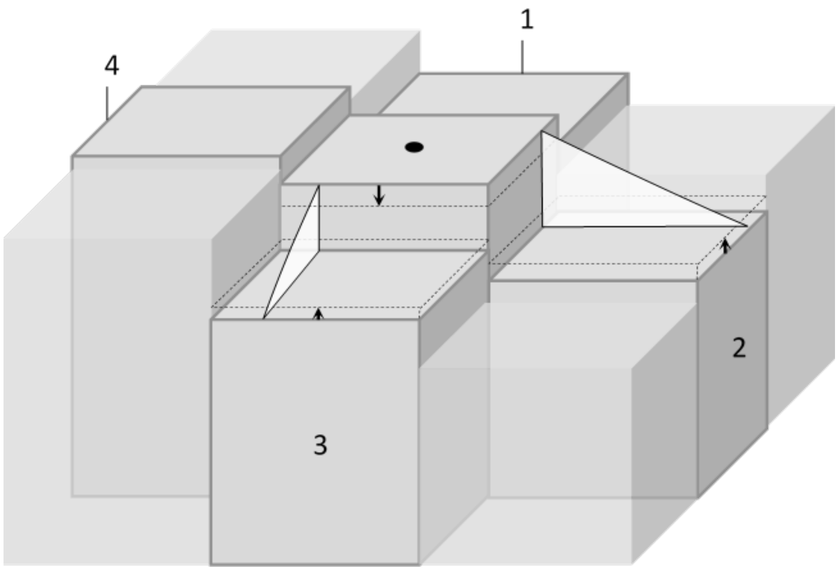


Figure 6: Schematic of the sediment distribution technique used to distribute sediment to cells with lower elevations. In the example, the angle between the central cell and cells [2] and [3] exceeds the threshold for diffusion. Sediment is removed from the central cell and redistributed to these cells.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

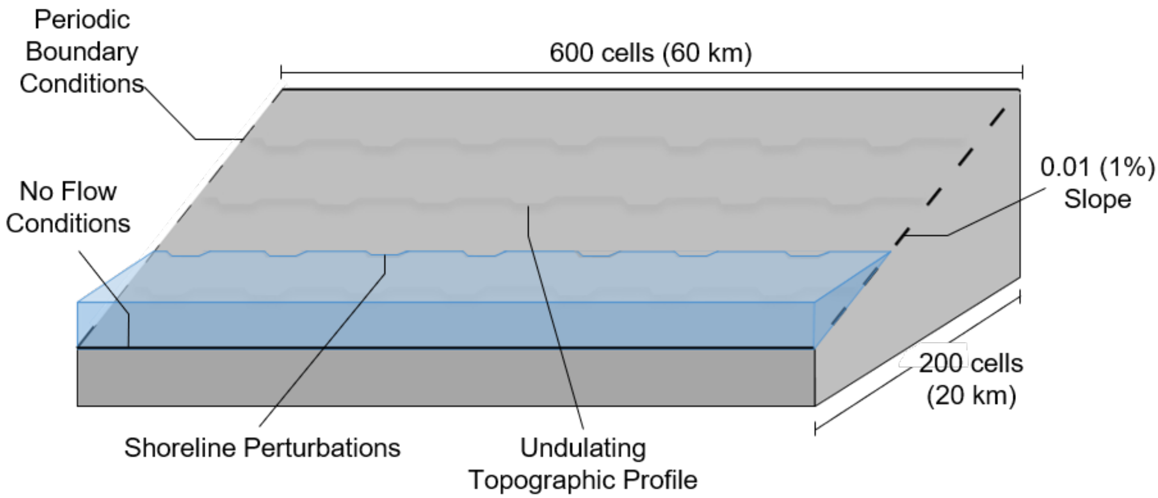


Figure 7: A schematic of CEM2D's model set-up and initial conditions used for simulations presented in this paper.

