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Characterization of wind-blown sediment transport with height in a highly mobile dune (SW Spain)

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ABSTRACT

The Valdevaqueros dune is located at one of the windiest points of Europe, where the frequent occurrence of strong easterly winds has generated a highly mobile dune. Several rotating cup anemometers in vertical array and a self-designed vertical sand trap, were placed to retain the drift sands at different heights over the surface in order to determine theoretical and actual sand transport rates in the Valdevaqueros dune system. General results show that 90% of the wind-blown sand is transported within the first 20cm above the dune crest surface. Theoretical transport rates based on different empirical formulae were 0.33 to 0.78 times the in-situ sand transport rate detected, which was $2.08 \cdot 10^{-2} kgm^{-1}s^{-1}$ under moderate wind power (mean speed ranging from 8.4 to $17.9 ms^{-1}$). Analysis of different statistical grain-size parameters helped to understand sand transport distribution at different heights.

KEYWORDS **Dune mobility. Aeolian sand transport. Sand trap. Anemometer. Average grain size.**

INTRODUCTION

It has been widely demonstrated that coastal dune systems represent beach sand reservoirs, especially during extreme episodes of wave storms, equinoctial spring tides or washovers generated by tsunamis (Morales *et al.,* 2008), all of which have actually occurred in SW Spain (Gutiérrez-Mas *et al.*, 2009). Therefore, sand dunes play an essential role in sedimentary beach equilibrium by protecting the littoral fringe from erosion.

It is assumed that under extremely high wind stress, vegetation is destroyed and dunes are reactivated. However, in some dune fields, mobile and stabilised dunes can coexist (Tsoar *et al.*, 2009). In this sense, coastal dunes can be stabilised or remobilised in response to changes in wind force (Levin *et al.*, 2007).

Dune stabilisation is applied when original conditions of the dune development have been altered; reflecting differences in the vegetation cover, sediment supply or an increase in the migration rates. All these modifications influence aeolian sediment transport across the subaerial portion of the system (Jackson and Nordstrom, 2011). During the 1980 and 1990s, interest in transverse dunes under uni-directional wind regime motivated field measurements; this was prompted by the improved understanding that sand dune dynamics were not a simple response to regional wind patterns but a complex interaction between dune morphology and wind flow (Livingstone *et al.*, 2007).

Measuring the saltation flux is more complicated in the field than in the wind tunnel because of the high temporal and spatial unsteadiness of natural wind compared to simulated wind tunnel flow. Averaging transport data over time may be acceptable for very fine particles, such as aeolian dust, but will lead to serious errors in the case of sand because the saltation process itself is also discontinuous in space and time (Goossens *et al*., 2000).

As documented by Jackson and Nordstrom (2011), deterministic models of aeolian transport developed in the laboratory are often poor predictors of transport monitored in the field (Bauer *et al*., 1996, 2009), largely due to the greater complexity of natural systems (Sherman *et al*., 1998; Wiggs *et al*., 2004; Davidson-Arnott *et al*., 2005; Hesp *et al*., 2009; Walker *et al*., 2009).

On beaches, aeolian sand transport is limited to the lowest 0.25m above the surface and the decrease of sand content with height is exponential (Arens and van der Lee, 1995). For narrow beaches with onshore winds, the total sediment transport rate across the dune line will be less than that predicted for a wide beach because of the constraint imposed by the fetch effect. However, as the angle of wind approach becomes oblique, as it is in the case of the Valdevaqueros transverse dune field (Navarro *et al*., 2007), the available fetch becomes progressively longer, transport limitations imposed by the fetch effect are negligible, and transport enhancement across the dune line is to be expected (Bauer and Davidson-Arnott, 2003).

Although the study of sand particle sizes is fundamentally important for understanding the process of non-uniform saltation (Shao and Mikami, 2005), few experimental measurements have been undertaken to date to characterize aeolian sand transport. In Spain, *e.g*., Serra *et al*. (1997) obtained interesting aeolian sand transport results by empirical and experimental procedures at the Ebro Delta dunes during a year.

Thus, the aim of this paper is focused on the assessment of several sand transport aspects, including the characterisation of grain size distribution with height by means of sand trap measurements. Furthermore, the employment of a vertical array of anemometer cups allows the comparison of actual sand transport rates to theoretical sand transport results from different classical formulae.

STUDY AREA

The Valdevaqueros dune system is located 10km westwards from Tarifa (South Spain) in a littoral fringe that presents a mean tidal range of 1.5m (Fig. 1). Its geographical location (very near the Strait of Gibraltar) and its particular weather conditions make this transgressive dune field one of the biggest in the southern Europe (Gómez-Pina *et al*., 2007), with a height of 40m over the lowest low water level (LLWL). The dune migrates towards the NW, developing ridges perpendicularly oriented to the dominant wind flow. Migration rates up to 17.5myear^{-1} have been measured during the last decades due to the strong and frequent easterly winds (Muñoz-Pérez *et al*., 2009).

Through a study of two decades of wind data and application of the Fryberger (1979) method, a sand rose at Tarifa was obtained with a very high sand drift potential, close to 10,000 vector units. Additionally, it was determined that nearly the 75% of the time the wind was above the threshold speed, which demonstrates that the Valdevaqueros dune field has one of the highest sand transport capacities in Europe (Navarro *et al*., 2011).

