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Highlights

- Sand dune aerodynamics investigated within a computational study
- Simulation of different experimental setup
- Comparison between computational results and experimental measurements
- Emerging 3D coherent, mushroom-like flow structures in a nominally 2D setup
- Some good practices in dune aerodynamics are recommended

Sand transverse dune aerodynamics: 3D Coherent Flow Structures from a computational study

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Abstract

The engineering interest about dune fields is dictated by the their interaction with a number of human infrastructures in arid environments. Sand dunes dynamics is dictated by wind and its ability to induce sand erosion, transport and deposition. A deep understanding of dune aerodynamics serves then to ground effective strategies for the protection of human infrastructures from sand, the so-called sand mitigation. Because of their simple geometry and their frequent occurrence in desert area, transverse sand dunes are usually adopted in literature as a benchmark to investigate dune aerodynamics by means of both computational or experimental approaches, usually in nominally 2D setups. The present study aims at evaluating 3D flow features in the wake of a idealised transverse dune, if any, under different nominally 2D setup conditions by means of computational simulations and to compare the obtained results with experimental measurements available in literature.

Keywords: dune aerodynamics, Computational Wind Engineering, 3D flow, mushroom-like coherent flow structures

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1 1. Introduction

The engineering interest about dune fields is dictated by their interaction
with a number of human infrastructures in arid environments, such as roads and
railways, pipelines, industrial facilities, farms, buildings (e.g. Alghamdi and Al-Kahtani, 2005). Some of such undesired effects are shown in Figure 1. The



Figure 1: Windblown sand interaction with anthropic activities: megadunes surrounding a road and farmlands in Dunhuang, Gansu Province, PRC. Photo: I.A. Inman, 2007 (a), linear dunes encroaching Nouakchott, capital of Mauritania. Landsat 1565-10032-6, 1974 (b), loose sand covering the Aus to Lüderitz railway line, Namibia. Photo: K. Dierks, 2003 (c)

development, shape and migration of dunes depend fundamentally on availabil-6 ity of mobile sediment, on the incoming wind directionality, and on the flow structures of local disturbed wind ("topographically forced wind" in Geomor-8 phology literature), that is on the wind ability to induce sand erosion, transport q and deposition. In particular, coherent flow structures embedded within fluid 10 flow fields are considered to govern the magnitude, form and scaling of sedi-11 ment transport events (Bauer et al., 2013), and the dune shape in turn. Hence, 12 a wind-focused perspective has been adopted in aeolian dune geomorphology in 13 order to investigate the former to explain the latter. In wind engineering, a deep 14 understanding of dune aerodynamics serves to ground effective strategies for the 15 protection of human infrastructures from sand, the so-called sand mitigation. 16 In areas of constant wind direction and under high sand availability, the trans-17

- ¹⁸ verse dune which has nearly fixed profile in the direction perpendicular to the
- ¹⁹ wind is the prevailing dune type (Livingstone and Warren, 1996). Furthermore,
- ²⁰ ideal sharp-crested transverse dune, i.e. without crest-brink separation (Bauer

et al., 2013), are usually adopted in fundamental aerodynamic studies for their geometric simplicity. Previous studies (e.g. Lancaster, 1995) have revealed that transverse dunes generally have upwind (windward, stoss) slope angles ranging between $2^{\circ} \leq \alpha_u \leq 20^{\circ}$ and downwind (leeward) slope angles ranging between $28^{\circ} \leq \alpha_d \leq 34^{\circ}$, i.e. around the sand friction static angle. For sake of clarity, a simplified 2D scheme of the transverse dune geometry and of the flow around it is given in Figure 2. The aerodynamic behaviour of sand dunes in atmospheric



Figure 2: Ideal sharp crest, transverse dune aerodynamics scheme

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boundary layer belongs to the very general class of bluff bodies and to the gen-28 eral one of hills (for a review, see e.g. Bitsuamlak et al., 2004). The incoming 29 wind flow is first fairly decelerated at the upwind toe, then strongly accelerated 30 along the dune upwind face straight up to crest. The separation of the boundary 31 layer then occurs at the crest itself. The naturally inclined downwind face is 32 surrounded by a reversed flow region, whose extent is one of the key parameters 33 describing the flow. Reattachment of the boundary layer occurs far downstream 34 the dune crest, being x_r the so-called reattachment length. The latter quantity 35 is experienced in sharp-edge bluff body aerodynamics to be highly sensitive to 36 a number of setup parameters (e.g. Reynolds number, surface roughness, in-37 coming turbulence). Much more detailed 2D topological mapping of the wake 38 region for isolated transverse dunes under crest-normal flow can be recovered 39 in literature (e.g. Walker and Nickling, 2002, 2003; Delgado-Fernandez et al., 40 2011). 41