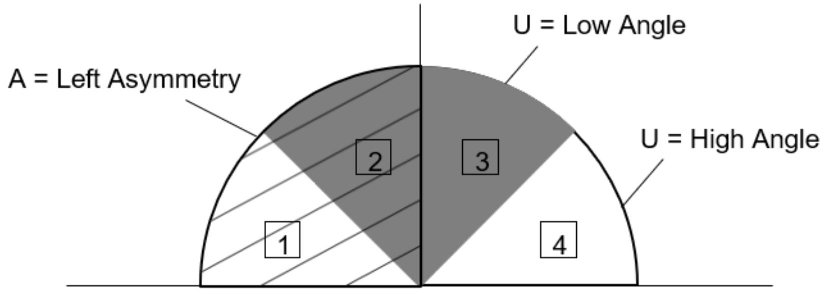
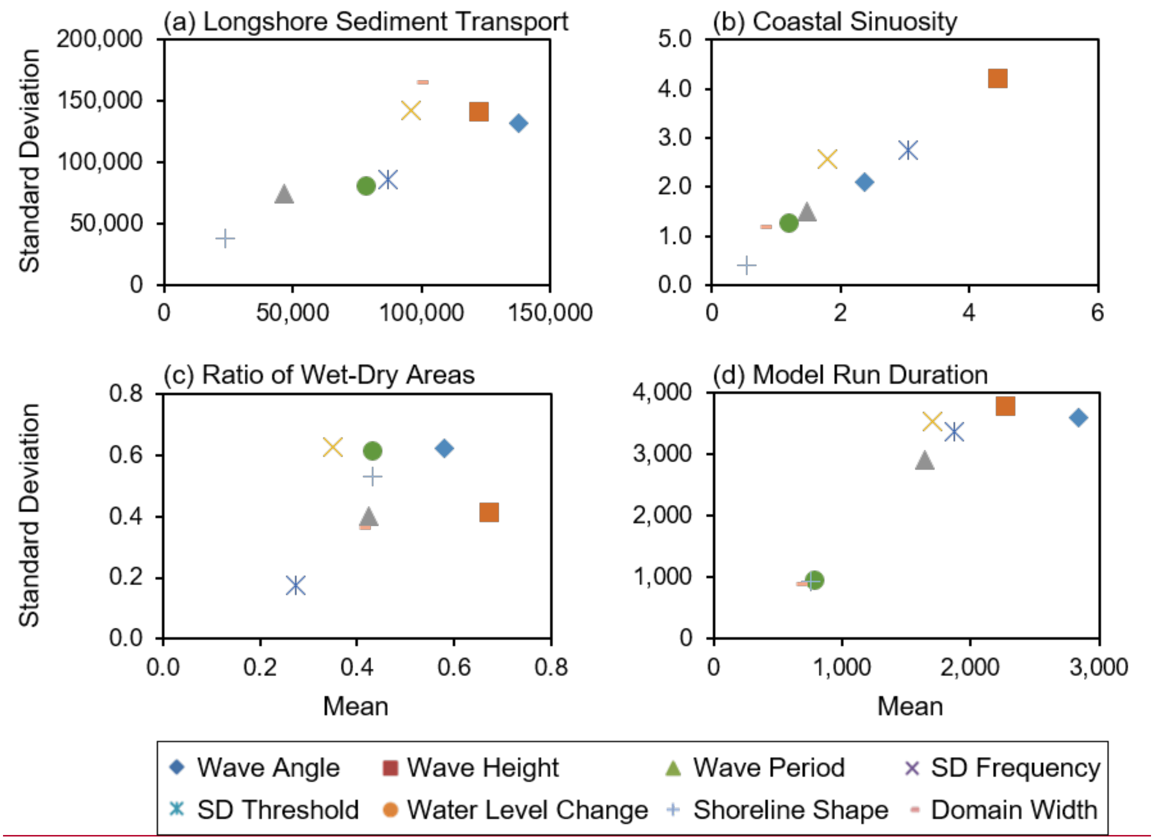


Figure 8: Schematic showing the wave angle direction, defined by the wave climate asymmetry (A) and the proportion of high to low angle waves (U) with the numbers denoting the four bins.



(a) Longshore Sediment Transport
(b) Coastal Sinuosity
(c) Ratio of Wet-Dry Areas
(d) Model Run Duration
Standard Deviation
Mean
200,000
150,000
100,000
50,000
0
0
50,000
100,000
150,000
5.0
4.0
3.0
2.0
1.0
0.0
0
2
4
6
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
4,000
3,000
2,000
1,000
0
0
1,000
2,000
3,000
Wave Angle
Wave Height
Wave Period
SD Frequency
SD Threshold
Water Level Change
Shoreline Shape
Domain Width