Aerial photographs from 1956 show that the Valdevaqueros dune was part of an old bypass dune field that extended from the Valdevaqueros cove in the east to Bolonia beach in the west (see Fig. 1). Since then, several management activities have been implemented, such as sand extractions, dune reshaping, sand fencing and marram plantations with the aim of controlling the sand advance towards the military area and, currently, a local road. Further information can be found in Muñoz-Pérez *et al*. (2009) and Navarro *et al*. (2011).

According to Román-Sierra *et al*. (2013) sediments at the Valdevaqueros beach and dune are composed mainly by well-sorted quartz sands. The mean grain size at the beach range from 0.29 to 0.47mm, while sediments at the dune crest range from 0.28 to 0.34mm.

METHODOLOGY

Wind velocity characterisation

Wind velocity data for the study area has been obtained from the nearest meteorological station, which is located closer to the Strait of Gibraltar in the town of Tarifa, 10km from the Valdevaqueros dune system. Although this anemometer gauge is located 41 metres above the mean sea level, which approximately corresponds to the current dune elevation, the use of a local anemometer is needed to document the wind velocity profile above the dune surface as well as short-term velocity fluctuations near ground.

The wind velocity profile was obtained by means of a portable vertical anemometer tower on the dune crest during 198 minutes on the 27 March, 2012. According to Rodríguez Santalla *et al*. (2009), mean, minimum and maximum flow speeds and direction were measured using this vertical mast with five rotating cup anemometers which were employed in vertical arrays: at 3.5, 30, 60cm, 1.18 and 1.35m with a wind vane (Fig. 2), with a sampling frequency of 60s.

FIGURE 1. Location of the Valdevaqueros dunefield (SW Spain).

According to Knott and Warren (1981), the high inertia of some instruments can result in the mean wind speed being overestimated by as much as 15%. However, cup anemometers show an almost linear relationship between the rate of rotation and wind speed, and are unaffected by variations in air temperature or density (Pye and Tsoar, 2009).

Sand movement measurement by sand trap

The rate of sand transport can be measured either in the wind tunnel or in the field by means of sand traps. It must be taken into account that field traps are usually larger than those used in wind tunnel experiments (Pye and Tsoar, 1990). Although the results obtained from any sand trap can only be regarded as approximate, since interference with the airflow is unavoidable (Bagnold, 1941), experiments in the field are consistent with the seasonal behaviour of the wind patterns, vegetal cover, and moisture content, which altogether favour higher net aeolian sand transport during summer periods (Alcántara-Carrió and Alonso, 2001).

Some authors have used horizontal sand traps partially or totally buried in the sand (Owens, 1927; O'Brien and Rindlaub, 1936; Belly, 1964, among others) as they do not disturb the flow to the same degree as vertical traps at high wind velocities. However, in this case, they would need to be very long to trap grains with flattened saltation trajectories (Horikawa and Shen, 1960).

Since the research area has a very high sand transport capacity due to its proximity to one of the windiest points in Europe and thus, sand drift occurs nearly 75% of the time that the east wind blows (as mentioned above), no trap is able to catch considerable amounts of sand (several kg). Therefore, in order to characterise sand transport with height at the research dune field, an improved Bagnold vertical sand trap was designed in a rectangular box,

FIGURE 2. Vertical anemometer tower with rotating cups placed at five different heights above the dune surface.

100cm in height and 40cm wide, with 10 compartments in the front slit, similar to the one depicted by Sherman *et al.* (2014). Each chamber had a height of 10cm with a fine wire mesh of 0.125mm in the rear slit to allow wind flow to reduce the stagnation pressure (Fig. 3).

Consistent with Davidson-Arnott *et al.* (2008) and Waever and Wiggs (2011), sand transport was measured with a vertical sand trap for a period of 15 minutes over the dune crest and foot, respectively, by using an apron cloth around the trap to avoid the scour caused by the wind drift, as similarly employed by Cabrera and Alonso (2010). Figure 4 shows the cross-dune profile with the locations of the sand trap and anemometers. Sand trap was placed oriented against the dominant wind direction.

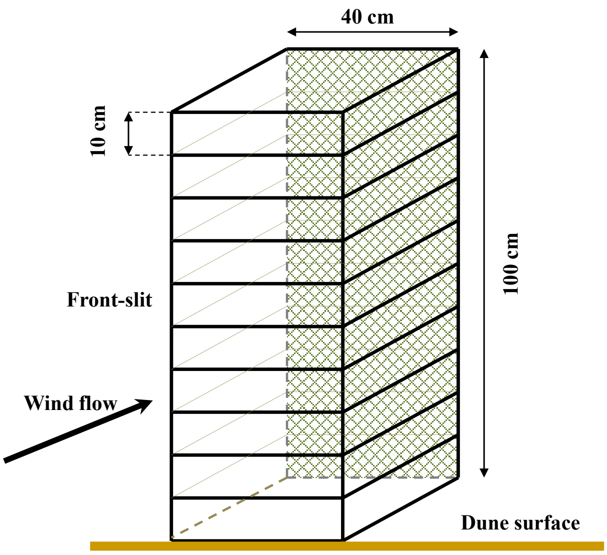

FIGURE 3. Schematic diagram of the vertical sand trap.

