RC1, Sjoukje de Lange (main comments)

Thanks for writing this great manuscript. You did a great job in exploring various experimental conditions for sand-clay ripples by current/wave dominated conditions. I think you did a very thorough job with a lot of literature research. It is generally well written (although the amount of numbers in the text can be distracting), and the figures are nice and clear. It won't be much work to get this manuscript ready for publication! It will be a very valuable contribution to the scientific community.

We welcome the Reviewer's generally very favourable comments on our manuscript and thank her for the time taken in reading through it so carefully. Please note that we have incorporated revisions into the manuscript in response to your feedback. The modified sections are now highlighted in red for your convenience.

However, I should provide some critical notes.

(1) First of all, on first sight I find it hard to differentiate this paper from Wu's earlier publication in 2022 on deep cleaning. It might be worth it to state this difference a bit more, already in the abstract. In the introduction the difference becomes clear, but readers might be confused and mix up the two papers after only browsing through the abstract.

We agree and have now made a clearer distinction from Wu et al. (2022) concerning winnowing (deep cleaning) in the abstract.

[L12-13: '…in coastal and estuarine environments. While laboratory research on ripples forming in these types of mixed-bed environments is relatively limited, it has identified deep cleaning, the removal of clay below the ripple troughs, as an important factor controlling ripple development. New large scale flume experiments …']

(2) Following up on that, it is good that the conclusions in the 2022 paper are largely confirmed. However, this causes repetition of many of the findings. For example, the decrease in height/length etc with clay content already known from 2022 paper, and so is the notion of deep cleaning, and the longer time till onset/equilibrium of the ripples. The new finding of this publication is the phase diagram. It would be good to focus more on this, rather than a data analysis of the raw results. Maybe it is possible to compile it in more comprehensive graphs instead of rough visualization of data, such as done in the 2022 publication.

We accept that there is overlap between this paper and the 2022 deep-cleaning paper. The idea in the present paper is that it is a synthesis, which pulls together the 2018 and 2022 papers as well as the fine sand Baas et al. (2013) paper and consolidates the findings. The 2022 and 2013 papers certainly showed a reduction in the dimensions with clay concentration. However, here we take this a step further by determining the constant of proportionality for the wave and wave-current ripples based on the orbital diameter and identifying the drop in hydraulic conductivity as a potential mechanism. While the main result is the phase diagram, there are a number of prerequisites to the discussion that are required before the phase diagram can be set forth. We hope that the revised abstract, introduction and conclusions, and re-ordering of the discussions, make this clearer.

[A revised introduction and conclusions have been added to the end of this document]

(3) Regarding readability, it's generally very easy to read. However, in the results a lot of numbers are given, including many abbreviations. Additionally, many comparisons are made. It causes me to get lost in your data, and I miss the main message. Maybe it would help to start giving the main take away, and support this with numbers, rather than giving a lot of numbers from which the reader has to derive the conclusion themselves, making it hard to read and hard to concentrate.

We plan to incorporate a nomenclature list, which will facilitate readers' comprehension of symbols used throughout the text, ensuring ease of understanding. In addition, we have streamlined reference to T_η and T_λ, which are not relevant to the discussion section:
[L208-220: '…, small ripples appeared at t = 10 min. Thereafter, ripple dimensions developed gradually over a period of around seven hours, stabilising to an equilibrium height and wavelength of 13.9 and 137 mm (Figure 3e and f). The equilibrium ripples retained … At C_0 = 10.8% (WC2), small ripples again appeared at t = 10 min and grew to equilibrium dimensions of η_e = 5.6 mm and λ_e = 125 mm. The small ripples formed at C_0 = 10.8% (WC2) were three-dimensional with discontinuous, sinuous crestlines in plan view. In cross-section, these ripples were asymmetric and flatter, with RSI = 1.6 and RS = 0.04 (Figure 4e, Table 2). The general trends in T_η and T_λ with C_0 were similar to those found by Wu et al. (2022). For the C_0 = 16.3% (WC2) case, the bed …']

We have also substantially reduced reference to specific numbers in the conclusions (see the revised conclusion at the end of this document), to help emphasise the main message, in addition to the restructuring listed above. We believe these modifications will significantly enhance the readability and clarity of the paper.