⁴² While the 2D flow structures above have been extensively scrutinized and re-

viewed in Livingstone et al. (2007), very little is known about three-dimensional 43 coherent flow structures in the wake (for an updated review, see Bauer et al., 44 2013). On one hand, in the Geomorphology community, such 3D coherent flow 45 structures past nominally 2D dunes are usually ascribed to: i. oblique incom-46 ing wind, i.e. where a yaw angle $\alpha_C > 45^\circ$ gives rise to helical vortices in the 47 wake (Allen, 1970; Walker and Nickling, 2002), and/or ii. small crest irregu-48 larities, inducing spanwise flow in the wake, spanwise swirling of the reversed 49 flow, and secondary recirculation zones (see the recent CFD simulations and 50 field measurements in Jackson et al., 2011, 2013; Delgado-Fernandez et al., 51 2013, respectively). It is worth pointing out that from an aerodynamic point 52 of view both occurrences involve a 3D setup. On the other hand, to the writers 53 best knowledge, 3D coherent structures in the wake of genuine 2D setups (i.e. 54 ideal transverse dune under normal wind) remain elusive and scarcely studied 55 in literature, if any. Difficulties in both wind tunnel facilities and measurement 56 techniques, and in 3D computational simulations are conjectured by the writers 57 and other authors (e.g. Walker and Nickling, 2003) to be the cause of such lack 58 of knowledge. 59

On one side, Wind Tunnel (WT) tests in the aeolian field adopt scaled dune models spanning across the whole test section width (i.e. S = w), and with rather low values of the dune aspect ratio (span/chord ratio S/L), e.g. S/L = 1.28 in Walker (2000) and Walker and Nickling (2003), $1.92 \le S/L \le 10.32$ in Dong et al. (2007); Qian et al. (2009), S/L = 5.4 in Liu et al. (2011)). Such values of the aspect ratios:

• are by far lower than the ones adopted in other bluff body aerodynamics problems characterised by separation, reversed flow and reattachment, especially when 3D flow features are expected (see for instance Bruno et al., 2014);

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are suspected to significantly affect the 3D features of the flow in the wake,
 because of the tips effects due to interaction between the boundary layers
 surrounding the dune and the WT side walls. For instance, in Walker and

Nickling (2003, Figure 5a, page 1119) the normalised shear stress profile
along the WT midline (i.e. .46 m far from the WT side wall) does not
reach nil value in the conjectured reattachment area nor elsewhere in the
dune wake.

⁷⁷ More generally, difficulties in WT studies are recognised in the proper scaling of
⁷⁸ different setup lengths, i.e. the ones related to the dune geometry, the surface
⁷⁹ roughness, the turbulent length scale of the turbulent incoming flow (Walker
⁸⁰ and Nickling, 2003).

On the other side, the fundamental computational (CFD) studies on the flow 81 field over the transverse dune (e.g. Parsons et al., 2004a,b; Schatz and Herrmann, 82 2006; Araújo et al., 2013) usually consider simplified 2D condition (see Living-83 stone et al., 2007, for a review). Only recently, Liu et al. (2011) have compared 84 the simulated flow around a transverse dune obtained in 2D and "2.5D" condi-85 tions between them and with WT measurements. The "2.5D" heading indicates 86 that despite the computational domain is 3D, its height and width are equal to 87 half the WT working section dimensions where reference experimental test are 88 performed. In other terms, both left-to-right and bottom-to-top symmetry of 89 the flow are conjectured to reduce the domain size and related computational 90 costs. Under such an assumption, interesting preliminary results are obtained. 91 In particular, 3D flow features of the flow in the near wake of the 2D dune are 92 qualitatively observed (Liu et al., 2011, Figure 8a, page 884). According to the 93 writers, some questions immediately follow. Which aerodynamic phenomena 94 underly and/or trigger the 3D flow features observed in the cited experiments 95 and computational simulations? In particular, do the WT side wall effects play 96 any role in generating such 3D structures? That is, would similar structures 97 having corresponding characteristic lengths obtain if the same dune had, in the 98 limit, an infinitely long span (i.e., an infinite aspect ratio)? 99

The present study aims at shedding some light on such issues. The sensitivity of the 3D features of the wake to the setup geometrical scaling is studied. In particular, the domain size and the related inlet and side boundary conditions

are the retained parameters of the study. In such a perspective, the present 103 study takes the baton relay from the stimulating study of (Liu et al., 2011) 104 conceived in the Geomorphology community, and develops it according to the 105 knowledge background of Bluff Body Aerodynamics. The adopted computa-106 tional approach is expected to efficiently complement the wind tunnel studies in 107 exploring a huge number of setup conditions, where a single parameter is varied 108 at the time and border, or even unphysical, conditions can be scrutinized. The 109 experimental setup of Liu et al. (2011) is adopted as the reference one. The 110 obtained computational results are compared with the experimental ones avail-111 able in literature. Finally, a deeper insight in the 3D emerging coherent flow 112 structures in the wake is provided. 113

¹¹⁴ 2. Wind flow modelling and computational approach

The incompressible, turbulent, separated, unsteady flow around the dune profile is modeled by the classical Time-dependent Reynolds Averaged Navier-Stokes (T-RANS) equations, which, in Cartesian coordinates, read:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

