

Barchan-barchan repulsion investigated at the grain scale

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Key Points:

- We investigate numerically both the fluid flow and motion of grains for understanding the mechanisms behind barchan-barchan repulsion
- We measure the flow rate of grains and show that there is, indeed, greater erosion on the downstream barchan
- The disturbed flow impacting the downstream barchan induces higher erosion (of its grains) and low accumulation (of upstream grains)

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Abstract

Barchans are dunes of crescent shape found on Earth, Mars and other celestial bodies. Among the different types of barchan-barchan interaction, there is one, known as chasing, in which the dunes remain close but without touching each other. In this paper, we investigate the origins of this barchan-barchan repulsion by carrying out grain-scale numerical computations in which a pair of granular heaps is deformed by the fluid flow into barchan dunes that interact with each other. In our simulations, data such as position, velocity and resultant force are computed for each individual particle at each time step, allowing us to measure details of both the fluid and grains that explain the repulsion. We show the trajectories of grains, time-average resultant forces, and mass balances for each dune, and that the downstream barchan shrinks faster than the upstream one, keeping, thus, a relatively high velocity although in the wake of the upstream barchan. In its turn, this fast shrinkage is caused by the flow disturbance, which induces higher erosion on the downstream barchan and its circumvention by grains leaving the upstream dune. Our results help explaining the mechanisms behind the distribution of barchans in dune fields found on Earth and Mars.

Plain Language Summary

Barchans are crescent-shaped dunes with horns pointing downstream, formed by the action of a roughly unidirectional flow over a limited quantity of sand. These bedforms are usually found in barchan fields on Earth and Mars, where barchans interact with each other. Among the different types of barchan-barchan interaction, there is one in which the dunes remain close but without touching each other, known as chasing. In this paper, we investigate the barchan-barchan chasing by carrying out numerical simulations in which we compute the fluid flow and the dynamics of each individual grain for a pair of barchans interacting with each other. We show the trajectories of grains, time-average resultant forces, and mass balances for each dune, and that the downstream barchan shrinks faster than the upstream one, keeping, thus, a relatively high velocity although in the wake of the upstream barchan. We also show that the faster shrinkage is caused by the flow disturbance, which induces higher erosion (of its grains) and low accumulation (of grains leaving the upstream dune) on the downstream barchan. Our results provide new insights into the distribution of barchans found on Earth, Mars, and other celestial bodies.

1 Introduction

Barchans are dunes of crescent shape formed by the action of a roughly unidirectional flow over a limited quantity of sand, being commonly found in dune fields on Earth, Mars and other celestial bodies (Bagnold, 1941; Herrmann & Sauermann, 2000; Hersen, 2004; Elbelrhiti et al., 2005; Claudin & Andreotti, 2006; E. J. R. Parteli & Herrmann, 2007; Courrech du Pont, 2015). Within those fields, corridors of size-selected barchans are frequently observed, where intricate barchan-barchan interactions have proven essential for size regulation (Hersen et al., 2004; Hersen & Douady, 2005; Kocurek et al., 2010; Génois, Hersen, et al., 2013; Génois, du Pont, et al., 2013; Assis & Franklin, 2020, 2021; Assis et al., 2022). Among the different types of barchan-barchan interaction, there is one, known as chasing (Assis & Franklin, 2020, 2021), in which the dunes remain close but without touching each other. This interaction pattern is, in a certain way, counter-intuitive, since the downstream dune is in the wake of that upstream. However, Assis and Franklin (2021) showed that the downstream dune erodes faster than the upstream one, decreasing in size and increasing its speed, outrunning then the upstream dune.

The short-range interaction of barchans, including barchan-barchan collision (i.e., when they touch each other), was the object of several studies over the last decades, most of them carrying out measurements of eolian barchans (Norris & Norris, 1961; Gay, 1999;

67 Vermeesch, 2011; Elbelrhiti et al., 2008; Hugenholtz & Barchyn, 2012), experiments with
68 aquatic barchans (Endo et al., 2004; Hersen & Douady, 2005), and numerical simulations
69 (A. Lima et al., 2002; E. Parteli & Herrmann, 2003; Schwämmle & Herrmann, 2003; Durán
70 et al., 2005, 2009; Katsuki et al., 2011; Génois, du Pont, et al., 2013; X. Zhou et al., 2019).
71 Although they increased considerably our knowledge on barchan-barchan interactions,
72 those studies have some drawbacks. In the eolian case, time series for barchan-barchan
73 interactions are incomplete, given their long timescale (of the order of decades). In the
74 case of numerical simulations, they consisted of continuous, simplified discrete, or agent-
75 based models, so that they contained simplifications that precluded some interaction pat-
76 terns of taking place. In common, these studies measured or computed the dynamics of
77 barchans at the bedform scale, and, therefore, the dynamics at the grain scale was not
78 known.

79 To the authors' knowledge, the first study to inquire specifically into the dune-dune
80 repulsion mechanism was Bacik et al. (2020), who investigated experimentally the dy-
81 namics of a pair of two-dimensional (2D) dunes in a narrow Couette-type circular chan-
82 nel. In their experiments, they placed two piles of grains inside the channel filled with
83 water, and paddles on the water free surface imposed a turbulent flow that deformed the
84 piles into two-dimensional dunes that interacted with each other over long times. For
85 this 2D case, the authors found that turbulent structures formed in the wake of bedforms
86 induce dune-dune repulsion, preventing dunes from touching each other. Bacik et al. (2020)
87 inferred that the same mechanism could be also valid for two barchans of comparable
88 size, which was later proved true by Assis and Franklin (2020, 2021). As previous stud-
89 ies, Bacik et al. (2020) conducted measurements at the bedform scale.

90 Recently, we inquired into barchan-barchan interactions by conducting experiments
91 in a water tank (Assis & Franklin, 2020, 2021; Assis et al., 2022), with measurements
92 carried out at both the bedform and grain scales. In the experiments, the initial config-
93 urations (aligned or off-centered), initial conditions, grain types (diameter, density and
94 roundness), pile masses, initial distances, and water flow rates were varied, and from the
95 results we found five interaction patterns for both aligned and off-centered configurations:
96 (i) chasing, when dunes do not touch each other; (ii) merging, when collision occurs and
97 the dunes merge; (iii) exchange, when collision occurs and, just afterward, a small barchan
98 is ejected; (iv) fragmentation-chasing, when collision does not occur and the downstream
99 dune splits; and (v) fragmentation-exchange, when fragmentation initiates before col-
100 lision with one of the split parts takes place. Although our findings explained some as-
101 pects of interactions at the grain scale, information such as forces acting on each grain
102 and the dynamics of hidden (totally or partially buried) grains were not accessible. In
103 another front, following Alvarez and Franklin (2020, 2021), we carried out CFD-DEM
104 (computational fluid dynamics - discrete element method) of isolated barchan dunes (N. C. Lima
105 et al., 2022). In the simulations, we used LES (large eddy simulation) for the fluid, with
106 the smaller scales of the order of the grain diameter. With those simulations, we could
107 measure information missing in experiments, such as those listed above (forces on each
108 grain, for instance). To the best of our knowledge, these are the only grain scale simu-
109 lations of barchans carried out to this date. If successfully conducted for barchan-barchan
110 interactions, all the missing details for understanding the different patterns would be avail-
111 able.

