

UCLA

UCLA Previously Published Works

Title

Can active sands generate dust particles by wind-induced processes?

Permalink

<https://escholarship.org/uc/item/1g56n9v0>

Journal

Earth and Planetary Science Letters, 506

ISSN

0012-821X

Authors

Swet, Nitzan

Elperin, Tov

Kok, Jasper F

et al.

Publication Date

2019

DOI

10.1016/j.epsl.2018.11.013

Peer reviewed

1Can active sands generate dust particles by wind-induced processes?

2Nitzan Swet¹, Tov Elperin², Jasper F. Kok³, Raleigh L. Martin³, Hezi Yizhaq⁴, Itzhak Katra¹

3¹Department of Geography and Environmental Development, Ben Gurion University of the Negev,
4Beer-Sheva, Israel.

5²Department of Mechanical Engineering, The Pearlstone Center for Aeronautical Engineering Studies,
6Ben-Gurion University of the Negev, Beer-Sheva, Israel.

7³Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, USA.

8⁴Department of Solar Energy and Environmental Physics, BIDR, Ben-Gurion University of the Negev,
9Israel.

10:Email addresses

11Nitzan Swet – swet@post.bgu.ac.il

12Tov Elperin – elperin@bgu.ac.il

13Jasper F. Kok – jfkok@ucla.edu

14 Raleigh L. Martin – raleighmartin@gmail.com

15Hezi Yizhaq – hezi.yizhaq1@gmail.com

16Itzhak Katra – katra@bgu.ac.il

17Abstract

18Mineral dust emission is a major process in determining the global dust cycle. Surfaces
19composed of sand grains (dunes, sand sheets) cover more than 10 % of the Earth land
20surfaces, but also common on Mars. Active (dune) sands have been identified recently as
21dust sources in northern Africa, China, and elsewhere. Previous studies on dust emission
22from active sands suggested that dust can be generated by different aeolian mechanisms
23that are related to (i) re-emission of settled dust particles, (ii) clay coating removal, and (iii)
24abrasion of the sand grains. However, little empirical evidence of dust emission from active
25sands under natural conditions of wind (aeolian) transport has yet been reported. This study
26integrates wind tunnel experiments and high resolution laboratory sand analyses to explore
27aeolian dust emission from active sands with conditions simulating the natural processes of
28saltation. Sand samples from three sites with different characteristics of grain size, dust

content, morphology, and mineralogy were used in the experiments. The aeolian experiments were conducted under various wind velocities. No dust emission was recorded for shear velocities below the saltation threshold. Increasing the wind velocity above the saltation fluid threshold caused an increase in atmospheric PM_{10} concentrations, the magnitude of which depended on the specific shear velocity and the saltation flux. The initial content of dust-sized particles in the sand sample was found to influence PM_{10} emission. Higher PM_{10} concentrations were recorded from sand samples initially containing more than 2 % of dust-sized particles. The experiments identify clay coatings removal as the dominant mechanism over time of dust emission in typical active sand dunes (< 2 % dust content) with an addition of re-emission of existing dust-sized particles (< 63 μm). The rate of such re-emission is determined by the initial amount of dust-sized particles in the sand bed. The dust emission observed in this study indicates that, in addition to the classic dust sources of non-sandy soils, sand bodies should also be taken into consideration in determining global dust emission.

Keywords: Aeolian processes; Dust sources; PM_{10} ; Wind tunnel; Saltation

1. Introduction

Aeolian (wind-driven) dust emission has a major impact on a variety of environmental and socioeconomic issues. Airborne dust particles can affect climate (Nenes et al., 2014; Kok et al., 2017), biogeochemical cycles (Jickells et al., 2005), and soil ecology (Okin et al., 2004; Field et al., 2010). Substantial loss of nutrients and clays by dust emission reduces the soil fertility, leading to soil loss and degradation (Katra et al., 2016a). Dust events significantly increase air pollution (Katra et al., 2014a; Krasnov et al., 2016) and thus can impact human health (Vodonos et al., 2015). Models estimate that the global dust emission rate is between 500 $Tg\ yr^{-1}$ and ~ 4000 $Tg\ yr^{-1}$ (Evan et al., 2015; Huneeus et al., 2010; Kok et al., 2014a, 2017; Shao et al., 2011). Comparisons of model results against dust measurements still show

54large discrepancies (Evan et al., 2014; Huneus et al., 2010; Kok et al., 2014b) due to a
55number of major gaps in our understanding of dust source dynamics and mechanisms of dust
56emission. It is commonly assumed that dust sources consist of soils rich in clay and silt sized
57particles ($< 63 \mu\text{m}$ in diameter). These fine particles are subjected to cohesive inter-particle
58forces and therefore rarely occur as loose particles in soil but as part of aggregates.
59Therefore, impacts by saltating particles (sandblasting) have been found to play a major role
60in dust emission from soil aggregates (Alfaro et al., 1997; Kok et al., 2012, 2014a; Shao et al.,
611993; Shao, 2008; Swet and Kutra, 2016).

62 Little attention has been paid to the contribution of active sand dunes as dust sources.
63The possibility to generate dust, i.e., clay ($< 2 \mu\text{m}$ in diameter) and silt (between 2 and $63 \mu\text{m}$
64in diameter) sized particles from active sands has been suggested over the years. Active sand
65refers to un-stabilized (loose) sand-sized particles that are available for wind transport. Most
66studies dealing specific with active sand have proposed aeolian abrasion of the grains as the
67mechanism for dust generation (Bhattachan et al., 2012; Bullard et al., 2004, 2007; Crouvi et
68al., 2012; Sweeney et al., 2016; Wright et al., 1998). Aeolian abrasion refers to the reduction
69in the physical size and angularity of parent sands due to the impact of saltators at the sand
70bed or by particle collisions in the air (Bagnold, 1937; Jerolmack and Brzinski, 2010;
71Jerolmack et al., 2011; Kuenen, 1960). However, dust that is apparently generated by active
72sands may also be produced through other mechanisms: re-emission of dust previously
73trapped in dunes from exogenous sources (Muhs et al., 2008), and/or by the detachment of
74clay-rich coatings present on the surfaces of sand grains (Bullard and White, 2005). Studies
75have shown that many of the sand bodies worldwide consist of clays and iron oxides coatings
76above the sand grains (Walden and White, 1997).

77 A recent remote sensing study identified that over 40 % of dust storms in Northern Africa
78originate from areas covered by sand dunes (Crouvi et al., 2012). The occurrence of fine
79particle production from sand has also been deduced from field (Crouvi et al., 2008, 2012;

80Jerolmack and Brzinski, 2010; Jerolmack et al., 2011; Sweeney et al., 2016) and experimental
81(Bullard et al., 2004, 2007; Bullard and White, 2005; Kuenen, 1960; Smalley and Vita-Finzi,
821968; Whalley et al., 1982; Wright, 2001) studies. Field studies proposing aeolian abrasion as
83the primary generator of dust particles are based on identification of downwind fining of
84aeolian sediment. However, the observed spatial fining trends may also result from sorting or
85fractionation caused by differences in transportability of different grain sizes (Roskin et al.,
862014). In addition, the few existing studies on dust generation from active sand were
87performed under conditions that do not directly reproduce the natural processes of
88saltation. Thus, our understanding of aeolian dust emission from sands remains limited.