Due to the small capacity of many vertical sand traps (Horikawa and Shen, 1960; Leatherman, 1978; Knott and Warren, 1981; Illenberg and Rust, 1986; Arens and van der Lee, 1995; Cabrera and Alonso, 2010), they could be filled within very few minutes and would be of little value in terms of providing massive sand transport rates from extremely high sand fluxes. In this sense, samples trapped at different heights can be compared herein to provide insight into the changes in grain size populations during transport.

Sampling efficiencies range from 15% to 85% for both conventional array traps and step-like array traps, while a harmonised ideal sampling efficiency for vertical sand traps could be considered 75% at the present stage (Li and Ni, 2003).

Sand grain analysis and characterisation

Grain size analysis is of great utility for the identification of sand sources transported by wind. Sand samples retained in each trap chamber over the crest were analysed by dry sieving following the recommendations proposed by Syvitski (1991) and the laboratory procedures of USACE (2008). Following the procedure applied by Román-Sierra *et al.* (2013), a stack of successive mesh sieves of 2, 1.0, 0.71, 0.5, 0.35, 0.25, 0.125 and 0.075mm were mounted on an electrically powered shaker machine operating at 2.6rpm and 300taps·min^{-1} during an optimal sieving time of 15min for dune sand sample.

Consistent with Alcántara-Carrió *et al.* (2010), four principal statistical parameters of the sand-trap samples – mean grain size, sorting, skewness and kurtosis– have been computed in order to know which transport modes occur according to sand distribution with height. These parameters were determined arithmetically and geometrically (in metric units), and logarithmically (in phi units) by extraction of relevant percentile values from graphic plots (Folk and Ward, 1957) and by the mathematical method of moments (Krumbein and Pettijohn, 1938; Folk, 1974; USACE, 2008).

Theoretical and actual sand transport computation

Under atmospheric stability, the velocity profile above the viscous sublayer of the aerodynamically rough surfaces can be calculated by the Prandtl-von Karman's logarithmic equation, also called the law of the wall, through which the mean wind speed (uz) at a certain height z can be found:

$$\frac{u_z}{u_*} = \frac{1}{k} \cdot ln\left(\frac{z}{z_0}\right) \forall z \succ z_0 \qquad \text{[eq. 1]}$$

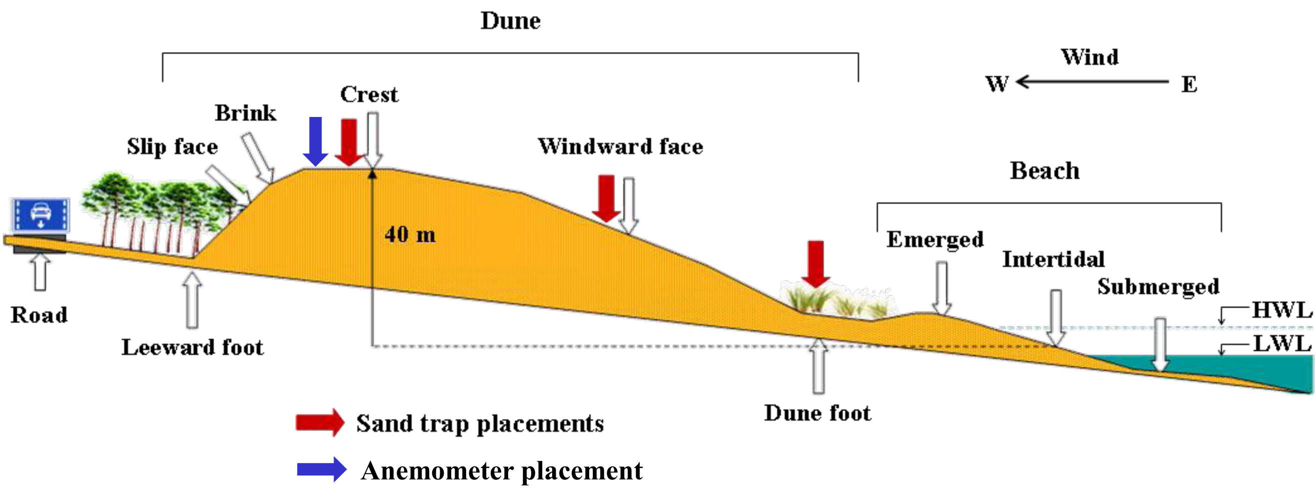

FIGURE 4. Cross-dune profile with the placement of sand trap and vertical anemometer tower.

where u_* is the wind shear velocity, k is the universal constant that defines the Von Karman turbulent boundary layer (k=0.40), z is the height above the surface, and z_0 is the aerodynamic roughness length of the surface, which is found to be approximately d/30, being d the grain size. An increase in the roughness length of the surface results in an increase of the friction velocity.

