

Author's Response to Reviewer Comments

Authors comments in **bold**, text added to the manuscript are in **red**.

We would like to thank all three 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. Within our responses, text highlighted in red is that which has been changed or added to the manuscript.

Editor:

Thanks for your patience. Could you please address the comments of Reviewers #2 and #3 in revised version of the manuscript? In particular I suggest that you provide more details in the model description and numerical schemes being used and include more model validation (as required by the GMD guidelines https://www.geoscientific-model-development.net/about/manuscript_types.html#item1)

Thanks. Stay safe and well

Lutz Gross, GMD Topical Editor

Thank you for the overview and positive comments on our manuscript. We address all the comments to each of the reviewers below. With regard to the model validation issue you raise, we would like to bring to your attention that our paper is framed as a Development and Technical Paper, that according to the GMD guidelines should “provide an evaluation against standard benchmarks, observations, and/or other model output as appropriate”. As such our new 2D model is evaluated against the performance of an existing 1D version of the model; this evaluation is similar but of course distinct from validation. We fully address this point in response 6 to Reviewer 2.

Reviewer 1:

I am glad to see that the authors have made a considered and substantive effort to address my concerns and those of the other reviewer.

The power of CEM is in its demonstration of shoreline changes wrought by gradients in alongshore sediment transport. I think the major step still to come will be in marrying these changes in CEM2D v1.1 to the cross-shore profile with those gradients in alongshore flux, and seeing how that fully integrated consideration of the nearshore sediment-transport system affects modelled scenarios. (The authors allude to this caveat in the paragraph at L395.)

This work seems to me in the spirit of "geoscientific model development" – and relieving the assumption here of shoreline-parallel bathymetric contours is an important developmental step toward some potentially very interesting scientific questions.

Reviewer 2:

1	<p>11 - CEM assumes a constant active cross-shore profile shape and the sediment transport is computed integrated in the surf-zone, for example with the CERC formula. Therefore, the sediment is added/removed horizontally. CEM2D claims to take the sediment from the numerical-grid cells in vertical, this is a great addition but brings inconsistencies when sediment transport is still computed with an integrated formula as in CERC and this sediment is only taken from the adjacent cell to the shoreline, this cell could not be representative of the active profile, could cut it in half, or be double. Therefore, it could introduce changes in the profile shape that would be artifacts of the model grid or the sediment redistribution scheme.</p> <p>(similar question: 15.r The cross-shore profile shape is of great relevance and modelling its evolution is not trivial, proof that CEM2D mimics the profile shape evolution.)</p> <p>“The evolution of landforms is more gradual in CEM2D...” could you proof this is an improvement over CEM to match natural landform evolution?</p>
	<p>In CEM, the change in horizontal fill of each shoreline cell is calculated based on how much sediment is moved and the distribution of this sediment across the shoreface assuming shore-parallel contours. Our approach is not so dissimilar from this but rather than distributing the volume of transported sediment across the shoreface assuming shore-parallel contours, CEM2D redistributes sediment across the profile using a steepest descent method that is compatible with the 2D profile. Similar steepest descent techniques are widely implemented in landscape evolution models, such as SIBERIA (Willgoose et al., 1991) and GOLEM (Tucker and Slingerland, 1994).</p> <p>The CERC formula is usually used for uniform cross-shore profiles and whilst we technically have a dynamic profile, a threshold is used in the sediment distribution method which limits the slope angle that can be achieved. In doing this, the slope retains an average profile as can be seen in Figures 13, 16 and in the contours shown in Figures 11 and 14. Whilst this limits the dynamism of the bathymetric profile, it remains consistent with the use of the CERC formula in this iteration of the model. The methods employed here enable CEM2D to be a steppingstone towards a more complex representation of coastal evolution at this timescale and addition of vertical sediment storage was also necessary in order to model changes in the water level.</p> <p>An alternate method for looking at more complex wave transformations was employed by Limber et al., (2017), who coupled the CEM with SWAN. SWAN carried out the complex and computationally expensive wave transformations over a non-uniform bathymetry and CEM used the transformed wave conditions in the CERC equation but retained a cross-parallel profile. This coupling could prove a useful concept for future iterations of CEM2D, with the added advantage that the bathymetry evolves in CEM2D, not just SWAN. This will however increase the computational time of the model, it's complexity and it's application to longer-term coastal change. In this iteration of the model we have taken a step towards achieving more complex coastal change without significantly increasing the complexity of bathymetric evolution of wave transformations. We recognise the limitations of this, but also highlight the advantages.</p>

	<p>However, we note the point the review has made here and we have made the numerical schemes used for the sediment distribution method clearer in the manuscript, which now reads:</p> <p>L135: “Sediment flux is calculated using the same equations as CEM (Eq. 1) and threshold-determined upwind or central finite-difference techniques (Ashton et al., 2001; Ashton and Murray, 2006a), but because CEM2D represents sediment transport in two-dimensions, an alternate method for distributing sediment across the surf zone is used. Rather than assuming shore-parallel contours, material is dispersed across the surf zone based on a steepest descent method (Fig. 6). The method ensures that sediment is distributed across the active profile and remains consistent with transport calculations using the integrated CERC formula, but that there is dynamism in this process that takes into account the elevation of a cell and its neighbours that is consistent with the 2D representation of the domain.”</p> <p>The sediment transport method (including sediment distribution across the surf zone) and wave climate representation are two elements within the model that we feel should be increased in complexity simultaneously, if either are to be altered. This is a significant task that would allow a more site-specific application of this model, but this is not the intention of this version of the model. This study was designed to demonstrate that the technical developments of CEM2D enable it to remain parsimonious and simulate fundamental shoreline shapes, as per the original CEM, but with added functionalities including the ability to vary the water level. We feel we have been able to do this in this manuscript. We do however take note of your comments and appreciate your thoughts on this topic; we endeavor to continue developing CEM2D for a range of applications and where we intend for a more site-specific application, we will be looking further into addressing the complexity of these components.</p> <p>Ashton and Murray (2006) state that CEM was not designed to represent or predict the time evolution of any one specific coast or the specific development style of natural shoreline features; this also applies to CEM2D. This is not the principal purpose of these modelling exercises, although we indicate that we are assessing meso-scale behaviors, but it is rather to explore the relationship between shoreline feature types and wave climate characteristics. In response to your comments and to ensure that the reader is clear on these points we have now emphasized this point in the text:</p> <p>L327: “Whilst CEM and CEM2D are not designed to represent the temporal evolution of specific coastal environments and this metric should not therefore be compared between the models (Ashton and Murray, 2006a), we note that the evolution of landforms is more gradual in CEM2D.”</p>
2	<p>12 - Figure 17 shows that under sea level rise the landscape feature under the same wave climate is different, could you verify this is a natural behavior? For example, you could find a spot in the world where large scales features developed during a transgressive period, proof that with your model you can mimic the spatial scale and shape of these features, and with CEM the resultant feature would be different.</p>
	<p>We have added additional text to the manuscript to address this comment:</p>

L399: “Observing the effects of sea level rise on coastal features, including their ability to migrate with the shoreline or how their morphology changes at this temporal scale is challenging. Evidence of submerged shorelines and landforms that formed during transgressive periods can be removed by high energy waves and storm events, rapid migration of systems and by sediment transport that consumes or removes remnant features (Shaw et al., 2009). Notable submerged shorelines are found in the Bras d'Or Lakes, Nova Scotia, and are suggested to have been well-preserved by the rapid onset of sea level rise (Shaw et al., 2009). Tombolos, spits, cusate forelands and barrier beaches are identifiable on multibeam sonar imagery in the Lakes down to -24 m, above the early Holocene water level at -25 m (Shaw, 2006). Evidence of enclosed bodies of water within cusate forelands and the stranding of landforms at this lower sea level demonstrates in situ drowning and the preservation of landforms between -7 to -24 m evidences the ability of some landforms to migrate (Shaw, 2006; Shaw et al., 2009). Barrier islands and spits in the Bras d'Or Lakes are also found to rebuild at the proximal end of previously submerged landforms (e.g. Dhu Point and West Settlement) or migrate landward to form cusate barriers in response to rising water levels (e.g. Goose Pond) (Taylor and Shaw, 2002).”

3 13 - Thanks for the answer, I am curious to know which model is doing alright, could you proof your model is improving the results given by CEM? I do agree that CEM2D evolves different landscapes due to the redistribution scheme, but this could be a numerical artifact, it needs any kind of verification.

We are not attempting to replicate any particular system in detail, so it is difficult to assess whether CEM or CEM2D is better at replicating any given specific natural systems (see also response number 1 and the changes made in the text). We have however qualitatively demonstrated that the fundamental shoreline shapes are represented better in CEM2D (see response number 14).

What we have been able to show is that we can mimic fundamental shoreline shapes according to the driving wave conditions and evaluated these outputs against the CEM and natural systems. The intention of CEM2D is to continue using the model for this purpose, but it can obtain additional information and further exploratory capabilities with the addition of a variable bathymetry and ability to simulate a variable water level. We agree that model evaluation is an important step in model development, and we have addressed this point in response number 6, in line with GMD guidelines.

4 14- I am surprised, it is not a numerical instability, however it is a directional bias inherited from the model routines... in any case is a model artifact, I cannot read this in line 239. If CEM2D develops more complex topography and it is different than CEM results, please, proof that your model reproduces natural landscape evolution better than CEM. You could add in Section 5.2 the examples you mention and highlight the differences between CEM2D and CEM in comparison to the natural

	<p>feature. Nowadays, you can easily obtain accurate wave climates around the world from ERA5 reanalysis (40 years dataset) so that you can compute A,U.</p>
	<p>Our emphasis in this manuscript is not to compare the accuracy of shorelines shapes generated in CEM and CEM2D (see response number 3). We are showing that the model can simulate fundamental shoreline shapes according to the driving wave conditions, but with its added functionalities we can also use it to look at the dynamics of the surf zone and responses to sea level rise. We have evaluated the behaviours of the model against a number of case studies and standard benchmarks.</p> <p>Having said that, in further response to your question, there are examples where CEM2D generates features that are more representative of natural systems compared to CEM. These examples include Benacre Ness, Long Point spit and Spurn Point. We have expanded on the text within the manuscript to reflect and highlight this point:</p> <p>L289: “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 compared to CEM”</p> <p>L303: “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. The presentation of both sand waves and reconnecting spits in CEM2D would suggest that this model may be able to better represent the conditions found at Long Point Spit.”</p> <p>L314: “Whilst CEM2D better represents the influence of low angle waves on coastal evolution at Spurn Point, it is of note that this is a complex feature which is influenced by conditions that could be having a greater impact on coastal evolution, including estuarine processes and dredging activities, that are not included in either CEM or CEM2D.”</p> <p>We have also noted where the CEM2D underperforms compared to CEM:</p> <p>L282: “Considering that all site-specific conditions controlling the evolution of capes are not represented in CEM2D or CEM, the models are able to predict a comparable shoreline type to that observed in this natural system although CEM2D overpredicts the directional skew.”</p> <p>Finally, the reference to model artifacts is now given in L259, onwards:</p> <p>“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 cusped 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</p>