89 Sand dunes cover around 20 % of arid areas worldwide, and about half of them are
90considered as active sand dunes (Ashkenazy et al., 2012; Pye and Tsoar, 2009). Sand dunes
91are also a dominant formation covering wide areas of other planets as Mars and Venus
92(Claudin et al., 2006; Runyon et al., 2017). Typical active sand dunes are characterized by
93more than 98 % of sand-sized grains (63-2000 μm) with a size distribution mode of 200-300
94 μm (Ahlbrandt, 1979). In addition to sand dunes, there are other forms of active sand with
95different particle composition. Sandy soils contain relatively high percentages of clay-silt
96particles (up to ~ 10 %). Many of these arid soils are located in close proximity to dust
97sources and are subjected to aeolian deposition of airborne dust. Another sand form is
98mega-ripple fields composed of fine sand and very coarse sand with a mode of up to 2000
99 μm (Yizhaq and Katra, 2015). It can be hypothesized that different active sand compositions
100will respond differently to aeolian processes and produce different rates and types of dust
101emission over time.

102 Understanding the role of active sand as a dust source can provide a more accurate
103estimation of quantities and particle characteristics of global dust loading to the atmosphere,
104thereby reducing uncertainties in chemical transport and global climate models. It can also
105contribute to our understanding of sand transport and landscape development on both Earth

106and Mars. The aim of this study is to quantify dust emission from active sands under
107different conditions simulating the natural processes of saltation. The study integrates
108targeted laboratory experiments and sand analyses to fill this apparent research gap.

1092. Materials and Methods

1102.1. Sand samples

111Three samples of active sand were utilized to represent different sand particle compositions.
112Sand was collected from two dunefields in the northwestern Negev (N_1 and N_2), Israel, and
113from Oceano Dunes, California (C_1). In both sites there is an ongoing in-situ study of dust
114emission. The Negev dunefield is located in the eastern part of the Sinai-Negev Erg (Fig. S1).
115Currently some dunes are partially stabilized by biological crusts, but their crests are still
116active (Tsoar et al., 2008; Zaady et al., 2014). The Negev dune sand has a typical size of sand
117for active dunes (mode at $\sim 250 \mu\text{m}$; Roskin et al., 2014). The N_1 sample was taken from an
118active linear sand dune, and contains less than 2 % (by volume) of clay and silt-sized
119particles. N_2 was sampled in sand at the northernmost edge of the Negev dunefield. The
120sand of N_2 is composed of active sand with relatively high percentages of silt and clay sized
121particles ($< 63 \mu\text{m}$) of up to 10 %. The higher amount of dust in N_2 compared with N_1 is due
122to the proximity of N_2 to the Negev loess plane. Nevertheless, this region is associated with
123particle-size fractionation of aeolian sand transport along the Sinai-Negev erg (Roskin et al.,
1242014).

125 The Oceano dunefield on the Central Coast of California (Fig S1) was formed by strong
126onshore sea breezes transporting sand derived from fluvial deposits (Cooper, 1967), and thus
127contains a mixture of quartz, feldspar, and other minerals (Huang et al., 2018; Bedrossian
128and Schlosser, 2007). The sample from C_1 is composed of relatively coarse sand particles
129(mode $> 400 \mu\text{m}$) with low amount ($< 1 \%$) of dust sized particles (Huang et al., 2018; Martin
130et al., 2018). Sand samples from each site were taken from the upper 2-cm layer of the dunes
131for wind tunnel experiments and laboratory analyses.

1322.2. Aeolian experiments

133Laboratory wind tunnel experiments were performed to quantify dust emission from the
134sand samples. The experiments were conducted under various wind velocities, above and
135below the saltation threshold, to examine two components of dust emission: re-emission of
136loose dust particles in the sand samples by direct aerodynamic lifting (no saltation), and dust
137emission caused by saltation impacts onto the sand surface. For each wind velocity and sand
138sample, the wind profile was measured at different heights (cm) above the tunnel bed: 2,
1393.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, and 45 (Fig. S2). These wind profiles were used for
140determining shear velocities (u_* , m s^{-1}) following the logarithmic *law of the wall*.

141 The aeolian experiments were performed using the boundary-layer wind tunnel of Ben-
142Gurion University (BGU) described in Katra et al. (2014b). The BGU wind-tunnel is an open
143circuit tunnel consisting of three parts: an entrance cone, a test section, and a diffuser (Fig.
144S2). Air is sucked in through the bell-shaped entrance by a fan located at the end of the
145diffuser. The cross sectional area of the tunnel is $\sim 0.7 \times 0.7$ m and the working length is 7 m
146for measurements in the test section. The boundary layer in the wind tunnel is ~ 12 cm
147above the tunnel bed (Fig S2). For each experimental run at a specific shear velocity, the
148saltation flux remains constant (± 10 %) and does not fade or intensify over time (Katra et al.,
1492014b; Schmerler et al., 2016). Instruments installed in the wind tunnel enable the
150determination of the following parameters (Fig. S2B): (i) wind velocity in vertical and
151horizontal cross sections by micro-vane probes (www.kimo.com) for calculation of shear
152velocity (u_*); (ii) collection of saltating sand grains by an array of traps oriented along the
153wind direction for calculating average saltation mass flux ($\text{kg m}^{-1} \text{s}^{-1}$) over time. The traps
154were placed at heights of 2.5, 4.5, 6.5, 8.5 and 10.5 cm above ground, and each trap had a
155cross-sections of 2×1 cm; (iii) dust concentrations ($\mu\text{g m}^{-3}$) of particles that are less than 10
156 μm in aerodynamic diameter (PM_{10}) recorded by a light-scattering device, DustTrak DRX 8534
157(www.tsi.com), in the range of 0.001–150 mg m^{-3} (± 0.1 % of reading) at 1-second intervals

placed at 25 cm above the tunnel bed; (iv) collection of suspended dust by active (isokinetic filter) gravimetric samplers that include a pump to maintain a constant flow and an inertial Anderson impactor (Andersen Instruments Inc., USA) for dust characteristic analyses.

In each experiment, the sand was placed in a ~ 3-cm thick layer on the full length of the wind tunnel bed. The first test was conducted under a free stream wind speed of 4 m s^{-1} , corresponding to a shear velocity of 0.28 m s^{-1} , below the saltation threshold for each sample. The test was run for a relatively short time of 900 seconds. The second test was run under higher wind shear velocities and above the saltation threshold of the different samples, at $u_* = 0.30\text{--}0.36 \text{ m s}^{-1}$ ~ 5 m s^{-1} to ~ 8.5 m s^{-1} , measured at 25 cm above the tunnel bed). In this case, dust emission can be a result of sand abrasion and/or removal of coatings, but also by aerodynamic lifting of loose particles that are held between the coarser sand grains and may be released upon their movement or impacts during the saltation transport. The time duration of each experiment (shear velocity) was up to 9000 seconds (150 min), which is much longer than a single wind shear velocity would typically be sustained in the field. Wind events can last for hours, but the cumulative time of specific shear velocity at a specific direction will be significantly shorter.