For typical aeolian dune sands (0.1–1.0mm), Bagnold (1941) showed that the theoretical transport rate (q_B) varies approximately as the square root of the grain diameter (d) relative to an average diameter of 0.25mm (D) and the cube of the wind shear velocity (u_*):

$$q_B = C \cdot \sqrt{\frac{d}{D}} \cdot \frac{\rho_a}{g} \cdot u_*^3 \qquad \text{[eq. 2]}$$

where the constant C is 1.5 for uniform sands, 1.8 for dune natural sands (used herein), 2.8 for poorly sorted sands and 3.5 for pebbles. The variation in the coefficient C indicates that the sand transport is higher over a surface of poorly sorted sand or pebbles than over a surface of uniform sand. This is because sand saltates more readily over a hard surface or a surface containing larger particles (Pye and Tsoar, 1990).

Other authors based their researches on Bagnold's formula, developing new equations to obtain the wind transport rate. Zingg (1953) proposed a similar equation substituting C by 0.83 and raising d/D to 3/4, so that the formula would be more suitable for a wider range of particle sizes:

$$q_z = C \cdot \left(\frac{d}{D}\right)^{\frac{3}{4}} \cdot \frac{\rho_a}{g} \cdot u_*^3 \qquad \text{[eq. 3]}$$

When the wind shear velocity is below the threshold velocity ($u_* < u_{*t}$) (Belly, 1964), eq. 2 suffers from the limitation that it can predict unrealistic transport rates. To correct this, Kawamura (1964) developed a transport equation taking into account the threshold velocity, *i.e.* the critical shear velocity that must be achieved to initiate motion:

$$q_K = K \cdot \frac{\rho_a}{g} \cdot (u_* - u_{*t}) \cdot (u_* + u_{*t})^2 \qquad \text{[eq. 4]}$$

where K is a constant of value 2.78. Field measurements showed that K ranges from 2.3 to 3.1 for beach sands of a mean diameter of 0.3mm (Horikawa *et al.*, 1986).

Lettau and Lettau (1978) modified Kawamura's equation, where C1 is equal to 4.2:

$$q_L = C_1 \cdot \sqrt{\frac{d}{D}} \cdot \frac{\rho_a}{g} \cdot u_*^2 \cdot (u_* - u_{*t}) \qquad \text{[eq. 5]}$$

In our case, a unique master sample obtained from blending the sediment retained in the 10 compartments of the sand trap was employed for the transport rate computation.

Hence, once the friction velocity has been obtained for each height, the theoretical sand transport can be determined applying the aforementioned expressions, by considering the mean grain size of a master sample from the dune crest within the computation. On the other hand, retained sand from each compartment of the sand trap has been used for the computation of the actual sand transport, taking into account sand trap dimensions (100cm height x 40cm wide) and time exposition (15min) (eq. 2).

$$q_r = \frac{W_s}{(0.4m \cdot 900s)} \qquad \text{[eq. 6]}$$

where W_S is the sand weight obtained by the sand trap during 15min and q_r the real sand transport rate for the dune crest area in $kgm^{-1}s^{-1}$. Results have also been obtained in $m^3m^{-1}year^{-1}$, considering a dry density of $2650kg/m^3$ and an average porosity of 40% (Román-Sierra *et al.*, 2014).

TABLE 1. Statistical parameters of the sand samples collected on the dune crest from each sand trap compartment. D_{50}: Mean grain size; Sorting; Skewness; Kurtosis; Z: Height of each chamber related to the dune surface

Z (cm)	D50 (mm)	σ (Φ)	α (Φ)	κ (Φ)
100-90	0.27	0.75	0.50	0.79
90-80	0.33	0.78	-0.17	0.89
80-70	0.28	0.74	0.48	0.79
70-60	0.26	0.65	0.28	0.96
60-50	0.29	0.76	0.37	0.91
50-40	0.27	0.57	-0.24	0.91
40-30	0.27	0.56	-0.26	0.88
30-20	0.26	0.50	-0.29	0.83
20-10	0.25	0.51	-0.25	0.84
10-0	0.29	0.58	-0.53	1.22

RESULTS

Changes in sand grain size with height

Mean grain size (D_{50}) of the master samples obtained by the sand trap at the dune foot and crest, show values of 0.3mm and 0.28mm, respectively. Although sand trap was placed in both the dune foot and the crest with the same duration, sand retained by the trap on the dune foot was not enough to obtain a successful grain size analysis at each height, but for the dune crest. Thus, Table 1 shows the values of the four principal grain statistical parameters for each sand trap height at the dune crest: mean diameter, sorting, skewness and kurtosis. It can be seen that mean grain size and skewness parameters presented more heterogeneous values. The mean grain size of the sand collected in each trap compartment ranged from 0.25mm to 0.33mm (Table 1).

Consistent with Román-Sierra *et al.* (2013), standard deviation values reveal moderately well-sorted sediments for each dune sample, ranging from 0.50 to 0.78Φ, those retained at lower heights being better sorted.

Samples retained in the upper compartments are mainly composed by very fine materials, while negative values predominate on samples near the surface, which are very coarse-skewed. In this sense, skewness generally tends to becomes positive with height (Table 1).

Regarding kurtosis, most samples follow a platykurtic distribution (values from 0.79 to 0.88Φ) tending to be mesokurtic (from 0.91 to 1.22Φ), which confirms the presence of different grain sizes within the analysed sand samples.