112 In this paper, we inquire into the origins of the repulsion mechanism of the chas-
113 ing pattern by carrying out LES-DEM computations. In the simulations, solved at the
114 scale of grains, a pair of granular heaps is deformed by a water flow into barchan dunes
115 that interact with each other, and we compute data such as position, velocity and re-
116 sultant force for each individual particle at each time step. We show the trajectories of
117 grains, time-average resultant forces, and mass balances for each dune, and that the down-
118 stream barchan shrinks faster than the upstream one. Therefore, the downstream barchan
119 keeps a relatively high velocity although in the wake of the upstream one. We also show

120 that, in its turn, the fast shrinkage of the downstream barchan is caused by the flow dis-
 121 turbance, which induces higher erosion on the downstream barchan and its circumven-
 122 tion by grains leaving the upstream dune (so that deposition of grains from the upstream
 123 dune is small). Our results represent a contribution for understanding the mechanisms
 124 behind the distribution of barchans in dune fields on Earth, Mars, and other celestial bod-
 125 ies.

126 2 Materials and Methods

127 We carried out Euler-Lagrange simulations, in which the fluid flow is com-
 128 puted in an Eulerian grid while the solid particles are tracked in a Lagrangian
 129 framework. We used the same model described in N. C. Lima et al. (2022), where
 130 the fluid is solved with LES by using the open-source CFD code OpenFOAM
 131 (<https://openfoam.org>), and the motion of grains is solved with DEM by using
 132 the open-source code LIGGGHTS (Kloss & Goniva, 2010; Berger et al., 2015).
 133 The coupling between CFD and DEM is done by the open-source code CFDEM
 134 (www.cfdem.com, Goniva et al., 2012).

135 The Lagrangian part (DEM) computes the linear and angular momentum equa-
 136 tions for each solid particle (grain), given by Equations 1 and 2, respectively,

$$m_p \frac{d\vec{u}_p}{dt} = \vec{F}_p, \quad (1)$$

$$I_p \frac{d\vec{\omega}_p}{dt} = \vec{T}_c, \quad (2)$$

137 where, for each grain, m_p is the mass, \vec{u}_p is the velocity, I_p is the moment of inertia, $\vec{\omega}_p$
 138 is the angular velocity, \vec{T}_c is the resultant of contact torques between solids, and \vec{F}_p is
 139 the resultant force (weight, contact and fluid forces), given by

$$\vec{F}_p = \vec{F}_{fp} + \vec{F}_c + m_p \vec{g}, \quad (3)$$

140 In Equation 3, \vec{g} is the acceleration of gravity and, for each grain, \vec{F}_c is the resultant of
 141 contact forces between solids and \vec{F}_{fp} is the resultant of fluid forces. For the contact forces
 142 and torques, \vec{F}_c and \vec{T}_c , respectively, we consider a Hertzian model, in which contact forces
 143 are decomposed into normal and tangential components, as shown briefly in the Support-
 144 ing Information (for more details, see N. C. Lima et al., 2022). For the resultant of fluid
 145 forces, \vec{F}_{fp} , we consider Equation 4,

$$\vec{F}_{fp} = \vec{F}_d + \vec{F}_p + \vec{F}_\tau + \vec{F}_{vm}, \quad (4)$$

146 where \vec{F}_d is the fluid drag, \vec{F}_p is the force due to pressure gradient, \vec{F}_τ is the force due
 147 to the deviatoric stress tensor, and \vec{F}_{vm} is the virtual mass force (we neglect the Bas-
 148 set, Saffman, and Magnus forces because they are usually negligible in CFD-DEM sim-
 149 ulations, Z. Y. Zhou et al., 2010). As in previous works, we neglect torques caused di-
 150 rectly by the fluid in the angular momentum (Equation 2), since those due to contacts
 151 are much higher (Tsuji et al., 1992, 1993; Liu et al., 2016).

152 Because the fluid is water, the Eulerian part (LES) computes the incompressible
 153 mass and momentum equations, given by Equations 5 and 6, respectively,

$$\nabla \cdot \vec{u}_f = 0, \quad (5)$$

$$\frac{\partial \rho_f \vec{u}_f}{\partial t} + \nabla \cdot (\rho_f \vec{u}_f \vec{u}_f) = -\nabla P + \nabla \cdot \vec{\tau} + \rho_f \vec{g} - \frac{N}{V} \vec{F}_{fp}, \quad (6)$$

154 where \vec{u}_f is the fluid velocity, ρ_f is the fluid density, P the fluid pressure, $\vec{\tau}$ the devia-
 155 toric stress tensor of the fluid, \vec{g} is the acceleration of gravity, N is the number of grains
 156 in a given cell and V is the cell volume. More details of the used model and numerical
 157 implementation are available in N. C. Lima et al. (2022).