Before each experiment, the PM_{10} background levels were measured inside the tunnel to account for noise in the measured PM_{10} signal. The measured background levels (~ $0.30 \mu\text{g m}^{-3}$) were subtracted from the data recorded during the experiment. In order to optimize the measurement procedure, the sand was manually recycled in the tunnel during these long tests to allow a sufficient sand supply and ensure a saturated airstream and steady-state saltation. Each test was repeated 3 times to determine the mean values of saltation and dust

emission. The recorded PM_{10} concentrations were converted into mass flux (F_{PM}) emitted from the soil surface ($\text{kg m}^{-2} \text{ s}^{-1}$) based on the wind tunnel dimensions and area of the sand bed:

183

$$(1) \quad F_{PM} = C_{PM} V_t / (A_p t)$$

184 Where C_{PM} is the recorded PM concentrations ($\mu\text{g m}^{-3}$), V_t is the volume air in the
185 wind tunnel (3.43 m^3), A_p is the area of the experimental plot (4.9 m^2), and t is time
186 (in Seconds) see Katra et al., 2016b. The PM_{10} ($\text{kg m}^{-2} \text{ s}^{-1}$) was used to calculate the
187 sandblasting efficiency a (m^{-1}):

188

$$(2) \quad a = F_{PM} / Q$$

189 Where Q ($\text{kg m}^{-1} \text{ s}^{-1}$) is the total horizontal sand flux integrated over all sand grain sizes (see
190 Kok et al., 2014a).

191 All of the above procedures were performed also on dust-free 'clean' sand to separate
192 between the mechanisms of dust emission. The raw sand (bulk samples) underwent a series
193 of gentle rinsing and washing to remove the loose dust-sized particles. Following the results
194 obtained for the bulk samples (see section 3; Fig. 4), in which the dust emission of C_1 sample
195 stopped after a period of time (reduced to the background values), and following a
196 preliminary experiment on 'clean' sand from C_1 sample, in which no dust emissions were
197 detected, the wind tunnel experiments on 'clean' sand were conducted only for N_1 and N_2
198 samples. 2.3. Particle analyses

199 Physical and chemical properties of the sand (from the tunnel bed before the aeolian
200 experiments and from the sand traps during the experiments) and of the dust (collected
201 during the experiments) were analyzed in the laboratory.

202 The Particle Size Distribution (PSD) was analyzed using an ANALYSETTE 22 MicroTec Plus
203 (Fritsch) laser diffractometer, which measures particles in the size range of $0.08\text{--}2000 \mu\text{m}$.
204 PSD data were calculated using the Fraunhofer diffraction model with a size resolution of 1
205 μm using MasControl software. The software was employed to determine the mean

206diameters, median diameters, modes of multi-modal distributions, sorting values, and size
207fraction weights. Mineralogical composition was analyzed using the X-ray power diffraction
208(XRPD) method (Philips 1050/70 power diffractometer). A Panalytical Empyrean Powder
209Diffractometer equipped with position sensitive detector X'Celerator was used. Data were
210collected in the $q/2q$ geometry using Cu K_{α} radiation ($\lambda=1.54178 \text{ \AA}$) at 40 kV and 30 mA.
211Scans were run during ~15 min in a $2q$ range of $4-60^{\circ}$ with step equal to $\sim 0.033^{\circ}$. Elemental
212composition analyses were performed by the X-Ray Fluorescence (XRF) method using an XRF
213spectrometer PANalytical Co., model Axios (wavelength dispersive -WDXRF, 1kW). The
214Omnian software was used for the quantitative analysis. Morphological and chemical
215characteristics of the particles were examined using a Scanning Electron Microscope (SEM)
216(Quanta 200, FEI). The high magnification ($6 \times$ to $> 1,000,000 \times$) enabled the analysis of the
217smallest dust particles ($< 2 \mu\text{m}$). Chemical analysis in this device was performed using the
218Energy Dispersive X-ray Spectroscopy (EDS). Sand-grain roundness was assessed for each
219SEM image using the grain roundness chart of Powers (1953).

2203. Results

221The PSDs of the three bulk samples used in the aeolian experiments are presented in Fig. 1.
222All the samples are characterized by a distribution with a single mode in the range of sand-
223sized particles. However, there are significant differences ($P \leq 0.05$) in the size mode and in
224the initial dust content between the samples. N_1 contains a relatively high percentage (58.7
225%) of medium-sized sand (250-500 μm), whereas N_2 is characterized by a relatively large
226amount (64.4 %) of fine sand (63-250 μm) compared to the N_1 dune (23.5 %). C_1 has a much
227coarser composition with 44.7 % of sand larger than 500 μm . All the samples contain dust-
228sized particles ($< 63 \mu\text{m}$) that can be found between or attached to the sand grains. N_2 dune
229can be considered as a "dusty" sand sample with 8.00 % content of dust-sized particles as
230opposed to only 1.81 % in N_1 and 0.95 % in C_1 (Fig. 1). In all the samples, over 60 % of the

dust sized fraction is fine particles ($< 20 \mu\text{m}$), which are subject to long-term suspension (Kok et al., 2017). The PM_{10} part out of the dust content is 64 % in N_2 and ~ 40 % in N_1 and C_1 samples.

Mineralogical analyses (XRPD) of the samples show that N_1 and N_2 consist of over 90 % quartz sand grains, while the C_1 sample is a mixture of quartz (45 %) and feldspar (K-silicate 30 % and Na-silicate 22 %) grains. From the SEM images it seems that N_1 and N_2 sand grains are characterized as sub-rounded grains with a relatively smooth surface (Fig. 2A, B). C_1 is composed of mostly sub-angular and angular sand grains (Fig. 2C). The feldspar sand grains look more angular and their surfaces are more abraded compared with the surfaces of the quartz sand grains (Fig. 2C). Clay and iron-rich coatings are found on top of the sand grains in all of the tested samples (Fig. 2D, E, F). Clay minerals were found also as part of the loose dust-sized particles ($< 63 \mu\text{m}$) within the sand samples (Fig. 2A).

Subjecting the bulk N_1 , N_2 , and C_1 samples to a range of wind velocities in the boundary layer wind tunnel (Fig. 3) revealed a distinct pattern in the measured atmospheric PM_{10} concentrations ($\mu\text{g m}^{-3}$), depending on initial dust content in the sand sample, shear velocity, and saltation flux (Fig. 1; Table 1). At low wind shear velocities below the saltation threshold of all samples ($< 0.29 \text{ m s}^{-1}$), no PM_{10} emissions were recorded (Figs. 3A, C, E). The threshold shear velocities were measured by a careful and gradual increase of the wind velocity in the tunnel to the moment of which the sand grains entered saltation transport. The recorded thresholds were 0.29 m s^{-1} (N_2), 0.30 m s^{-1} (N_1), and 0.33 m s^{-1} (C_1). Notably, the wind-tunnel observed threshold at C_1 is similar to the 0.32 m s^{-1} fluid threshold shear velocity calculated independently from field measurements by Martin and Kok (2018). At a wind shear velocity of 0.30 m s^{-1} , PM_{10} emission was recorded only in the N_2 sand (Fig. 3C) as a response to the initiation of saltation transport (Table 1). In the N_1 and C_1 samples, this wind was not sufficient for dust emission (Fig. 4A, E). In the N_1 sample, only a small amount of sand grains were ejected into saltation, while no sand transport was observed in the C_1 sample (Table 1).