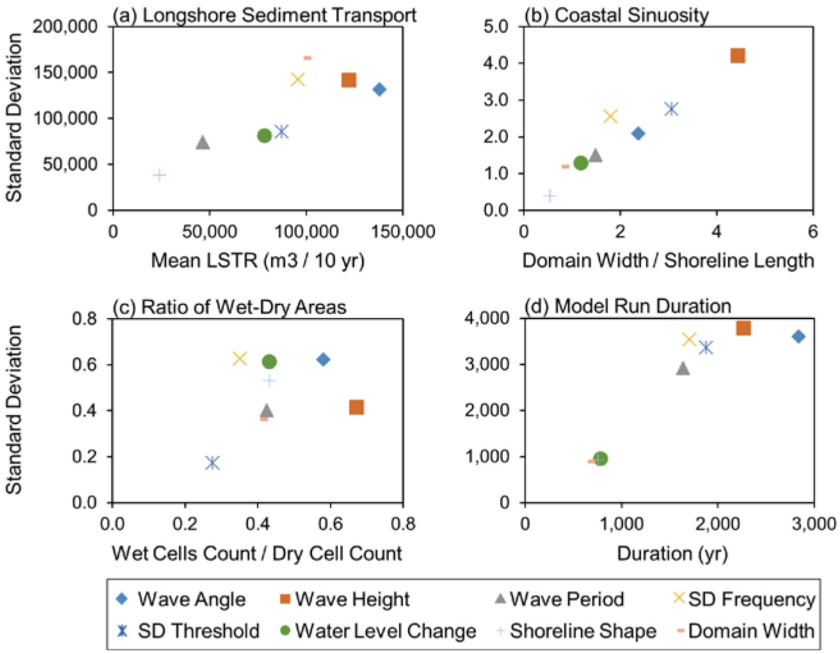
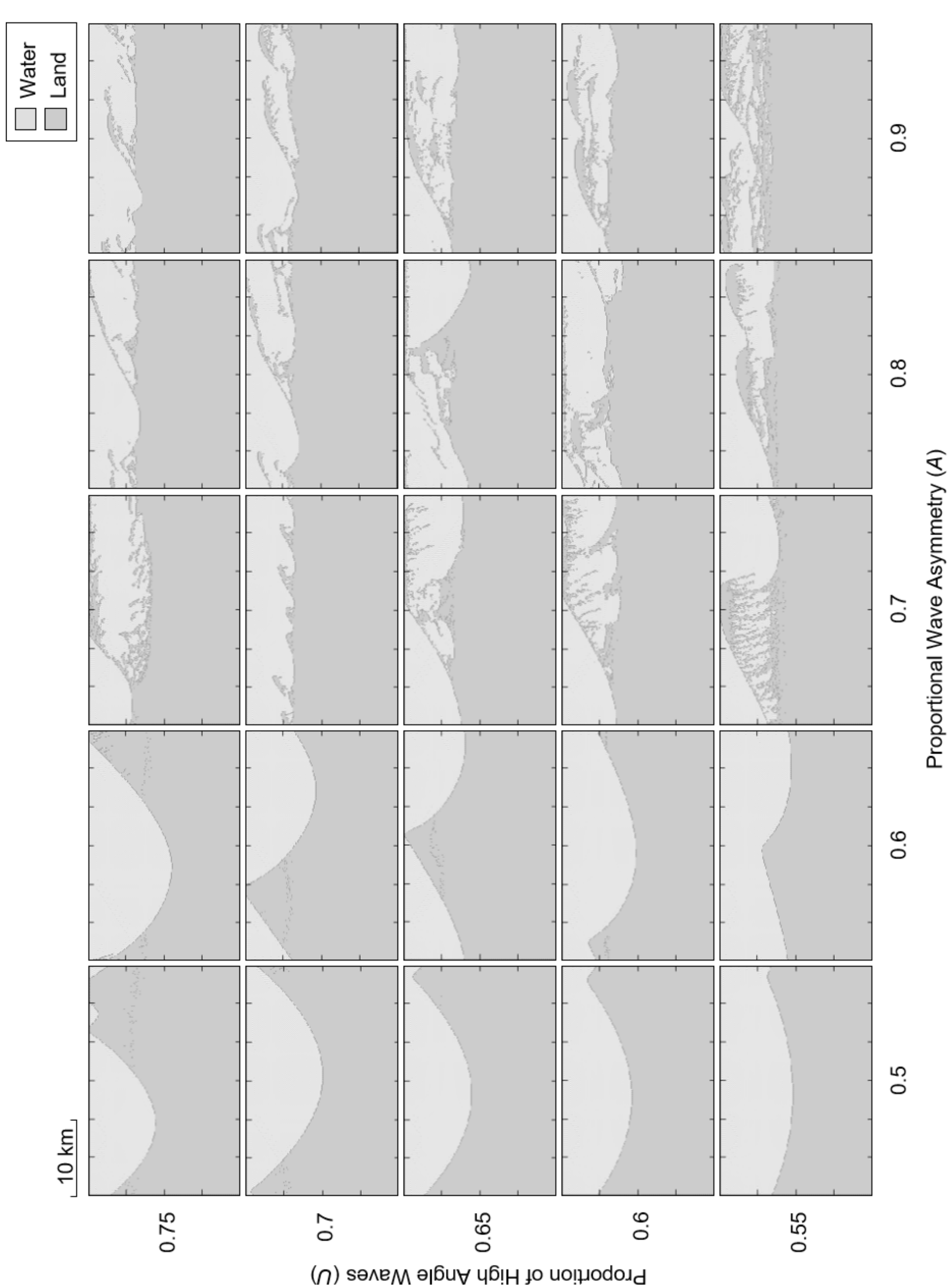


Figure 9: The mean and standard deviation of results from the input factors, according to the four behavioural indices labelled a-d.


Water
Land
10 km
0.75
0.7
0.65
0.6
0.55
Proportion of High Angle Waves (U)
0.5
0.6
0.7
0.8
0.9
Proportional Wave Asymmetry (A)