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$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j} \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \Big[\nu \Big(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \Big) \Big] - \frac{\partial}{\partial x_j} (\overline{u'_i u'_j}), \tag{2}$$

where $\overline{u_i}$ is the averaged velocity, u' the velocity fluctuating component, \overline{p} the averaged pressure, ρ the air density and ν the air kinematic viscosity. The SST $k - \omega$ turbulence model first proposed by Menter (1994) and further modified in Menter et al. (2003) is used to close the T-RANS equations:

$$\frac{\partial k}{\partial t} + \overline{u}_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\sigma_k \nu_t + \nu \right) \frac{\partial k}{\partial x_i} \right] + \tilde{P}_k - \beta^* k \omega \tag{3}$$

$$\frac{\partial\omega}{\partial t} + \overline{u}_i \frac{\partial\omega}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\sigma_\omega \nu_t + \nu \right) \frac{\partial\omega}{\partial x_i} \right] + \alpha \frac{\omega}{k} P_k - \beta \omega^2 + (1 - F_1) \frac{2\sigma_\omega}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial\omega}{\partial x_i}, \tag{4}$$

where k is the turbulent kinetic energy, ω its specific dissipation rate and ν_t the so-called turbulent kinematic viscosity. The kinetic energy production term \tilde{P}_k is modeled by introducing a production limiter to prevent the build-up of turbulence in stagnation regions:

$$\tilde{P}_k = \min(P_k, 10\beta^*k\omega) \quad \text{being} \quad P_k \approx 2\nu_t D_{ij} \frac{\partial \overline{u}_i}{\partial x_i}$$

For sake of conciseness, the definition of the blending function F_1 and the values of the model constants are omitted herein. Interested readers can find them in Menter et al. (2003). The SST $k - \omega$ turbulence model is selected for the current application because of its proven accuracy in bluff body aerodynamics in general (Menter et al., 2003) and in dune aerodynamics in particular (Liu et al., 2011).

At the ground and dune surfaces the so-called sand-grain roughness wall func-134 tions are selected for the current application because of their wide use in environ-135 mental CWE in general (e.g. Blocken et al., 2007a) and the proofs of adequacy 136 obtained in previous 3D simulations of sand dune aerodynamics by Liu et al. 137 (2011); Jackson et al. (2011, 2013). In particular, standard wall functions (Laun-138 der and Spalding, 1974) with roughness modification (Cebeci and Bradshaw, 139 1977) are applied. The equivalent sand grain roughness height is determined 140 as $K_s = 9.793 z_0/C_s$, where $C_s = 0.5$ is the roughness constant and z_0 is the 141 aerodynamic roughness. All the application setups involve $z_0 = 0.1$ mm and 142 shear velocity $u^* = 0.512$ m/s, both estimated in wind tunnel tests. It follows 143 $K_s = 1.96$ mm, and non-dimensional roughness height $K_s^+ = K_s u^* / \nu \approx 70$, in 144 the so-called transitional regime Blocken et al. (2007a). 145

The adopted computational domains and the conditions imposed at their boundaries are the object of a parametrical study. They are detailed in the next Section.

The OpenFoam©Finite Volume open source code is used in the following to numerically evaluate the flow-field. The cell-centre values of the variables are interpolated at face locations using the second-order Central Difference Scheme for the diffusive terms. The convection terms are discretised by means of the so-called Limited Linear scheme, a 2nd order accurate bounded Total Variational Diminishing (TVD) scheme resulting from the application of the Sweby

limiter (Sweby, 1984) to the central differencing in order to enforce a mono-155 tonicity criterion. The pressure-velocity coupling is achieved by means of the 156 pressure-implicit PISO algorithm, using a predictor-corrector approach for the 157 time discretisation of the momentum equation, whilst enforcing the continuity 158 equation. The space discretization is accomplished by a predominantly struc-159 tured grid of hexahedral control volumes. Unstructured patterns locally occur 160 at the intersection between the surface-fitted grid boundary layer and the carte-161 sian grid in the higher part of the domain. The denser grid is located close 162 to the wind tunnel floor and side walls, and to the dune surface. The grid in 163 the whole domain and its detail around the dune surface are shown in Figure 164 3(a) and (b), respectively. The height of the control volume adjacent to the



Figure 3: Computational grid in the whole domain (a) and close to the dune (b)

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wall $n_w = 2n_p$ is driven by the sand-grain roughness wall function requirements 166 (Blocken et al., 2007b). In particular, n_w should i. provide a sufficiently high 167 mesh resolution in the normal direction n to the surface, ii. comply with the 168 standard requirement on dimensionless wall unit $30 < n^+ = n_p u^* / \nu < 100$, and 169 iii. be longer than twice the sand grain roughness height, $K_s = 1.96$ mm in 170 the considered setup. The third requirement obeys to the need of avoiding grid 171 cells with centre points within the physical roughness height. Both the second 172 and third requirements limit the grid density at wall. In the following, n_w is 173

set equal to $n_w = 0.2h = 5$ mm in order to satisfy at best the above criteria. 174 The n^+ value along the flat surface far upwind and downwind from the dune 175 is $n^+ = 80$, while its values along the dune surface vary from $n^+ = 70$ and 176 $n^+ = 35$ at the dune upwind and downwind toes, respectively, to $n^+ = 110$ at 177 the dune crest. The ratio $n_p/K_S = 1.28$ is larger but close to unit: hence no 178 significant further grid refinement at wall can be done within the adopted wall 179 treatment. The advancement in time is accomplished by the implicit two-step 180 second order Backward Differentiation Formulae (BDF) method. The adopted 181 time step is equal to $\Delta t = 0.00025$ [s], i.e. $\Delta t u_{ref}/h = 0.1$ dimensionless time 182 unit. 183