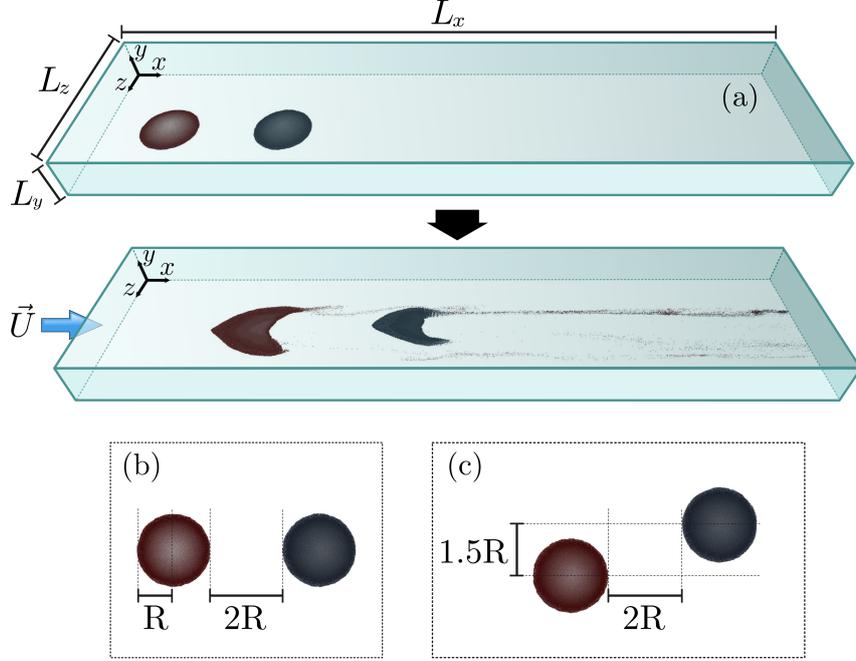


Figure 1. (a) Layout of the numerical setup, showing the channel dimensions, the flow direction, the initial piles, and their evolution at a posterior time. (b) and (c) Relative positions of the initial piles (top view) for the aligned and off-centered cases, respectively. In both cases, the upstream pile was initially placed at 3 cm from the CFD inlet.

158 The CFD domain consists in a 3D channel of size $L_x = 0.4$ m, $L_y = \delta = 0.025$ m
 159 and $L_z = 0.1$ m, where x , y and z are the longitudinal, vertical and spanwise directions,
 160 respectively. We note that, for saving computing time, the vertical dimension $L_y = \delta$ cor-
 161 responds to the channel half height, i.e., the channel centerline (the real channel height
 162 is 2δ). With that, the CFD domain has periodic conditions in the longitudinal and span-
 163 wise directions, no-slip conditions on the bottom wall, and free slip on the top bound-
 164 ary ($y = \delta$). The channel Reynolds number based on the cross-sectional mean velocity
 165 U , $Re = U2\delta\nu^{-1}$, is 14,000, and the Reynolds number based on shear velocity u_* , Re_*
 166 $= u_*\delta\nu^{-1}$, is 400, where ν is the kinematic viscosity of the water. The granular mate-
 167 rial forming each initial heap consisted of 10^5 glass spheres, with sizes randomly distributed
 168 (in a Gaussian distribution) within $0.15 \text{ mm} \leq d \leq 0.25 \text{ mm}$. The boundary conditions
 169 for the grains were solid wall at the bottom boundary, free exit at the outlet, and no grain
 170 influx at the inlet (the number of grains in the domain decreased along time, in the same
 171 way as in our previous experiments, Assis & Franklin, 2020, 2021; Assis et al., 2022). The
 172 current setup is similar to those shown in N. C. Lima et al. (2022), where the DEM and
 173 LES parameters were extensively tested and compared with experiments. Therefore, a
 174 complete description of CFD meshes and convergence, DEM parameters, and tests and

175 validation can be found in N. C. Lima et al. (2022), and more details of the numerical
 176 setup are available in the Supporting Information.

177 Prior to simulations of barchan-barchan interactions, we carried out LES simu-
 178 lations of pure water flow in the periodic channel, until reaching a fully-developed turbu-
 179 lent flow. The results were stored to be used as initial condition for the fluid in the LES-
 180 DEM simulations. The next step was then to completely stop the water flow and let the
 181 grains settle by free fall, forming two conical piles with radius $R \approx 0.0145$ m and height
 182 $h \approx 0.003$ m. The piles were distant $2R$ from each other in the longitudinal direction,
 183 and either 0 (for the aligned case) or $1.5R$ (for the off-centered case) in transverse di-
 184 rection, as shown in Figures 1b and 1c, and the upstream pile was initially placed at 3
 185 cm from the CFD inlet. The final step was, thus, to impose the turbulent flow stored
 186 in a previous step.

187 3 Results

188 3.1 Morphology

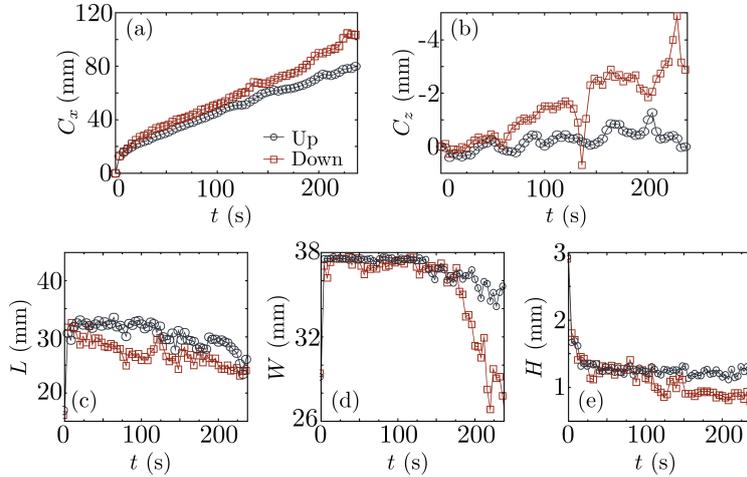


Figure 2. Morphodynamics of interacting barchans in the aligned case. (a) Longitudinal displacement C_x , (b) transverse displacement C_z , (c) length L , (d) width W , and (e) height H of barchans. In the graphics, Up stands for the upstream barchan and $Down$ for the downstream barchan, and we fixed the origins of C_x and C_z of each dune in the centroid of the respective initial pile.

189 As soon as the water flow is imposed in the domain, the conical piles are deformed
 190 into two barchan dunes that interact with each other, as can be observed in the snap-
 191 shots (with some transparency for better observing grain migration) of Figures 4a and
 192 5a for the aligned and off-centered cases, respectively. Snapshots without transparency
 193 (Figure S1) and movies showing the evolution of bedforms are available in Supporting
 194 Information. The behavior for these flow conditions is similar to those observed in our
 195 previous experiments (Assis & Franklin, 2020, 2021), with the downstream barchan shrink-
 196 ing and moving faster than the upstream one (*chasing* pattern), most noticeable in the
 197 aligned case. This is evinced in Figures 2 and 3, showing the time evolution of longitu-
 198 dinal and transverse displacements (C_x and C_z , panels (a) and (b)), length (L , panel (c)),
 199 width (W , panel (d)), and height (H , panel (e)) of dunes for the aligned and off-centered
 200 cases, respectively. In Figures 2a-b and 3a-b, the longitudinal and transverse displace-
 201 ments were computed based on the centroid of each dune, and we fixed the origins of C_x