It is worth highlighting that after comparing standard deviations with skewness values (Fig. 5), it can be appreciated that well-sorted samples, which are mainly retained within the first 50cm of height, have negative skewness, *i.e.* they are coarse-skewed (indicating a coarse grain size distribution with a tail of finer particles). Results agree with the statement of Folk and Ward (1957), if standard deviation is a function of mean size, and if skewness is also a function of mean size, then sorting and skewness can bear a mathematical relation to each other (Fig. 5).

Sand transport rates obtained by the sand trap

Figure 6 show the sediment weights retained by the sand trap at the dune foot and crest, respectively, for the given 10 intervals: 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90 and 90–100cm, after 15 minutes of exposure.

Over the dune foot (Fig. 6A) a total of 209g was retained by the sand trap within the aforementioned period of time (*i.e.* $0.84kgh^{-1}$), 47% of the transported sediment kept concentrated within the first 10cm above the surface and 16% was retained in the following 10cm. Over the dune crest (Fig. 6B) an amount of 7.5kg (approximately 35 times the value found for the dune foot, *i.e.* nearly $30kgh^{-1}$) was retained by the vertical sand trap. At this dune area, 60% of the sand was detected in the first 10cm over the surface while 30% was retained in the following trap compartment (10–20cm), *i.e.* the 90% was retained in the first 20cm over the crest surface, while at the dune foot the 63% was kept at the same height interval, detecting minimum percentages of sediment at the upper compartments. In both cases, sand weight follows a decreasing potential distribution with height with an R-squared of 0.92 and 0.96 for the dune foot and crest, respectively.

Sediment retained by the sand trap over the dune crest has been used to compute the actual aeolian sand transport at this point. Consistent with the amount of sand weighted from each compartment, maximum sand transport rates have been identified for the lowest levels of the sand trap, with values with a magnitude order ranging from 10^{-2} just above the surface to $10^{-5}kgm^{-1}s^{-1}$ within the upper 50cm, as can be observed in Table 2.

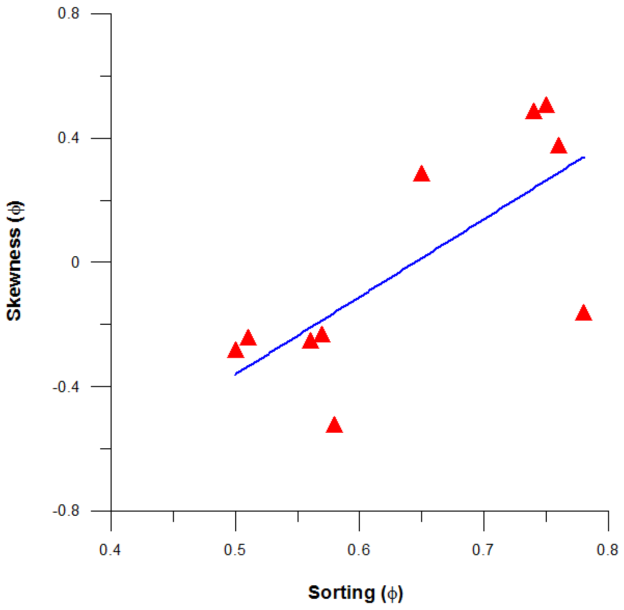

FIGURE 5. Distribution of sorting vs. skewness parameters for the sand trap samples at the dune crest. Linear fit is shown with a blue line.

Therefore, in the overall 100cm-air column the transport rate has been of $2.08 \cdot 10^{-2}$kgm^{-1}s^{-1}, (*i.e.* a total of 412m^{3}m^{-1}yr^{-1}), being the average during the research time interval, with average wind velocities ranging from 8.41 to 11.78ms^{-1}. Under similar wind conditions, Jackson and Nordstrom (2013) identified sand transport rates of 40.2 to 43.5kgm^{-1}h^{-1} (*i.e.* $11.2 \cdot 10^{-2}$ to 12.1 kg·m^{-1}s^{-1}) by using sand traps over the foredune crests at the coast of New Jersey (USA). Serra *et al.* (1997) obtained average sand transport rates of 33–41m^{3}m^{-1}yr^{-1} (1.7–$2.1 \cdot 10^{-3}$kgm^{-1}s^{-1}) for a highly changing wind velocity with average wind speeds ranging from 6.7 to 12.4ms^{-1}, while sand traps employed by Cabrera and Alonso (2010) reflected rates of $2.18 \cdot 10^{-4}$ and $3.07 \cdot 10^{-4}$kg·m^{-1}s^{-1} under average wind speeds of 5.2ms^{-1}.

Theoretical transport rates obtained from the velocity profile

The vertical wind velocity profile at the dune crest has been represented in Figure 7. Wind speed just above the dune surface ranged from 5.69 to 11.51ms^{-1}, with a mean wind speed of 8.41ms^{-1}, while the upper anemometer gauge recorded averaged minimum and maximum values of 9.9 and 25.5ms^{-1}, respectively. Mean values show that wind speed increased progressively from 30kmh^{-1} just above the surface to 42kmh^{-1} at a height of 1.18m. Maximum values appeared from 1.18 to 1.35m, showing an exponential increase of wind speed of 34% at that height, while minimum differences in wind speed were detected from 0.30 to 0.60m (5.4%).