	<p>model versions, the routines will require updating which would also necessitate that sediment transport methods be altered accordingly.”</p>
5	<p>15- In science it is not enough with saying it, we need validation/proof that CEM2D mimics the natural landscape evolution. Please, validate that your model could be used for landscape prediction, validate that the shape, spatial scale, and temporal scale matches the natural behavior.</p> <p>In section 5.2.1. CEM2D under $A=0.55$ and $U=0.6$ doesn't show any feature like the Carolinas, in any combination of A and U is not possible to develop large scale Cuspate Forelands with wave lengths longer than 50km or amplitudes greater than 10km.</p> <p>The model has not been designed to predict landscape evolution in any particular location. This would require validation at the site-specific scale. Whilst this is something we envisage for future modelling development, this version is not designed for this purpose. It is rather designed to be exploratory and explore theories of high angle wave instability that we observe in nature.</p> <p>We have noted the directional skew, but also shown in the model that symmetrical wave climates generate symmetrical features and asymmetric generate skewed features. This would theoretically explain the slight asymmetry in the Carolina Capes but we also note that the model overpredicts this skew due to directional bias. This example was also used by Ashton and Murray (2006) who noted that the timescale of cape development within CEM does not align with their formation, but that the model is able to demonstrate the role of high angle wave instability in their formation. The wavelength and amplitude of landforms in the model are restricted to the size of the domain. If therefore the intention was to model a specific system, the domain would be setup so that the boundaries would be sufficiently far enough to not influence the development of the landform. This was not our intention in this case.</p> <p>According to the GMD guidelines, a Development and Technical Paper should “provide an evaluation against standard benchmarks, observations, and/or other model output as appropriate”. We have provided such evaluation in Section 5 of the manuscript and have endeavored to strengthen these evaluations in response to other comments by the reviewers. In particular, we have built upon comparisons between observed natural features and outputs of CEM2D (e.g. Spurn Point and Long Point Spit Section 5.2.3), demonstrating the strengths of the model compared to CEM. We have also added further evaluation about the variable water level component in the model against observations of shoreline change in the Bras d'Or Lakes, Nova Scotia (Section 5.5).</p> <p>Our paper therefore aligns with the spirit of GMD and highlights the behavior of the system and the model. Specific validation is not a requirement, but we do evaluate the model against CEM and we now highlight this in the text as outlined below.</p>
6	<p>16. Presenting a new model requires validation</p>

Truly validating models at this scale in this field is a significant challenge given that data is limited, although we strongly agree suitable testing and evaluation of model outputs is important.

GMD's guidelines for Development and Technical Papers are to "provide an evaluation against standard benchmarks, observations, and/or *other model output* as appropriate". There are no standard benchmarks or observations available for model performance so here we have *evaluated* the model against previous model output – that from the original CEM.

Our manuscript highlights that CEM2D builds on many concepts developed in the original CEM retaining many of the fundamental ideas and implementation of equations. Therefore, an important process in the *evaluation* of CEM2D was to ensure that it maintained the ability to simulate shoreline shapes as in CEM, that we have discussed in this manuscript. Here it is important to note that the original CEM and CEM2D were not designed to simulate any particular shoreline in detail, but as we have shown here, to connect theories of high angle wave instability to the shoreline shape and wave conditions of natural environments; we have used a number of examples in the manuscript to do this.

We have made our methods of evaluating the performance of CEM2D clearer, by adding the following text:

L73: "Validation of exploratory models like CEM2D is limited and particularly in this case, where there is a lack of data showing the evolution of coastal systems under changing wave patterns and water levels over such long time periods. CEM2D's performance is therefore here evaluated against 'standard' CEM simulation results from varying wave climates and directions."

L172: "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 of CEM2D we evaluate our simulation results against the original CEM outputs (as described subsequently). Full validation would require time series of bathymetric field data for the duration and range of wave climates and wave directions simulated, and this is not presently available. However, similar to how (Ashton and Murray, 2006) visually compare their simulation findings to coastal features including the Carolina Capes, we too compare our outputs to a series of examples."

L412: "The purpose of this study was to provide an overview of the development and application of CEM2D and its ability to represent coastal systems compared to other existing coastal evolution models of its kind. The behaviour of the model has been evaluated against results from the existing Coastline Evolution Model (CEM), upon which CEM2D has been built. Results have also been compared to accepted theories of coastal morphodynamics and to the behaviour of a number of natural coastal environments. These evaluation techniques have demonstrated that CEM2D is able to simulate shoreline instabilities in accordance with theories of high-angle wave instability, to mimic the behaviour of natural environments under given wave climate conditions and to generally reproduce the results of the original one-line

	<p>CEM, although some differences are observed as discussed throughout (Ashton and Murray, 2006a)."</p> <p>L446: "We have described the structure of the model, outlined the governing mathematical equations, presented outputs from the sensitivity testing and evaluated CEM2D's ability to simulate the behaviour and evolution of coastal systems, by comparing against other model results, theories of coastal evolution and natural systems."</p>
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7	<p>17. In case the model takes all the sand from the shore cell, if the shore cell is half the active profile width is taking too much sand from the vertical. I think it is inconsistent this numerical scheme with an integrated sediment transport formula. You need to take sediment at cell level...otherwise you introduce spurious bed level updates (that later you try to smooth out with your redistribution technique).</p> <p><i>"activating the sediment distribution method at this frequency causes instability in the model and it is therefore activated less frequently"</i></p> <p>Why do you think this happens?</p>
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This question is similar to question 11, which we have responded to in response number 1 of this document.

In response number 1, we have addressed concerns over inconsistencies with using the CERC formula with a non-uniform bathymetry. We have made further improvements to the way in which the sediment distribution scheme is described in the manuscript and we hope that this now makes the method much more transparent.

To address the second point, instabilities due to moving too much sediment too quickly is a common problem in numerical modelling and is not unique to CEM2D. The two principal parameters for this method include the frequency that the method is employed and the threshold for movement. Both of these parameters were tested and were included in the sensitivity test to determine the most suitable values (see Section 5.1).

8	<p>19. It is not enough to say that the results are applicable to timescales of 10 to 100 years, show what are the model outcomes at those timescales, do the results mimic shoreline rates found in nature? In general, you must validate that the model mimics the time scale of large-scale feature formation. What is the spin-up of the model?</p>
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The spin-up period is approximately 10 years, and this has been considered in the analysis of the results. The following text has been added to the manuscript to state this:

L189: "The models were run over a simulated period of 3,000 years, to allow time for the model to spin-up (~10 years**), to reduce the potential influence of initial conditions and to allow sufficient time for the coastal systems to evolve."**

The exploratory nature of CEM2D is such that it is designed to look at behaviours that occur within millennial timescales. This is in accordance with the origins of the model and how CEM was designed and applied (Ashton, Murray and Arnault, 2001). For instance, Ashton and Murray (2006) noted that the timescale of cape development within CEM did not align with the formation of the Carolina Capes but nevertheless what was intended was to demonstrate that the driving wave conditions could lead to cape development (see also response number 5). We agree that this has not been expressed particularly well in the manuscript and have altered the text in-line with the timescales quoted by Ashton et al., (2001) that are clearer to interpret:

L29: “Simulating changes in coastal geomorphology up to millennial timescales and up to hundreds of kilometres”

- 9 20. Again, this is an inconsistency, you claim to develop complex bathymetries that is proven to affect shoreline feature development (Limber et al., 2017), but you don't account for changes in wave transformation. I think from your new Figure 17, this affects the results output by CEM2D.

The study by Limber et al., 2017 computes wave transformations in SWAN, with only updating of the shoreline in CEM and is therefore not entirely comparable to other methods.

The complexity of the bathymetric evolution, including cross-shore sediment transport processes and the complexity of the wave transformation equations should be updated concurrently. Whilst we have updated the representation of the bathymetry, it remains simplistic in the cross-shore diffusion of sediment and its maintenance of an average slope angle. There is a balance between increasing the complexity and increasing the efficiency and usefulness of a model and we are currently at this point. If we are to update the wave transformations, we feel we would also need to update the dynamics of the bathymetric profile. Whilst this is intended in future iterations, it is not included in this version of the model as we are attempting to retain its parsimonious nature.

Reviewer 3:

- 10 Please present more details on the governing equations, variables, shoreline identification, transport schemes, diffusion schemes, etc. I think my biggest confusion of the model is role of the sediment fraction variable 'Fi'. In CEM, $F_i=1$ means a sandy cell, $F_i=0$ means an ocean cell, and $0 < F_i < 1$ is a shoreline cell. This variable is very important because it allows the shoreline to have a “partial cell representation”. The $0 < F_i < 1$ value of F_i is used to determine the location of the shoreline. And as Ashton & Murray (2006) put it “the fractional value within a cell represents the cross-shore extension of the sub-aerial shore” This fractional shoreline cell approach can be seen in Fig 4 of the current manuscript. This approach seems somewhat in contrast to the “full cell” shown in Fig 2 of the current manuscript.

Thus my confusion is: does CEM2D use the variable F_i and a partial cell representation of the shoreline or not? It is very hard to tell from the current manuscript. From what I have read, I'm

	<p>guessing not, because the wet or dry cells can be simply identified as those that are below or above sea level, respectively. The problem with the “full cell” representation (that is the lack of a partial cell identification) is that the shoreline angle only exist with an angular resolution of 45 degree increments. See figure 2 for example, where the angle of the shoreline on the left half of the figure is either zero or 45 degrees. The shoreline angle on Figure 4 of the current manuscript instead has a much more subtle variation in the shoreline angle. And, of course with longshore transport, the angle of the shoreline relative to the waves is critical to determining the transport (see Eq. 1).</p> <p>Therefore, in my opinion, the text / figures greatly need to improve to clarify some critical details about the model. For example, Figures 2 and 4 are so similar, yet also seem to present contrasting representations of the shoreline.</p>
	<p>Additional details have been added to the manuscript regarding the numerical schemes in the model, including the transport and diffusion equation (see response number 1).</p> <p>The reviewer is right that the F_i variable is not currently used in this version of CEM2D. However, we look two cells either side of a shore cell to determine the shoreline angle so the angle may be 0, 22.5, 45, 67.5 or 90 degrees. We agree that this can limit the resolution of the shoreline angle but not to the extent of 0, 45, 90 as above. We acknowledge that this is a limitation of our approach, but the results demonstrate that because the wave angle used in the calculations uses both the local shoreline <i>orientation</i> (θ) <i>and the approaching wave angle</i> (ϕ_b), which varies on every iteration, a range of coastal landforms that evolve under various high-angle wave scenarios can be modelled.</p> <p>We do however appreciate your discussion on this point and note that this is not clearly explained in the text. To make this clearer we have updated the text to reflect our response:</p> <p>L121: “The variable F_i is not used in CEM2D to represent the partial horizontal fill of sediment, rather, each cell contains values for depth of sediment to the continental shelf, elevation of sediment above the water level or depth of water (Fig. 4b). Having these additional values of sediment fill in the vertical enables CEM2D to represent two-dimensional coastlines with greater topographic detail compared to the original CEM, as illustrated in Fig. 4.”</p> <p>L128: “The boundary between wet and dry is used to locate the shoreline (Fig. 5), using the same shoreline search technique as CEM. Once the shoreline is located, as per CEM, Linear Wave Theory is used to transform the offshore wave climate and the CERC formula to calculate sediment flux between the one-line shoreline cells (Equation 1). The limitations of not calculating the horizontal sediment fill of each cell (F_i) influences the sediment transport equations, by reducing the angular resolution of the local shoreline. However, as shown in the results, the model remains capable of simulating fundamental shoreline shapes.”</p> <p>We understand the confusion with Figure 2 and Figure 4 and we have made alternations to the figure placements to ensure that it is clear that the original Figure 2 (now Figure 5) is purely a reference to CEM2D and the original Figure 4 (now Figure 3) is for CEM. The rest of the figure numbers have also been updated accordingly. The original Figure 4 (now Figure 3) caption has also been updated:</p> <p>“Plan-view schematic of CEM” as opposed to “Plan-view schematic of CEM2D”</p>

