

Dear Author,

Many thanks for your revised manuscript and your careful and elaborate response to the reviewers. I would also like to thank the reviewers for their thorough and constructive comments, which were very helpful. Both reviewers agree that the research is robust and convincing and addresses an important knowledge gap in the field. Their comments mainly concerned the structure and clarity of the manuscript rather than the scientific content.

I am pleased to see that you have addressed all of the reviewers comments and that the manuscript improved substantially as a result. The paper is now clear and convincing, and I am therefore happy to see it published after some minor textual adjustments, which I added below.

Best wishes,  
Anne

Response to associate editor.

We would like to sincerely thank for the constructive comments. We have answered them below.

Our comments are highlighted in blue. New text from the manuscript is highlighted in yellow.

L10: Asymmetric tidal dunes with intermediate ( $10-17^\circ$ ) to low-angle slopes ( $< 17^\circ$ ). I think you mean: Asymmetric tidal dunes with intermediate ( $10-17^\circ$ ) to low-angle slopes ( $< 10^\circ$ )?

Thank you for pointing it out. Yes, that is right. It must have been overlooked. It is now changed as "... to low-angle slopes ( $< 10^\circ$ )."

L64 - L90: this paragraph is very long. For readability, I would suggest splitting this paragraph into one that describes flow over angle-of-repose dunes and high angle dunes, and a paragraph describing intermediate and low-angle dunes.

Thank you for the suggestion. We also agree with your suggestion to improve readability of this paragraph. It is now splitted into two paragraphs with the first paragraph describing the flow and turbulence structures over angle-of-repose and high-angle dunes and with the second paragraph describing that over intermediate- and low-angle dunes. It is now written as "

Dune morphology influence the flow and turbulence structures primarily through the lee side geometry (Kwoll et al., 2016). In particular, the steep face, which is the lee side slope downstream of the crest that is steeper than the mean lee slope and its adjacent segments, strongly governs whether flow separation is permanent, intermittent or absent. When flow separation forms, the steep face controls the shape, extent and intensity of the flow separation and the resulting turbulent wake (Fig. 1) (Lefebvre et al., 2016; Lefebvre and Cisneros, 2023). The overall characteristics of the mean flow and turbulence structures over angle-of-repose dunes are already well documented (Nelson et al., 1993; Mclean et al., 1994; Bennett and Best, 1995; Venditti and Bennett, 2000; Best, 2005; Lefebvre et al., 2014). Above angle-of-repose dunes (Fig. 1a), flow accelerates over the stoss side until it reaches the crest and decelerates over the lee side forming a permanent flow separation zone where a reverse flow is observed. A shear layer, which separates the flow recirculation cell from the overlying undisturbed flow, forms and expands. Kelvin-Helmholtz instabilities develop along this separated shear layer where strong velocity gradient become unstable, generating periodic roll-up and shedding of vortices that give rise to a large turbulent wake. This turbulent wake expands upward and advects over the stoss side of the adjacent dune. Below this turbulent wake, a newly formed internal boundary layer develops, with a logarithmic velocity profile. Because of the resulting flow structure, a maximum horizontal velocity located at the crest develops and is expected to generate high bottom shear stress capable of generating bedload and suspended sediment transports contributing to the morphodynamic changes of bottom topography. Over high-angle dunes (Fig. 1b), a flow separation and turbulent wake are found, but their size and intensity are reduced compared to those above angle-of-repose dunes (Lefebvre and Cisneros, 2023; Kwoll et al., 2016; Kwoll et al., 2017).