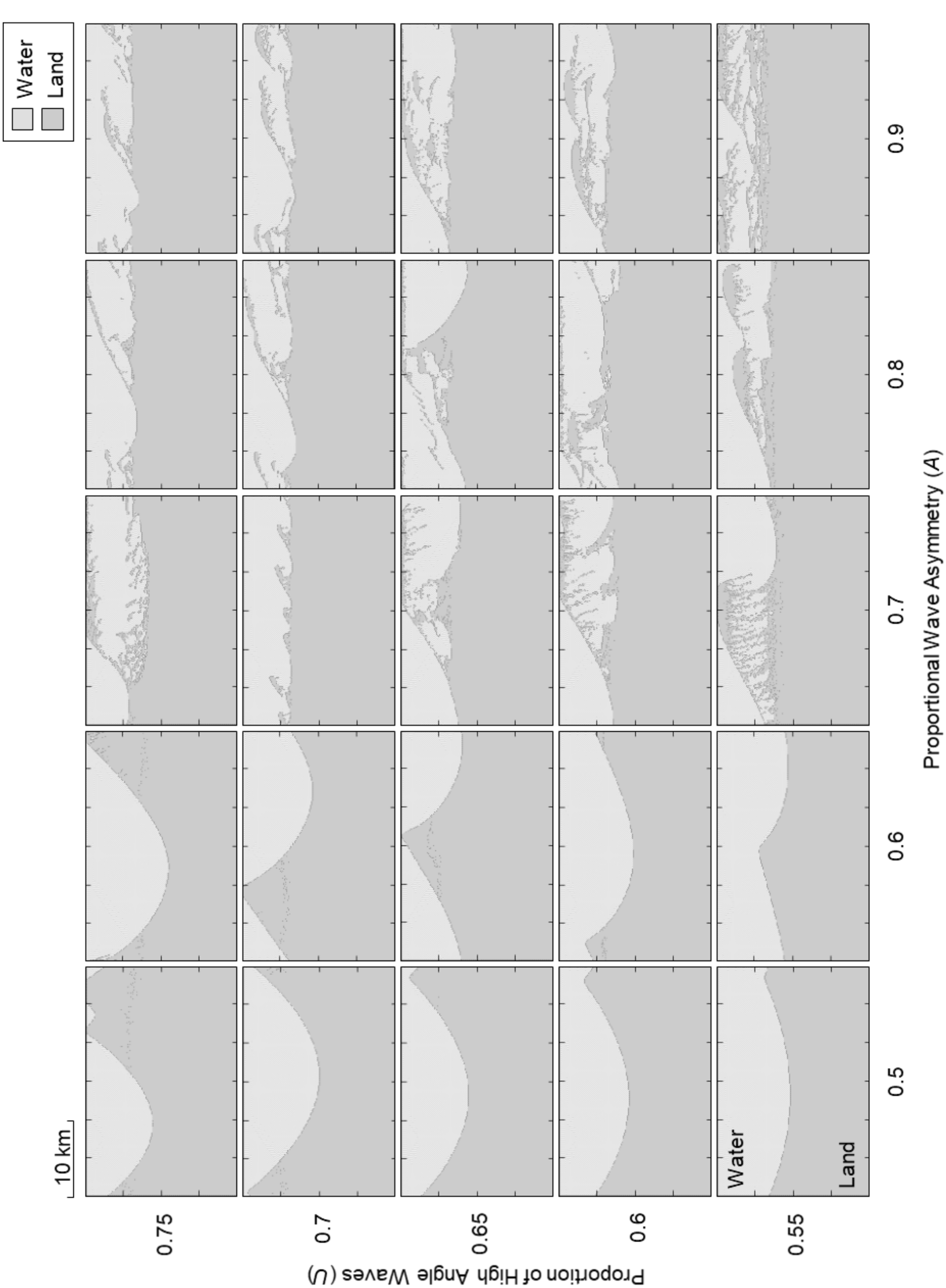


Figure 10: A matrix of results from CEM showing final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and are not inclusive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