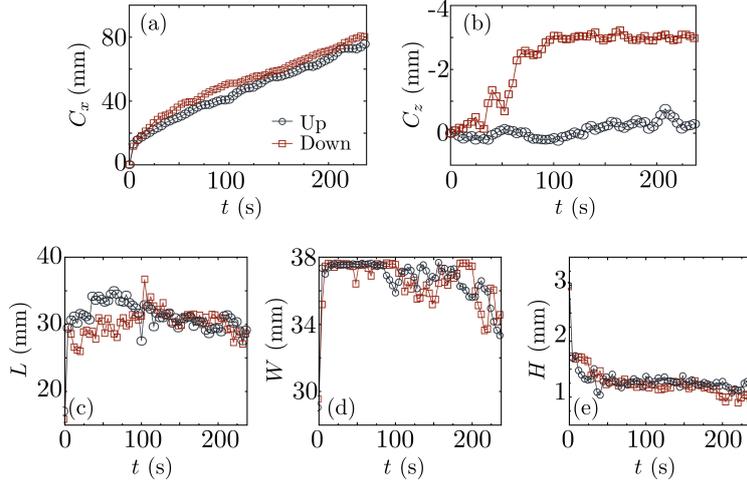


Figure 3. Morphodynamics of interacting barchans in the off-centered case. (a) Longitudinal displacement C_x , (b) transverse displacement C_z , (c) length L , (d) width W , and (e) height H of barchans. In the graphics, *Up* stands for the upstream barchan and *Down* for the downstream barchan, and we fixed the origins of C_x and C_z of each dune in the centroid of the respective initial pile.

202 and C_z in the centroid of the respective initial pile. In the aligned case, we observe a higher
 203 decrease in L , W and H for the downstream dune than for the upstream one, while its
 204 longitudinal displacement C_x increases faster than that of the upstream barchan, indi-
 205 cating an augmentation of the longitudinal separation along time. In the off-centered case,
 206 L , W , H and C_x vary in a similar way for both barchans, indicating that they keep roughly
 207 the same longitudinal separation along time. The variations in the longitudinal separation
 208 are visible in the snapshots shown in Figures 4a and 5a.

209 In both cases, the transverse displacement C_z of the upstream dune remains close
 210 to zero, while that of the downstream dune increases in modulus as a consequence of its
 211 motion in the transverse direction, as also observed in previous experiments (Assis & Franklin,
 212 2020, 2021). The reason for the transverse motion is related to the exchange of grains
 213 between barchans, described in Subsection 3.2. In the aligned case, we note that Fig-
 214 ure 2b shows two large peaks for C_z due to clumps of grains that are ejected from and/or
 215 absorbed by the downstream barchan.

216 3.2 Motion of grains and mass exchange

217 One advantage of discrete simulations in comparison with our previous experiments
 218 (Assis & Franklin, 2020, 2021) is the knowledge of the instantaneous position of all grains,
 219 and the possibility of tracking each one of them along time. With that, typical trajec-
 220 tories and velocities of grains can be computed, as well as the resultant force acting on
 221 each of them. Next, we will focus the discussion on grains exchanged between barchans,
 222 see Figure S2 in Supporting Information for graphics showing velocity fields of grains mov-
 223 ing over barchans.

224 We, thus, inquired into the trajectories of grains that migrate from one barchan
 225 to the other, and identified the points of origin and destination of those grains in order
 226 to compute statistics and the mass flow rate by regions. For example, Figures 4b–d and
 227 5b–d show a portion of the mass exchange between barchans for the aligned and off-centered
 228 cases, respectively. In Figures 4b and 5b, we plot trajectories of grains leaving the up-

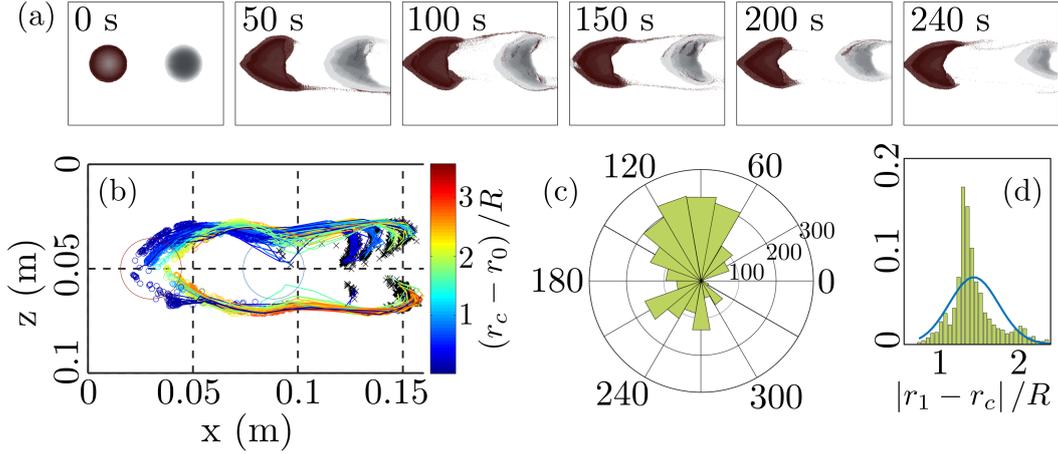


Figure 4. Mass exchange in the aligned case. (a) Snapshots with transparency showing the grains of each dune (top view) at different instants (appearing in maroon for the upstream barchan and gray for the downstream one due to the percentage of transparency adopted). (b) Trajectories of grains leaving the upstream barchan and reaching the downstream one, in which the colorbar indicates the dune longitudinal position when the considered grain started its motion. The large circles indicate the initial piles (top view), the small circles the initial position of the considered grain when it started moving on the upstream barchan, and the x's indicate their respective final positions (when stopping) on the downstream barchan. (c)–(d) Number of grains N from the upstream barchan reaching the downstream one, in polar coordinates (with origin on the centroid of the upstream barchan): (c) frequency of occurrence of N as a function of the angle (the origin is aligned with the flow direction), and (d) probability density function (pdf) of N as a function of the radial position. In the figure, R is the radius of the initial pile, r_1 is the initial radial position of grains leaving the upstream barchan, and r_c and r_0 are, respectively, the instantaneous and initial positions of the centroid of the upstream dune.