257 Increasing the wind shear above the saltation threshold ($\geq 0.33 \text{ m s}^{-1}$) resulted in dust
 258 emission and enhanced PM_{10} concentrations for all sand samples. For each constant shear
 259 velocity experimental run, the dust emission over time was characterized by a distinct
 260 pattern of an initial sharp rise in PM_{10} concentrations, followed by a gradual decline until
 261 stabilizing at low values (Fig. 3B, D, F). However, clear differences in PM_{10} concentrations can
 262 be detected between the sand samples (Fig. 3B, D, F). The average PM_{10} concentration
 263 produced by the N_2 sample was ~ 8 times higher than by N_1 , although both sand samples
 264 produced very similar saltation fluxes (Table 1). The saltation flux (Table 1) of the courser
 265 saltating particles of C_1 ($418 \text{ } \mu\text{m}$; Fig. 4) was found to be greater than in
 266 N_1 and N_2 samples under shear velocity of 0.36 m s^{-1} , although the amount of particles
 267 entering transport is expected to be lower than in N_1 and N_2 samples. However, the
 268 calculated sandblasting efficiency (m^{-1}), which is the ratio of the dust emission flux ($\text{kg m}^{-2} \text{ s}^{-1}$)
 269 to the sand saltation flux ($\text{kg m}^{-1} \text{ s}^{-1}$), is substantially smaller for C_1 than for the samples from
 270 the other sites under all shear velocities. In all samples there was an increase in sandblasting
 271 efficiency with shear velocity (Table 1). The highest efficiency obtained was for the N_2
 272 sample, although associated saltation fluxes were similar to those from the N_1 sample. The
 273 efficiency recorded for C_1 sample is considered as relatively low but with a close proximity to
 274 those found in a field experiment in Oceano dunes (10^{-6} m^{-1} ; Huang et al., 2018). The
 275 sandblasting efficiency reduces in all sand samples as the PM_{10} emission decreases over time,
 276 while the saltation flux remains constant. The efficiency results obtained for all of the sand
 277 samples (10^{-7} to 10^{-4} m^{-1}) were found as smaller than typical non-sandy soils (10^{-4} to 10^{-2} m^{-1})
 278 (Kok et al., 2012).

279 Following the results of the bulk sand samples (Fig. 3), only N_1 and N_2 samples were
 280 washed of loose dust particles to examine the emission mechanisms. The cleaning of the
 281 sand samples did not have any mineralogical, chemical, or physical effect on the sand grains
 282 or on the coatings on the grain surfaces (Fig. 5). The cleaning of the sand only reduced the

283 amount of dust-sized particles in the sand to a minimum of no more than 0.6 % in both N₁
284 and N₂ samples (Table. S1). The PM₁₀ concentrations produced from the 'clean' sand were
285 lower than those from the bulk samples (Fig. 6), while the saltation fluxes did not change
286 ($2.89 \times 10^{-3} \text{ kg m}^{-1} \text{ s}^{-1}$ for 'clean' N₁ and $2.98 \times 10^{-3} \text{ kg m}^{-1} \text{ s}^{-1}$ for 'clean' N₂). The resulted dust
287 emission from N₁ and N₂ 'clean' sand samples show similar PM₁₀ concentrations (red line, Fig.
288 6) with $56.5 \mu\text{g m}^{-3}$ and $60.5 \mu\text{g m}^{-3}$, respectively.

289 The dust emitted during the aeolian experiments was collected for laboratory analysis
290 (Fig. 7). The SEM images indicate that the emitted dust from the N₁ and N₂ bulk samples are
291 composed mostly of clay minerals (Fig. 7A, B). The chemical and mineralogical composition
292 of the emitted dust of the bulk samples was similar to that of the loose dust-sized particles
293 found between sand grains and to the coatings on top of the grain surfaces (Fig. 2). Only a
294 few isolated quartz fragments were found among the dust particles. In the C₁ sample, the
295 emitted dust consists of a mixture of clays, feldspar, and quartz particles, in comparable
296 quantities (Fig. 7C). The quartz fragments were relatively coarser (30-40 μm) than the
297 feldspar and the clay particles (< 20 μm). The analysis of the emitted dust from the 'clean'
298 sand samples (N₁ and N₂) show similar composition to those of the bulk samples, with mostly
299 clay minerals and only some single coarser quartz fragments (> 40 μm) (Fig. 7D, E).

3004. Discussion

301 By subjecting three distinctive natural sand samples to a range of wind strengths in a
302 laboratory wind tunnel, we were able to simulate the process of dust emission from active
303 sands during aeolian saltation. Throughout the experiments, it was found that dust emission
304 from the sand samples was directly associated with the occurrence of saltation transport,
305 where PM₁₀ emission occurs only in the presence of saltation (Fig. 3; Table 1). As such, direct
306 aerodynamic entrainment of dust was not detectable. Dust emission from active sand in our
307 experiments thus requires that wind strength exceeds the threshold shear velocity, which in

turn depends on the surface PSD (Bagnold, 1937; Kok et al., 2012; Schmerler et al., 2016). In the N_2 sample, the PSD (mode of 251 μm) is finer than for the N_1 and C_1 samples (modes at 342 μm and 461 μm , respectively), and therefore its threshold shear velocity is lower (0.29 m s^{-1}).

For a specific shear velocity and saltation flux, the dust emission flux appears to be primarily controlled by the dust-sized particle content of the sand surface. The results show that when the wind shear was strong enough ($\geq 0.33 \text{ m s}^{-1}$) the saltation flux of N_1 and N_2 samples was similar (Table 1). However, the recorded PM_{10} and therefore the calculated sandblasting efficiency were much higher for N_2 than for N_1 (Table 1). The reason for these differences can be explained by the higher initial content of dust in the N_2 sand sample. N_2 contains relatively high amounts of dust-sized particles, especially PM_{10} particles (Fig. 1). It is hypothesized that the dust flux emitted per unit horizontal saltation flux increases sharply with the content of fine particles (Kok et al., 2014a; Marticorena and Bergametti, 1995). In the C_1 sample, for which the highest saltation fluxes were recorded, the PM_{10} concentration (and thus also sandblasting efficiency) was much lower. C_1 is composed of coarser sand with a mode of 417 μm (Fig. 1), and therefore the sand grains will enter into saltation transport only at higher wind velocities (Table 1), and thus dust emission will also be confined to higher wind velocities (Fig. 3), although the number of saltating particles for the C_1 sample can be much smaller than in N_1 and N_2 samples for a specific wind shear velocity. Therefore, the relatively low sandblasting efficiency of C_1 , which is consistent with field measurements at the collection site (Huang et al., 2018), is likely related to the low initial PM_{10} content (0.41%).

The PM_{10} emission patterns observed in the wind tunnel experiments (Fig. 3) provide evidence for the relative importance of three possible dust emission mechanisms for sandy surfaces: (i) re-emission of previously settled dust particles in the sand (Muhs et al., 2008), (ii) clay coating removal from sand grains (Bullard and White, 2005), and (iii) abrasion of the

sand grains (Bhattachan et al., 2012; Bullard et al., 2007; Sweeney et al., 2016; Wright et al., 1998). The sharp increase in dust concentrations obtained at the beginning of saltation (Fig. 3B, D, F) can be generated from one or all of mechanisms listed above. However, the subsequent gradual decrease in the PM₁₀ concentrations may indicate gradual exhaustion of the limited supply of loose dust particles for direct re-emission as the saltation flux remains the same over time (Zhang et al., 2016). From the results it seems that N₁ and N₂ samples have comparable sand characteristics of mineralogy, grain roundness, and saltator PSD, in addition to the similar saltation fluxes (Fig. 2; Fig. 4; Table 1); thus, no difference is expected in the mechanism generating the dust emission. Therefore the differences observed in the sandblasting efficiency and thus in the PM₁₀ emission (Table 1) can thus be related to the higher initial content of loose dust-sized particles in N₂ (Fig. 1).