¹⁸⁴ 3. Application setup

Three setups are adopted and the resulting flow are compared. All of them 185 adopt a sharp-crested transverse dune, and generally refer to the experimen-186 tal setup described by Liu et al. (2011). Besides such main reference, critical 187 comparison is also made to other measurements provided in Dong et al. (2007); 188 Qian et al. (2009); Walker and Nickling (2003), the former two being obtained 189 for several incoming speeds, the latter in slightly different experimental condi-190 tions. Table 1 summarizes the main features of the cited experimental setups, 191 where z_0 is the dune and floor aerodynamic roughness and u_{ref} is the incom-192 ing reference speed. It follows that the reference Reynolds number is equal to 193 $Re_h = u_{ref}h/\nu = 1.7e + 4.$ 194

The setups differ in both the size of the analytical domain in space and in the corresponding applied boundary conditions (b.c.). The domain size and the kind of b.c. adopted in the setups are depicted in Figure 4, while the profiles of the incoming wind (mean velocity u_x , turbulence intensity *It* and length scale *Lt*) are plotted in Figure 5. The setups are briefly commented in the following:

s1 only 1/4 of the wind tunnel working section volume is retained. Symmetry
 conditions are imposed on the vertical plane because of the conjectured
 symmetry of the flow. Free stream b.c.s are set on the upper horizontal

Table	1:	Experimental	setups
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Authors	h	α_u	α_d	L/h	S/L	u_{ref}	z_0
	[mm]	[deg]	[deg]	[-]	[-]	[m/s]	[mm]
Liu et al. (2011)						10	
Dong et al. (2007)	25	10	30	7.4	5.40	8,10,12,14	0.1
Qian et al. (2009)						8,10,12,14	
Walker and Nickling (2003)	80	8	30	9.0	1.28	$8,\!13,\!18$	n.a.

plane to disregard the influence of the WT upper wall. The incoming 203 mean wind velocity and turbulence intensity profiles are fitted on the 204 WT measurements (Liu et al., 2011, estimated shear velocity $u^* = 0.512$ 205 m/s), while turbulence length scale is conjectured constant and equal to 206 Lt = 5 mm because of the lack of experimental data (Figure 5). The 207 spatial grid involves about 4.e + 5 control volumes. This setup is often 208 retained in CFD practice to reduce the number of grid volumes and related 209 computational costs when the WT conditions are to be emulated (e.g. in 210 Liu et al., 2011). The setup is intended to discuss the accuracy of such an 211 approach; 212

s2 the setup exactly reproduces the size of the WT working section in Dong 213 et al. (2007); Qian et al. (2009); Liu et al. (2011). No-slip b.c.s are set 214 at the four alongwind boundary planes to model the WT walls. A com-215 plementary simulation (s2-a, Figure 4) is preliminary performed along an 216 empty channel to replicate the WT approaching section described in Liu 217 et al. (2011). Periodic conditions at the inlet and outlet of s2-a are set to 218 obtain a fully self-developed, horizontally homogeneous incoming bound-219 ary layer flow (Blocken et al., 2007b). The resulting u_x , It and Lt profiles 220 are then imposed at the inlet of the main domain (Figure 5). The spatial 221 grid in s2-b involves about 1.5e + 6 control volumes. The setup aims 222

at removing the ansatz introduced in s1 in order to suggest best practice guidelines in CFD simulations of WT tests;

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s3 The side walls of the WT working section are replaced by spanwise periodic 225 conditions. Two domain spanwise lengths are considered: $w_{3a} = w_2$ is set 226 in setup s3a, and $w_{3a} = 4w_2$ in setup s3b. The height of the domain 227 is set equal to 12h, i.e. larger than the range suggested in Franke et al. 228 (2007) $4h < h_{WT} < 10h$ for external flows in Wind Engineering. The 229 spatial grid in s3b involves about 2.7e + 6 control volumes. The setup 230 aims at comparing the results to the ones obtained in the s2 setup and 231 at evaluating 3D flow features, if any, under 2D, "external" incoming 232 flow conditions. The profiles of the incoming turbulent length scale and 233 turbulence intensity are set in accordance to Richards and Norris (2011) 234 to replicate an external flow. 235



Figure 4: Scheme of the adopted setup conditions (not in scale) including b.c. (wind from left to right)

In all setups, Neumann conditions ("outflow" in Figure 4) involving the velocity
field and the pressure (null normal component of the stress tensor) as well as k
and ω are imposed at the outlet boundary. No-slip conditions are imposed at the
floor surface and at the WT walls, if any. Uniform initial conditions are imposed