229 stream barchan and reaching the downstream one. In the figures, the colorbar indicates
 230 the dune longitudinal position when the considered grain started its motion, where r_c
 231 and r_0 are, respectively, the instantaneous and initial positions of the centroid of the up-
 232 stream dune. Large circles represent the initial piles of radius R , small circles the ini-
 233 tial position of the considered grain when it started moving on the upstream barchan,
 234 and the x's indicate their respective final positions (when stopping) on the downstream
 235 barchan. We note that we have not plotted in Figures 4b and 5b the lines correspond-
 236 ing to all trajectories (in order to avoid saturating the image with trajectory lines). All
 237 the circles and x's are, however, plotted in these figures, and we used a velocity thresh-
 238 old corresponding to $0.1u_*$ for the starting and ending of motions. We first observe (as
 239 well as in Figures 4a and 5a) that most of those grains, after leaving the upstream dune
 240 by its horns (or one of them in the off-centered case), circumvent the downstream dune
 241 until arriving in its lee-side/recirculation region, where they accumulate. The major dif-
 242 ference between aligned and off-centered cases is that in the aligned case grains leaving
 243 both horns of the upstream barchan circumvent the downstream dune, while in the off-
 244 centered case only grains from one horn (the one closer to the downstream dune) circum-
 245 vent the downstream barchan before settling on the lee side.

246 In order to analyze the ensemble of those migrating grains, we computed the number
 247 of grains N that left the upstream barchan and reached the downstream one (over

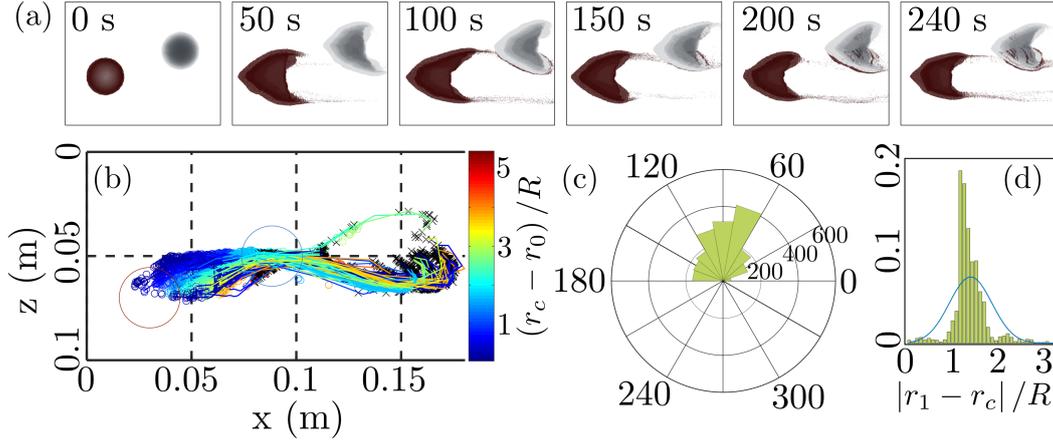


Figure 5. Mass exchange in the off-centered case. (a) Snapshots with transparency showing the grains of each dune (top view) at different instants (appearing in maroon for the upstream barchan and gray for the downstream one due to the percentage of transparency adopted). (b) Trajectories of grains leaving the upstream barchan and reaching the downstream one, in which the colorbar indicates the dune longitudinal position when the considered grain started its motion. The large circles indicate the initial piles (top view), the small circles the initial position of the considered grain when it started moving on the upstream barchan, and the x's indicate their respective final positions (when stopping) on the downstream barchan. (c)–(d) Number of grains N from the upstream barchan reaching the downstream one, in polar coordinates (with origin on the centroid of the upstream barchan): (c) frequency of occurrence of N as a function of the angle (the origin is aligned with the flow direction), and (d) pdf of N as a function of the radial position. In the figure, R is the radius of the initial pile, r_1 is the initial radial position of grains leaving the upstream barchan, and r_c and r_0 are, respectively, the instantaneous and initial positions of the centroid of the upstream dune.

248 240 s), and identified their respective positions of origin in polar coordinates (with co-
 249 ordinates' origin on the centroid of the upstream barchan). With these numbers, we com-
 250 puted the frequency of occurrence of N as a function of the angle, and the probability
 251 density function (pdf) of N as a function of the radial position, which are shown, respec-
 252 tively, in Figures 4c and 4d (for the aligned case) and 5c and 5d (for the off-centered case),
 253 where r_1 is the initial radial position of grains leaving the upstream barchan. We observe
 254 a large asymmetry in Figure 5c, which was already expected since the downstream barchan
 255 receives grains from just one of the horns of the upstream barchan, but there is also an
 256 asymmetry in the aligned case. In this latter case, due to initial fluctuations in the mass
 257 exchange, the downstream dune becomes asymmetrical and migrates in the transverse
 258 direction toward the horn that sheds more grains. This was observed in our previous ex-
 259 periments (Assis & Franklin, 2020, 2021), and can be also observed in Figure 4a. There-
 260 fore, in the off-centered case most grains migrating to the downstream barchan have their
 261 origin in the region close to one of the horns, while in the aligned case the migrating grains
 262 have their origin on the flanks of the upstream barchan, with an asymmetry that increases
 263 over time as the downstream dune moves in the transverse direction. As a consequence,
 264 in the aligned case those grains start moving in upstream regions near the dune flanks,
 265 follow a path along the periphery of the upstream barchan until reaching its horns, and
 266 from there are shed toward the downstream barchan, as can be seen in the movies S1
 267 and S2 available in the Supporting Information and in those of Assis and Franklin (2021).

268 We note that in the aligned case part of the grains on the toe of the downstream barchan
 269 migrate toward the lee side of the upstream dune entrained by its recirculation region.
 270 Trajectories of grains migrating from the downstream to the upstream barchan are avail-
 271 able in Figure S3 of Supporting Information. In addition, we computed the velocity field
 272 of moving grains, for which we present the time-averaged fields in Figure S2 of Support-
 273 ing Information. We can observe larger velocities over the upstream barchan than over
 274 the downstream one, indicating that the larger erosion over the downstream dune is due
 275 to a larger density of moving grains. Indeed, this is the case for the aligned case at all
 276 times, and for the off-centered case at the beginning of interactions, as can be seen in
 277 the graphics of the density of moving grains shown in Figures S4 and S5 of Supporting
 278 Information.