All smaller comments can be found in the attached pdf document. Please contact me if you have any questions regarding my feedback!
We have included the highlighted sections of text from the pdf in our responses below

RC1, Sjoukje de Lange (smaller comments)
(4) L14: 'experiments seek to address this by considering …'
what exactly? For me it sounds like you want to do lab research on mixed-ripples, simply because it has not been done before. I'm not sure what "this" is that requires addressing
We agree that further clarification is necessary here. We have made the following changes to the text:
[L14-17: '… New large-scale flume experiments seek to address this sparsity in data by considering two wave–current conditions with initial clay content, C_0, ranging from 0 to 18.3%. The experiments record ripple development and pre- and post-experiment bed clay contents, to quantify clay winnowing. The present experiments are combined with previous wave-only, wave–current and current-only experiments to produce a consistent picture that shows larger and smaller flatter ripples over a range of wave–current conditions and C_0. …']

(5) L18-19: '… C_0 > 10.6%, likely associated with hydraulic conductivity.'
I would specifiy this to "an increase in hydraulic conductivity"
We accept this, but it is a decrease not an increase in hydraulic conductivity. The text has been changed.
['… C_0 > 10.6%, likely associated with a 3-orders of magnitude decrease in hydraulic conductivity.']

(6) L19-20: 'Accompanying the sudden change in steepness is a gradual linear decrease in wavelength with C_0 for C_0 > 7.4%, which may …'
just wondering (without having read the rest of the paper), is this also related to this hydraulic conductivity?
We do not think so, as it is a gradual rather than sudden change.

(7) L26-27: 'Winnowing occurs for both flat and rippled beds, but the rate is two orders of magnitude smaller for flat beds.'

this line feels a bit misplaced, as it states a result, at a location where you would expect a discussion/implication

We agree with the Reviewer and have relocated this sentence about winnowing to an earlier position in the abstract, as shown below, so that the abstract ends with the previous sentence.

[L19-27: '… Accompanying the sudden change in steepness is a gradual linear decrease in wavelength with C_0 for $C_0 > 7.4\%$. Ultimately, for the highest values of C_0, the bed remains flat, but clay winnowing still takes place, albeit at a rate two orders of magnitude lower than for rippled beds. For a given flow, the initiation time, … which has important implications for morphodynamic modelling.']

(8) L28: **'1 Introduction'**

I think you did a great job explaining the importance of phase diagrams under these specific conditions. However, why do we care about clay winnowing? It would be good to add a few sentences about this.

The winnowing of clay causes mixed sand–clay ripples to return to clean sand ripples so as a mechanism it is important. Deep cleaning, which removes clay from below the active layer provides a greater supply of clean sand to form ripples. Also on a more practical level, we make use of winnowing to go from high to low clay content experiments. This has been addressed in the updated introduction at the end of the document, which includes a contrast between the 2018 and 2022 papers.

(9) L36-37: '… vice versa ~~for coastal and estuarine management and ecological balance maintenance~~, especially as such areas may'

We are not sure why this has been deleted as there is no comment, but this phrase has been removed from the modified introduction in any case (see revised introduction at the end of this document).

(10) L61-63: 'under combined flows and revealed the formation of small flat ripples with an initial clay content, C_0, greater than 10.6% under hydrodynamic conditions that would generate large equilibrium ripples in clean sand.'

I find this sentence a little bit confusing. I understand you want to say that the ripples with clay are smaller than the clean-sand equivalent (right?), but I would suggest rephrasing.

We accept this and have rephrased the sentence:

['Wu et al. (2022) were the first to consider ripple dynamics in sand–clay mixtures under combined flows. Their study showed that small flat ripples formed for initial clay contents, C_0, greater than 10.6%, under hydrodynamic conditions that formed large equilibrium ripples in clean sand.']

(11) L66-67: 'Wu et al. (2022) also found that the clay loss rate from the bed was much lower when $C_0 > 10.6\%$, as the stronger cohesion resisted further ripple development.'

It might we worth it to briefly relate this to Schindlers Sticky Stuff paper (although it is unidirectional flow focussed on dunes).

Schindler et al. (2015) showed that increasing C_0 reduces dune size in unidirectional flow, but they did not quantify the clay loss, so this reference cannot be used here. Schindler et al. (2015) is discussed in the context of the 3D phase diagram (L456), but was mistakenly omitted from the reference list. This has now been corrected (L664).

(12) L75-77: '… under different hydrodynamic conditions; (2) to compare clay winnowing efficiency, based on quantifying bed clay content during ripple development, under different flow conditions;'

Based on the introduction, it is unclear to me why we care about clay winnowing. Would it be possible to expand a bit on this?
We have now linked these three points more closely together (see also RC1.8):
[L74-77: '… The three specific objectives of this study were: (1) to compare ripple development and occurrence on beds with similar initial clay contents under different hydrodynamic conditions; (2) to compare clay winnowing efficiency during ripple development, under different flow conditions; and (3) to propose a new phase diagram for bedforms generated in sand–clay substrates to systematise the experiments, using the knowledge gained from objectives 1 and 2.']

(13) L94: '… flow conditions of increased relative current strength, with $U_c \approx 0.3$ m s^{-1} and'
do I understand correctly that Uc does not vary between the two new experiments?
Yes, that is correct, only the wave strength was changed.