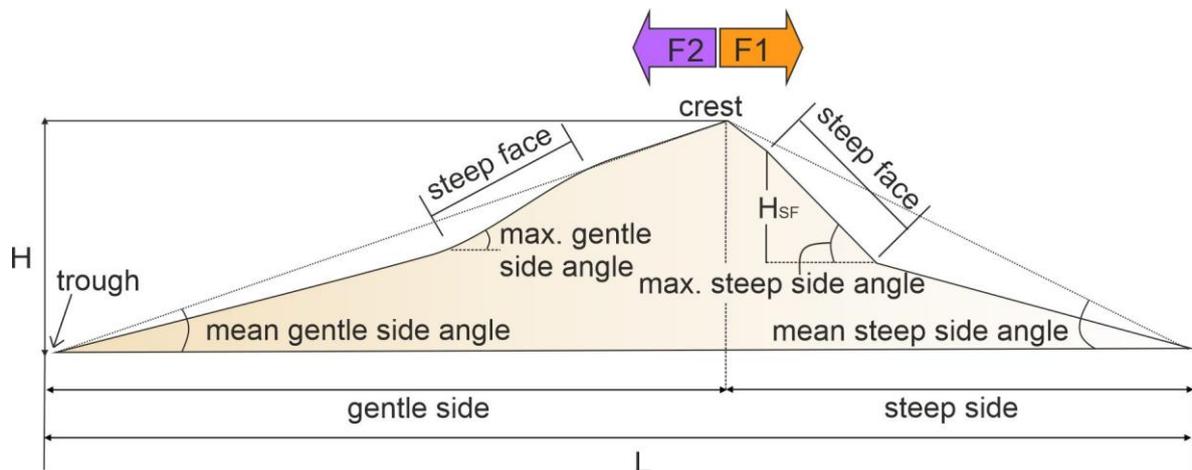
Intermediate-angle dunes (Fig. 1c) rarely have a permanent flow separation but are likely to possess an intermittent flow separation (Kostaschuk and Villard, 1996; Roden, 1998; Best and Kostaschuk, 2002; Sukhodolov et al., 2006; Lefebvre and Cisneros, 2023). Turbulence is weaker than over high-angle dunes, but will usually display a distinct wake above the trough (Lefebvre and Cisneros, 2023). For low-angle dunes (Fig. 1d), several studies report the absence of permanent flow separation and some intermittent flow separation may be present (Kostaschuk and Villard, 1996; Roden, 1998; Carling et al., 2000; Best and Kostaschuk, 2002; Sukhodolov et al., 2006; Kwohl et al., 2016). Turbulence over low-angle dunes is expected to be weaker than that of high-angle dunes and might be even similar to that over a flatbed condition (Kline et al., 1967). While these earlier findings highlight the importance of lee side geometry, the conditions under which flow separation transitions between nonexistent, intermittent and permanent separation and how these transitions reorganise turbulence are still not fully resolved for intermediate to low-angle dunes.”

L106- 101: I appreciate the addition of clear research questions as suggested by the reviewers. I would suggest adding a sentence on how these questions follow from the research gaps identified in the previous paragraphs.

We have added a sentence on how these questions follow from the research gaps identified in the previous paragraphs. The additional sentence was added in Line 110 as “By addressing these questions, we aim to bridge the gaps on the understanding of flow and turbulence dynamics between angle-of-repose to high-angle dunes and intermediate- to low-angle dunes. Furthermore, we want to characterise the influence of bidirectionality on flow over dunes and, hence, provide elements of a realistic representation of flow over natural tidal dunes.”

Figure 4: could you add “Hsf” to this figure? As it is used in later figures (e.g., Figure 9), this would help readers interpret the term by looking at Figure 4 without needing to revisit the text.