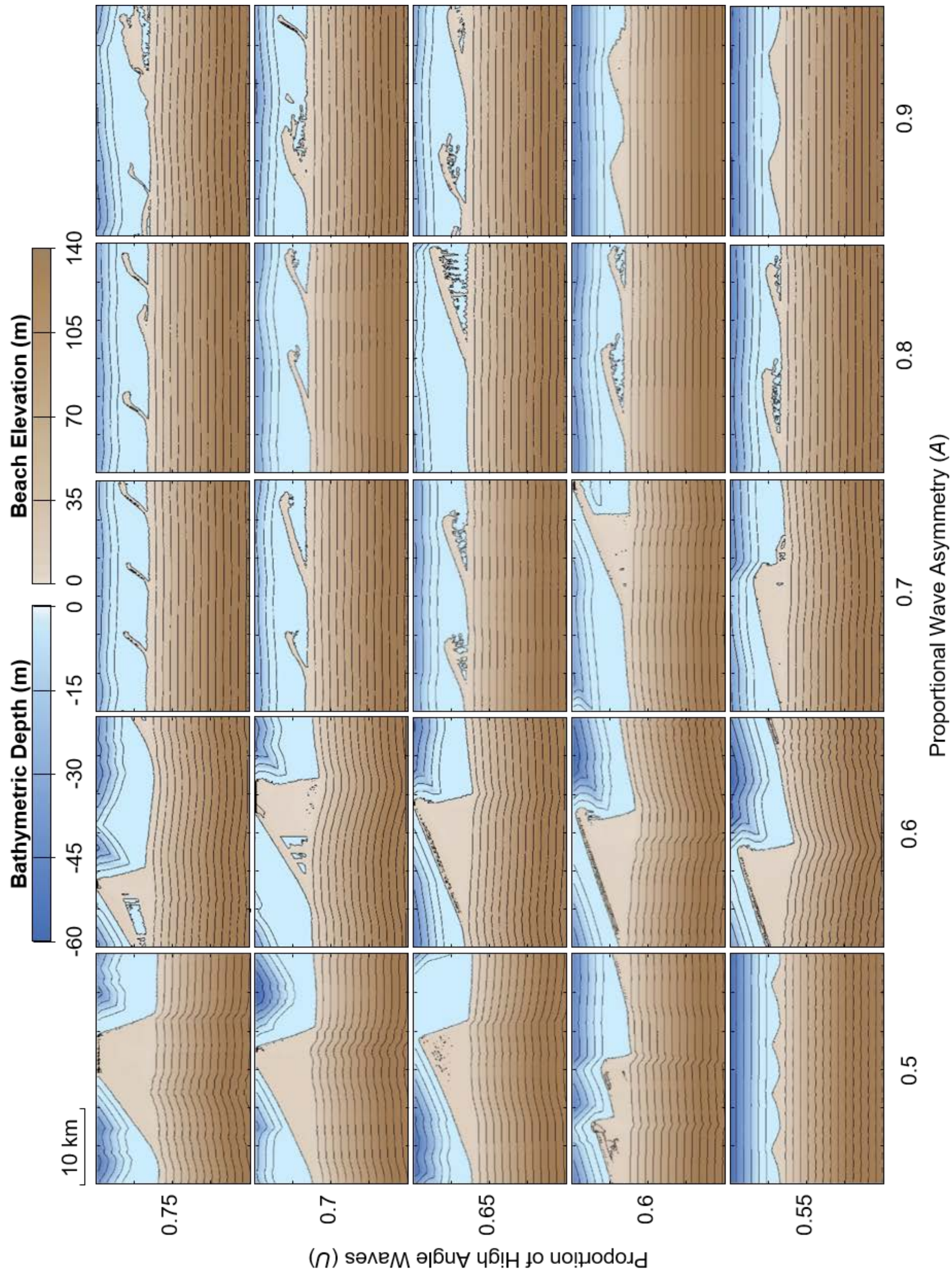


Figure 11: A matrix of results from CEM2D showing two-dimensional final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and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

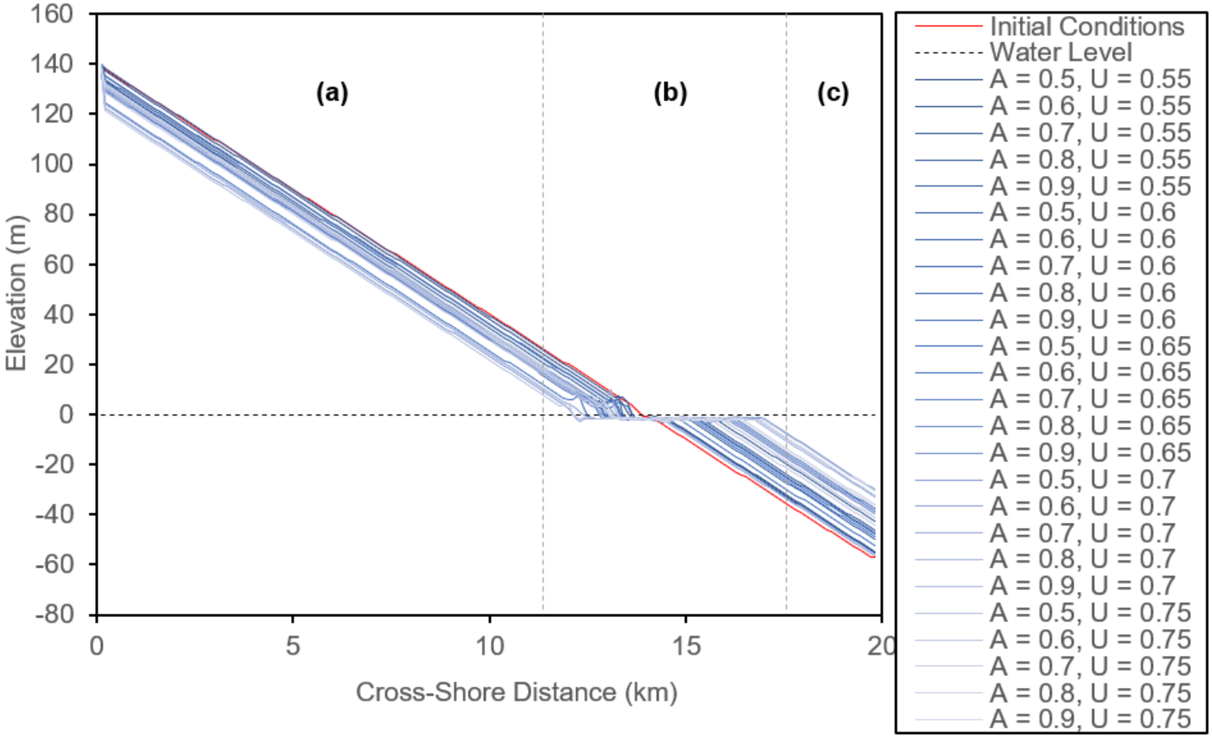


Figure 12: Cross-shore profiles taken for each of the twenty-five simulations ~~shown as a 3D line graph~~, with water level shown as a ~~white band across the transect~~dashed line and the initial cross-shore profile as a solid red line. Labelled are the (a) beach surface, (b) dynamic shoreline and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