(14) L103: '…, with C_0 of 9.9%, 13.1%, and 18.3% in channels 1 to 3, were under WC3 flow'
maybe write "strong" flow conditions or something like that, so that the reader does not need to flip back and forth to the table?
The idea is that the numbering system represents the relative strength of the current from weakest WC1 to strongest WC3, see L96-97 as well as L146-147 of the table, precisely so that it is not necessary to keep looking at the table, but perhaps this was not clear enough so we have made the text more explicit.
[L96-97: 'The wave–current flow conditions (WC1, in Table A1 from Wu et al., 2022; WC2 and WC3, in Table 1) are numbered according to increasing relative current strength, from the weakest, WC1 to the strongest, WC3. The experiments involved …'
L146-147: '[1]The flow code represents the relative current strength, where WC1 (Wu et al., 2022, Table A1) is the weakest and WC3 is the strongest.']

(15) L104: '… (Table 1). The beds in Run 2 remained essentially flat after 650 min. In Run 3, …'
this seems like it belongs in the results?
We can see how the Reviewer might think this, but the sentence is really only describing what is stated in Table 1, which describes the flow conditions and the general nature of the bed: rippled or flat.

(16) L111: 'in each channel before and after the run, after the water had been drained.'
did the drainage cause any sediment to be remobilized? And if not and drainage was very slow, how did you prevent the clay depositing in the ripples troughs?
The draining of the flume was sufficiently slow, and the deposition of material had a minimal effect as it was only a surface dusting of clay.

(17) L111-112: 'Furthermore, the flow was temporarily stopped during the runs at pre-set times …'
I got a bit a similar question here - was the stopping time short enough to prevent deposition of the suspended material?
The cores were taken before the clay had a chance to settle out, so this was not really an issue either, a sentence has been added to explain this.
[L113: '… length of 90 mm. These short pauses in the experiments resulted in negligible bed deposition of suspended clay particles due to their slow settling velocity. Details of the']

(18) L115-116: '… was excluded from the analysis, because the sediment in this channel was not sufficiently well mixed.'
how did you discover this issue?
This was determined through core samples which has now been added to the text.
[… because core samples collected from the flat bed showed that the sediment in this channel …]

(19) L135: 'were co-linear. Whilst θ_0 is clearly affected by grain size, it is assumed that the other …'
I'm not sure what you mean with this? What are co-linear experimental flows?
This simply means the wave and current are aligned.

(20) L145: 'Table 1 Experimental parameters'
I'm kinda missing the logic behind how this table is ordered. It seems to be on run/channel, which has very little physical meaning to me. Why not organize it either on C_0 content, flow code, or current intensity?
These are organised in the order in which the experiments were conducted to take advantage of natural winnowing even when the bed remained flat (see L101-102).

(21) L168-169: '… growth. Finally, the sediment concentration profiles were characterised by a Gaussian-type function.'
why was this done?
This was done to be consistent with the results in Wu et al. (2022) and also because the core results were sometimes quite noisy and these help as trend lines (see Figure 5).

(22) L175: 'marked C - current-dominant, WC - wave-current, W - wave-dominant, NM - no motion'
out of curiosity: is there a way to discriminate between current ripples, wave ripples and mixed ripples in terms of geometry? And if so, does the height/length/etc of the ripples observed in these WO/WC/C regimes match the expected geometry?
The Reviewer is jumping the gun here, as we discuss this in the results section. The categorisation here is based solely on the wave and current strength with reference to Baas et al. (2021).

(23) L176: 'WO – washout. The threshold of motion …'
what will be in the upper right corner of this diagram, for even stronger currents than washout conditions?
In principle flat featureless upper stage plane beds, as found by Baas et al. (2021), but we could not generate these in the present experiments. In angular wave–current cases there is also the occurrence of lunate ripples to consider. We have added a sentence to the text to point this out.
[L141: '… threshold of motion, $\theta_c+\theta_w = \theta_0$. It is anticipated that ultimately above washout there are flat featureless upper stage plane beds (for waves and currents at angles this may be complicated by the occurrence of lunate ripples, Baas et al., 2021). The reason that not all conditions …']

(24) L184: '147.9 mm, required a longer $T_\lambda = 302$ min (Figure 3a and b; Table 2). As shown in …'
I would love to see a figure that plots equilibrium time (and/or initiation time?) with clay content!

The reason we have not shown these is because similar plots were shown in Wu et al. (2018, 2022) and they are not relevant to the discussion. Also, the initiation time is already shown in Figure 7g versus θ_{0E}.

(25) L189: 'Figure 3. Development …'
why are figure a and b not having the same width as the other figures? I would either make them the same width, or scale the x-axis similarly (thereby decreasing the size of them even more).
We agree that this makes the figure look untidy so will make the Figure 3a,b subplots the same width.