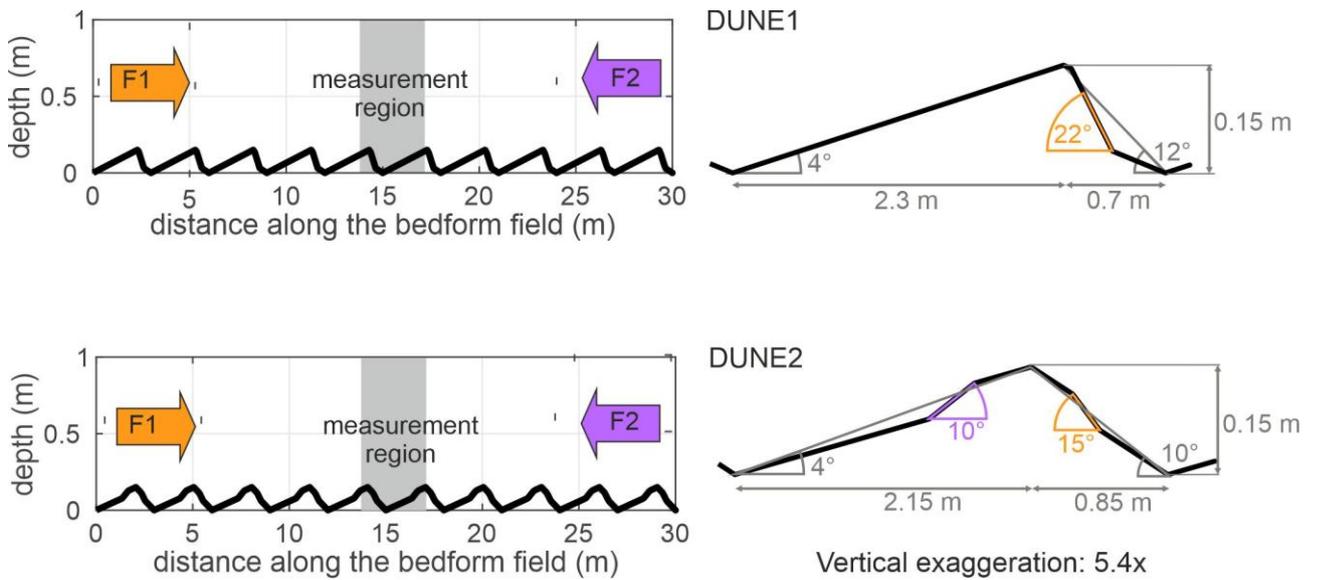
We have added the label “Hsf” in Figure 4 and also added in the Figure text caption the definition of Hsf. The modified Figure 4 is shown below.



**Figure 4. Schematic diagram of tidal dune morphology.  $H$  is the bedform height,  $H_{SF}$  is the steep face height,  $L$  is the bedform length,  $F1$  refers to the flow that is aligned with the dune asymmetry (i.e., the flow is directed from the gentle stoss to the steep lee slope) and  $F2$  refers to the flow that is opposing the dune asymmetry (i.e., the flow is directed from the steep stoss to the gentle lee slope).**

L142: figure 5 is mentioned here (before figure 4). I understand the placement of figure 5 in the next section, but at the same time, the shape of the experimental dunes is already very relevant in this section. Could you move the figure forward?

We have moved forward Figure 5 into Section 2.2. It is now reordered as Figure 4 as shown below



**Figure 4. Laboratory tidal dunes and experimental flume setup.**

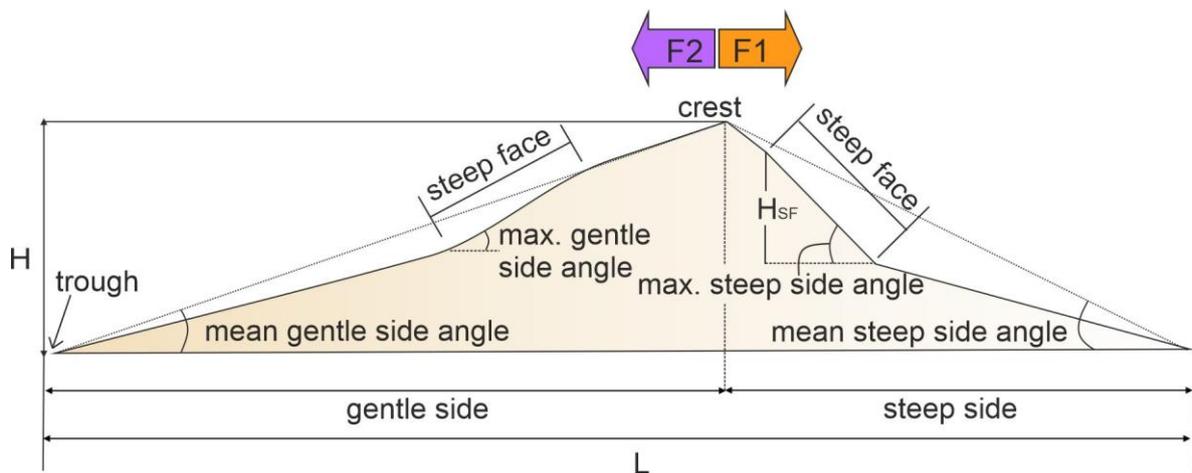
Corresponding changes have been also made as a result of reordering of Figures 4 and 5.