11	<p>There is no mention of potential physical / numerical instability of the model, unlike in Ashton & Murray (2006). In CEM, the numerical scheme to shift between a central scheme and an upwind scheme (when a critical angle of 42 degrees is exceeded) is key to the model's stability. Are similar schemes used in CEM2D? This should be discussed.</p>
	<p>The same scheme is employed in CEM2D and we have added additional details to the manuscript to detail this, with reference to Ashton and Murray (2006):</p> <p>L87: “The angle of the deep-water wave crest and local shoreline orientation determines the direction of sediment transport between cells. If the local relative wave angle is less (greater) than the angle which maximises sediment transport, sediment flux is calculated using a central (upwind) finite-difference technique (Ashton et al., 2001; Ashton and Murray, 2006a).”</p> <p>L135: “Sediment flux is calculated using the same equations as CEM (Eq. 1) and threshold-determined upwind or central finite-difference techniques (Ashton et al., 2001; Ashton and Murray, 2006a), but because CEM2D represents sediment transport in two-dimensions, an alternate method for distributing sediment across the surf zone is used. Rather than assuming shore-parallel contours, material is dispersed across the surf zone based on a steepest descent method (Fig. 6). The method ensures that sediment is distributed across the active profile and remains consistent with transport calculations using the integrated CERC formula, but that there is dynamism in this process that takes into account the elevation of a cell and its neighbours that is consistent with the 2D representation of the domain.”</p>
12	<p>Like the previous reviewers, I found myself wondering how the longshore transport redistributed in the cross-shore, and thus how the offshore bathymetry changes in response to growing shoreline perturbations? (In CEM this is handled by extrapolating the sub-aqueous shoreface slope away from the shoreline) I assume that this is handled only via the diffusion scheme, but it is not obvious that this is the case in the manuscript.</p>
	<p>We appreciate that both reviewers have made reference to the sediment distribution method and so we have added an additional section to explain this method in more detail. Please see response number 1 for further details.</p>
13	<p>I was quite surprised to see the strong difference between CEM and CEM2D in Figures 10, 11, and 18. Why are they so different if this update is still relatively straightforward? (As an aside, I recommend using the same color scheme to the CEM results (e.g., blue and tan instead of gray, even though there is no gradation due to topography in CEM) as for the CEM2D results. This would greatly improve the readers ability to compare the results.</p>
	<p>The color scheme used in Figure 10 for CEM results has been updated to match results of CEM2D in Figure 11.</p>

Although we have retained the core of CEM and the ability to simulate fundamental shoreline shapes, the additional functionalities in CEM2D are relatively complex in terms of the representation of the domain and sediment distribution methods. This leads to differences in the outputs, although the model is still able to replicate the relationship between high angle wave instability and coastal landform evolution. We have highlighted throughout the manuscript where differences are observed between CEM and CEM2D and have added further detail for clarity:

L71: “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.”

L269: “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. **The distribution method allows sediment accumulations to be detached from the continuous shoreline without becoming static and so transport across the entire domain, including on the lee side of a spit, is less limited.**”

L282: “Considering that all site-specific conditions controlling the evolution of capes are not represented in CEM2D or CEM, the models are able to predict a comparable shoreline type to that observed in this natural system **although CEM2D overpredicts the directional skew.**”

L289: “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 **compared to CEM.**”

L307: “**The presentation of both sand waves and reconnecting spits in CEM2D would suggest that this model may be able to better represent the conditions found at Long Point Spit.**”

L313: “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. **Whilst CEM2D better represents the influence of low angle waves on coastal evolution at Spurn Point, it is of note that this is a complex feature which is influenced by conditions that could be having a greater impact on coastal evolution, including estuarine processes and dredging activities, that are not included in either CEM or CEM2D.**”

L319: “The spatial scale of shoreline features differs between results from CEM and CEM2D. Metrics from the end of each run, as shown in Fig. 10 and Fig. 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 (Fig. 18).”

	<p>L327: “Whilst CEM and CEM2D are not designed to represent the temporal evolution of specific coastal environments and this metric should not therefore be compared between the models (Ashton and Murray, 2006a), we note that the evolution of landforms is more gradual in CEM2D. This is likely as a result of differences in the representation of the domain and in the distribution of sediment.”</p> <p>L335: “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.”</p> <p>L413: “The behaviour of the model has been evaluated against results from the existing Coastline Evolution Model (CEM), upon which CEM2D has been built. Results have also been compared to accepted theories of coastal morphodynamics and to the behaviour of a number of natural coastal environments. These evaluation techniques have demonstrated that CEM2D is able to simulate shoreline instabilities in accordance with theories of high-angle wave instability, to mimic the behaviour of natural environments under given wave climate conditions and to generally reproduce the results of the original one-line CEM, although some differences are observed as discussed throughout (Ashton and Murray, 2006a).”</p>
14	<p>I know that CEM and CEM2D are typically applied in high wave angle, high wave asymmetry conditions ($U, A > 0.5$), but do these models work when in low wave angle, low wave asymmetry conditions ($U, A < 0.5$)? These low wave angle, low wave asymmetry conditions ($U, A < 0.5$) persist for most coastlines, in general. I would like to see the behavior of this model in a more ordinary test case such as the diffusion of a Gaussian shaped shoreline bump to evaluate the differences between CEM and CEM2D, rather than going straight to the cases of flying spits.</p> <p>The model has been designed and its application intended for high wave angle environments. It is already being applied for symmetrical ($A = 0.5$) and asymmetric ($A > 0.5$) wave climates. It would be interesting to apply the model to low wave angle environments in the future, but it wasn't the intention of his study. Thank you for the suggestion, we have taken this on board for future work.</p>

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

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

20 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 ~~up to millennial timescales and up to hundreds of kilometres~~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 synthesisist investigations, which have more traditionally been the focus of research into coastal behaviours (Fig. 1) (van Maanen et al., 2016).

35 Reductionist or ‘bottom-up’ models are designed to investigate small scale processes that act over relatively short timescales (Fig. 1) (van Maanen et al., 2016). They typically simulate complex behaviours by including a large range of processes that could influence the evolution of the system using more detailed calculations at higher resolutions (van Maanen et al., 2016). Using these types of models for mesoscale applications would be computationally expensive and inefficient, since there are a large number of processes that could be simulated over relatively long time scales (van Maanen et al., 2016). Decisions
40 would have to be made about which processes to include, since each process adds computational expense and additional uncertainty, which can propagate errors or inaccuracies over long simulated timescales (Hutton, 2012; Murray, 2007). Mesoscale models, like many types of model, should be parsimonious and include only fundamental processes that capture the main physical dynamics of a system, thus minimising model uncertainty (Wainwright and Mulligan, 2013).

45 Synthesisist 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 pertaining to spatially explicit research questions (Murray, 2007). As such, synthesisist models are relatively limited in their ability to provide a level of understanding and prediction of coastal behaviours that is required for mesoscale research (Murray, 2007).

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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
55 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 coastal 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 vary the water level in model but are transect based and do not
60 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.

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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. Validation of exploratory models like CEM2D is limited and particularly in this case, where there is a lack of data showing the evolution of coastal systems under changing wave patterns and water levels over such long time periods. CEM2D's performance is therefore here evaluated against 'standard' CEM simulation results from varying wave climates and directions.

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 (F_i) that represent its horizontal fill across the domain. The F_i 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 angle of the deep-water wave crest and local shoreline orientation determines the direction of sediment transport between cells. If the local relative wave angle is less (greater) than the angle which maximises sediment transport, sediment flux is calculated using a central (upwind) finite-difference technique (Ashton et al., 2001; Ashton and Murray, 2006a).

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, Q_s is the sediment flux (m^3/day), K is a calibration coefficient, H_b is the breaking wave height (m), ϕ_b is the breaking wave angle ($^\circ$) and θ is the local shoreline orientation ($^\circ$). 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):

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

where W is the cell width and D_i 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. 32) (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. 43).

Where a shoreline cell overfills with sediment ($F_i > 1$), 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. 54(a)). The variable F_i is not used in CEM2D to represent the partial horizontal fill of sediment, rather, —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. 54(b)). Having these additional values of sediment fill in the vertical Having these additional values enables CEM2D to represent two-dimensional coastlines with greater topographic detail compared to the original CEM, as illustrated in Fig. 54. 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 (Fig. 5), using the same shoreline search technique as CEM. Once the shoreline is located, as
130 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 the one-line shoreline cells (Equation 1). The limitations of not calculating the horizontal sediment fill of each cell (F_i) influences the sediment transport equations, by reducing the angular resolution of the local shoreline. However, as shown in the results, the model remains capable of
135 simulating fundamental shoreline shapes.

Sediment flux is calculated using the same equations as CEM (Eq. 1) and threshold-determined upwind or central finite-difference techniques (Ashton et al., 2001; Ashton and Murray, 2006a), but because CEM2D represents sediment transport in two-dimensions, an alternate method for distributing sediment across the surf zone is used. Rather than assuming shore-parallel contours, material is dispersed across the surf zone based on a steepest descent method (Fig. 6). The method ensures that sediment is distributed across the active profile and remains consistent with transport calculations using the integrated CERC formula, but that there is dynamism in this process that takes into account the elevation of a cell and its neighbours that is consistent with the 2D representation of the domain. 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
140 the surrounding cells based on the slope between cells and an angle of repose (Fig. 6).

The sediment distribution method ~~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
155 nearshore profile to evolve dynamically, rather than assuming an even distribution across the nearshore profile and forming
160

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 of CEM2D we evaluate our simulation results against the original CEM outputs (as described subsequently). Full validation would require time series of bathymetric field data for the duration and range of wave climates and wave directions simulated, and this is not presently available. However, similar to how (Ashton and Murray, 2006) visually compare their simulation findings to coastal features including the Carolina Capes, we too compare our outputs to a series of examples. 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 (~10 years), 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

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: cusplate, 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):

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

where d_{ij} denotes the value of the j -th elementary effect ($j = 1, \dots, r$) of the i -th input factor (and where r is the number of repetitions), $y(x_1 x_2, \dots, x_k)$ 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 (6) 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 1 and the behavioural indices in Table 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.

250 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
255 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 Fundamental Shoreline Features

260 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
265 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 cusped 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
270 necessitate that sediment transport methods be altered accordingly.