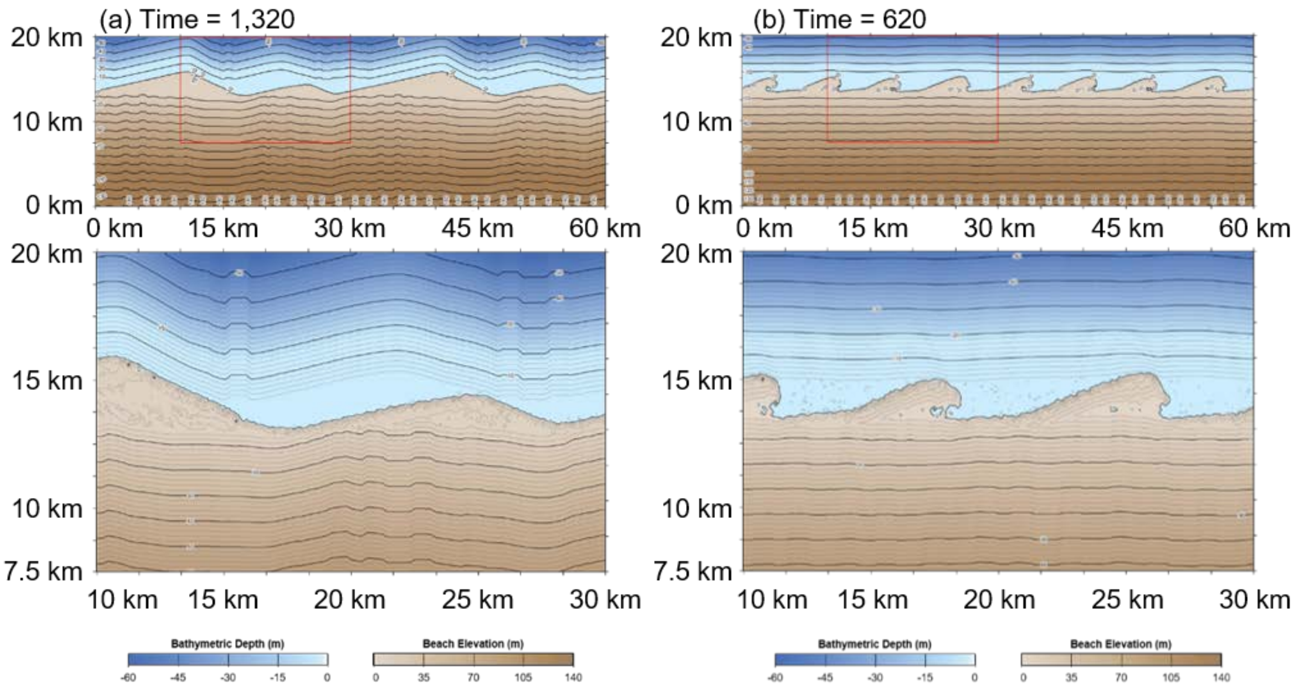


Figure 13: Morphology plots showing outputs of (a) A = 0.6, U = 0.6 at Time = 1,320 and (b) A = 0.7, U = 0.65 at Time = 620.

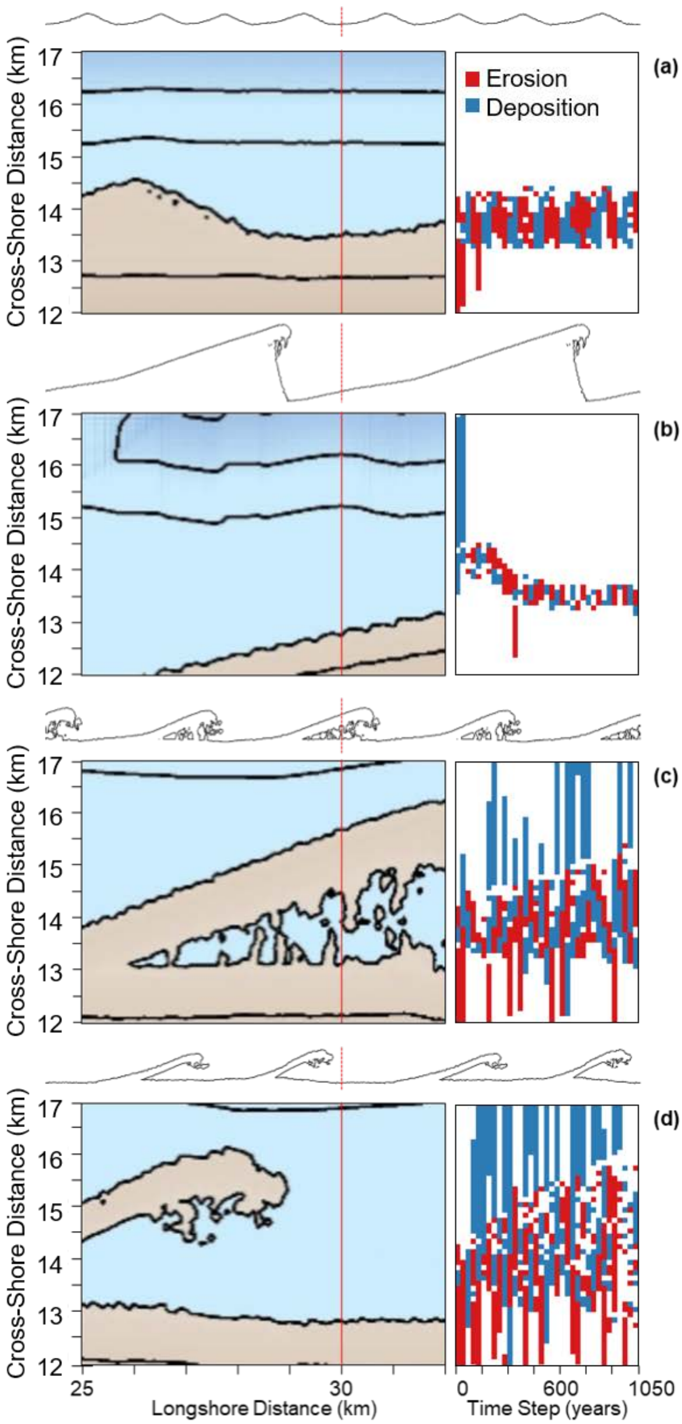


Figure 14: Shoreline Morphologies (left) and volume stacks (right) for four simulations where the wave climate is defined by (a) A = 0.5, U = 0.55, (b) A = 0.6, U = 0.6, (c) A = 0.7, U = 0.65 and (d) A = 0.8, U = 0.7. The red line marks the cross-shore transect where the change in volume at 30 year time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