In Line 142, text “Fig.5” was changed to “Fig. 4”. It was rewritten as “The shapes and dimensions of the laboratory dunes are depicted in Fig. 4 and their morphological properties are summarised in Table 1.”

In Line 156, text “Fig. 4” was changed to “Fig.5”. It was rewritten as “The relevant morphological parameters of a tidal dune are depicted in Fig. 5”

In Line 163, text “Fig. 4” was also changed to “Fig. 5”. It was rewritten as “The corresponding mean and maximum angles are also shown in Fig. 5”.

Fig. 4 have become Fig. 5 as shown below



**Figure 5. Schematic diagram of tidal dune morphology.  $H$  is the bedform height,  $H_{SF}$  is the steep face height,  $L$  is the bedform length,  $F1$  refers to the flow that is aligned with the dune asymmetry (i.e., the flow is directed from the gentle stoss to the steep lee slope) and  $F2$  refers to the flow that is opposing the dune asymmetry (i.e., the flow is directed from the steep stoss to the gentle lee slope).**

In Line 185, text “Fig. 5” was changed to “Fig. 4”. It was rewritten as “The two laboratory dunes and the setup inside the recirculating flume are shown in Fig. 4.”

The result section has many paragraphs with just 1 sentence. Please group them (e.g. by describing both dunes of F1 in one paragraph) and remove unnecessary breaks and add linking words/transition words where necessary (“however”, “similarly” etc). For example, the first three paragraphs (first 4 sentences), and L 306 -311, should be one paragraph etc.

We have reorganised the Results section to incorporate the suggestion for better structure.

L271-290 have been reorganised as “

The time-averaged flow fields for both dunes with F1 and F2 flow setups are shown in Fig. 8. For DUNE1\_F1, a strong deceleration zone characterised by slow mean streamwise velocity and downward directed mean vertical velocity is observed over the steep lee side of the dune. A gradually accelerating flow characterised by the increasing mean streamwise velocity and an upward directed mean vertical velocity is seen above the gentle stoss side of the dune. For DUNE2\_F1, the same flow pattern as that of DUNE1\_F1 can be observed although its magnitude is decreased especially the mean streamwise velocity.

When the flow is reversed and is now directed from the steep stoss to the gentle lee slope (F2 flow), the acceleration-deceleration flow pattern reverses its occurrence above the dunes. For DUNE1\_F2, a weaker deceleration zone compared to that of DUNE1\_F1 is observed over the gentle lee side as evident from the gradually decreasing pattern of the mean streamwise velocity. As the stoss side is now steeper than the lee side, a strong upward mean vertical velocity is observed indicating the influence of flow reversal on the mean flow characteristics. The same flow characteristics are observed for DUNE2\_F2 with some subtle features due to the presence of short steep section at the gentle lee side. At the location of the short steep section (ca  $x = 38.0$  m), a stronger deceleration zone characterised by slower mean streamwise velocity and stronger downward mean vertical velocity than the rest of the flow structure above the gentle lee slope of the dune is observed. Overall, these observations confirm the influence of topographic forcing on the time-averaged flow fields. “

L306-311 have been reorganised as “

In order to determine the extents of permanent and intermittent flow separations, the positions of the lines showing the 0% and 50% intermittency factor are calculated (Fig. 10). For DUNE1\_F1, an intermittent flow separation extending the entire steep lee side of the dune is detected. Below this intermittent flow separation, a permanent flow separation is limited only to the steep face of the dune. Above DUNE2\_F1, the intermittent flow separation becomes almost limited to the steep face and the permanent flow separation is significantly limited in extent compared to DUNE1\_F1.

Above DUNE1 and when the flow is directed from the steep stoss to the gentle lee slope (i.e., DUNE1\_F2), no permanent flow separation or intermittent flow separation are detected (Fig. 10c). For DUNE2\_F2, no permanent flow separation is detected over the gentle lee side of the dune. Interestingly, a small intermittent flow separation is detected over the short steep section (ca.  $x = 38 - 38.5$  m), which has a slope  $10^\circ$ .”