(26) L193: 'intervals. The yellow lines are the best-fit curves for clean sand (a, b).'
in c and d, right?
The yellow lines are in c and d, but they have been taken from (a, b). This has been clarified in the text.
['The yellow lines in c and d are the best-fit curves for clean sand from (a, b).']

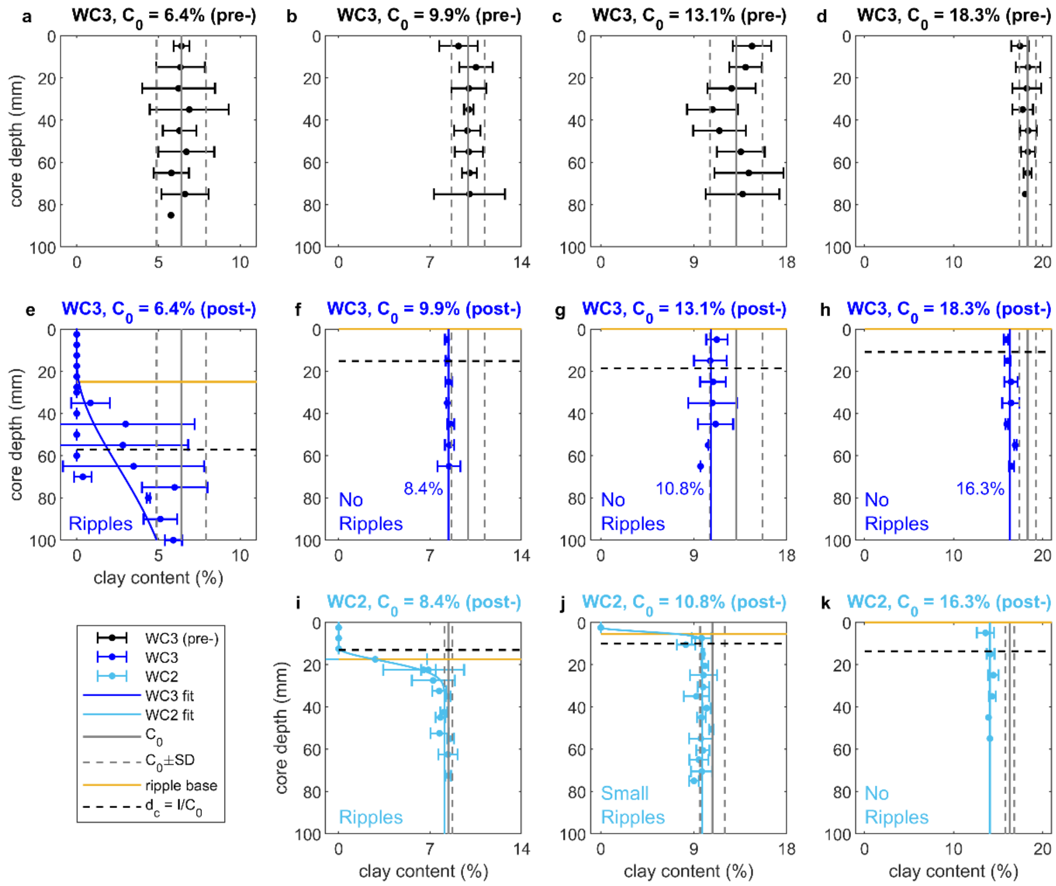
(27) L195: 'Figure 4. Plan view …'
love this figure! Would it be possible to use the same scale bar for each figure though? That would clean up the figure a bit.
Unfortunately, if all of the scales are the same, definition will be lost in e and f, but we will reduce it to the two-colour bars for the common scales for a-d and e and f, and change the caption to explain this.

(28) L223: 'Table 2. Bedform characteristics'
this table is differently organised than table 1
This is correct. Unlike Table 1, which is based on the experimental order (see above), this is grouped according to flow type to aid in the description of bedform types in the results.

(29) L237-238: 'active layer (Figure 5e). The equivalent clean-sand depth (black horizontal dashed line), $d_c = I/C_0$, was 57 mm, more than two times the ripple height (25 mm).'
interesting! I hope to read something about this in the discussion!
This is the deep cleaning that is shown in figure 8.

(30) L252: '… for WC3 conditions (pre- a–d and post- e–h) and for WC2 conditions (pre- f–h …'
since the headers of figure a-d indicate "initial" in it, why not indicating "end" (or something equivalent) in the headers of e-k?

We accept that this figure is a little confusing and have changed 'initial' to (pre-) in Figures 5a-d and added (post-) to Figures 5e-k, so that the terminology is consistent with the caption. However, it is important to stress that Figures 5f-h are the pre-experiment cores for WC2 (L252). To emphasise this point, we have added the depth-mean post-experiment value in blue for Figures 5f-g, as this represents C_0 values for Figure 5i-k.



(31) L264: '... In the present experiments under WC2 conditions, this discontinuity in equilibrium'

So why not under WC3 conditions? (maybe you talk about it later, but this is the first question popping up when reading this).