Comparing the PM₁₀ emission patterns of the bulk samples to those of the 'clean' sand samples can provide further evidence for the relative importance of the different dust emission mechanisms (Fig. 6). Both 'clean' sand samples of N₁ and N₂ emitted very similar and relatively low amounts of PM₁₀ over time ($u=0.36 \text{ m s}^{-1}$), while the bulk samples showed significant differences in PM₁₀ concentration in the beginning of each experiment (Fig. 6). After a period of time when the loose dust is emitted, the dust emission from the bulk samples reaches the minimum value of the 'clean' sand emission of $\sim 0.06\text{-}0.1 \mu\text{g m}^{-3}$ (N₁ after ~ 300 seconds; N₂ after ~ 7000 seconds, Fig. 3). The differences in PM₁₀ concentrations found between the bulk samples (Fig. 3) can be related to the initial amount of loose dust-sized particles in the sand (Fig. 1). Therefore it can be assumed that in typical dune sands like the N₁ sample, which contains $< 2 \%$ of dust-sized particles, the re-emission of loose dust is relatively minor (Fig. 6A) and the continuous PM₁₀ emission over time (Fig. 3B, D) is controlled by clay coating removal and/or abrasion.

The analysis of the emitted dust particles collected during the aeolian experiments provides further evidence for the relative contributions of the different dust emission

mechanisms. The dust emitted from the N_1 and N_2 bulk samples consisted mostly of very fine particles of clay minerals (Fig. 7A, B), indicating similar primary dust sources from loose dust particles contained in the pore spaces among sand bed grains and from the coatings on these sand grains (Fig. 2). The fact that the dust emitted from the 'clean' sand of both N_1 and N_2 samples had barely any PM_{10} quartz particles (Fig. 7D, E), and that the clay dust particles are similar to the coatings found on top of the 'clean' sand grains (Fig. 5), [indicate](#) the dominance of the clay coating removal mechanism in these samples.

The kinetic energy reached by coarse grains (C_1) during saltation is higher than for finer grains (i.e., sand in the N samples) (Kok et al., 2012), thereby enhancing their potential for aeolian abrasion. In addition, the relatively sharp-edged grains of C_1 have greater potential to break during saltation to produce coarse dust particles. Saltation of rounded sand like N_1 and N_2 was found to be less efficient than saltation of angular sand at generating dust in abrasion (Bullard et al., 2004; Kuenen, 1960; Whalley et al., 1982; Wright et al., 1998). In typical active desert sand dunes, where quartz sand grains (N_1 , N_2) tend to be smaller and more rounded (compared to coastal sites as C_1), aeolian abrasion is therefore suggested to play a very minor role as a dust generator. In addition, the relatively large-sized quartz dust particles (20-63 μm) that may be released by abrasion will not suspend for long distances in a wind event as the fine dust ($< 20 \mu m$) (Kok et al., 2017; Mahowald et al., 2014; Nenes et al., 2014). Consequently, dust emission by aeolian abrasion is likely to play a relatively small role in global dust emissions.

The dust emission flux (Table 1) recorded from all of our sand samples are considered as very low compared to those produced by many other global dust sources. For example, the results obtained for N_2 sample were 10 times lower than those received during aeolian wind tunnel experiments in natural (undisturbed) Loess soils (northern Negev-Israel), which contain more than 40 % dust-sized particles under similar wind velocity of $\sim 7 m s^{-1}$ (Swet and Kutra, 2016; Tanner et al., 2016). However, even the lower PM_{10} concentrations from

386active sands can be significant when considering the wide extent of dune fields around the
387globe. A quantitative assessment of the potential of dust emission from global active sand
388dunes is thus needed to establish its contribution to the global dust cycle.

389 It should be noted that the aeolian saltation and dust emission in our experiments differ
390from natural settings in two key ways. First, whereas our experiments sustained a constant
391wind velocity and direction over a long duration to utilize the full emission potential of the
392sand bed, typical wind gust events that enable dust emission are significantly shorter in time.
393Second, whereas dust was only emitted from the wind tunnel during any particular
394experimental run, surface dust supply in natural sand dunes can be renewed by deposition of
395dust originating from nearby source areas. Thus, the depletion of dust under sustained wind
396and non-renewing conditions may have led to lower dust emission rates in our experiments
397than in similar natural settings.

3985. Conclusions

399Large discrepancies in global dust emission models arise from a number of major gaps in our
400understanding of the dust emission mechanisms from different source areas. This study
401utilized aeolian experiments to explore the potential for dust emission from sands containing
402different sample compositions, and to distinguish the different mechanisms of dust
403generation from sand. We provided empirical evidence that dust can be emitted from active
404sands under natural conditions of saltation, where significantly higher PM_{10} concentrations
405were generated from sands that initially contained more than 2 % dust.

406 The results obtained in this study provide insight into the dust generation mechanisms
407from active sand dunes. Our results indicate that the dominant dust emission mechanism
408over time for typical active sand dunes (< 2 % dust content) is clay coatings removal, with a
409relatively small contribution from re-emission of loose-settled dust. In sands containing

410higher amounts of dust-sized particles, the relative contribution of the re-emission
411mechanism increases drastically.

412 Despite the commonly accepted hypothesis for dust emission from active sands by the
413aeolian abrasion mechanism, this study suggests, based on analyses of emitted dust
414particles, that abrasion has only a minor contribution to dust generation from active sands,
415and largely produces coarse dust particles ($> 30 \mu\text{m}$). Although the dust emission rates from
416sand recorded in this study are lower in comparison to emission rates from classic dust
417sources of non-sandy soils, the spatial extent of sand bodies is substantial, such that they
418should be taken into consideration in determining global dust emissions. Further analyses of
419the characteristics of dust emitted from sand dunes, such as chemical composition and size
420distribution, are needed for better representation of dust in climate models.

421**Acknowledgments**

422We thank Yue Huang for her help in sand sampling in Oceano dunes and for providing
423comments that helped improve the manuscript. The study was supported by a grant from
424the United States-Israel Binational Science Foundation (2014178), and by the U.S. National
425Science Foundation (NSF) Postdoctoral Fellowship EAR-1249918 to R.L.M. and NSF grant
426AGS-1358621 to J.F.K.

427**6. References**

428Ahlbrandt, T.S., 1979. Textural parameters of aeolian deposits. In McKee E.D., (ed.) A Study of
429 Global Sand Seas. U.S. Geological Survey Prof. Paper, Vol. 1052, 21-52.