Four principle shoreline shapes evolve under the driving wave conditions including cusped 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
275 flying spits due to the increased complexity of CEM2D's sediment handling and distribution methods. The distribution method allows sediment accumulations to be detached from the continuous shoreline without becoming static and so transport across the entire domain, including on the lee side of a spit, is less limited. Each of these four features types are compared to natural systems subsequently that are subject to comparable wave climate conditions.

5.2.1 Cusped Forelands

280 Symmetrical wave climate conditions ($A=0.5$) are shown to form cusped 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 cusate 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 models ~~is~~ are able to predict a comparable shoreline type to that observed in this natural system although CEM2D overpredicts the directional skew.

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 Fig. 10) and CEM2D (Figure Fig. 11). However, CEM2D has a greater sensitivity to this parameter and the features show a greater skew down-drift. For instance, under $A=0.6$ and $U=0.75$ cusate 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 compared to CEM. 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 form 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. The presentation of both sand waves and reconnecting spits in CEM2D would suggest that this model may be able to better represent the conditions found at Long Point Spit.

315 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. Whilst CEM2D better represents the influence of low angle waves
320 on coastal evolution at Spurn Point, it is of note that this is a complex feature which is influenced by conditions that could be
having a greater impact on coastal evolution, including estuarine processes and dredging activities, that are not included in
either CEM or CEM2D. 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

325 The spatial scale of shoreline features differs between results from CEM and CEM2D. Metrics from the end of each run, as
shown in Figures Fig. 10 and Fig. 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
330 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 18Fig. 12).

Whilst CEM and CEM2D are not designed to represent the temporal evolution of specific coastal environments and this
metric should not therefore be compared between the models (Ashton and Murray, 2006a), we note that theThe evolution of
335 landforms is more gradual in CEM2D. This is 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).

340

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
345 and the rates at which these features form.

5.4 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. 42(b)13b). The lower nearshore profile tends to be influenced to a lesser degree (Fig. 42(e)13c) 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. 4213). 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. 4213). 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. 4314). 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. 4314). 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. 4415). This is illustrated in the volume stacks in Fig. 44-15 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 Fig. 16), 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 Fig. 16).

As in Figure 14 Fig. 15, Figure 16 Fig. 17 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 extent 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 Fig. 18). As also shown in Figure 17 Fig. 18, 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 Fig. 16). Where the wave climate is symmetrical, cusate 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 Fig. 18b), but submergence of these features under a rising sea level leads to the formation of a lagoon-waterbody in the low-lying centre-interior of the landform. Where the wave climate is defined by $A = 0.7$, $U = 0.65$ (Figure 17e Fig. 18c), 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 Fig. 18d, flying spits are shown to evolve with and without sea level rise, where the wave climate is highly asymmetric. The difference between these two simulations is that under a rising water level, the flying spits keep pace with the migrating shoreline and also 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. 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.

Observing the effects of sea level rise on coastal features, including their ability to migrate with the shoreline or how their morphology changes at this temporal scale is challenging. Evidence of submerged shorelines and landforms that formed

during transgressive periods can be removed by high energy waves and storm events, rapid migration of systems and by sediment transport that consumes or removes remnant features (Shaw et al., 2009). Notable submerged shorelines are found in the Bras d'Or Lakes, Nova Scotia, and are suggested to have been well-preserved by the rapid onset of sea level rise (Shaw et al., 2009). Tombolos, spits, cusped forelands and barrier beaches are identifiable on multibeam sonar imagery in the Lakes down to -24 m, above the early Holocene water level at -25 m (Shaw, 2006). Evidence of enclosed bodies of water within cusped forelands and the stranding of landforms at this lower sea level demonstrates in situ drowning and the preservation of landforms between -7 to -24 m evidences the ability of some landforms to migrate (Shaw, 2006; Shaw et al., 2009). Barrier islands and spits in the Bras d'Or Lakes are also found to rebuild at the proximal end of previously submerged landforms (e.g. Dhu Point and West Settlement) or migrate landward to form cusped barriers in response to rising water levels (e.g. Goose Pond) (Taylor and Shaw, 2002).

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 compared to~~ other existing coastal evolution models of its kind. The behaviour of the model has been evaluated against results from the existing Coastline Evolution Model (CEM), upon which CEM2D has been built. Results have also been compared to accepted theories of coastal morphodynamics and to the behaviour of a number of natural coastal environments. These evaluation techniques have demonstrated that CEM2D is able to simulate shoreline instabilities in accordance with theories of high-angle wave instability, to mimic the behaviour of natural environments under given wave climate conditions and to generally reproduce the results of the original one-line CEM, although some differences are observed as discussed throughout~~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 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.

445 Using CEM2D to model how this profile changes over time can inform the stability and future behaviour of features.

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

450 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

455 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

460 ~~evaluated assessed~~ CEM2D's ability to simulate the behaviour and evolution of coastal systems, by comparing against other model results, theories of coastal evolution and natural 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

465 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:

470 <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.

475 10 Competing Interests

The authors declare that they have no conflict of interest.

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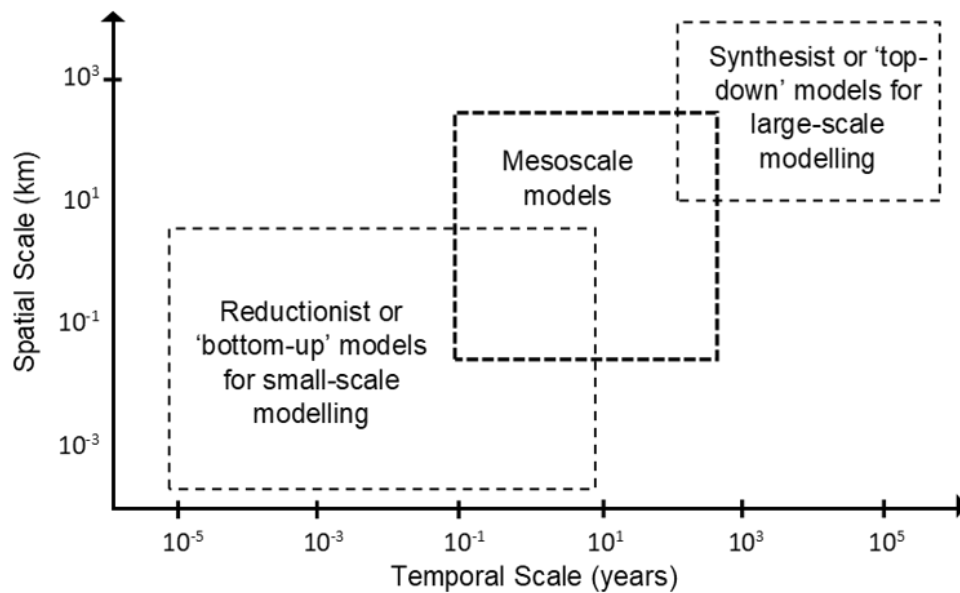
575

Table 1: A table listing the eight input factors from CEM2D used in the sensitivity analysis of Morris Method.

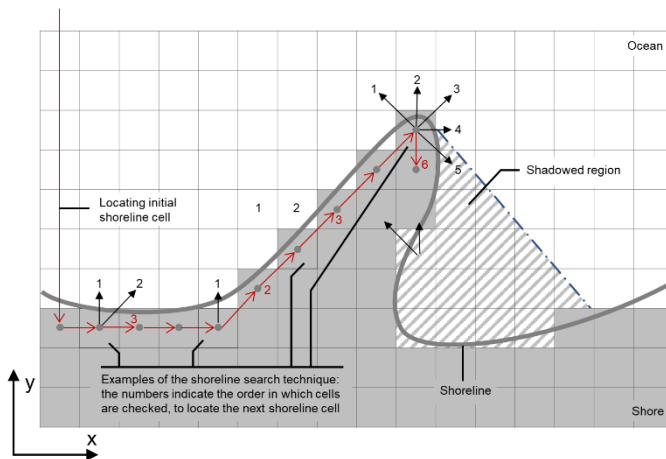
Code	Factor	Intervals	Minimum	Maximum	Justification
1	Wave Angle (°)	5	1	5	The wave climate is fundamental to driving sediment transport processes in CEM2D.
2	Wave Height (m)	5	1	6	
3	Wave Period (s)	5	1	14	
4	Sediment Redistribution Frequency (iterations)	5	10	50	The sediment redistribution method is 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	

580 **Table 2: A table showing the 4 behavioural indices used in the Morris Method and the frequency that data is recorded in each simulation.**

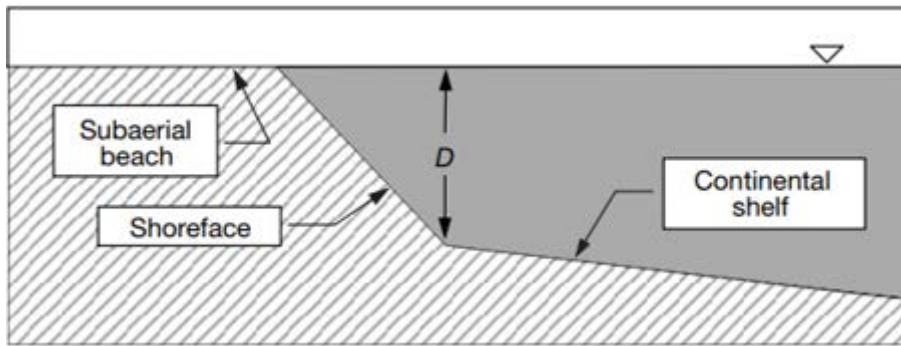
Number	Behavioural Index	Recording Frequency
1	Longshore sediment transport rate (m ³ / 10 years)	3650 model iterations (10 simulated years)
2	Coastal sinuosity	3650 model iterations (10 simulated years)
3	The ratio of wet-dry areas	300 model iterations (300 simulated days, to align with each diffusion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



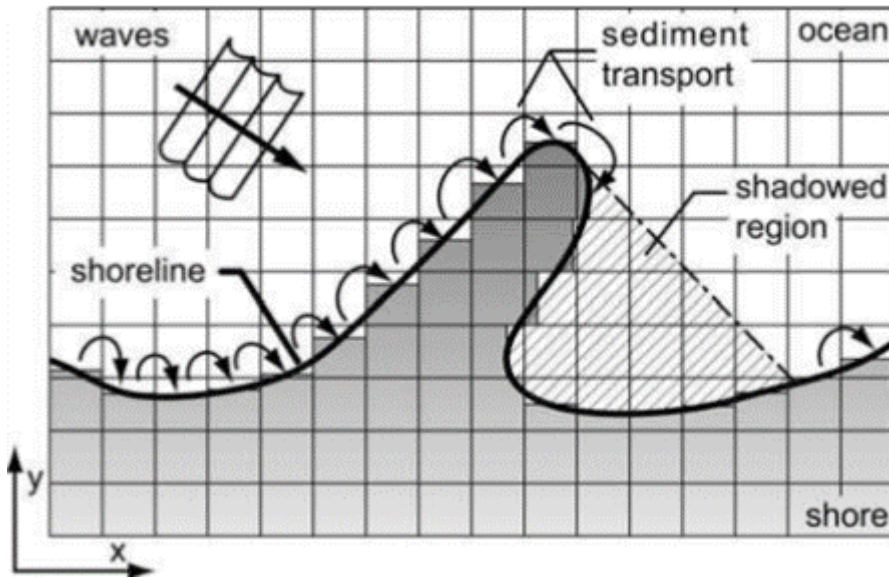
585 **Figure 1: Spatial and temporal ranges for traditionally reductionist and synthesist models, with mesoscale models highlighted in grey within the scale appropriate for coastal management (adapted from Gelfenbaum and Kaminsky, 2010; van Maanen et al., 2016).**