This is because, for WC3 conditions, the higher clay contents are below threshold, so no ripples formed, which we discuss in the threshold of motion section.

(32) L284-285: 'Other than this reduction in steepness, current strength was found to have a modest influence on ripple geometry;'

Interesting!

(33) L290: '..., D_{50} = 0.45 mm, may have resulted in a greater tendency towards 2D symmetric ripples,'

Didn't Baas show in his 1994 paper that ripples always develop towards 3D linguoid structures when in equilibrium? How would you use that finding compared to yours? Sedimentology (1994) 41, 185-209.

The Baas (1994) ripples are for unidirectional flow, which tend to be far more asymmetric and linguoid. The present ripples, while formed by waves and currents, are wave-dominated (below the diagonal $\theta_c = \theta_w$ line in Figure 2). So, the present experiments are much more 2D and straight-crested in character than Baas' linguoid ripples, with only subtle changes in the ripple character as a result of the current as stated above (L284-285).

(34) L304-306: 'described by $\lambda_e = \alpha d_{wc}$, where α is the constant of proportionality (= 0.62, according to Wiberg and Harris, 1994) and d_{wc} is the orbital diameter enhanced by the current. Appendix B explains how d_{wc} is determined based on a sinusoidal wave. The …'
Although you explained this in a bit more detail in the appendix, I think the storyline would benefit from a longer explanation here. The result is beautiful, and leads to an important figure in your paper. It's a shame it remains unclear what ad_{wc} exactly is until doing a deeper dive into the appendix. additional question - is there a physical explanation behind this equation?
We accept that this could be made clearer in the main text. The orbital diameter is an important parameter for wave ripples as it represents the distance a neutrally buoyant particle will move in half a wave cycle and controls wave ripple spacing. Thus, when a wave and current are added together the particle will move further and d_{wc} will be larger. We have added a sentence to the text to reflect this:
['… and d_{wc} is the orbital diameter enhanced by the current. The orbital diameter scales the ripple spacing, as it represents the distance a neutrally buoyant particle can move in half a wave cycle (Clifton and Dingler, 1984). With the addition of a current, this particle can move further and Appendix B explains how d_{wc} is determined based on a sinusoidal wave.']

(35) L314: 'where C_{0m} = 7.4%, such that α = 0.31 when …'
what would happen if you would choose 8% here?
While making C_{0m} = 8% might seem tempting based on L295, it worsens the fit, as C_{0m} = 7.4%, which corresponds to the upper limit of Wu et al.'s (2018) experiments, best describes the data in Figure 6b. We therefore would prefer to keep it as 7.4%. A phrase has been added to L295 to explain where the 7.4% value comes from.
[L295: '7.4% (the upper limit of Wu et al.'s (2018) experiments). Interestingly …']

(36) L318: 'Figure 6. Equilibrium …'
great figure, love how it all collapses!
Thank you.

(37) L323: '**4.2 The enhanced threshold of motion**'
how would this story hold if you would use the calculations as proposed in van Rijns 2019 paper https://doi.org/10.1061/(ASCE)HY.1943-7900.0001677 It might be quite applicable to your story.
For coarse sand, van Rijn (2019) used the exact same equation for the threshold of motion (see L129-130 and his eq. 1a). However, here we are inferring what the enhanced threshold would have to be, based on whether or not ripples form, so his enhancement might be different, but on L381-388 we are using his explanation for the different coarse and fine threshold enhancements (in L382 and L678 the year should be 2019 as above since it is the same reference).

(38) L369-370: 'Figure 7 clearly shows that for the wave-only and wave-current cases, the initiation time is related to the fraction of the wave cycle when shear stresses are above threshold.'

is this the take-away from the figure? I had a hard time reading through the text trying to find why you were suddenly looking at wave-orbit-time scales. Maybe you can clarify the aim before diving in the analysis?
This section is all about choosing a value for P_θ in eq. (7) for the enhanced threshold that is consistent with the results: below threshold for flat featureless beds and above threshold for rippled beds (L324-338) based on the size of the maximum stress in the wave cycle (= $\theta_c+\theta_w$). This may not have been made clear enough, so a phrase has been added to L331. This is a necessary first step that is required before Figure 7 can be shown, as it determines the position of the yellow lines in each case. Figures 7a-f confirm the choice of P_θ, but provide more detail by showing the time varying signal, eq. (8). Thus, Figure 7g is the main additional information provided by the figure that summarises the time-varying behaviour.
[L331: 'For combined co-linear wave–current flow, the threshold line is described by θ_{0E} = $\theta_c+\theta_w$, where $\theta_c+\theta_w$ is the maximum stress in the wave cycle.']