430Alfaro, S.C., Gaudichet, A., Gomes, L., Maillé, M., 1997. Modeling the size distribution of a
431 soil aerosol produced by sandblasting. *Journal of Geophysical Research: Atmospheres*,
432 102(D10), 11239-11249. <https://doi.org/10.1029/97JD00403>

433 Ashkenazy, Y., Yizhaq, H., Tsoar, H., 2012. Sand dune mobility under climate change in the
 434 Kalahari and Australian deserts. *Climatic Change*, 112(3-4), 901-923.
 435 <https://doi.org/10.1007/s10584-011-0264-9>

436 Bagnold, R.A., 1937. The Transport of Sand by Wind. *The Geographical Journal*, 89(5), 409.
 437 <https://doi.org/10.2307/1786411>

438 Bedrossian, T.L., Schlosser, J.P., 2007. Review of Vegetation Islands, Executive Summary,
 439 Oceano Dunes SVRA, Sacramento, CA: California Geological Survey.

440 Bhattachan, A., D'Odorico, P., Baddock, M.C., Zobeck, T.M., Okin, G.S., Cassar, N., 2012. The
 441 Southern Kalahari: a potential new dust source in the Southern Hemisphere?
 442 *Environmental Research Letters*, 7(2), 24001. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/7/2/024001)
 443 [9326/7/2/024001](https://doi.org/10.1088/1748-9326/7/2/024001)

444 Bullard, J.E., McTainsh, G.H., Pudmenzky, C., 2004. Aeolian abrasion and modes of fine
 445 particle production from natural red dune sands: an experimental study. *Sedimentology*,
 446 51(5), 1103-1125. <https://doi.org/10.1111/j.1365-3091.2004.00662.x>

447 Bullard, J.E., McTainsh, G.H., Pudmenzky, C., 2007. Factors affecting the nature and rate of
 448 dust production from natural dune sands. *Sedimentology*, 54(1), 169-182.
 449 <https://doi.org/10.1111/j.1365-3091.2006.00827.x>

450 Bullard, J.E., White, K., 2005. Dust production and the release of iron oxides resulting from
 451 the aeolian abrasion of natural dune sands. *Earth Surface Processes and Landforms*,
 452 30(1), 95-106. <https://doi.org/10.1002/esp.1148>

453 Claudin, P., Andreotti, B., 2006. A scaling law for aeolian dunes on Mars, Venus, Earth, and for
 454 subaqueous ripples. *Earth and Planetary Science Letters*, 252(1-2), 30-44.
 455 [https://doi:10.1016/j.epsl.2006.09.004](https://doi.org/10.1016/j.epsl.2006.09.004)

456 Cooper, W.S., 1967. Coastal dunes of California, Geological Society of America, 1-147.
 457 <https://doi.org/10.1130/MEM104-p1>

458Crouvi, O., Schepanski, K., Amit, R., Gillespie, A.R., Enzel, Y., 2012. Multiple dust sources in
459 the Sahara Desert: The importance of sand dunes. *Geophysical Research Letters*, 39(13).
460 <https://doi.org/10.1029/2012GL052145>

461Crouvi, O., Amit, R., Enzel, Y., Porat, N., Sandler, A., 2008. Sand dunes as a major proximal
462 dust source for late Pleistocene loess in the Negev Desert, Israel. *Quaternary Research*,
463 70(2), 275–282. <https://doi.org/10.1016/J.YQRES.2008.04.011>

464Evan, A.T., Flamant, C., Fiedler, S., Doherty, O., 2014. An analysis of aeolian dust in climate
465 models. *Geophysical Research Letters*, 41(16), 5996–6001.
466 <https://doi.org/10.1002/2014GL060545>

467Evan, A.T., Fiedler, S., Zhao, C., Menut, L., Schepanski, K., Flamant, C., Doherty, O., 2015.
468 Derivation of an observation-based map of North African dust emission. *Aeolian*
469 *Research*, 16, 153–162. <https://doi.org/10.1016/J.AEOLIA.2015.01.001>

470Field, J.P., Belnap, J., Breshears, D.D., Neff, J.C., Okin, G.S., Whicker, J.J., Painter, T.H., Ravi, S.,
471 Reheis, M.C., Reynolds, R.L., 2010. The ecology of dust. *Frontiers in Ecology and the*
472 *Environment*, 8(8), 423–430. <https://doi.org/10.1890/090050>

473Huang, Y., Kok, J.F., Martin, R.L., Swet, N., Katra, I., Gill, T.E., Reynolds, R.L., Freire, L.S., (under
474 review) Fine dust emissions from coastal Oceano Sand Dunes. *Journal of Geophysical*
475 *Research*.

476Huneeus, N., Schulz, M., Balkanski, Y., Griesfeller, J., Kinne, S., Prospero, J., ... Zender, C.
477 (2010). Global dust model intercomparison in AeroCom phase I. *Atmospheric Chemistry*
478 *and Physics Discussions*, 10(10), 23781–23864. [https://doi.org/10.5194/acpd-10-23781-](https://doi.org/10.5194/acpd-10-23781-2010)
479 2010

480Jerolmack, D.J., Brzinski, T.A., 2010. Equivalence of abrupt grain-size transitions in alluvial
481 rivers and eolian sand seas: A hypothesis. *Geology*, 38(8), 719–722.
482 <https://doi.org/10.1130/G30922.1>

483 Jerolmack, D.J., Reitz, M.D., Martin, R.L., 2011. Sorting out abrasion in a gypsum dune field.
 484 Journal of Geophysical Research, 116(F2), F02003.
 485 <https://doi.org/10.1029/2010JF001821>
 486 Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., ... Torres, R.
 487 (2005). Global iron connections between desert dust, ocean biogeochemistry, and
 488 climate. Science (New York, N.Y.), 308(5718), 67–71.
 489 <https://doi.org/10.1126/science.1105959>
 490 Katra, I., Gross, A., Swet, N., Tanner, S., Krasnov, H., Angert, A., 2016a. Substantial dust loss of
 491 bioavailable phosphorus from agricultural soils. Scientific Reports, 6.
 492 <https://doi.org/10.1038/srep24736>
 493 Katra, I., Elperin, T., Fominykh, A., Krasovitev, B., Yizhaq, H., 2016b. Modeling of particulate
 494 matter transport in atmospheric boundary layer following dust emission from source
 495 areas. Aeolian Research, 20, 147–156. <https://doi.org/10.1016/j.aeolia.2015.12.004>
 496 Katra, I., Arotsky, L., Krasnov, H., Zaritsky, A., Kushmaro, A., Ben-Dov, E., 2014a. Richness and
 497 diversity in dust stormborne biomes at the southeast mediterranean. Scientific Reports,
 498 4, 5265. <https://doi.org/10.1038/srep05265>
 499 Katra, I., Yizhaq, H., Kok, J.F., 2014b. Mechanisms limiting the growth of aeolian megaripples.
 500 Geophysical Research Letters, 41(3), 858–865. <https://doi.org/10.1002/2013GL058665>
 501 Kok, J.F., Ridley, D.A., Zhou, Q., Miller, R.L., Zhao, C., Heald, C.L., ... Haustein, K., 2017. Smaller
 502 desert dust cooling effect estimated from analysis of dust size and abundance. Nature
 503 Geoscience, 10(4), 274–278. <https://doi.org/10.1038/ngeo2912>
 504 Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and
 505 dust. Reports on progress in Physics, 75(10), 106901. [https://doi.org/10.1088/0034-](https://doi.org/10.1088/0034-4885/75/10/106901)
 506 4885/75/10/106901
 507 Kok, J.F., Mahowald, N.M., Fratini, G., Gillies, J.A., Ishizuka, M., Leys, J.F., Mikami, M., 2014a.
 508 An improved dust emission model – Part 1: Model description and comparison against