Averages and standard deviations of minimum, mean and maximum wind speeds (ms^{-1}) recorded by the anemometer tower at a given height over the dune surface are shown in Table 3. Mean speed values in the vertical array approximately ranged from 8.4 to 17.9ms^{-1} with standard deviations ranging from 1 to 2.42m/s. Maximum standard deviations have also been detected in the upper anemometer gauge.

As can be observed in Figure 8, wind regime during the recording period had a remarkable East component (71%). The most frequent and strongest winds blew from the ESE direction.

Shear velocities for each height have been computed by means of the law of the wall (eq. 1). For the calculation of the aerodynamic roughness length (z_0= d/30) a master sample obtained from the different weights retained in the sand trap (D_{50}= 0.28mm) has been used. The friction velocity just above the dune surface turns to be relatively higher than that computed for the following height because close to very smooth ground surfaces the wind speed decreases and viscous forces become predominant. Hence, in a very limited region immediately adjacent to the surface, the turbulent flow becomes laminar, in what is called the laminar sub-layer (Pye and Tsoar, 1990).

Theoretical sand transports for each height have been computed applying the transport equations in

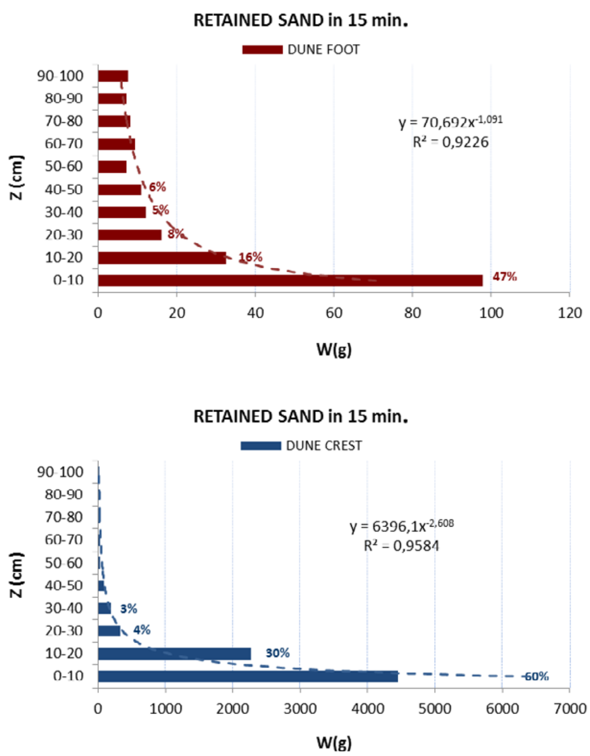

FIGURE 6. Sand weight (W) retained by the trap on the dune foot (A) and dune (B) crest during 15 minutes.

TABLE 2. Sand weight and real transport rate obtained from the sand trap at the dune crest

Z (cm)	weight (g)	weight (%)	q_r (kg m^{-1} s^{-1})	q_r (m^3 m^{-1} y^{-1})
90-100	16	0.21	4.44E-05	0.88
80-90	36	0.48	1.00E-04	1.98
70-80	26	0.35	7.22E-05	1.43
60-70	30	0.40	8.33E-05	1.65
50-60	35	0.47	9.72E-05	1.93
40-50	89	1.19	2.47E-04	4.90
30-40	190	2.54	5.28E-04	10.47
20-30	333	4.45	9.25E-04	18.35
10-20	2268	30.33	6.30E-03	124.95
0-10	4455	59.57	1.24E-02	245.45
TOTAL	7478	100	2.08E-02	412

the methodology section. Close to the surface, where creeping and saltation processes are dominant, transport rates range from $0.7{\cdot}10^{-2}$ to $1.6{\cdot}10^{-2}$kgm^{-1}s^{-1}, *i.e.* 135.65 to 322.69m^{3}m^{-1}yr^{-1} (Table 4), while at the upper height sand transport ranges from $2.5{\cdot}10^{-2}$ to $7.2{\cdot}10^{-2}$kgm^{-1}s^{-1}, *i.e.* 486.93 to 1421.92m^{3}m^{-1}yr^{-1}. Maximum transport rate values are always obtained from the Bagnold and, Lettau and Lettau equations. Therefore, average sand transport rates range from $0.9{\cdot}10^{-2}$ to $2.3{\cdot}10^{-2}$kgm^{-1}s^{-1}, *i.e.* approximately 179.80 to 457.23m^{3}m^{-1}yr^{-1}.

Comparison between theoretical and experimental sand transport

The actual sand transport at the Valdevaqueros dune crest has been compared to the theoretical sand transport rates extracted from equations 2, 3, 4 and 5. Table 4 shows the ratio between the real sand transport rate, which was obtained from the sand trap transport measurement and the theoretical sand transport rates for each formulation.