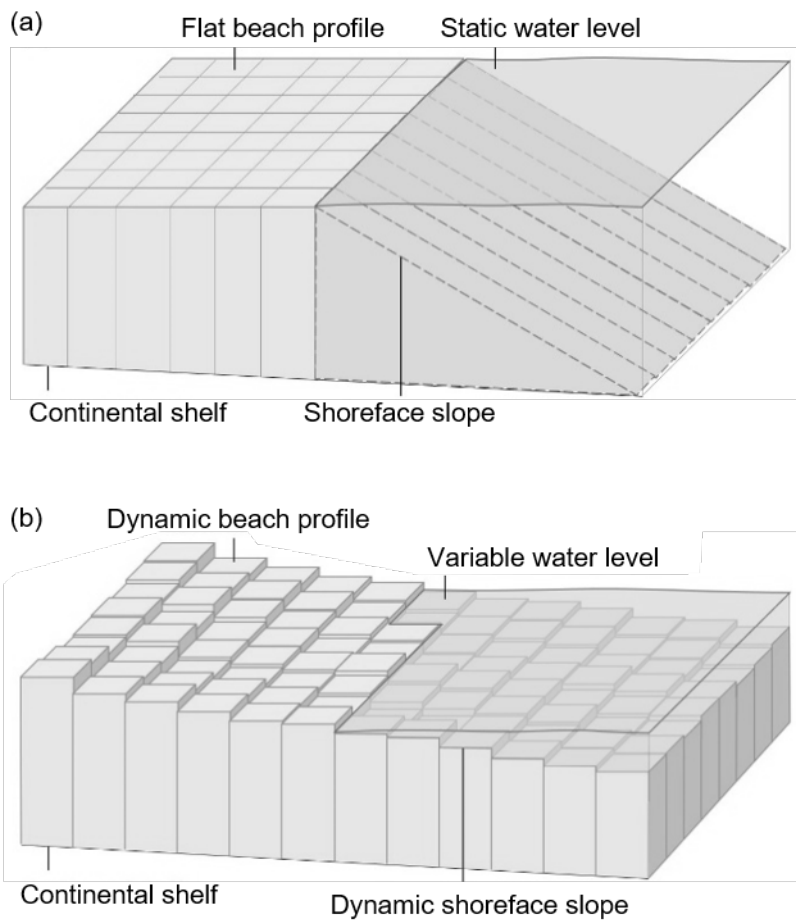
590 **Figure 2: A schematic of the shoreline search technique used in CEM (and CEM2D) to map the X and Y location of the shoreline cells. The number in square brackets denotes the shoreline cell number that is associated with a particular X and Y value and the number on each arrow is the iteration of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



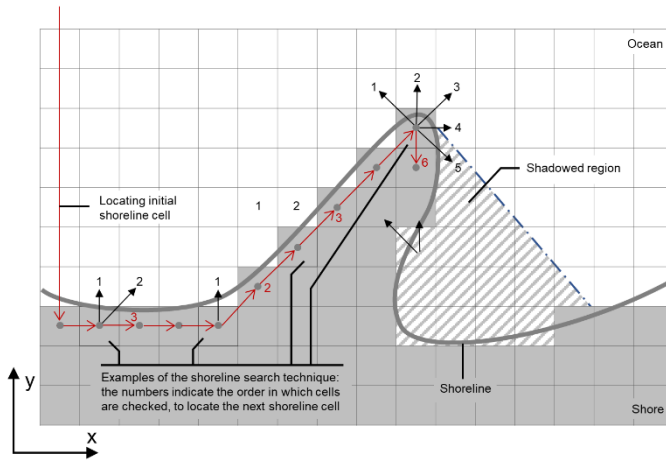
|595 **Figure 32:** Cross-sectional profile of CEM showing the location of the depth of closure, where the shoreface slope intersects the continental shelf slope (after Ashton et al., 2001).



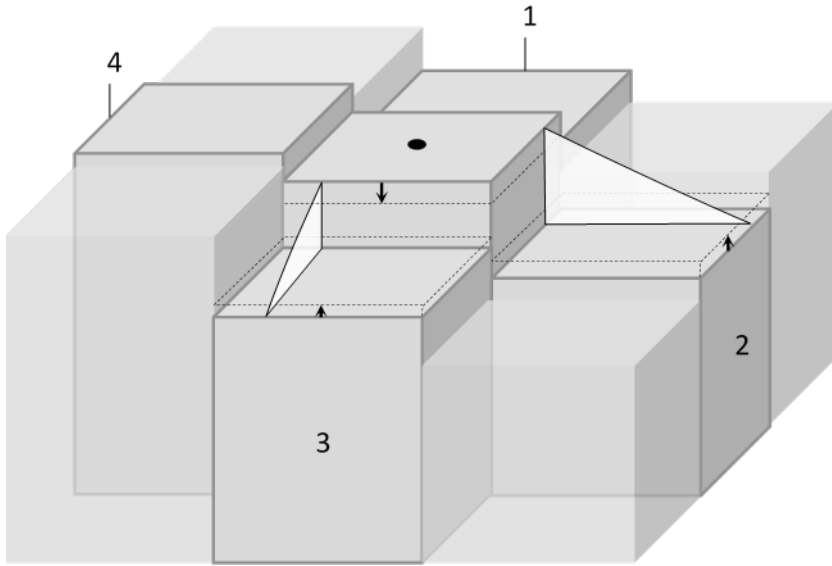
600 **Figure 43:** Plan-view schematic of CEM showing the shadow zone that is formed when protruding sections of coastline prevent waves from approaching the shoreline (Ashton and Murray, 2006a).Plan-view schematic of CEM2D showing the shadow zone that is formed when protruding sections of coastline prevent waves from approaching the shoreline (after Ashton and Murray, 2006a).



605 **Figure 54:** Schematics of CEM (a) and CEM2D's (b) profiles, illustrating the difference in structure and dimensionality of the two models.



610 **Figure 25:** 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.



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

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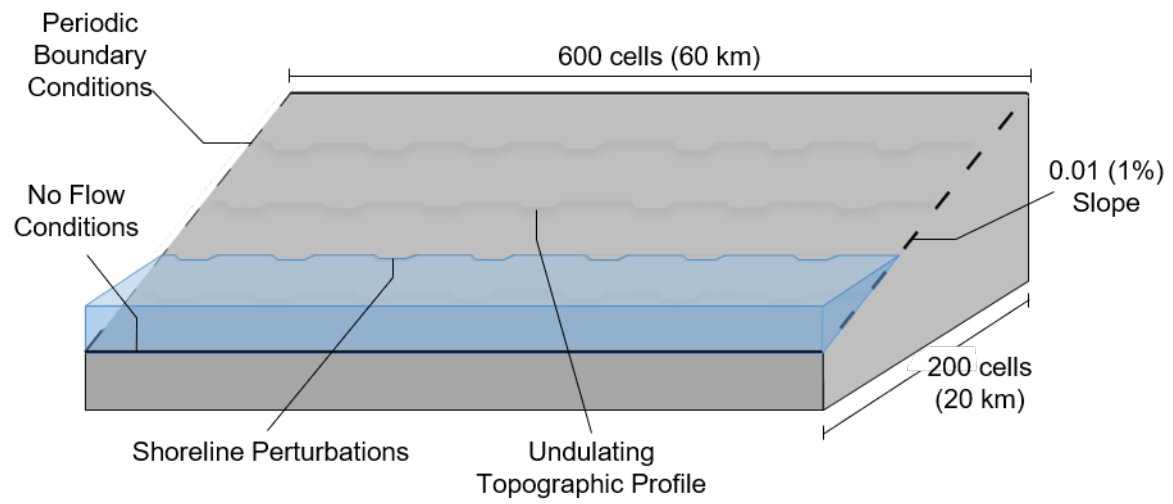


Figure 7: A schematic of CEM2D's model set-up and initial conditions used for simulations presented in this paper.