(39) L379: '…. 1+6.4C_0, D_{50} = 0.143 mm,'
is the D_{50} really a good measure to describe clay-sand mixtures? It really just consists of two modi, and the D_{50} is a value that does not mean much in this case.
While we accept that D_{50} of the mixture will be distinct from D_{50} of the sand, D_{50} of the mixture, or any other representative measure of the mixture, will vary in time and between experiments and so will not help in their characterisation. D_{50} of the sand remains constant in the experiments and provides a useful way of grouping them together, and there is also a clear sand-grain size dependence in the enhancement in eq. (6). Also, in L432-439, we do use D_{10} of the mixture to explain the sudden potential drop off of hydraulic conductivity and ripple steepness.

(40) L386-387: 'Thus, the thicker clay layer around the coarser grains likely causes increased enhancement of the threshold of motion, which has also been found in field observations (Harris et al., 2016).'
So like the hiding-exposure effect? Or does this have nothing to do with it?
No, this is opposite to the hiding-exposure effect, which tends to make coarser grains easier to move and finer grains harder to move.

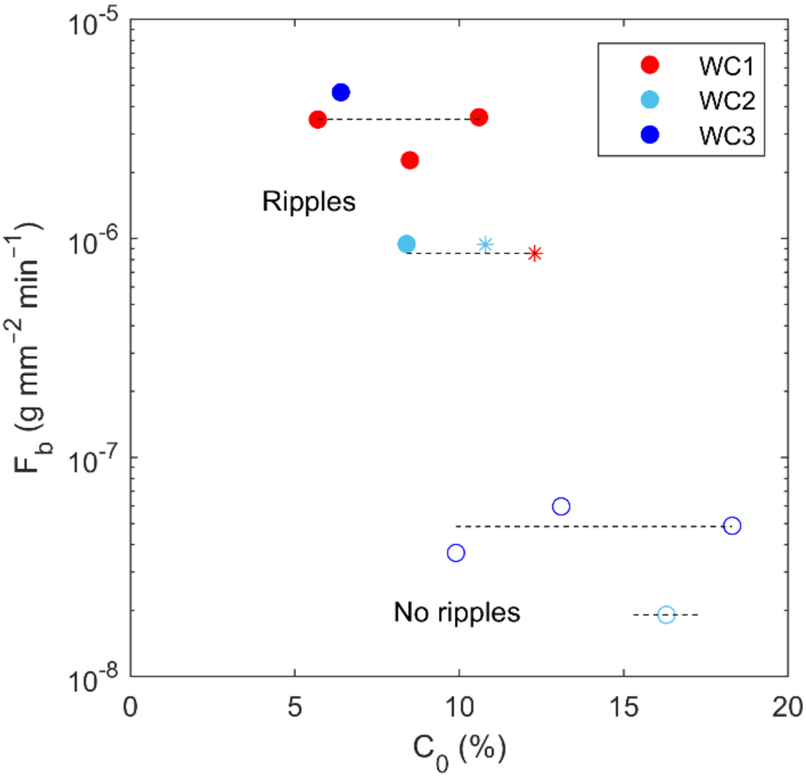
(41) L395: '**4.3 The potential factors controlling the deep cleaning of clay**'
I'm still not entirely sure why this is important?
We hope that our responses and suggested changes to the introduction and conclusions (RC1.1, RC1.8) have helped to make this clearer. However, we recognise that this section requires an opening sentence to set out the significance of winnowing:
[L396: 'Winnowing is an important mechanism in ripple development, because it provides the necessary supply of clean sand in the active layer from which ripples can grow. Significant clay …']

(42) L440: 'This reduction in hydraulic conductivity alone, does not fully explain the behaviour …'
so you did not measure this right? it's purely from the theoretical analysis?
That is correct, we did not measure the hydraulic conductivity.

(43) L446: 'Figure 8. Average clay mass flux …'
I'm not so sure about this figure. I find it pretty hard to interpret, mostly because it's hard to interpret all the colours and type of markers. Would there be a way to make this clearer? For example by shortly describing the experiments, rather than using their abbreviations? All the

colours and abbreviations distract me, causing that I don't really understand what the purpose of this figure is.

The idea of this figure is to try to quantify the clay loss, as it relates to deep cleaning, which is important for providing the supply of clean sand available to build ripples. It is really only an order of magnitude plot, showing the difference between ripples and no ripples, and should be viewed as such. Throughout the manuscript we have tried to use consistent colours for the different cases WC1-WC3, Wu et al. (2018) and Baas et al. (2013) and symbols for large, small and no ripples. We feel this is the most concise way to describe the different conditions and ripple types, since using weak, medium and strong wave will soon get very confusing and affect readability (see RC1.14). However, we accept that this is distracting in Figure 8, so have reduced the legend to the three colours representing WC1–WC3, explained the different symbols without abbreviations in the figure caption instead and labelled the two main groupings: ripples and no ripples. Also, for clarity the caption no longer lists the values of C_0 for WC1. While this does not completely address the Reviewer's concerns, we feel the various colours and symbols should be retained so that the cases can be distinguished from one another.