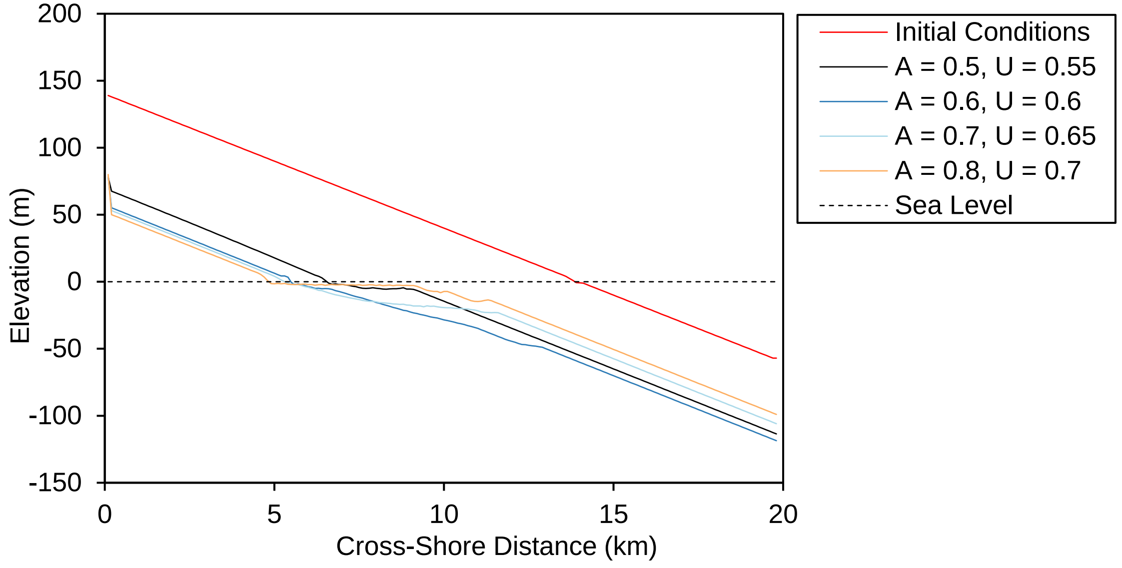


Figure 15: Cross-shore coastal profiles for four simulations where the wave climate is defined by (a) A = 0.5, U = 0.55, (b) A = 0.6, U = 0.6, (c) A = 0.7, U = 0.65 and (d) A = 0.8, U = 0.7. The initial profile is given as a solid red line and the water level as a dashed black line.