Figure 5: Vertical profiles of the inlet boundary conditions

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at the beginning of the time-dependent simulations. The simulated time for each 240 setup is equal to about $Tu_{ref}/h = 4000$ dimensionless time units, long enough 241 to guarantee the convergence of the first and second statistical moments in time 242 for all the flow variable, following the convergence check proposed by Bruno 243 et al. (2010). The simulations have been performed thanks to the Optiflow 244 pc cluster (32 nodes with 4 cores each, 4 Gb RAM per node, Intel Nehalem 245 2.8 GHz clock, 1.4 Tflops). An overall cpu time of about 25 hours on 63 cores 246 results for the complete parametrical study. 247

248 4. Results

249 4.1. Setup effects on the overall flow regime

In this section, the time dependent behavior of the simulated flow in the three setups is discussed with reference to both bulk and local quantities. The former is defined as the aerodynamic coefficient $C_D(t)$ of drag force per spanwise unit length that results from integration of the stress field on the dune downwind face, Figure 6(a). The Power Spectral Density of the drag coefficient is plotted versus the dimensionless frequency $f^* = fh/u_{ref}$ in Figure 6(b).



The PSDs in both s1 and s2 setups clearly show a well defined peak at about

Figure 6: Time dependent flow: PSD of the drag coefficient

 $f^* \approx 0.05 = St$, that conversely disappears in s3a and s3b setups (both notated 257 "s3" in the following, if not specified otherwise, for the sake of simplicity). At 258 such Strouhal number St the power density in setup s1 is one order of magni-259 tude higher than the one in s2, that is in turn by far greater than in s3. The 260 high frequency fluctuations $(f^* > 3e - 1)$ are due to spurious numerical oscil-261 lations of the solution. In summary, the drag force resulting from s3 is almost 262 steady $(std(C_D) \approx 5.6e - 7)$, while very weak to moderate time fluctuations in 263 the remaining setups ($std(C_D) \approx 7.3e - 5$ and $std(C_D) \approx 1.e - 3$ in s2 and 264 s1, respectively) suggest a localized unsteadiness of the flow. To prove such



Figure 7: Time dependent flow: spanwise position of the time dependent phenomena

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 $_{266}$ conjecture, the time history of the longitudinal component of the velocity u_x

is plotted for the three setups and at two probes in the wake (Figure 7). In 267 s1 and s2, the closer the probe to the WT side wall, the larger the velocity 268 fluctuations, while in s3 the flow in the wake is almost steady everywhere. An 269 instantaneous field of the z-vorticity on the plane z/h = 1 for s2 is provided in 270 the same Figure to shed some light on the underlying fluid flow phenomenon. 271 In fact, the interaction between the separated boundary layer at the dune crest 272 and the attached one along the WT sidewall induces a 3D flapping along the 273 latter. 274

As previously introduced, the reattachment length x_r is one of the most relevant 275 quantities in transverse dune aerodynamics. In the adopted computational ap-276 proach, the reattachment point is evaluated as the one in which the longitudinal 277 component τ_x of the shear stress change sign downwind the dune downwind toe. 278 Heaving in ming the weak variability in time of the overall flow, the time aver-279 aged reattachment point $(t - avg(x_r))$ is evaluated, while its spanwise trend is 280 described by the reattachment line, i.e. $t - avg(x_r(y))$. The latter ones obtained 281 in the three setups are plotted in Figure 8. 282

- ²⁸³ The following remarks follow:
- very significant WT wall effects take place close to the dune tips in both s1 and s2 setups. In particular:
- in s1 such effects propagate along all the dune span, so that a mean ingful estimate of the reattachment length can be obtained by span wise averaging nor by adopting a point wise value, e.g. at the mid
 plane;
- in s2 the spanwise variability due to the WT side wall is limited to a distance from the wall of about $d \approx 1.5L$, clearly related to the unsteady plumes pointed out in Figure 7. A central segment with nearly constant x_r can be recognized: at the vertical mid plan $(y = 0) x_r \approx 6.35h$, pretty close to the value measured by Dong et al. (2007) $(x_r \approx 6h)$ in the same setup conditions;
- 296

• unexpectedly, a quasi-periodic, "festoon-shaped" spanwise reattachment



Figure 8: Spanwise dependent flow: variation of the reattachment line

297	line emerges from both simulations s3a and s3b. Such a trend allows to
298	estimate some spanwise statistics.
299	- The first two statistical moments of the reattachment length, i.e. its
300	mean value $y - avg(t - avg(x_r))$ and standard deviation $y - std(t - avg(x_r))$
301	$avg(x_r))$, are:
302	s3a $y - avg(t - avg(x_r)) = 5.04h, y - std(t - avg(x_r)) = 0.82h;$
303	s3b $y - avg(t - avg(x_r)) = 4.64h, \ y - std(t - avg(x_r)) = 0.88h.$
304	It is worth pointing out that the in both simulations the mean value
305	$y - avg(t - avg(x_r))$ is significantly lower than the one obtained at
306	the mid-plan in s2.
307	- Let us define a characteristic spanwise length (or wavelength) λ of
308	the reattachment line (see closeup view in Figure 8). Its spanwise
309	statistics are:

310	$s3a y - avg(t - avg(\lambda)) = 5.61h, y - std(t - avg(\lambda)) = 0.43h;$
311	s3b $y - avg(t - avg(\lambda)) = 5.75h, y - std(t - avg(\lambda)) = 0.36h.$
312	The value of the standard deviation $y - std(t - avg(\lambda))$ is small in
313	both simulations, that is the festoon shape is quite stable spanwise.
314 -	Finally it is worth pointing out that the spanwise dimension w_{3a} in
315	setup s3a accommodates 7 wavelengths (including the two halves at
316	the domain side), while the one $w_{s3b} = 4w_{s3a}$ in setup s3b accommo-
317	dates 27 waves plus an oscillation at midspan, i.e. at the far section
318	from the lateral periodic b.c.s.