['Figure 8. Average clay mass flux out of the bed, F_b, against clay content, C_0, for WC1 (red; Wu et al., 2022), WC2 (light blue) and WC3 (dark blue). Here solid circles, asterisks and open circles signify large, small and no ripples.']

(44) L449: '**4.4 Implications for paleowave climate predictions and bedform phase diagrams**'

great section!

Thank you.

(45) L469: 'dominant (W and SW; $\theta_c < 0.2\theta_w$), wave-current …'

what is the S in those subdivisions?

'S' stands for small as it says on the previous line in the text.

(46) L480: 'and therefore form roughness, which is proportional to η^2/λ.'

Form roughness? Where did you do an analysis on this? (sorry if I simply missed it, you all did a lot!)
No analysis has been done, but it is generally accepted that form roughness relates to the ripple dimensions (η^2/λ) and a reference has been added to clarify this.
['…, which is proportional to η^2/λ (Soulsby, 1997). In the specific case …']

(47) L490: 'Figure 9. Orthographic projection of the 3D phase …'
would it be possible to present these figures without all the abbreviations (NM, WO, SC...) in it? I would improve readability.
We accept that these abbreviations make the figures more difficult to read, but the problem is that these are needed to demarcate the regions and writing them out in full will make the figures far busier.

(48) L503-508: '… quasi-symmetric in geometry (ripple steepness, RS = 0.11; ripple symmetry index, RSI = 1.5), with equilibrium heights and wavelengths, $\eta_e \approx 15$ mm, $\lambda_e \approx 148$ mm. Under WC2 conditions, for C_0 = 8.4%, less steep, 2D and quasi-asymmetric (RS = 0.09 and RSI = 1.4) equilibrium ripples developed, with η_e = 13.9 mm, λ_e = 137 mm. However, for C_0 = 10.8%, equilibrium ripple dimensions drastically decreased to η_e = 5.6 mm, λ_e = 125 mm, and the ripples transformed to flatter, 3D and asymmetric geometries (RS = 0.04 and RSI = 1.6).'

Restructured Introduction and Conclusions

1 Introduction
In coastal and estuarine environments, the superimposition of waves and currents, termed combined wave–current flows, is a common occurrence. In these environments, which include continental shelves, the shoreface, and tidal flats, combined wave–current flows frequently form ripples on the seabed (e.g., Osborne and Greenwood, 1993; Li and Amos, 1999; Héquette et al., 2008; Gao, 2019). Ripple dynamics play a crucial role in sediment transport, which in turn affects the predictions of large-scale coastal morphodynamic numerical models (Brakenhoff et al., 2020), the underwater scour around civil engineering structures (Sumer et al., 2001), and the transport of nutrients and contaminants (Vercruysse et al., 2017). Moreover, combined-flow ripples have been found in the geological record, thus providing key information for reconstructing paleoenvironments (e.g., Myrow et al., 2006, Beard et al., 2017). It is therefore crucial to examine how combined-flow hydrodynamics control ripple dimensions and vice versa, particularly in muddy coastal and estuarine environments that are widespread in nature (Healy et al., 2002) and characterised by sediment consisting of a mixture of cohesive clay and non-cohesive sand. A full understanding of this process will ultimately prove significant for coastal and estuarine management and ecological balance maintenance, especially as such areas may face more extreme weather events in the context of climate change and sea level rise (e.g., Mousavi et al., 2011, Vitousek et al., 2017).
To date, however, there has been a scarcity of relevant literature on this topic. Wu et al. (2022) were the first to consider ripple dynamics in sand–clay mixtures under combined flows. Their study showed that small flat ripples formed for initial clay contents, C_0, greater than 10.6% under hydrodynamic conditions that formed large equilibrium ripples in clean sand. Moreover, Wu et al. (2022) demonstrated that clay winnowing efficiency plays a significant role in the development towards clean-sand-like ripples on mixed sand–clay beds. They also highlighted the process of deep cleaning of clay below ripple troughs for $C_0 \leq 10.6\%$, whereas Wu et al. (2018) revealed a more modest deep accumulation of clay beneath rippled beds under wave-alone conditions for $C_0 \leq 7.4\%$. This suggests a dynamic balance between loss and

accumulation of clay during ripple development. However, the key factors governing this dynamic balance, and the resulting ripple size, remain unclear, primarily due to the limited number of flow conditions considered thus far. This knowledge deficiency in mixed sand–clay experiments is reflected in the existing ripple predictors, i.e., bedform phase diagrams and empirical formulae, that are based exclusively on clean-sand experiments.