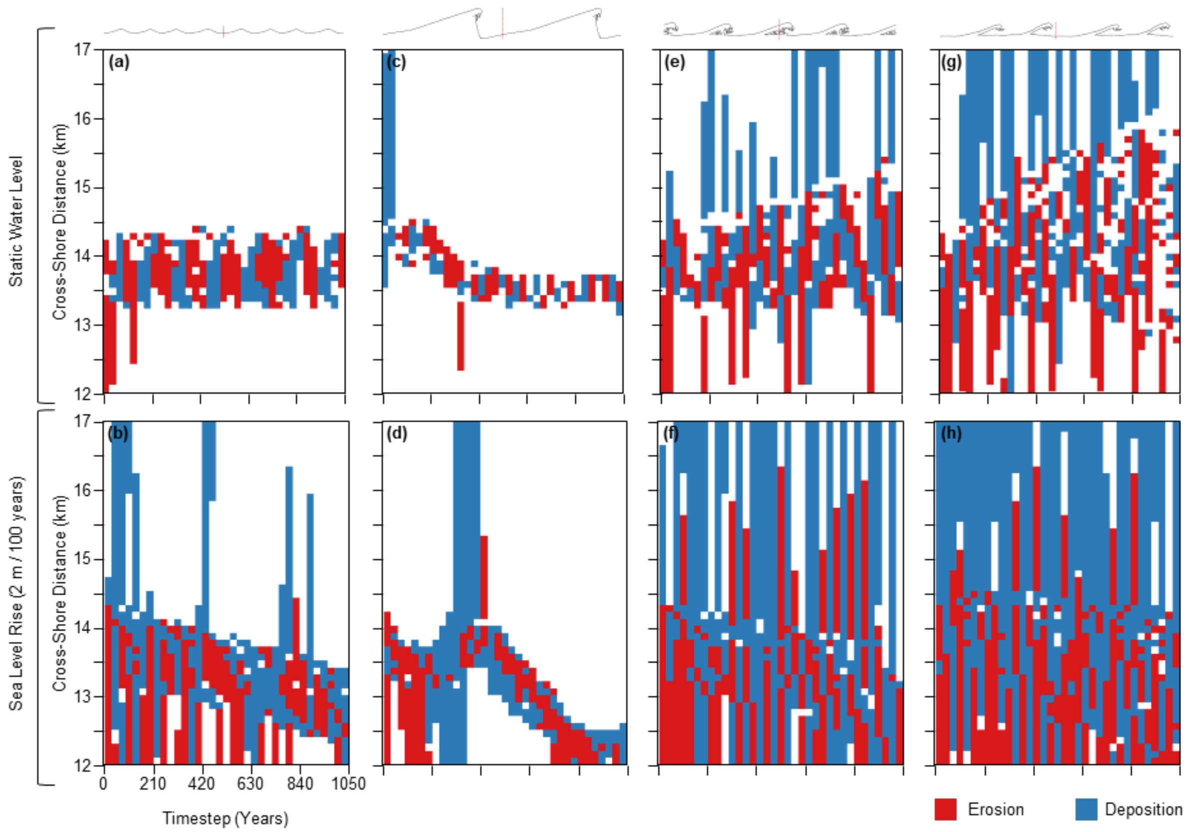


Figure 16: Volume stacks for four wave climate conditions defined by (a-b) A = 0.5, U = 0.55, (c-d) A = 0.6, U = 0.6, (e-f) A = 0.7, U = 0.65 and (g-h) A = 0.8, U = 0.7. Results with a static water level are shown along the top row (a, c, e, g) and with sea level rise at a rate of / 100 years along the bottom row (b, d, f, h). The shoreline outlines at the top of the figure are taken from the static water level scenarios and the red line marks the cross-shore transect where the change in volume at 30 year time intervals is recorded.

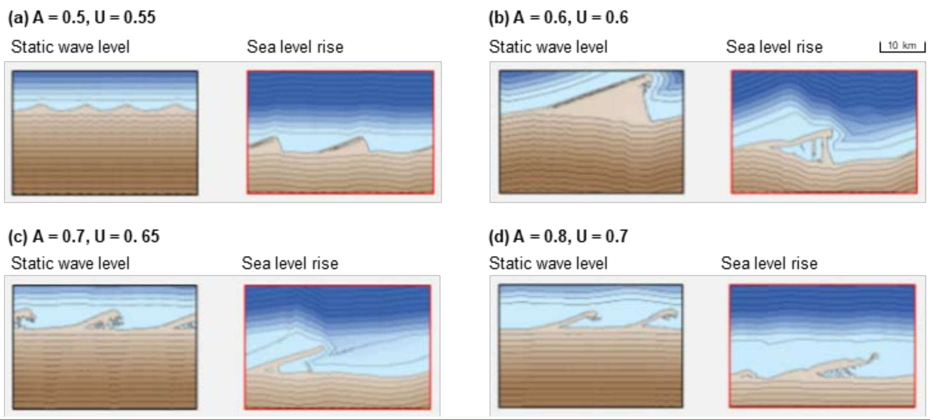
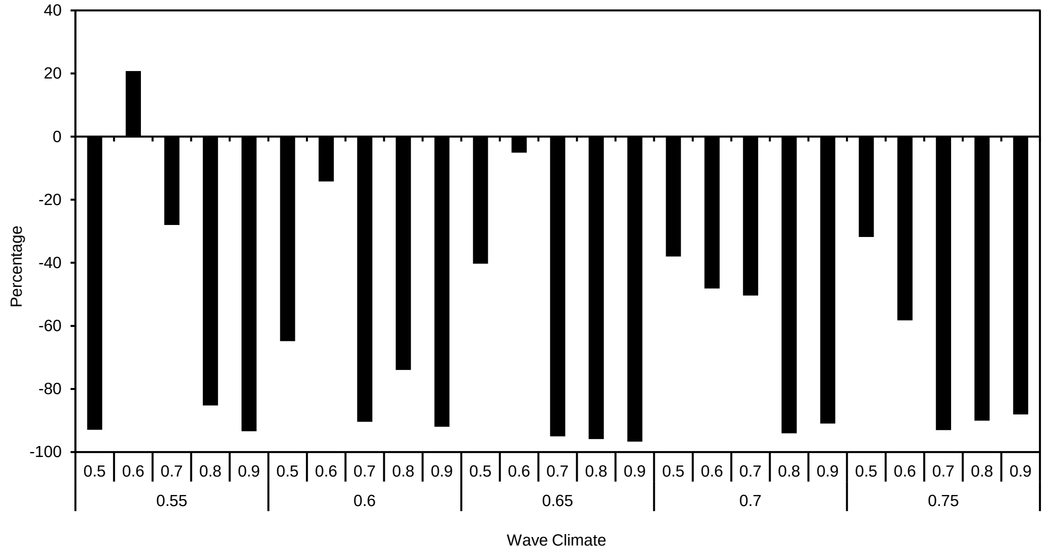


Figure 17: Coastal morphologies for four simulations where the wave climate is defined by (a) A = 0.5, U = 0.55, (b) A = 0.6, U = 0.6, (c) A = 0.7, U = 0.65 and (d) A = 0.8, U = 0.7, run with two water level scenarios including a static water level (left, black outline) and a rising sea level at a rate of 2 m / 100 years (right, red outline).



630 **Figure 18: Percentage difference between results of CEM2D and CEM. The wave climate given along the x-axis is defined according to the wave asymmetry (top row) and the proportion of high angle waves (bottom row).**