509 measurements. *Atmos. Chem. Phys.*, 14, 13023–13041. <https://doi.org/10.5194/acp-14->
510 13023-2014

511Kok, J.F., Albani, S., Mahowald, N.M., Ward, D.S., 2014b. An improved dust emission model –
512 Part 2: Evaluation in the Community Earth System Model, with implications for the use of
513 dust source functions. *Atmos. Chem. Phys.* 14, 13043–13061.
514 <https://doi.org/10.5194/acp-14-13043-2014>

515Krasnov, H., Katra, I., Friger, M., 2016. Increase in dust storm related PM10 concentrations: A
516 time series analysis of 2001–2015. *Environmental Pollution*, 213, 36–42.
517 <https://doi.org/10.1016/J.ENVPOL.2015.10.021>

518Kuenen, P.H., 1960. Experimental Abrasion 4: Eolian Action. *The Journal of Geology*, 68(4),
519 427–449. <https://doi.org/10.1086/626675>

520Mahowald, N., Albani, S., Kok, J. F., Engelstaeder, S., Scanza, R., Ward, D.S., Flanner, M.G.,
521 2014. The size distribution of desert dust aerosols and its impact on the Earth system.
522 *Aeolian Research*, 15, 53–71. <https://doi.org/10.1016/J.AEOLIA.2013.09.002>

523Marticorena, B., Bergametti, G., 1995. Modeling the atmospheric dust cycle: 1. Design of a
524 soil-derived dust emission scheme, *J. Geophys. Res. Atmos.*, 100(D8), 16415–16430.
525 <https://doi:10.1029/95JD00690>

526Martin, R.L., Kok, J.F., Hugenholtz, C.H., Barchyn, T.E., Chamecki, M., Ellis, J.T., 2018. High-
527 frequency measurements of aeolian saltation flux: Field-based methodology and
528 applications. *Aeolian Res.* 30, 97–114. <https://doi.org/10.1016/j.aeolia.2017.12.003>

529Martin, R.L., Kok, J.F., 2018. Distinct thresholds for the initiation and cessation of aeolian
530 saltation from field measurements. *Journal of Geophysical Research - Earth Surface*
531 (accepted manuscript).

532Muhs, D.R., Budahn, J.R., Johnson, D.L., Reheis, M., Beann, J., Skipp, G., ... Jones, J.A., 2008.
533 Geochemical evidence for airborne dust additions to soils in Channel Islands National

534 Park, California. Geological Society of America Bulletin, 120(1-2), 106-126.
 535 <https://doi.org/10.1130/B26218.1>
 536 Nenes, A., Murray, B., Bougiatioti, A., 2014. Mineral Dust and its Microphysical Interactions
 537 with Clouds. In Mineral Dust (pp. 287-325). Dordrecht: Springer Netherlands.
 538 https://doi.org/10.1007/978-94-017-8978-3_12
 539 Okin, G.S., Mahowald, N., Chadwick, O.A., Artaxo, P., 2004. Impact of desert dust on the
 540 biogeochemistry of phosphorus in terrestrial ecosystems. Global Biogeochemical Cycles,
 541 18(2). <https://doi.org/10.1029/2003GB002145>
 542 Powers, M.C., 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary
 543 Petrology, 23(117-119).
 544 <https://doi.org/10.1306/D4269567-2B26-11D7-8648000102C1865D>.
 545 Pye, K., Tsoar, H., 2009. Aeolian Sand and Sand Dunes. Berlin, Heidelberg: Springer Berlin
 546 Heidelberg. <https://doi.org/10.1007/978-3-540-85910-9>
 547 Roskin, J., Katra, I., Blumberg, D.G., 2014. Particle-size fractionation of eolian sand along the
 548 Sinai-Negev erg of Egypt and Israel. Geological Society of America Bulletin, 126(1-2), 47-
 549 65. <https://doi.org/10.1130/B30811.1>
 550 Runyon, K.D., Bridges, N.T., Ayoub, F., Newman, C.E., Quade, J.J., 2017. An integrated model
 551 for dune morphology and sand fluxes on Mars. Earth and Planetary Science Letters, 457,
 552 204-212. <https://doi.org/10.1016/j.epsl.2016.09.054>
 553 Schmerler, E., Katra, I., Kok, J.F., Tsoar, H., Yizhaq, H., 2016. Experimental and numerical study
 554 of Sharp's shadow zone hypothesis on sand ripple wavelength. Aeolian Research, 22, 37-
 555 46. <https://doi.org/10.1016/J.AEOLIA.2016.05.006>
 556 Shao, Y., 2008. Physics and modelling wind erosion. Springer.
 557 Shao, Y., Raupach, M.R., Findlater, P.A., 1993. Effect of saltation bombardment on the
 558 entrainment of dust by wind. Journal of Geophysical Research, 98(D7), 12719.
 559 <https://doi.org/10.1029/93JD00396>

560 Shao, Y., Ishizuka, M., Mikami, M., Leys, J.F., 2011. Parameterization of size-resolved dust
561 emission and validation with measurements. *Journal of Geophysical Research*, 116(D8),
562 D08203. <https://doi.org/10.1029/2010JD014527>

563 Smalley, I.J., Vita-Finzi, C., 1968. The formation of fine particles in sandy deserts and the
564 nature of 'desert' loess. *Journal of Sedimentary Research*, 38(3), 766–774.

565 Sweeney, M.R., Lu, H., Cui, M., Mason, J.A., Feng, H., Xu, Z., 2016. Sand dunes as potential
566 sources of dust in northern China. *Science China Earth Sciences*, 59(4), 760–769.
567 <https://doi.org/10.1007/s11430-015-5246-8>

568 Swet, N., Katra, I., 2016. Reduction in soil aggregation in response to dust emission
569 processes. *Geomorphology*, 268, 177–183.
570 <https://doi.org/10.1016/j.geomorph.2016.06.002>

571 Tanner, S., Katra, I., Haim, A., Zaady, E., 2016. Short-term soil loss by eolian erosion in
572 response to different rain-fed agricultural practices. *Soil and Tillage Research*.
573 <https://doi.org/10.1016/j.still.2015.08.008>

574 Tsoar, H., Blumberg, D.G., Wenkart, R., 2008. Formation and Geomorphology of the North-
575 Western Negev Sand Dunes. Springer, Berlin, Heidelberg., 25–
576 48) https://doi.org/10.1007/978-3-540-75498-5_3

577 Vodonos, A., Friger, M., Katra, I., Krasnov, H., Zahger, D., Schwartz, J., Novack, V., 2015.
578 Individual Effect Modifiers of Dust Exposure Effect on Cardiovascular Morbidity. *PLOS*
579 *ONE*, 10(9), e0137714. <https://doi.org/10.1371/journal.pone.0137714>

580 Walden, J., White, K., 1997. Investigation of the controls on dune colour in the Namib Sand
581 Sea using mineral magnetic analyses. *Earth and Planetary Science Letters*, 125, 187–201.
582 [https://doi.org/10.1016/S0012-821X\(97\)00154-4](https://doi.org/10.1016/S0012-821X(97)00154-4).