L319-330 have been reorganised as “

Over DUNE1 and when the flow is directed from the gentle stoss to the steep lee slope (i.e., DUNE1\_F1), a large and wide horizontal velocity gradient,  $\partial \bar{u} / \partial z$ , is observed to develop past the brink point and dissipate downstream of the steep lee side and over the gentle stoss side of the next dune (Fig. 11a). The thickest portion of the velocity gradient can be found at the steep face (ca.  $x = 36.0$  m). This steep velocity gradient indicates the presence of a shear layer and significant vorticity. For DUNE2\_F1, a thin shear layer, almost attached to the bed and with a diffused-like structure, is observed (Fig. 11b).

Over DUNE1 and when the flow is now directed from the steep stoss to the gentle lee slope (i.e., DUNE1\_F2), a very thin and weak shear layer can be seen to develop very close to the bed (Fig. 11c). For DUNE2\_F2, characteristics of an attached shear layer similar to that of DUNE1\_F2 but with a slightly steeper velocity gradient within the short steep portion ( $10^\circ$  slope) can be detected (ca.  $x = 38 - 38.5$  m) (Fig. 11d).”

L337-353 have been reorganised as “

For DUNE1\_F1, a well-defined turbulent wake can be seen developing just downstream of the brink point above the steep face (Fig. 12a). It propagates downstream of the steep side until it dissipates over the gentle stoss side of the next dune. The strongest portion of the wake with maximum TKE of  $0.0089 \text{ m}^2/\text{s}^2$  is observed immediately downstream of the steep face (ca.  $x = 36.0 - 36.1 \text{ m}$ ). For DUNE2\_F1, the turbulence is further reduced with no defined wake structure and a more diffuse pattern can be detected (Fig. 12b). High TKE is concentrated within the immediate vicinity of the bed and diminishes towards the upper portion of the water column. Although not as strong as that of DUNE1\_F1, high TKE occurs within the trough and the immediate downstream portion of the gentle stoss side.

When the flow is now directed from the steep stoss to the gentle lee slope of the dune (F2 flow), a similar trend of TKE is observed for both dunes, DUNE1\_F2 and DUNE2\_F2 (Figs. 12c & d). High TKE is concentrated in the near-bottom region of the flow with no appreciable wake structure. The TKE in the near-bottom flow region diminishes further when there is no steep face present at all (Fig. 11c). Interestingly for DUNE2\_F2 (Fig. 12d), a slightly elevated TKE can be detected within the short steep portion (ca.  $x = 38 - 38.5 \text{ m}$ ) of the gentle lee slope of the dune but the extent is still limited in the very near-bottom region of the flow.”

L358-383 have been reorganised as “

For the four configurations tested in this study, the spatially-averaged Reynolds stresses,  $\langle \tau_{uw} \rangle$ , generally increase towards the bed with rapid increase starting from the crest level and then decreases from the zero mean bed elevation down to the dune trough (Fig. 13). The spatially-averaged Reynolds stresses are high when the flow is directed from the gentle stoss to the steep lee slope (F1 flow, Figs. 13a & c). For DUNE1\_F1, the maximum  $\langle \tau_{uw} \rangle$  is about 1.6 Pa at around  $z = -0.2 \text{ m}$ . This means that the spatially-averaged turbulent stresses are high just below mid-height of the dune. For DUNE2\_F1, the maximum  $\langle \tau_{uw} \rangle$  is reduced to about 0.6 Pa located near the trough ( $z = -0.4 \text{ m}$ ). This still imply that strong turbulent stresses are still occurring within the lower half of the dune height.

When the flow is directed from the steep stoss to the gentle lee slope (F2 flow), the spatially-averaged Reynolds stress profiles for both dunes have an almost comparable vertical structure (Figs. 13b & d). Flow reversal (i.e., F2 flow) reduces significantly the  $\langle \tau_{uw} \rangle$  magnitudes for both dunes. For DUNE1\_F2, the maximum  $\langle \tau_{uw} \rangle$  is reduced to about 0.2 Pa almost at the zero mean bed elevation. This still implies that strong turbulent stresses are still occurring around the dune mid-height. Similarly, for DUNE2\_F2, the maximum  $\langle \tau_{uw} \rangle$  is also 0.2 Pa just above the zero mean bed elevation.