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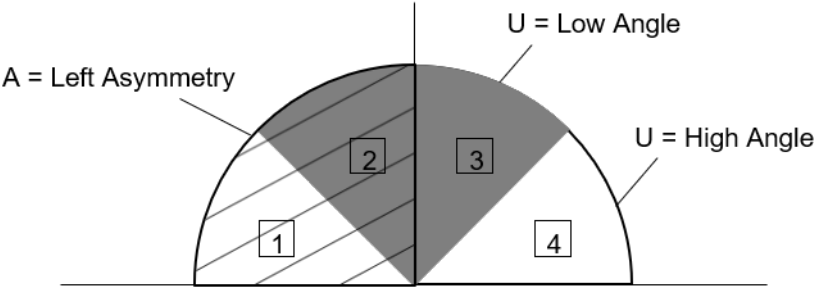
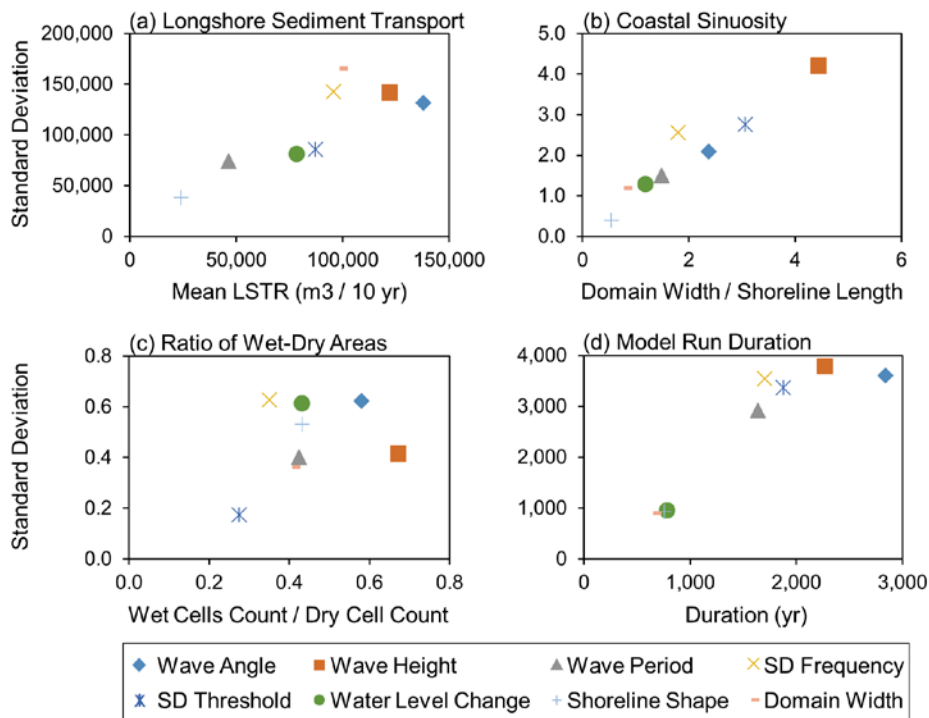
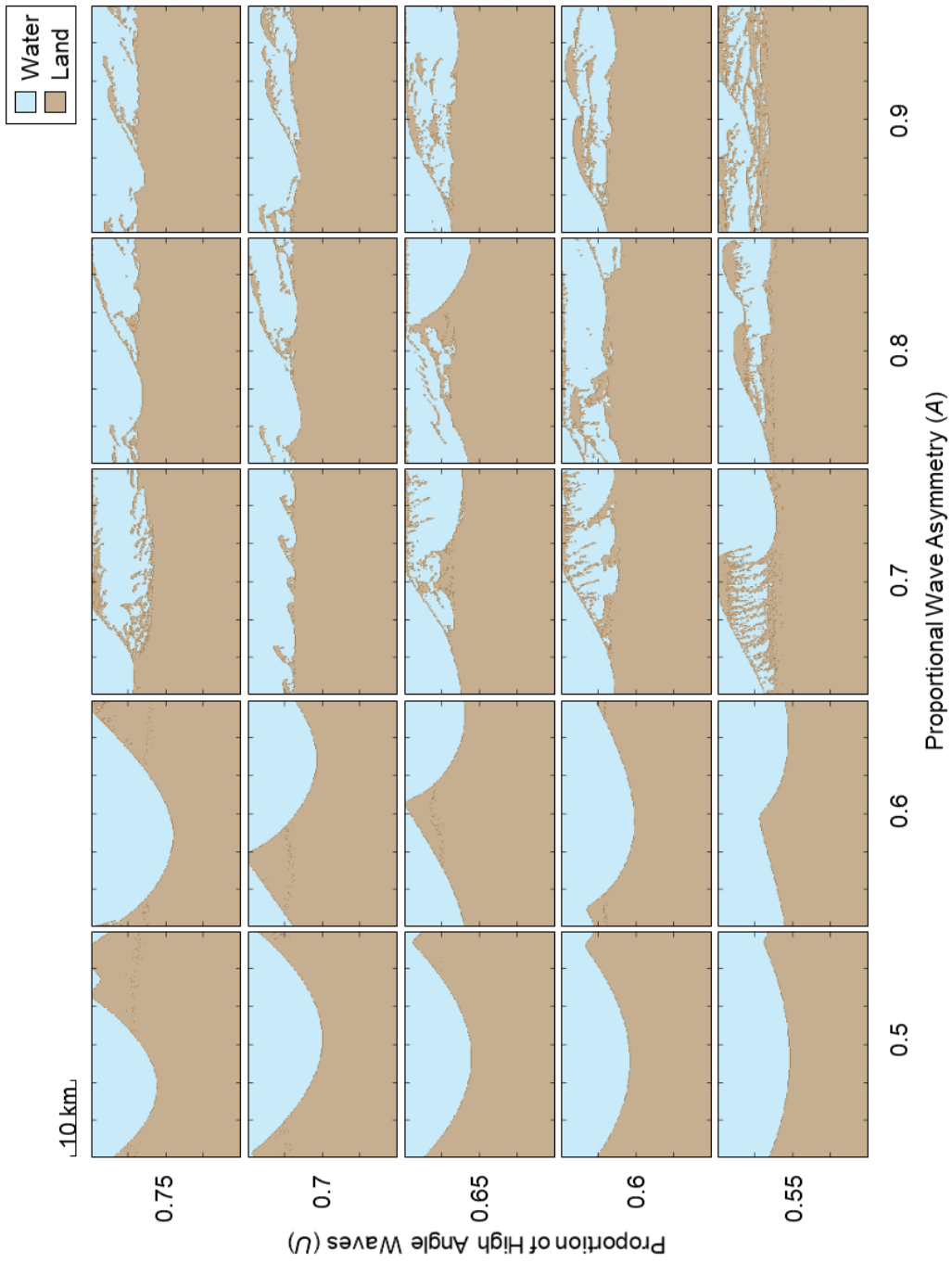


Figure 8: Schematic showing the wave angle direction, defined by the wave climate asymmetry (A) and the proportion of high to low angle waves (U) with the numbers denoting the four bins.



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



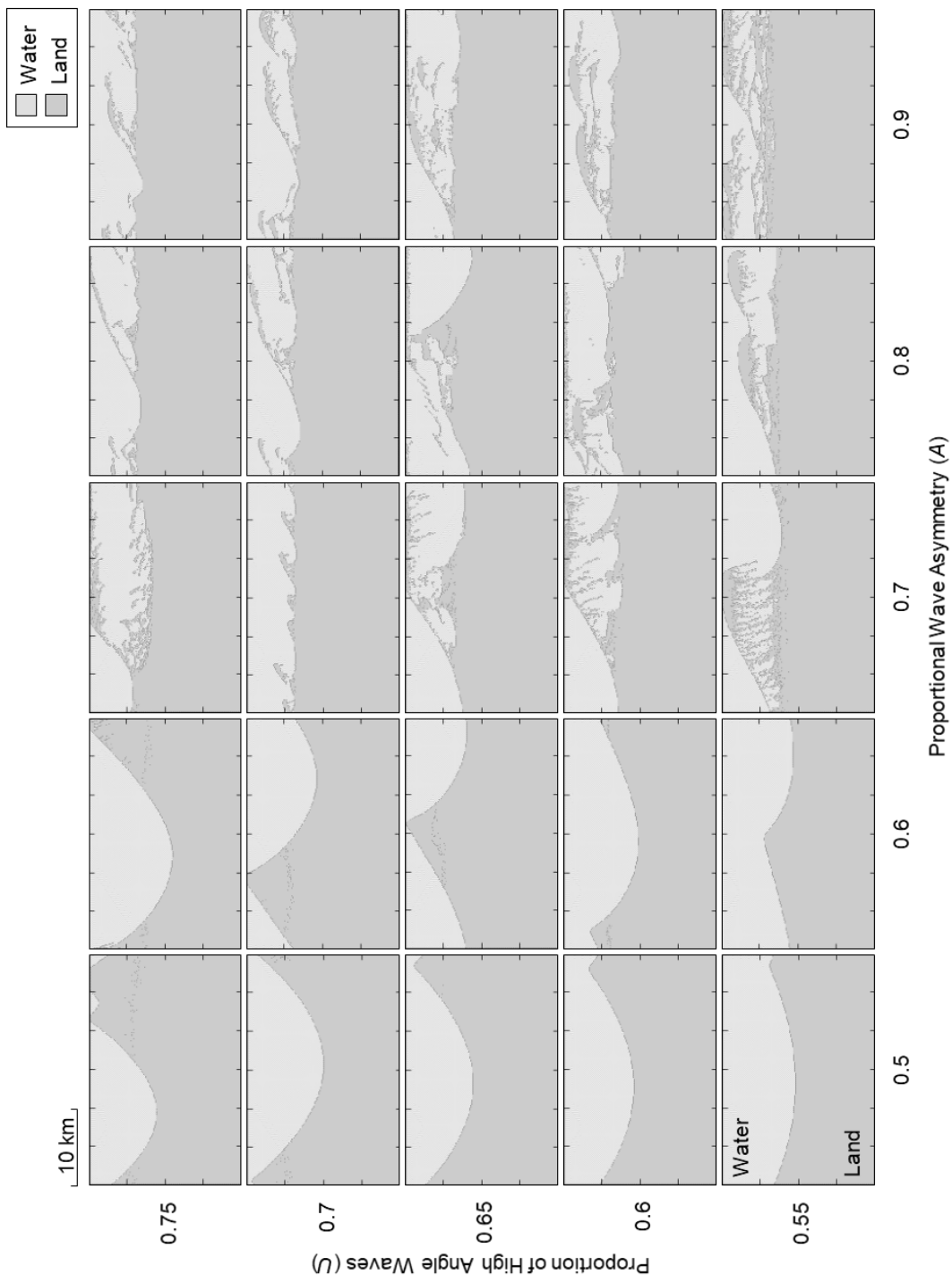


Figure 10: A matrix of results from CEM showing final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and are not inclusive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

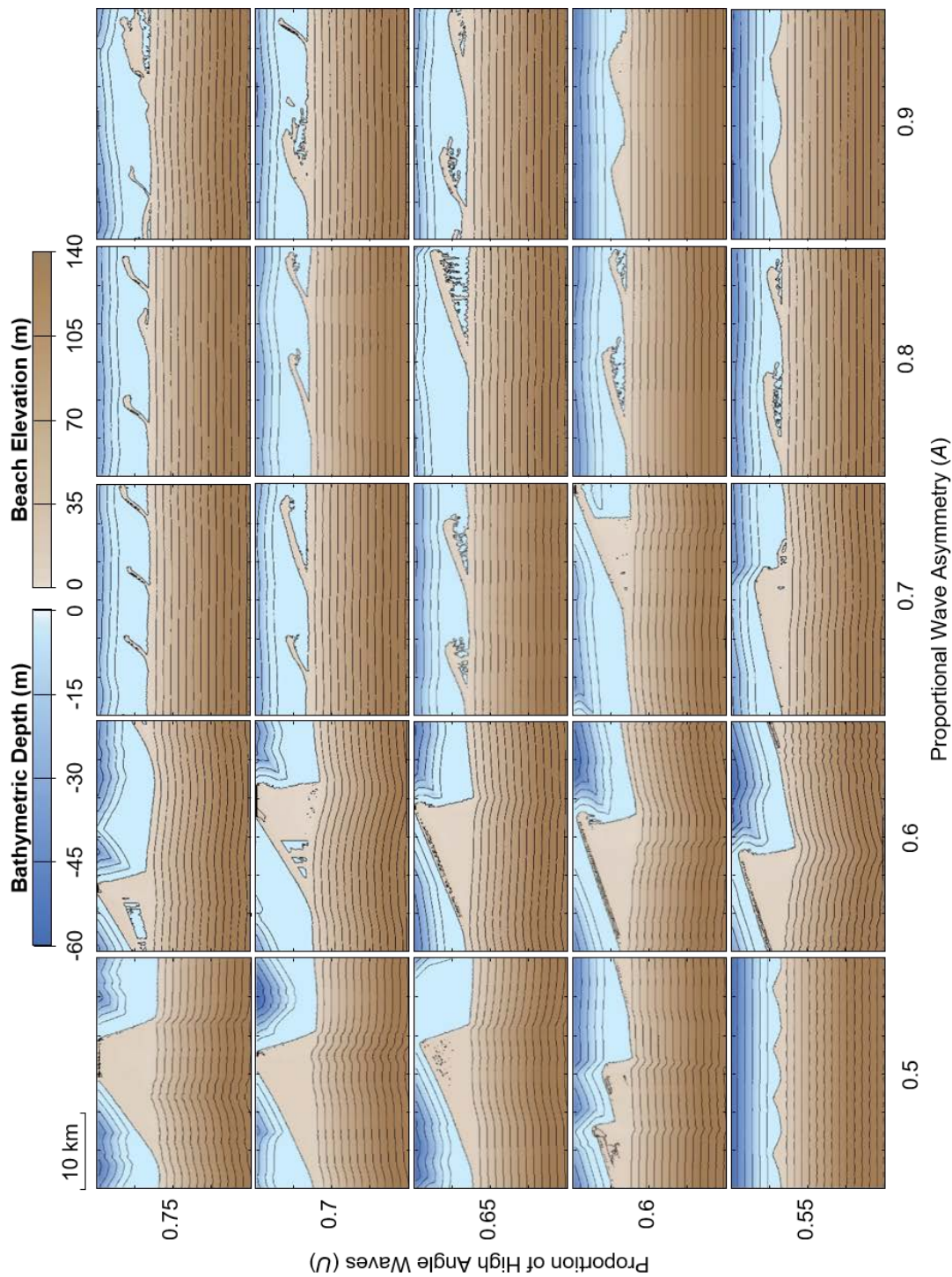


Figure 11: A matrix of results from CEM2D showing two-dimensional final shoreline morphologies as a function of the wave angle asymmetry (A) and proportion of high angle waves (U) approaching the coast relative to the local shoreline orientation. The outputs measure 20 km width and 30 km in length and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