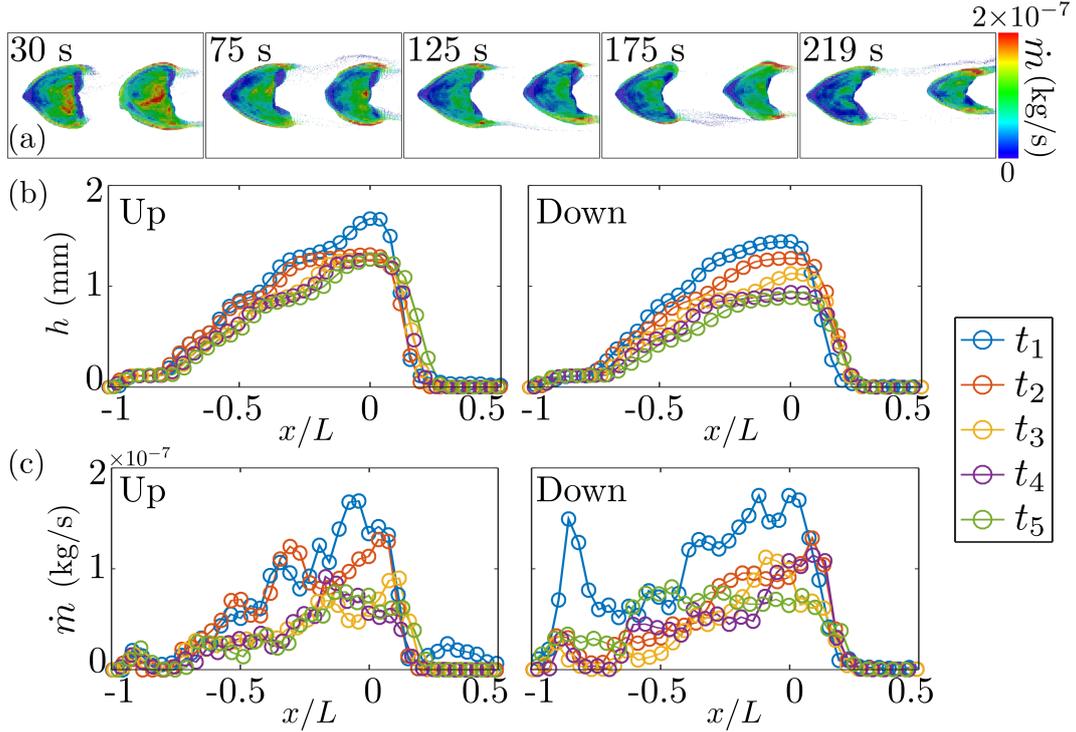


Figure 6. Mass exchange in the aligned case. (a) Snapshots showing the grains of each dune (top view) at different instants, colored in accordance with the average mass flow rate \dot{m} of the region they are in. The averages are computed in intervals t_1 to t_5 ($t_1 = 10\text{--}50$ s, $t_2 = 51\text{--}100$ s, $t_3 = 101\text{--}150$ s, $t_4 = 151\text{--}200$ s, $t_5 = 201\text{--}238$ s). (b) Profiles (height h as a function of the dimensionless longitudinal position x/L with origin at the dune crest) of the centerline for the upstream (Up) and downstream (Down) barchans. (c) Mass flow rate \dot{m} along the barchan by considering its central slice only (≈ 1.2 mm thick), averaged over the t_1 to t_5 intervals, for the upstream (Up) and downstream (Down) barchans.

279 In addition to velocities and trajectories, we computed averages of the mass flow
 280 rate \dot{m} by counting the number of grains moving over the barchans, which we multiplied
 281 by their weight and divided by the corresponding time interval and gravity. The aver-
 282 ages are computed in the following time intervals: $t_1 = 10\text{--}50$ s, $t_2 = 51\text{--}100$ s, $t_3 = 101\text{--}$
 283 150 s, $t_4 = 151\text{--}200$ s, and $t_5 = 201\text{--}238$ s. With that, we end with the space distri-
 284 bution of \dot{m} over both barchans, at different stages of the barchan-barchan interaction. For
 285 example, Figures 6a and 7a show top views of the grains of each dune for different time

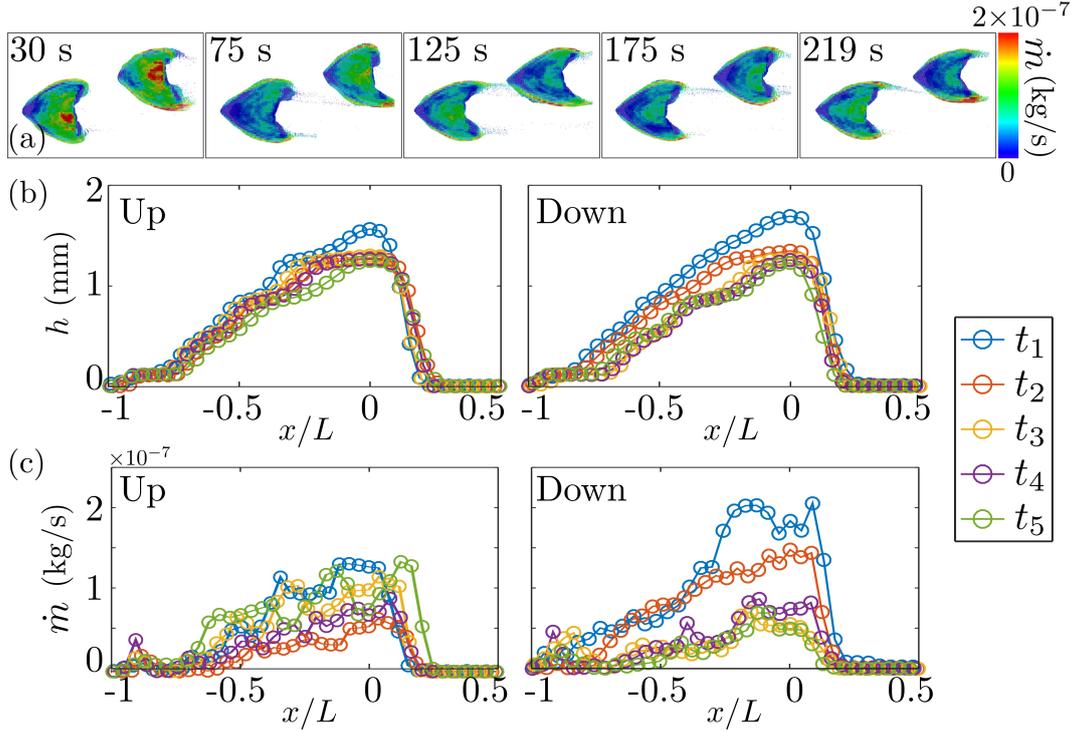


Figure 7. Mass exchange in the off-centered case. (a) Snapshots showing the grains of each dune (top view) at different instants, colored in accordance with the average mass flow rate \dot{m} of the region they are in. The averages are computed in intervals t_1 to t_5 ($t_1 = 10\text{--}50$ s, $t_2 = 51\text{--}100$ s, $t_3 = 101\text{--}150$ s, $t_4 = 151\text{--}200$ s, $t_5 = 201\text{--}238$ s). (b) Profiles (height h as a function of the dimensionless longitudinal position x/L with origin at the dune crest) of the centerline for the upstream (Up) and downstream (Down) barchans. (c) Mass flow rate \dot{m} along the barchan by considering its central slice only (≈ 1.2 mm thick), averaged over the t_1 to t_5 intervals, for the upstream (Up) and downstream (Down) barchans.