The spatially-averaged Reynolds stress profile can also provide a direct estimate of the total bottom shear stress as pointed out in previous studies (Nelson et al., 1993; Bennett and Best, 1995; Nikora et al., 2001; Mclean et al., 2008; Kwoil et al., 2016) by performing a regression analysis through the linear segment of the profile and projecting it downwards towards the zero mean bed elevation. The bed shear stress estimation shows a high coefficient of determination for all the linear fits (Fig. 13). For DUNE1\_F1, the linear fit is done above  $z = 0.2 \text{ m}$  and from this linear fit, the estimated total bottom shear stress,  $\tau_o$ , is 0.38 Pa. For DUNE2\_F1, the linear fit is above  $z = 0.34 \text{ m}$  with estimated  $\tau_o$  of 0.06 Pa.

When the flow is reversed and the flow is directed from the steep stoss to the gentle lee slope, a significant reduction in  $\tau_o$  is observed. Both DUNE1\_F2 and DUNE2\_F2 yield a  $\tau_o$  estimate of 0.04 Pa.

These findings show that flow bidirectionality can contribute to significant reduction of turbulence stresses regardless of the dune morphology.”

L390-416 have reorganised as “

The results of the quadrant analysis (Fig. 14) depict the percentages of observations for the four quadrant events. Quadrant 1 (Q1, outward interaction) events are fast water burst that moves upward and quadrant 3 (Q3, wallward, inward interaction) events are those slow water bursts that move downward. Both quadrants 1 and 3 are considered negative contributors to Reynolds stresses meaning that they contribute energy to the mean flow by extracting

energy from turbulence such as shear layer vortices and coherent flow structures. Quadrant 2 (Q2, ejection) events are low-momentum near-bed fluid being thrown-up into the flow and quadrant 4 (Q4, sweep events) are those high-momentum fluid from above sweeping down into the flow. Both quadrants 2 and 4 are considered positive contributors to Reynolds stresses. Conversely, these turbulent events extract energy from the mean flow contributing to turbulence production.

For the four configurations tested in this study, percentages of observations for outward interaction (Q1) and wallward interaction (Q3) events show an increasing trend above the bed. Elevated percentages for these two events occur within  $z = 0.4-0.8$  m above the bed for both dunes under both flow conditions (F1 and F2). On the other hand, percentages of observations for ejection (Q2) and sweep (Q4) events are highest near the bed and mid water column, especially for ejection events, and decrease toward the surface. Among the four quadrant events, the highest percentage of observations are observed mostly for ejection (Q2) events. High sweep (Q4) occurrences mainly take place in the very near-bottom flow region. These observations are common for both dunes under the two flow directions considered.

Some salient features specific to each dune and flow direction are also observed. For DUNE1\_F1, a very intense and high occurrence of ejection (Q2) events are detected at the steep face of the dune and are being brought up further into the water column toward the water surface. These high Q2 occurrences ejected from the steep face are merging to a broader region of high Q2 occurrence located within  $z = 0.3-0.7$  m from the bed. For DUNE2\_F1, the same pattern seems to occur also although it is not as pronounced as the previous dune.

When the flow is directed from the steep stoss to the gentle lee slope (F2 flow), the spatial distribution of high ejection (Q2) occurrences changes for both dunes (i.e., DUNE1\_F2 and DUNE2\_F2). High Q2 occurrences are observed concentrating at the mid-water column around  $z = 0.2-0.4$  m above the bed. Furthermore, high sweep (Q4) occurrences are also observed diminishing at the very near bottom for both dunes when the flow direction changes.”

L774 - 778: this whole section is a strong addition to the paper. However, I am not sure if the paper from De Lange (2021) is the best paper to cite in this way. How I interpreted the paper is that they attribute the variance in roughness to multi-kilometer depth variations and structures such as groynes, and not additional turbulence on the dune scale.

Thank you for pointing it out. We have restated L774-778 so the findings of De Lange et al (2021) could be properly cited as support to our findings. We have rephrased L774-778 as “

For example, de Lange et al. (2021) observed that dune size alone accounted for only one third of the variance in hydraulic roughness in the river Waal. They attributed the remaining variance in roughness to multi-kilometer depth variations and other anthropogenic impacts such as groyne structures. These findings point out the need for roughness parameterisations to account not only for dune size but also other topographic and anthropogenic impacts. For dunes that are found in natural tidal environments, the detailed shape of the dune and other hydrodynamic factors such flow reversals and flow directions should be taken into account in roughness estimations (Herrling et al., 2021).”