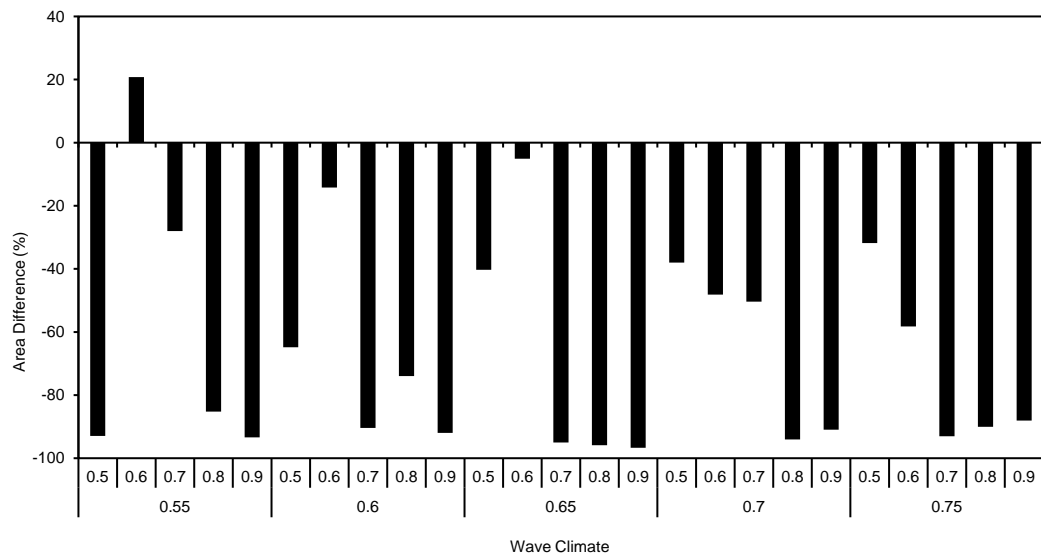


Figure 12: Areal difference (%) between results of CEM2D to CEM. The wave climate given along the x-axis is defined according to the wave asymmetry (top row) and the proportion of high angle waves (bottom row).

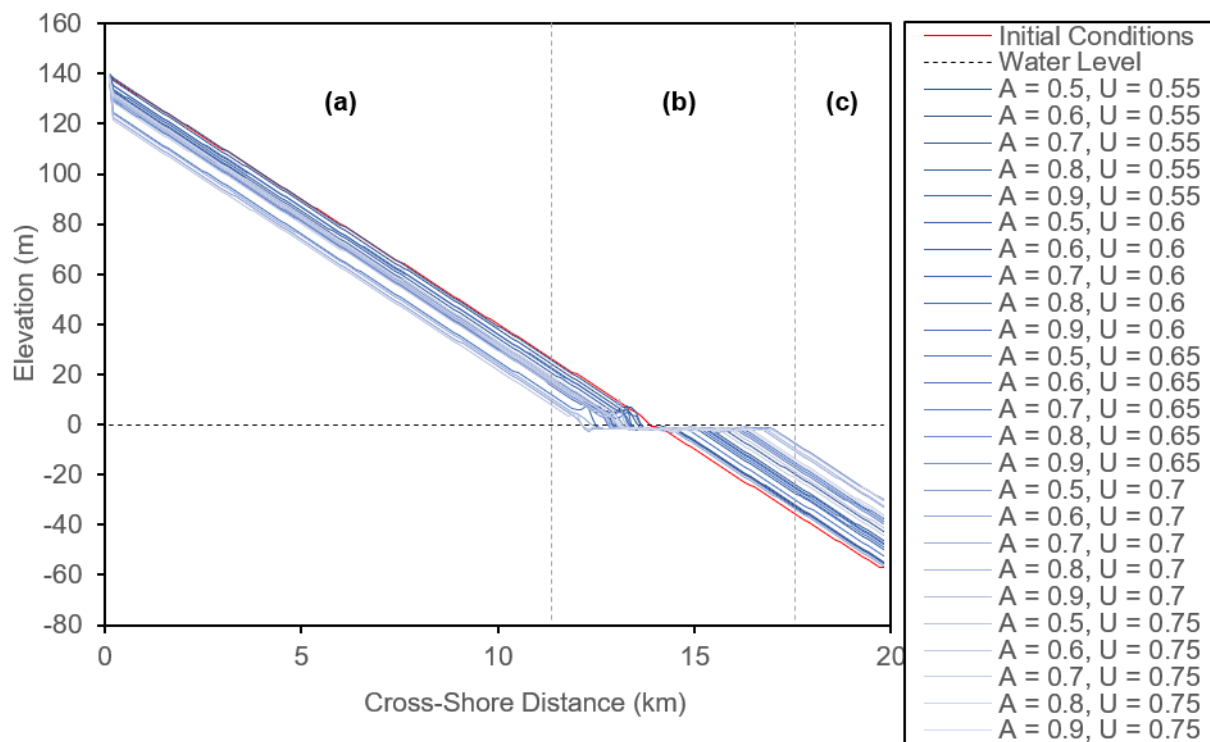


Figure 12.13: Cross-shore profiles taken for each of the twenty-five simulations, with water level shown as a dashed line and the initial cross-shore profile as a solid red line. Labelled are the (a) beach surface, (b) dynamic shoreline and upper nearshore and (c) the lower nearshore.

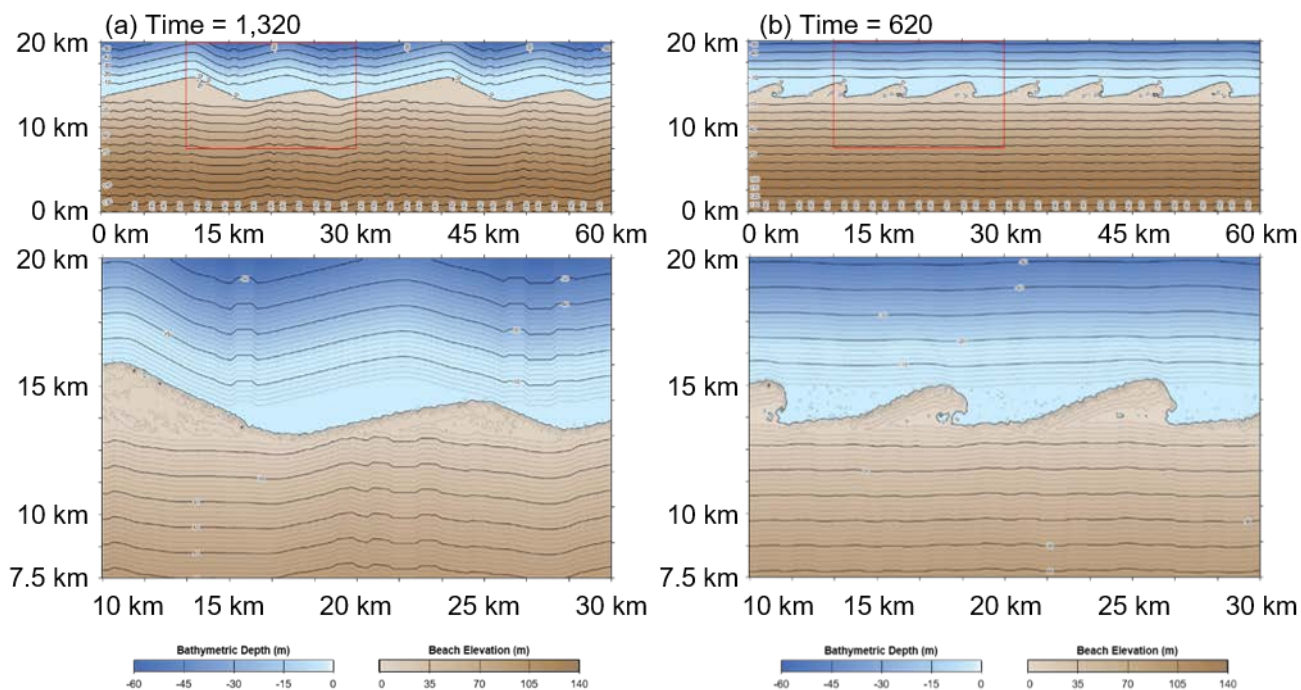


Figure 13.14: Morphology plots showing outputs of (a) $A = 0.6$, $U = 0.6$ at Time = 1,320 and (b) $A = 0.7$, $U = 0.65$ at Time = 620.