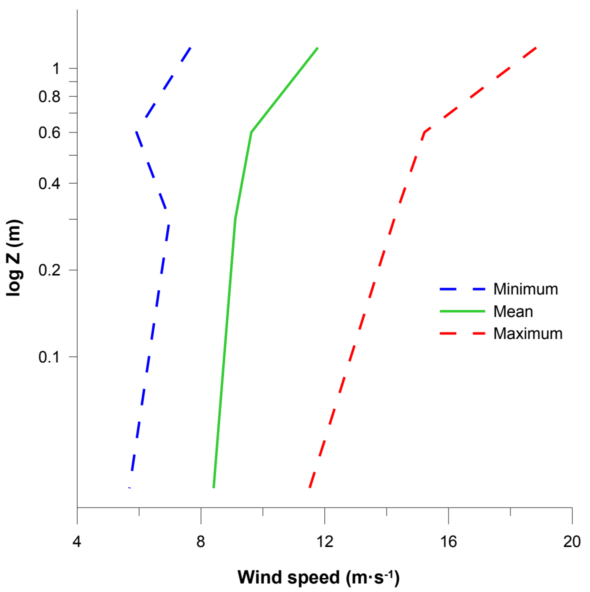

FIGURE 7. Vertical wind profile velocity (m·s^{-1}) for the dune crest area. Minimum, mean and maximum values were obtained during 198 minutes. Z (m): Height above the dune surface.

TABLE 3. Summary statistics from 198-minute anemometer time series (12:36 to 15:54) on March, 2012 during severe east winds

Height (m)	Average wind speed (m/s)					
	Min.	St. Dev.	Mean	St. Dev.	Max.	St. Dev.
1.35	9.96	4.53	17.86	2.42	25.53	2.49
1.18	7.66	0.78	11.78	1.60	18.84	2.35
0.60	5.92	0.88	9.63	1.84	15.22	1.60
0.30	6.99	0.67	9.11	0.99	14.24	1.73
0.035	5.69	0.74	8.41	1.23	11.51	1.16

DISCUSSION

Experimental results from sand trapping confirm that sand distribution with height follows a decreasing function, but this tendency is sharper above the dune crest than at the dune foot. After analysing grain size at the cross-dune profile, general trends confirm that both dune foot and dune crest sediments correspond to medium-grained sands. Results also confirm that sand is coarser at the dune foot and windward side than at the crest and leeward zone. Retained sand weight at the Valdevaqueros dune crest is considerably higher than at the dune foot as a result of grain size and wind velocity differences. This trend of the horizontal dune profile, in which there is reduction in the mean wind velocity in the toe region with a subsequent velocity acceleration up the windward slope to a maximum in the crest/brink region, is in close agreement with field and wind tunnel data presented by Lancaster *et al.* (1996), Wiggs *et al.* (1996), McKenna-Neuman *et al.* (1997, 2000) and Walker and Nickling (2002).

Because the sediment concentration of a sand mass flux decreases with height, the sampling efficiency increases rapidly with height above the bed surface. Hence, vertical traps seem to work adequately (efficiency>80%) at heights greater than 15mm above the bed. Closer to the bed, however, the open array trap catches about 70%. Since most of the transport takes place close to the surface, the overall efficiency of the field traps ranges from 50 to 70% (Rasmussen and Mikkelsen, 1998). As many vertical sand traps cannot be reoriented automatically in relation to wind direction changes, potential improvements on the design of this kind of traps could be taken into consideration in further researches. In spite of that, the placement of several anemometers and sand traps has showed to work successfully in the sand transport computation, given the amount of retained sand at the dune crest and the low wind direction variability at the area.

The implementation of the anemometer gauge has not only provided the extraction of the vertical wind profile velocity but also the identification of noticeable differences in wind speed with height. Whereas data registered from 1.18 to the upper anemometer at 1.35m show a significant wind speed increase of 34%, from 0.3 to 0.6m values are considerably similar (with 5.4% of increase). Hence, when deciding at which height the anemometer cups should be

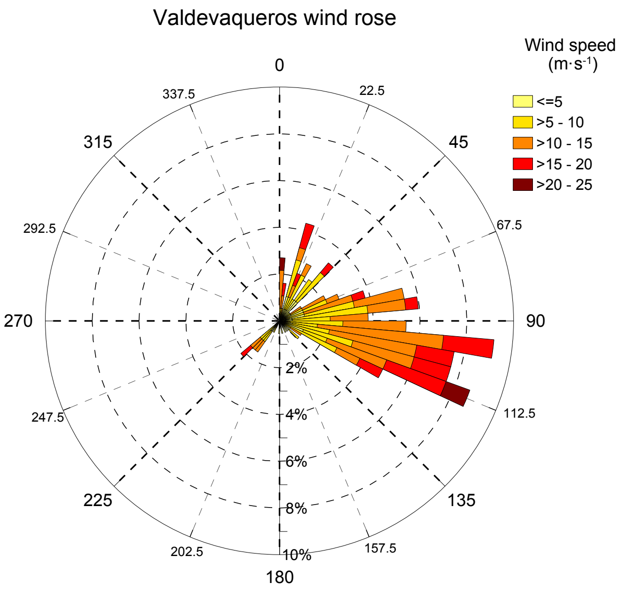

FIGURE 8. Valdevaqueros wind rose obtained during 198 minutes by the anemometer gauge for the dune crest area at 1.35m.

placed, it is important to consider where the wind velocity profile shows greater changes. In this case, if few devices are available, one of them could be placed close to the surface and the following one between 30 and 60cm over the dune surface.