Phase diagrams group similar bedform types and cross-sectional geometries for known hydrodynamic conditions and sediment properties (e.g., Van den Berg and Van Gelder, 1993). In the last thirty years, a substantial number of experimental studies has made progress in compiling combined-flow ripple phase diagrams (Arnott and Southard, 1990, Kleinhans, 2005, Dumas et al., 2005, Cummings et al., 2009, Perillo et al., 2014). Using a range of combined-flow conditions in an experimental flume, Perillo et al. (2014) expanded the bedform phase diagrams of Arnott and Southard (1990) and Dumas et al. (2005) by subdividing bedform types based on planform geometry. Baas et al.'s (2021) phase diagram, based on field observations of bedforms on an intertidal flat in the Dee Estuary, U.K., captured bedform types generated under a wider range of flow conditions, including those generated under waves and currents at angles to one another. Compared to wave-alone and current-alone ripple predictors, relatively few predictors are available for combined flow ripples. Tanaka and Dang (1996) modified a widely used predictor for wave ripples developed by Wiberg and Harris (1994) by considering the influence of grain size and the relative strength of the wave and current velocities on the ripple size. Khelifa and Ouellet (2000) developed a new formulation to predict ripple dimensions by introducing an effective combined-flow mobility parameter.

The experiments of Wu et al. (2022) were conducted under a single wave-dominated combined-flow condition, but further study considering wider hydrodynamic conditions are required for a more comprehensive understanding of the interaction between ripple development and winnowing-induced clay loss from beds. These insights are critical for the development of morphodynamic models applicable in muddy estuaries and the coastal zone. Therefore, the present study extends Wu et al.'s (2022) experiments and describes a systematically collected set of data from large-scale flume experiments on ripple development. This study also draws in available sand–clay experiments under current-alone and wave-alone conditions (Baas et al., 2013; Wu et al, 2018). The three specific objectives of this study were: (1) to compare ripple development and occurrence on beds with similar initial clay contents under different hydrodynamic conditions; (2) to compare clay winnowing efficiency during ripple development, under different flow conditions; and (3) to propose a new phase diagram for bedforms generated in sand–clay substrates to systematise the experiments, using the knowledge gained from objectives 1 and 2.

Conclusions

The present experiments examined ripple dynamics on cohesive beds under two different combined wave–current conditions with initial clay content, C_0, in the range from 0 to 18.3%. For the lowest C_0, these experiments produced quasi-asymmetric ripples, which are similar to their clean sand counterparts, with heights and wavelengths in the range $13.9 \leq \eta_e \leq 15$ mm and $137 \leq \lambda_e \leq 148$ mm, respectively, with the larger values corresponding to the strongest relative current, WC3. For higher C_0, smaller flatter ripples that were fully asymmetric, with $\eta_e = 5.6$ mm and $\lambda_e = 125$ mm, were produced. Finally, for the highest C_0, no ripples were produced and the bed remained flat.

Combining the present experiments with previous wave-only and wave–current experiments (Wu et al., 2018; 2022) demonstrates the existence of a large to small equilibrium ripple discontinuity at $C_0 = 10.6\%$, with two distinct ripple steepness (RS) groupings, RS ≥ 0.09 and RS ≈ 0.04, which is probably related to a three-orders of magnitude decrease in the hydraulic conductivity. The larger RS grouping shows a decrease from 0.14 to 0.1 with increasing current strength. Ripple wavelength was independent of initial clay content for $C_0 \leq 7.4\%$, but it decreased linearly with initial clay content for $C_0 > 7.4\%$. For $C_0 \leq 7.4\%$, the wavelength was proportional to the current-enhanced orbital diameter, d_{wc}, so that $\lambda_e = \alpha d_{wc}$, where $\alpha = 0.61$. For $C_0 > 7.4\%$, α decreased linearly, which could be important for paleoenvironment reconstruction, when λ_e is measured and d_{wc} is unknown. During the experiments, winnowing removed clay from both the active layer (crest to trough) and deep beneath it, in the case of most large ripples. Winnowing was quantified by the average mass flux of clay out of the bed over the duration of the experiments. Winnowing still occurred from flat beds, but compared to the large ripples the flux was typically two orders of magnitude smaller.

The ripple initiation time increased with initial clay content, and ultimately the bed remained flat when the initial clay content was large enough, demonstrating the enhancement of the threshold of sediment motion with increased initial clay content. When combined with the fine-sand, current-only experimental results of Baas et al. (2013), this allowed the enhancement of the threshold to be quantified for both coarse ($0.45 \leq D_{50} \leq 0.5$ mm) and fine ($D_{50} = 0.143$ mm) mixed sand–clay motion. On the basis of these enhancements, new 3D phase diagrams, involving the non-dimensional wave and current shear stresses and C_0 are proposed to characterise the two ripple size groupings under different flow conditions. This new 3D phase diagram framework should prove important to the morphodynamic modelling community.