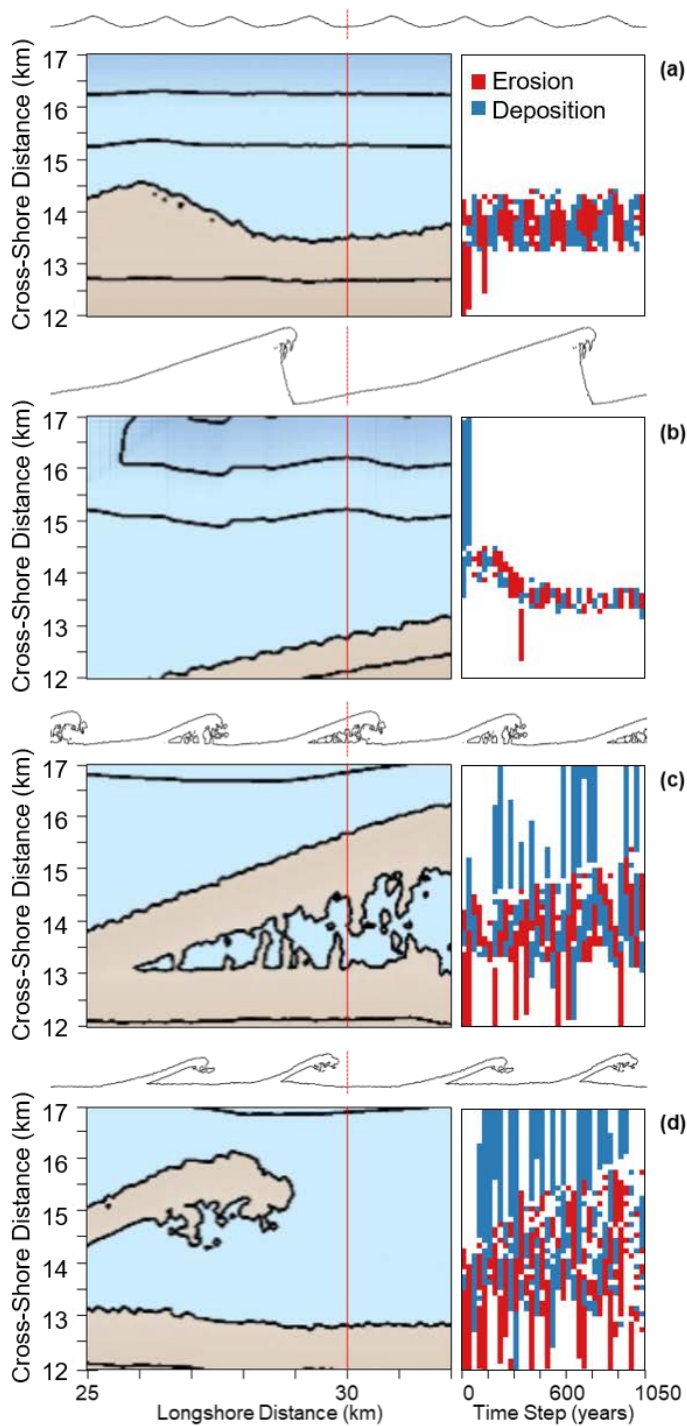
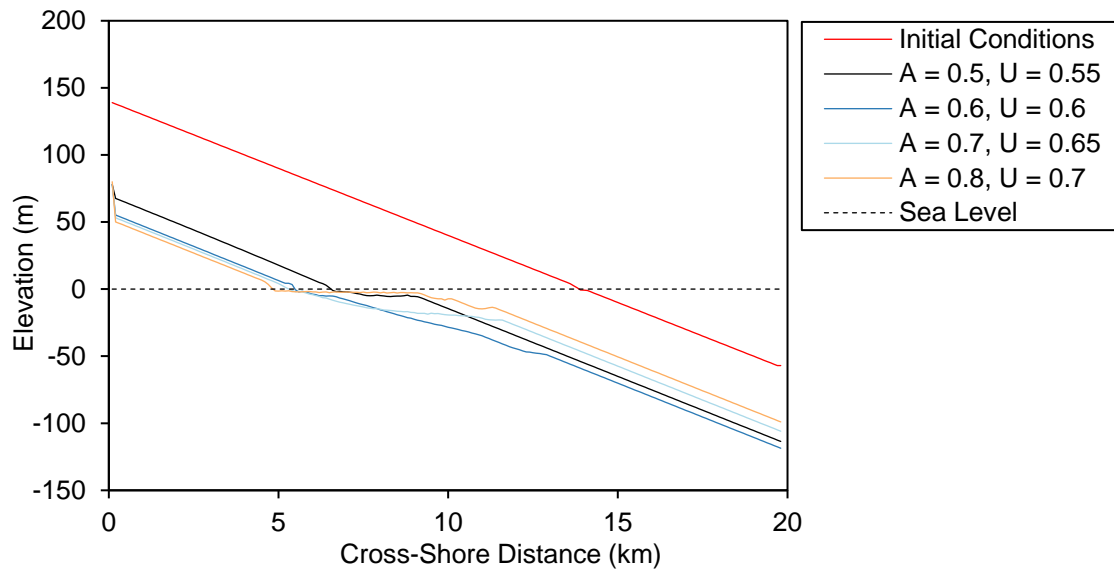
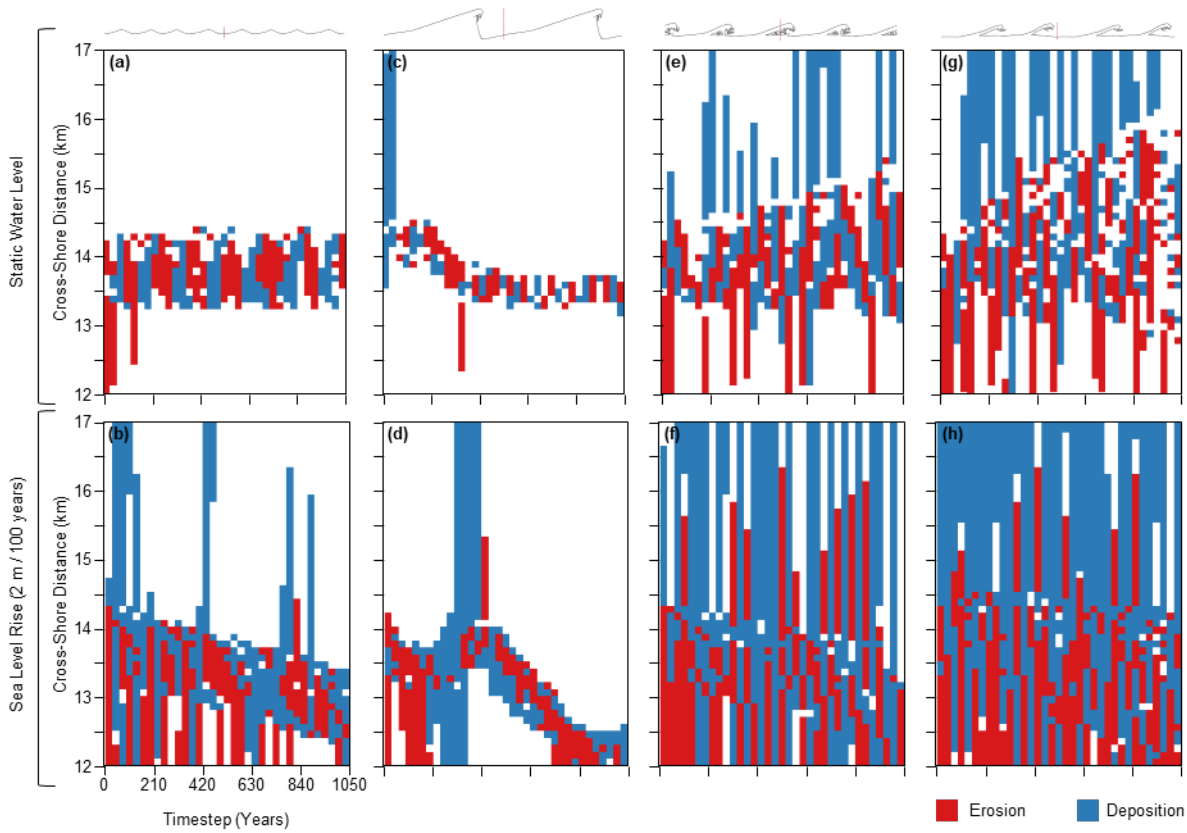


Figure 14-15: Shoreline Morphologies (left) and volume stacks (right) for four simulations where the wave climate is defined by (a) $A = 0.5$, $U = 0.55$, (b) $A = 0.6$, $U = 0.6$, (c) $A = 0.7$, $U = 0.65$ and (d) $A = 0.8$, $U = 0.7$. The red line marks the cross-shore transect where the change in volume at 30 year time intervals is recorded.



660 **Figure 1516:** 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.



665 **Figure 1617:** 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.

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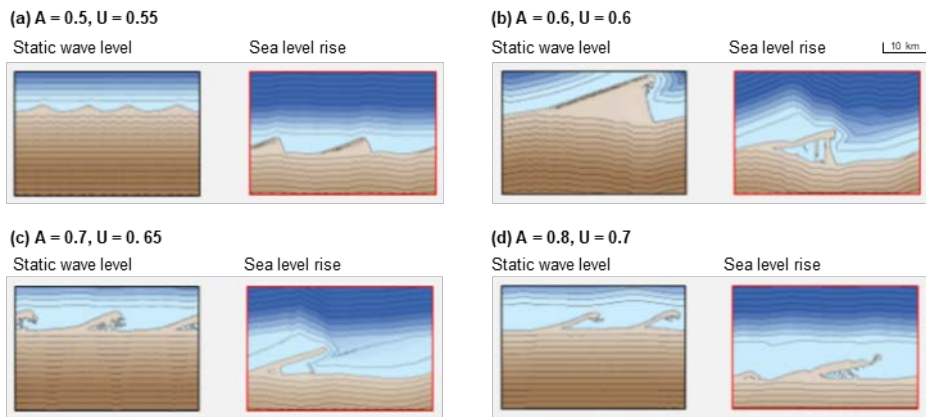


Figure 1718: Coastal morphologies for four simulations where the wave climate is defined by (a) $A = 0.5, U = 0.55$, (b) $A = 0.6, U = 0.6$, (c) $A = 0.7, U = 0.65$ and (d) $A = 0.8, U = 0.7$, run with two water level scenarios including a static water level (left, black outline) and a rising sea level at a rate of 2 m / 100 years (right, red outline).

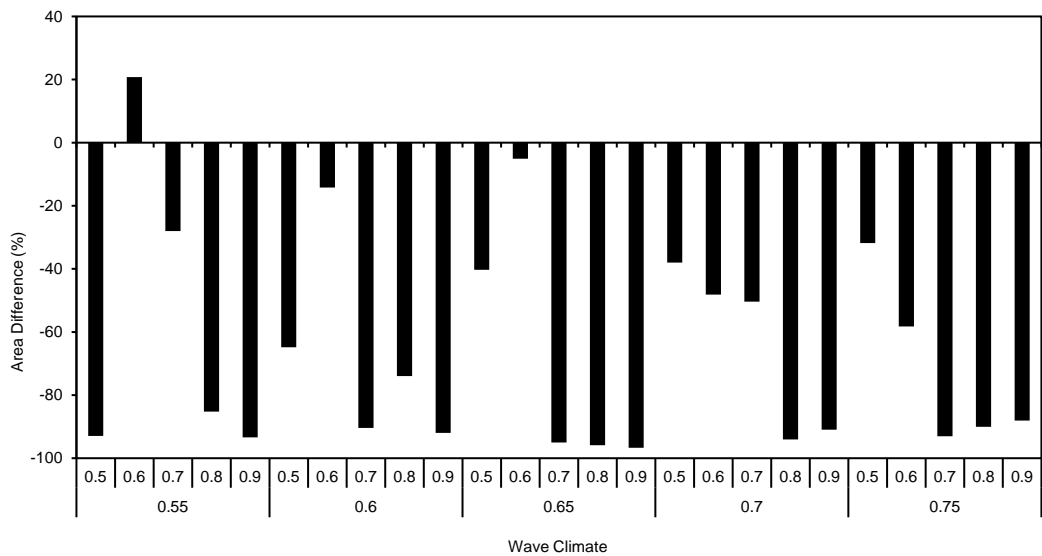


Figure 18: Percentage difference between results of CEM2D and CEM. The wave climate given along the x axis is defined according to the wave asymmetry (top row) and the proportion of high angle waves (bottom row).