583 Whalley, W.B., Marshall, J.R., Smith, B.J., 1982. Origin of desert loess from some
584 experimental observations. *Nature*, 300(5891), 433–435.
585 <https://doi.org/10.1038/300433a0>

586 Wright, J., 2001. Making loess-sized quartz silt: data from laboratory simulations and
587 implications for sediment transport pathways and the formation of “desert” loess
588 deposits associated with the Sahara. *Quaternary International*, 76–77, 7–19.
589 [https://doi.org/10.1016/S1040-6182\(00\)00085-9](https://doi.org/10.1016/S1040-6182(00)00085-9)

590 Wright, J., Smith, B., Whalley, B., 1998. Mechanisms of loess-sized quartz silt production and
591 their relative effectiveness: laboratory simulations. *Geomorphology*, 23(1), 15–34.
592 [https://doi.org/10.1016/S0169-555X\(97\)00084-6](https://doi.org/10.1016/S0169-555X(97)00084-6)

593 Yizhaq, H., Katra, I., 2015. Longevity of aeolian megaripples. *Earth and Planetary Science*
594 *Letters*, 422, 28–32. <https://doi.org/10.1016/J.EPSL.2015.04.004>

595 Zaady, E., Katra, I., Yizhaq, H., Kinast, S., Ashkenazy, Y., 2014. Inferring the impact of rainfall
596 gradient on biocrusts’ developmental stage and thus on soil physical structures in sand
597 dunes. *Aeolian Research*, 13, 81–89. <https://doi.org/10.1016/J.AEOLIA.2014.04.002>

598 Zhang, J., Teng, Z., Huang, N., Guo, L., Shao, Y., 2016. Surface renewal as a significant
599 mechanism for dust emission. *Atmos. Chem. Phys.* 16, 15517–15528.
600 <https://doi.org/10.5194/acp-16-15517-2016>

601 **Tables**

	0.28	0.30	0.33	0.36
N ₁ saltation	0.00	1.46×10 ⁻⁴	1.27×10 ⁻³	2.13×10 ⁻³
N ₂ saltation	0.00	1.22×10 ⁻³	1.19×10 ⁻³	2.29×10 ⁻³
C ₁ saltation	0.00	0.00	8.53×10 ⁻⁴	5.68×10 ⁻³
N ₁ PM ₁₀	0.00	0.01 (1.66×10 ⁻¹⁰)	13.64 (9.17×10 ⁻⁹)	66.08 (4.52×10 ⁻⁸)
N ₂ PM ₁₀	0.00	28.65 (5.66×10 ⁻⁹)	248.34 (8.92×10 ⁻⁸)	1065.86 (3.24×10 ⁻⁷)
C ₁ PM ₁₀	0.00	0.00	4.00 (6.67×10 ⁻¹⁰)	23.36 (2.03×10 ⁻⁸)
N ₁ efficiency	N/A	1.73×10 ⁻⁷	4.64×10 ⁻⁶	1.37×10 ⁻⁵
N ₂ efficiency	N/A	3.88×10 ⁻⁵	7.03×10 ⁻⁵	1.52×10 ⁻⁴
C ₁ efficiency	N/A	N/A	7.81×10 ⁻⁷	3.58×10 ⁻⁶

602 **Table 1.** Saltation flux by mass (kg m⁻¹ s⁻¹) of the bulk and the ‘clean’ sand; average
603 atmospheric PM₁₀ concentration (µg m⁻³) due to emitted PM₁₀ flux (kg m⁻² s⁻¹) from the bed
604 (average PM₁₀ flux in brackets); and sandblasting efficiency (m⁻¹) during the aeolian

605 experiments under the different shear velocities ($0.28\text{--}0.36\text{ m s}^{-1}$). The background values
606 were subtracted from the PM_{10} concentrations and fluxes. Note the different duration of the
607 aeolian experiments, 900 seconds for $0.28\text{--}0.30\text{ m s}^{-1}$ and 9000 seconds for $0.33\text{--}0.36\text{ m s}^{-1}$. In
608 all the experiments, the saltation rate remained approximately constant ($\pm 10\%$) while the
609 PM_{10} concentration and flux reduced over time.

610 **Figures caption**

611 **Fig. 1.** Average particle size distribution (PSD) of sand from N_1 , N_2 and C_1 sites obtained by the
612 laser diffraction technique. On the right side are statistical parameters of the distributions.
613 The sample PSDs are significantly different with $P < 0.05$.

614 **Fig. 2.** Scanning electron microscope (SEM) images of sand particles collected from N_1 (A), N_2
615 (B) and C_1 (C) sand samples. The red arrows in A point to dust-sized particles ($< 63\text{ }\mu\text{m}$) found
616 between the sand grains. In C the yellow arrows point to quartz grains, while the orange
617 arrows point to feldspar sand grains. D-F are close-up images of the coatings attached to
618 sand particles from N_1 , N_2 and C_1 , respectively. In the yellow box is a chemical composition
619 analysis (%) using SEM-EDS. The location of the EDS analysis is marked by an asterisk.

620 **Fig. 3.** PM_{10} concentrations [$\mu\text{g m}^{-3}$] following dust emission in the wind tunnel under various
621 shear velocities in N_1 (top), N_2 (middle), and C_1 (bottom). (A), (C) and (E) show results of the
622 experiments at the lower shear velocities (u^* of 0.28 and 0.30 m s^{-1}), for convenient display of
623 the results, the background values were not reduced from the lower shear velocities; (B), (D)
624 and (F) show dust emission over time (9000 seconds) at the higher shear velocities of 0.33 m
625 s^{-1} and 0.36 m s^{-1} . Note the different Y axis scales.

626 **Fig. 4.** Average particle size distribution (PSD) of the sand collected from the **saltation traps**
627 after the wind tunnel experiments ($u^* = 0.33\text{ m s}^{-1}$) for N_1 , N_2 and C_1 dune samples. On the
628 right are statistical parameters of the distributions ($P \leq 0.05$).

629 **Fig. 5.** Scanning electron microscope (SEM) images of the clean sand N_1 (A) and N_2 (C). B and
630 D are close-up images of the coatings attached to a sand particle. In the yellow box is a
631 chemical composition analysis (%) using SEM-EDS. The location of the EDS analysis is marked
632 by the asterisk.

633**Fig. 6.** PM₁₀ concentration [$\mu\text{g m}^{-3}$] before (black) and after (red) loose dust removal by
634washing of the N₁ (A) and N₂ (B) samples under shear velocity (u_*) of 0.36 m s⁻¹. The
635background levels were subtracted from all measured PM₁₀ concentration levels.

636**Fig. 7.** Scanning electron microscope (SEM) images of the emitted dust collected during the
637aeolian experiments for shear velocity of 0.33 m s⁻¹ from N₁ (A), N₂ (B) and C₁ (C) samples. D
638and E are images of the emitted dust from the 'clean' sand of N₁ and N₂, respectively. The
639yellow arrows point to quartz fragments, while the orange arrows in C₁ point to feldspar dust
640size particles (< 63 μm). All the remaining particles are composed of clay minerals with some
641carbonates and metallic materials. F is a close-up of different types of dust particles in the
642samples.