Within the vertical profile above the dune surface, there is not a clear general tendency to decrease the mean grain size with height, which proves that the mean grain size does not have to be the only important feature conditioning sand transport.

Standard deviation values suggest the aleatory presence of grains and bioclasts of elongated morphology which can be kept on the upper compartments by suspension, due to their shape and density. In fact, as it has been stated by Iversen *et al.* (1976), the threshold velocity is directly related to grain density, so that the less dense materials will be remobilised with lower wind velocities, which means that aeolian transport of the medium sand fraction is more intense when presenting carbonate content (Alcántara-Carrió *et al.*, 2001).

After comparing theoretical and experimental sand transport results, values confirm that within the first 20 centimetres above the dune surface, there is a massive sand transport at the research area, in which rates obtained in situ are 0.9 to 3 times greater than those computed from different classical formulae.

On the other hand, the theoretical sand transport rates above 1.18m are much greater than the average real values; possibly due to the aforementioned grain size characteristics and wind speed increase at that height, although in general, sand transport measurements in situ approximate the Bagnold, and the Lettau and Lettau equations.

Actual sand transport rates are close to values obtained in other active dune fields, despite sometimes obey to an order of magnitude greater than other researches (as Serra *et al.*, 1997 or Cabrera and Alonso, 2010), which can be explained by the singularity of the strong and frequent wind regime that occur close to the Strait of Gibraltar and the existence of a large sand supply at the Valdevaqueros dune system.

CONCLUSIONS

Experimental data from field research by means of an array of anemometer cups and sand trap measurements have been employed to obtain theoretical and actual sand transports over a highly mobile dune in the SW of Spain.

Theoretical sand transport based on several classical formulae has been computed from the obtained vertical wind profile within 1.35m, finding average transport rates from 180 to 457m^{3}m^{-1}yr^{-1}.

Results obtained by the sand trap implementation show that under a moderate wind speeds (from 8.4 to 17.9ms^{-1}) and low wind direction variability, sand transport at the dune

TABLE 4. Comparison between theoretical sand transports and the actual sand transport obtained from the sand trap experiment for each height. Notation: Z (m): Given height above the dune surface; u_z; Mean wind velocity; u_* (m·s^{-1}): Threshold wind velocity; q_B: Sand transport by Bagnold; q_Z: Sand transport by Zingg; q_K: Sand transport by Kawamura; q_L: Sand transport by Lettau and Lettau; q_r: Real sand transport

			Transport rates (m^3·m^{-1}·yr^{-1})				Q ratio			
Z (m)	u_Z (m·s^{-1})	u_* (m·s^{-1})	q_B	q_Z	q_K	q_L	q_B / q_r	q_Z / q_r	q_K / q_r	q_L / q_r
1.35	17.86	0.60	1026.49	486.93	493.50	1421.92	2.49	1.18	1.20	3.45
1.18	11.78	0.40	304.78	144.58	126.31	278.01	0.74	0.35	0.31	0.67
0.6	9.63	0.35	198.92	94.36	70.29	138.24	0.48	0.23	0.17	0.34
0.3	9.11	0.35	204.46	96.99	73.24	145.14	0.50	0.24	0.18	0.35
0.035	8.41	0.41	322.59	153.02	135.65	302.85	0.78	0.37	0.33	0.74
Average	11.36	0.42	411.45	195.17	179.80	457.23	1.00	0.47	0.44	1.11

crest becomes 35 times the sand transport at the dune foot. Sand distribution with height follows a decreasing potential equation in which 90% of the total is retained within the first 20cm above the crest surface, demonstrating a massive dynamics at that interval of height, where actual sand transport rates turn out to be up to 3 times the computed theoretical rates. Identified average sand transport above the dune crest is of 412m3m-1yr-1, an order of magnitude greater than those obtained at other dune fields, which confirms that the Valdevaqueros dune is located in one of the most windiest points in Europe. In our case, average experimental results seem to fit better with the equations of Bagnold and Lettau and, Lettau for the dune crest area.

Statistical grain size parameters as mean diameter, sorting, skewness and kurtosis for each sand trap sample have also been analysed in this study. General trends show that dune crest sediments correspond to medium-grained sands (D_{50}=0.28mm) that are better sorted, coarse-skewed and mesokurtic at lower heights. In addition, the unclear mean grain size distribution with height assumes the presence of grains of different morphology and density that interact in the transport process by suspension at upper heights. Therefore, all these parameters as well as the morphology and composition of the grains should be taken into account since the mean grain size is not the only important feature conditioning sand transport.

Field measurements have identified a sharp increase of 34% in wind speed from 1.18 to 1.35m above the crest surface, which obviously can reflect non-realistic sand transport rates. On the other hand, lower differences of 5.4% in wind speed have been detected from 0.30 to 0.60m. This vertical wind profile velocity can help to determine optimum heights where to place limited anemometer gauges in future researches to achieve more accurate sand transport rates.

Although most of vertical sand traps cannot be reoriented automatically according to wind direction variability, the employed sand trap works out considerably practical in this kind of active dune fields to achieve a preliminary but reliable sand transport approach.

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