In summary, the findings obtained in the Section prove significant effects of the WT side walls (s1 and s2) on the overall flow regime, and suggest that they inhibit the triggering of an almost periodic spanwise variability of the flow in the wake, as observed in external flow conditions (s3).

323 4.2. Comparison between WT measurements and CWE results

In this Section, comparisons between time-averaged WT measurements at 324 the dune midspan (y/L = 0) and the present computational results obtained in 325 the different setups are provided. Bearing in mind the quasi-periodic spanwise 326 reattachment line in s3 (Fig. 8), also spanwise statistics are evaluated for such 327 setup. The z-wise profiles of the longitudinal component of the velocity u_x have 328 been measured in WT tests by Liu et al. (2011) using PIV at different positions 329 in the the vertical mid plan (y = 0) of the WT working section. These profiles 330 are compared to the computational ones in Figure 9. The scatter with the WT 331 data around the upwind face (Figure 9, lines a-b) are probably due, according 332 to Liu et al. (2011), to the limitation of the PIV system, which cannot fully 333 resolve the high-speed gradient in the near-surface zone and leads to nonzero 334 wind speed at the surface. The agreement in the reversed flow region (Figure 335 9, lines e-f) is excellent for setup s2, that replicates the WT conditions. The 336 computational results from setup s1 strongly overestimate the speed deficit in 337 the near wake, while the $y - avg(t - avg(\overline{u}_x))$ in s3 is quite different form the 338



Figure 9: Horizontal velocity profiles: WT measurements (Liu et al., 2011) and present CWE results

centre plane one and from WT data. In the same setup, a significant spanwise
deviation occurs in the wake (Figure 9, lines e-f).

The measured x-wise profiles of the vertical component of the velocity u_y at 341 the level $z \approx h$ are reported in Qian et al. (2009). PIV technique has been 342 adopted on the WT vertical mid plan (y = 0, i.e. at a distance from the side 343 wall d/L = 2.7) at different reference velocities of the incoming wind. The u_{y} 344 profiles obtained in the three computational setups are compared among them 345 in Figure 10(a), while the profiles measured at midspan are compared in Figure 346 10(b) to the computational ones at different distance from the side wall in setup 347 s2. Considerable differences between s1 and s2 can be observed in the far wake 348 only, while a dramatic change in the vertical component of the velocity occurs in 349 s3 especially in the near wake. At the dune downwind face $(0 < x/h < 1.7h), u_y$ 350 changes its sign from positive (upward flow, s1 and s2) to negative (downward 351 flow, s3). In other terms, the 2D clockwise recirculating region which character-352



Figure 10: Vertical velocity profiles: WT measurements (Qian et al., 2009) and present CWE results

izes the near wake topology in s2 at mid line no longer holds and it is suspected to change in a 3D local flow (see the large spanwise standard deviation of u_y). A satisfactory agreement is observed between WT and computational approaches, if the same setup and distance from the side wall is adopted (blue points and continuous line in Fig. 10-b). Conversely, the closer the vertical plan to the side wall, the smaller the upward speed at the upwind face and the higher the downward speed at the downwind surface.

An analogous post processing is proposed for the x-wise profiles of the shear stress magnitude $|\tau|$ at the floor in Figure 11. The shear stress is a quantity of particular interest in windblown sand dynamics because above a given threshold value τ_t it induces the sand grain saltation, i.e. the sand bed erosion. Conversely, at $|\tau| < \tau_t$ sedimentation of the flying grains occurs(Bagnold, 1941). For such reason, the $|\tau|/\tau_t$ obtained by computations in the three setups is plotted in Figure 11(a). s1 fails in predicting the sedimentation just downwind the crest



Figure 11: Shear stress profiles: Wind Tunnel measurements (Walker and Nickling, 2003) and present CWE results

and the downwind toe. The lower the blockage ratio, the shorter the sedimen-367 tation length l_s , i.e. the closer to the dune the point from which erosion takes 368 place again. Once more, the spanwise variability of the profile along the wake is 369 significant in s3, and the sedimentation length varies from about 0.75L to 1.1L. 370 Figure 11(b) compares the shear stress magnitude profiles obtained in s2 with 371 the one measured by Walker and Nickling (2003) in their WT test by using 372 Irwin-type differential pressure sensors. It is worth pointing out that in this 373 case the experimental setup differs from the computational one in the dune 374 cross section, in the dune aspect ratio, and in the Reynolds number (see Table 375 1). On one hand, the smaller angle of the upwind face α_u in WT test induces 376 the lower shear stress magnitude along it. On the other hand, the $|\tau|$ profile 377 downwind the crest is mainly affected by the dune aspect ratio, i.e. by the 378 distance d of the measurement alignment from the WT side wall. In fact, a 379 very good agreement is obtained when the measurements at the WT mid plan 380

(i.e. $d = 0.5S/L \approx 0.65$) are compared to the computational profile at the same distance from the side wall. The closer the alignment to the side wall, the higher $|\tau|$ along the wake. In other terms, in this case study the WT wall side effects are by far larger than the ones induced by L/h and/or u_{ref} , even if much more emphasis is traditionally given to the latter than to the former.