286 instants, colored in accordance with the \dot{m} value of the region they are in, for the aligned
 287 and off-centered cases, respectively. We observe that, initially (t_1), \dot{m} is higher over the
 288 downstream than on the upstream barchan, indicating higher erosion on the former, with
 289 a consequent shrinkage and acceleration with respect to the upstream dune. With this
 290 data, it is possible to evaluate how \dot{m} varies longitudinally using, for instance, vertical
 291 slices cutting the dune. One slice of interest is that passing by the barchan centerline,
 292 for which the dune profiles at different intervals are shown in Figures 6b and 7b for the
 293 aligned and off-centered cases, respectively (*Up* referring to the upstream barchan and
 294 *Down* to the downstream one). The values of \dot{m} along the longitudinal direction are shown
 295 in Figures 6c and 7c, for which we computed \dot{m} by considering a vertical slice ≈ 1.2
 296 mm thick. With the exception of the t_1 interval, we observe approximately the same values
 297 of \dot{m} for both barchans, while for t_1 the values for the downstream barchan are higher.
 298 Values in the centerline are directly related with the dune celerity, since grains in this
 299 region spend long times within the barchan, of the order of many turnover times (Zhang
 300 et al., 2014). Therefore, because the downstream dune is the smaller one, similar values
 301 of \dot{m} in the centerline indicate that it moves faster than the upstream dune, explain-
 302 ing, thus, why the chasing pattern takes place (Assis & Franklin, 2020).

303 For the aligned case, we note a high peak close to the toe of the downstream barchan
 304 ($x/L \approx -0.75$) during the t_1 interval, which corresponds to the entrainment of grains from
 305 the downstream barchan toward the lee side of the upstream dune (as shown in Figure
 306 S3 in Supporting Information).

307 3.3 Resultant force on each grain

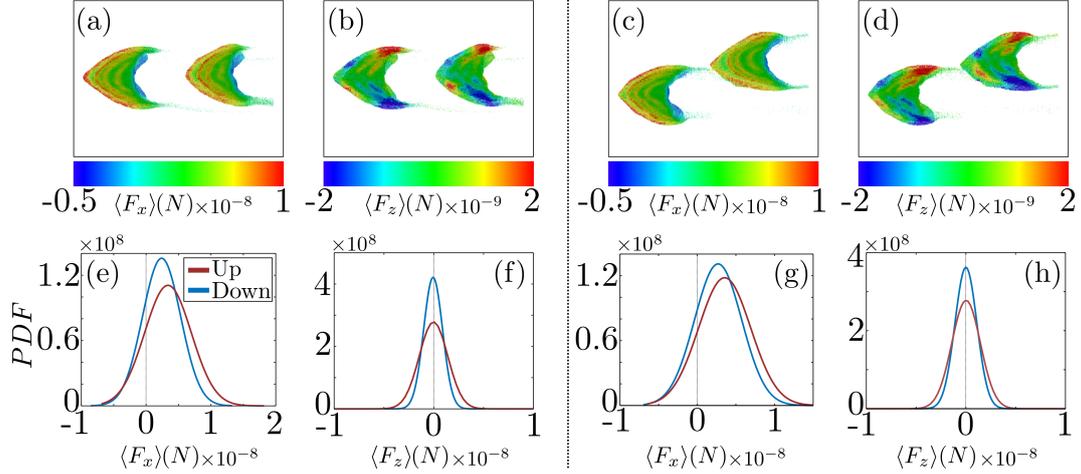


Figure 8. (a)-(d) Top view of dunes colored in accordance with the average resultant force in each region, (a) longitudinal force $\langle F_x \rangle$ for aligned dunes; (b) transverse force $\langle F_z \rangle$ for aligned dunes; (c) $\langle F_x \rangle$ for the off-centered dunes; and (d) $\langle F_z \rangle$ for the off-centered dunes. The averages were computed in the 101-150 s interval, by considering all the grains in each region (including those inside the barchans), and the relative position of morphologies plotted in panels (a)-(d) correspond to $t = 125$ s. The values of forces in N are presented in the colormap below each panel. (e)-(h) Histograms for the of longitudinal $\langle F_x \rangle$ and transverse $\langle F_z \rangle$ components of forces plotted in the maps of panels (a)-(d), respectively. In the legend, Up and Down stand for upstream and downstream barchans, respectively.

308 Because we compute Newton's second law for all particles at each time step, the
 309 value of the resultant force acting on each grain is available at all instants. This is a great
 310 advantage of discrete computations, since this information is inaccessible from experi-
 311 ments and field measurements. Given the large number of particles in our system (ini-
 312 tially 10^5 for each dune), we show next plots of the distributions of the resultant force
 313 acting on grains, averaged over small time intervals (49 s).

314 Figures 8a-d show the distributions of time-averaged resultant forces in different
 315 regions of the dune, where Figure 8a shows the longitudinal force $\langle F_x \rangle$ for aligned dunes,
 316 Figure 8b shows the transverse force $\langle F_z \rangle$ for aligned dunes, Figure 8c shows $\langle F_x \rangle$ for
 317 the off-centered dunes, and Fig. 8d shows $\langle F_z \rangle$ for the off-centered dunes. The averages
 318 were computed in the 101-150 s interval, by considering all grains in each region (includ-
 319 ing those inside the barchans), and the values of forces in N can be read on the colormap
 320 below each panel. Figures 8e-h show histograms for the of longitudinal $\langle F_x \rangle$ and trans-
 321 verse $\langle F_z \rangle$ components of forces shown in the maps of Figures 8a-d, respectively. Fig-
 322 ures of the instantaneous force acting on specific grains along time (Lagrangian track-
 323 ing), measured as they move from the upstream barchan toward the downstream one,
 324 are shown in Figure S6 in Supporting Information. We observe from Figures 8e and 8g
 325 that longitudinal forces on grains of both dunes have distributions that are approximately

326 the same, with the most probable value of downstream dunes having a slightly higher
 327 peak at slightly lower values. This shows that, throughout the interaction, grains of both
 328 dunes experience similar forces and, therefore, accelerations. This is in agreement with
 329 the similar values of \dot{m} found over both dunes (Figures 6 and 7). Concerning the trans-
 330 verse component of forces, Figures 8f and 8h show that the most probable values are al-
 331 most the same for both barchans, with grains on the upstream barchan experiencing a
 332 slightly larger range of values.

333 Interestingly, we observe in Figures 8a and 8c some patterns in the form of curved
 334 stripes. Those stripes have approximately the same curvature and wavelength as those
 335 formed by bidisperse grains over barchans, reported by Alvarez et al. (2021) and Assis
 336 et al. (2022). In these works, the authors attributed the stripes to an instability due to
 337 grain segregation only, but the distributions of forces might have an important role in
 338 their formation as well, although we do not have a physical explanation for the moment.

339 3.4 Fluid flow

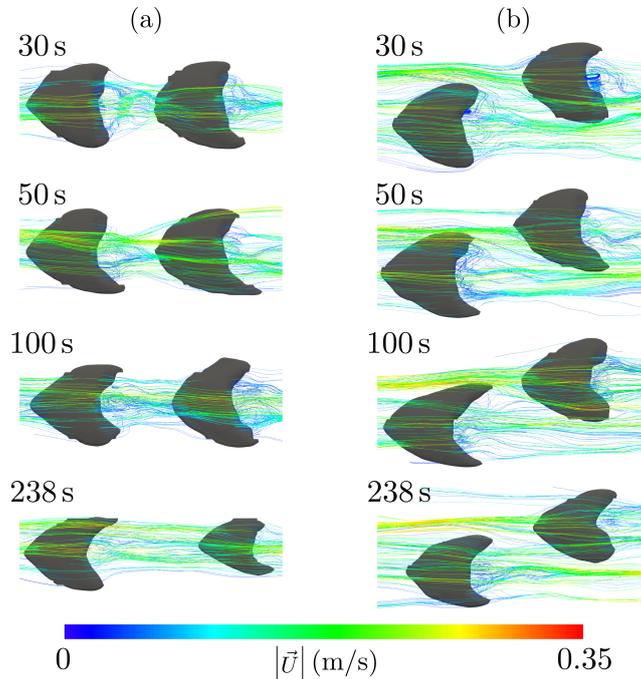


Figure 9. Trajectory lines of the flow over the barchans at different stages of the barchan-barchan interaction for the (a) aligned and (b) off-centered cases. The colors correspond to the magnitude of the velocity of water particles $|\vec{U}|$, the values of which can be read in the colorbar on the bottom of the figure. The corresponding time instants (within the time interval for the considered trajectories) are shown on the top left of each panel.

340 Finally, we inquire into the fluid flow, which is the mechanism of grain entrainment,
 341 and which we computed with a spatial resolution of the order of the grain diameter in
 342 the region close to the dune surface. Because of the large quantity of data, we present
 343 next typical trajectory lines at different stages of the barchan-barchan interaction.

344 Figures 9a and 9b show trajectory lines of the water flow over the barchans at dif-
 345 ferent stages of the barchan-barchan interaction, for the aligned and off-centered cases,
 346 respectively. These lines shed some light on the behavior of barchans and transport of

347 grains described in previous subsections. For example, for the aligned case, we observe
 348 at $t = 30$ s that the recirculation region of the upstream barchan reaches the downstream
 349 dune, explaining why grains from the downstream dune migrate toward the upstream
 350 one (as shown in Figure S3 in Supporting information). At later times, we observe that
 351 the downstream dune shrinks and moves faster than the upstream dune. In addition, ini-
 352 tially small asymmetries in the system make the downstream dune to move in the trans-
 353 verse direction ($t = 238$ s, for instance). For the off-centered case, we observe that lines
 354 from the free-stream flow impact directly half of the downstream dune (in the case shown,
 355 from its toe to the exposed horn on the top of the figure). As a consequence, only the
 356 trajectory lines that pass over one side of the upstream dune impact the downstream one,
 357 which tends to increase or sustain the asymmetry. In addition, in the region between the
 358 horn of the upstream barchan and the toe of the downstream one, the upstream flow ar-
 359 rives disturbed by that horn, with a certain amount of acceleration before impacting the
 360 downstream barchan (channeling effect, as shown by Bristow et al., 2018, 2019, 2020),
 361 contributing for maintaining the granular mobility and celerity of the downstream barchan.
 362 More details on the fluid flow can be seen in Figures S7 to S10 in Supporting Informa-
 363 tion, where profiles of the mean velocities and second-order moments over both the up-
 364 stream and downstream barchans are shown.

365 4 Conclusions

366 We carried out grain-scale numerical simulations to investigate the mechanisms be-
 367 hind the barchan-barchan repulsion, an interaction pattern known as *chasing* (Assis &
 368 Franklin, 2020). We showed that, with the exception of the beginning of interactions,
 369 where the mass flow rate \dot{m} is greater over the downstream dune, \dot{m} is roughly the same
 370 for both barchans, meaning a higher erosion rate on the downstream dune (since it is
 371 smaller due to the higher initial \dot{m}). We showed also that in the aligned case a great part
 372 of the grains leaving the upstream barchan reach the downstream one, but part of grains
 373 of the latter migrate to the upstream dune entrained by its recirculation region. In the
 374 off-centered case, only grains from one of the horns of the upstream dune reach the down-
 375 stream one. The transport of grains is corroborated by the trajectory lines of the fluid,
 376 which, in the aligned case, show that the recirculation region of the upstream dune reaches
 377 the toe of the downstream barchan and, afterward, small asymmetries make more lines
 378 from one side of the upstream dune to reach the downstream one, causing the transverse
 379 motion of the latter. In the off-centered case, only approximately half of the lines pass-
 380 ing over the upstream barchan reach the downstream dune, increasing or sustaining the
 381 off-centered configuration. Interestingly, the velocities of particles is slightly higher over
 382 the upstream dune, indicating that the higher erosion over the downstream barchan is
 383 due to a higher density of moving particles. Finally, we measured the resultant force act-
 384 ing on each grain and showed that the longitudinal component of time-averaged forces
 385 are similar for both dunes. Our results shed light on the reasons for the repulsion char-
 386 acteristic of the chasing pattern, helping to explain why sometimes barchans never touch
 387 each other. In addition, our findings can be used to refine current large-scale models (such
 388 as continuum models), determine the best sites for placing sensors in field studies or car-
 389 rying out remote sensing, and feed convolutional neural networks (CNNs) for analyzing
 390 large datasets.

391 Open Research

392 Data supporting this work were generated by ourselves and are available in
 393 Mendeley Data (N. C. Lima et al., 2024) under the CC-BY-4.0 license. The numeri-
 394 cal scripts used to post-process the numerical outputs are also available in Mendeley
 395 Data (N. C. Lima et al., 2024) under the CC-BY-4.0 license.

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