386 4.3. 3D Coherent Flow Structures

This final Section aims at providing a sound phenomenological reading of the 387 spanwise variability in simulated in external flow conditions (setup s3). A deeper 388 insight in the flow characteristics is then performed, thanks to the amount of in-389 formation available from computational simulations. Advanced post-processing 390 and flow visualization techniques are employed to this aim. In particular, the 391 velocity and shear stress vector fields are visualized on selected planes by us-392 ing the so-called Line Integral Convolution (LIC, Cabral and Leedom, 1993; 393 Stalling and Hege, 1995; Laramee et al., 2003). Some information are provided 394 herein, being a technique scarcely used in the Wind Engineering field. 395

LIC is based upon locally filtering an input texture along a curved stream line segment in a vector field and it is able to depict directional information at high spatial resolutions. The directional structure of a vector field can be graphically depicted by its stream lines, i.e. paths whose tangent vectors coincide with the vector field. Given a pixel \boldsymbol{x}_0 of the desired resulting image and numerically computed a streamline $\boldsymbol{\sigma}$, passing by $\boldsymbol{x}_0 = \boldsymbol{\sigma}(s_0)$, line integral convolution consists in calculating the intensity for that pixel as

$$I(\boldsymbol{x}_0) = \int_{s_0 - L}^{s_0 + L} k(s - s_0) T(\boldsymbol{\sigma}(s)) ds,$$
(5)

where s is the arc-length coordinate, T is an input texture, 2L is the filter length and k is a filter kernel normalized to unity. In LIC visualizations of fluid flows, a white noise or similar random image is chosen as input texture T. The convolution causes pixel intensities to be highly correlated along individual stream lines, but independent in directions perpendicular to them. In the resulting images the directional structure of the vector field is clearly visible. Figure 12(a) and (b) show the LIC visualization of the time-averaged velocity field on an ideal inclined plane ($\beta = 12^{\circ}$) crossing the near wake from the dune crest, and the LIC visualization of the time-averaged shear stress field on the dune downwind face and wake floor, respectively. In both figures, the direction of the filed is highlighted by superimposed arrowed lines. The most striking



Figure 12: Spanwise 3D coherent structures in the dune wake: time averaged velocity field (a), time averaged shear stress field colored by the its modulus (b)

413

⁴¹⁴ result is that in Figure 12(a), where the LIC of the time-averaged velocity field ⁴¹⁵ highlights quasi-steady, "mushroom"-like coherent flow structures having a pair ⁴¹⁶ of owl eyes each. These structures consists of two counterrotating foci with a ⁴¹⁷ free stagnation point downwind the crest and between the foci. The main di-⁴¹⁸ mensions of such structures are given in the figure. The corresponding LIC of

time-averaged shear stress field (Fig. 12-b) is even more complicated and char-419 acterized by a "skein"-like pattern. The pattern shape appears to be strongly 420 related with the mushroom-like structure, especially at the ground floor (i.e. 421 where the mushroom is closest to the floor). In order to shed some more light 422 in such a pattern, it is colored by the modulus of the same shear stress, and 423 the spanwise lines along which $\tau_y = 0$ and $\tau_x = 0$ (reattachment line, see also 424 Fig. 8) are superimposed. For both lines a geometrical reading with respect to 425 the LIC pattern can be provided: the former is the locus of points where the 426 tangent to the streamlines are aligned with the x-axis, while the latter is the 427 locus of points where the tangent to the streamlines are aligned with the y-axis. 428 The mushroom spanwise characteristic length is equal to the wavelength λ of 429 the "festoon" reattachment line. In particular, the spanwise maximum reat-430 tachment length correspond to the mushroom center, while the minimum value 431 takes place in between two consecutive mushrooms. 432

To the authors' best knowledge, analogous spanwise coherent flow structures
have been previously recognized at least in two studies involving nominally 2D
setups.

Similar spanwise mushroom-shaped flow structures have been visualized by 436 Schewe (2001) around an apparently different aerodynamic setup, i.e. the sep-437 arated flow around an airfoil at incidence in the critical regime. In fact, in 438 his pioneering and seminal work Schewe has observed and described in detail 439 mushroom-like flow structures (Figure 13), combined in different arrangements 440 for different values of the airfoil aspect ratio S/L (L = w), and bounded by dis-441 turbed regions close to the end plates. On the basis of the experimental results, 442 Schewe conjectures that: i. the occurrence and number of the mushroom-like 443 structures depend on the inclination of the base upper surface; ii. the spanwise 444 flow structure remains intact as $S/L \to \infty$; iii. the wavelength λ scales with the 445 sectional dimension(s) of the airfoil; iv. preferential or more natural spanwise 446 arrangements exist, in terms of number of cells and their wavelength. These 447 speculations seem to hold, to a certain extent, also in the present case study. 448 In fact: i. the downwind face of the dune and the base upper surface of the 449



Figure 13: Oil-flow pictures of the mushroom-like flow structures at the upper surface of an airfoil, after Schewe (2001)

airfoil share the same inclination with respect to the incoming wind ($\alpha_d \approx 30^\circ$); 450 ii. setup s3 confirms that the coherent flow structure is qualitatively unchanged 451 by passing from s3a to s3b, where the latter mimics an infinite aspect ratio of 452 the dune because of the periodic side b.c. and the increased spanwise length; 453 iii. the characteristic length λ of the mushrooms found by Schewe (2001) is 454 comparable to the one in s3, if both are scaled versus $h~(\lambda\approx 5.75h,$ Fig. 12-a, 455 $\lambda \approx 5.6h$, Fig. 13); iv. in both Schewe and present setups, stable arrangements 456 are characterized by a given number of spanwise aligned mushrooms. In Schewe, 457 an even number of vortices is always observed, but the end-plate disturbances 458 considerably extend spanwise; conversely, in s3 an odd number of mushrooms 459

emerges in both s3a (7) and s3b (27) setups (see Fig. 8), despite the spanwise length in s3b is four time the one in s3a. It is worth pointing out that the quasi-periodic mushroom structure is corrupted at midspan, if the dune length S = w is not an odd multiple of λ (s3b). Despite the analogies above, it is worth pointing out that the flow structures in Schewe (2001) are recognized only in the critical regime, while the occurrence of the same condition is unlikely in the present case study.

More recently, analogous 3D, global, quasi-steady vortices have been simulated 467 by Spalart et al. (2014) in an even more different fluid flow setup, i.e. the nom-468 inally 2D, high Reynolds number, fully developed turbulent Couette flow. The 469 RANS-based simulations of Spalart et al. (2014) (including the SST $k - \omega$ one), 470 successfully reproduce the same flow structures previously observed and sim-471 ulated in experiments and DNS, respectively. In the present perspective, it is 472 worth pointing out that: i. the vortices are arranged in a quasi-periodic z-wise 473 system of counter-rotating pairs (Fig. 1, Spalart et al. (2014)), analogously to 474 the arrangement in Figure 12(a); ii. the distribution of the skin-friction coef-475 ficient in the z direction (Fig. 6, Spalart et al. (2014)) qualitatively matches 476 the "festoon-shaped" spanwise reattachment line in Figure 8; iii. the simulated 477 flow structures hold in a wide range of Reynolds numbers, and the effect of the 478 vortices is only weakly dependent on Re. In their outlook, Spalart et al remark 479 that there is a convincing scale separation between the simulated flow structures 480 and the turbulence which is represented by the RANS model. The vortices have 481 a lateral scale much smaller than the scale of the geometry (which is infinite in 482 the setup), and random locations in z, giving them the nature of an instability. 483 The remarks above qualitatively hold also in the present case study. Despite 484 such analogies, it is worth pointing out that the flow structures in Spalart et al. 485 (2014) are somewhat triggered by an initial velocity field mimicking a periodic 486 system of counter-rotating vortex pairs in the (y-z) plane, while in the present 487 case study the mushroom-like structures spontaneously develop from uniform 488 initial conditions. 489

490

491 5. Conclusions

The present study points out some emerging 3D coherent flow structures 492 in the wake of a transverse dune under different setup conditions by means of 493 computational simulations and compares the obtained results with a number of 494 experimental wind tunnel measurements available in literature. The comparison 495 shows a good and robust agreement of the CWE results to WT data, and it goes 496 beyond: it puts in evidence common misunderstandings in setting up computa-497 tional and experimental models for CWE/WT validation. Some good practices 498 in dune aerodynamics CWE simulations and WT tests are recommended: i. 499 CWE-WT comparisons require the careful simulation of the WT setup, includ-500 ing the wind tunnel geometry; ii. forcing the flow symmetry by b.c. in CWE 501 can strongly affect the results; iii. high values aspect ratio are recommended in 502 WT test to replicate external flow conditions, e.g. $w/L \gg 10$. 503

Surprisingly, emerging mushroom-like, coherent flow structures in the dune wake 504 are clearly shown by a deep analysis of the CWE results. They are compared 505 to analogous flow structures arising from rather different aerodynamic setups 506 belonging to referential literature in fluid dynamics. It follows that the studied 507 setup can be ascribed to a wider class of 3D flows occurring under 2D nominal 508 conditions. According to the authors such class of flow seems to be of high 509 relevance in modern developments of fluid dynamics, and it still remain poorly 510 understood in its general features, if any. The authors hope further indepen-511 dent studies will appear and further develop their contribution. In particular, 512 the precise definition of the aerodynamic regime(s) at which mushrooms grow in 513 the dune near wake remain an open issue. An even wider computational study 514 would be required to discuss the permanence and/or changes of such coherent 515 flow structures form the model scale to the full scale, e.g. by varying Reynolds 516 number and/or surface roughness. 517

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