Implications of a Sandblasting Model for Dust Production by Wind Erosion in Arid Areas

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Introduction

Because of the large amounts of soil-derived dust emitted from them, deserts and arid areas constitute one of the major sources of natural aerosol on Earth (Andreae, 1994). The mass mean diameters of the particles present in the aerosol mode lie between 0.1 µm and about 20µm (Patterson and Gillette, 1977) and they are liable to be transported thousands of kms from their source. This has important consequences. For example, the departure of these particles that are rich in soil nutrients can contribute to desertification in the source areas. Dust emissions also modify Earth's climate. Crustal particles that become suspended in the troposphere alter Earth's radiative balance either directly, by absorbing or scattering visible and infrared radiations, or indirectly, by acting as Cloud Condensation Nuclei (C.C.N.), which implies albedo modifications at Earth surface. These optical effects largely depend on the particle sizes. Transport as well as climate modeling not only require estimations of the amount of dust released in source regions, they also need an accurate description of the size distribution of this dust (Balkanski et al., 1996).
Mainly under the influence of Gillette, the determination of the global mass of dust emitted from a given soil for various wind conditions has been the object of field research for a long time (Gillette et al., 1974; Gillette, 1977; Nickling and Gillies, 1989). When aerodynamic forces are exerted on the surface by the wind, the loose aggregates present in the soil are entrained into an horizontal movement (saltation process), and fine dust particles, light enough to be uplifted by wind turbulence, are released from these aggregates when they hit the ground (sandblasting process). Hence, it is usually assumed that the vertical flux of dust, F_{dust}, is related to the vertically integrated horizontal flux, F_h (Gillette, 1981). Until quite recently, it was considered that the sandblasting efficiency ratio $\alpha = F_{dust}/F_h$ could either be proportional to the wind friction velocity u* in the case of fine textured soils (Gillette and Passi, 1988; Nickling and Gillies, 1993), or independent of u* in the case of sandy soils (Gillette, 1981). But, since a first theory of sandblasting was published by Shao et al.(1993), it has become more widely accepted that the vertical dust flux should be proportional to the horizontal flux (Marticorena and Bergametti, 1995). Finally, mean values of α corresponding to various soil types were proposed (Marticorena et al., 1997), but recent field results (Sabre et al., this volume) seem to challenge the assumption that α is independent of u* for a given soil. As for the size distribution of dust, published data are very scarce. The only available results come from measurements of number or mass size distributions of naturally produced aerosols (Gillette et al., 1974; Schütz and Jaenicke, 1974; Gillette and Walker, 1977; d'Almeida and Schütz, 1983; Gomes et al., 1990; Gomes and Gillette, 1993). Unfortunately, either because the wind conditions were not determined in the experiments, or because the size distributions are limited to particles larger than 2 µm in mass diameter, no dependency of the dust size distribution on u* can be derived from these data.

Answers to all these questions lie in an accurate description of the physics of sandblasting. In an attempt to tend towards better understanding of this process, sandblasting experiments were recently conducted in a wind tunnel (Alfaro et al., 1997). Size distributions of aerosols produced by bombarding a clay target with monodisperse sand grains were measured in the 1-20 µm diameter range, at various wind speeds, and a theoretical sandblasting model based on the experimental results was proposed.

In this paper we first present an extension of the sandblasting theory to the submicron size range. Commonalities in the mass size distributions of soil-dust observed in source regions are then examined. Similarities between the field and wind tunnel results suggest we may use the sandblasting model to determine, at least qualitatively, the influence of both the soil aggregate size and the wind friction velocity on the characteristics of dust production. Namely, the sandblasting efficiency ratio, F_{dust}/F_h, and the dust size distribution are computed and when possible, compared to field or wind tunnel data.

Derivation of dust production from the sandblasting model

Extension of the sandblasting theory to the submicron range

In wind tunnel experiments (Alfaro et al., 1998), monodisperse quartz grains of mean size D_p (= 240 µm) were aimed at a kaolin clay target that was made of very fragile clusters of 8.6 µm clay aggregates. Analysis of the size distributions of the clay aerosol produced by the bombardment, at three different wind speeds, showed that this aerosol was a mixture of three types of particles: 8.6 µm aggregates, ‘ fine’ particles of 2.8 µm mean diameter and submicron particles of approximately 0.5 µm diameter. For three increasing values of the friction velocities (u* = 40 cm/s; 45 cm/s and 53 cm/s) the proportion of fine particles to aggregates increased while submicron particles remained absent. The submicron particles only appeared in the aerosol at higher values of the wind speed. This shift in the size distribution towards smaller particles when wind speed, or equivalently kinetic energy of the oncoming sand grains, increased, confirmed that the cohesion energy, e, of a particle within the soil was a decreasing function of its size (Smalley, 1970; Greeley & Iversen, 1985) and that release of a dust particle from the ground could only occur when the kinetic energy of individual saltating grains (e_c) at least equaled the dust particle binding energy. The proportions, p_{ag} and p_{fine}, of kinetic energy used respectively for the release of aggregates and of fine particles were then estimated, but no expression of the fraction, p_{sub}, of e_c that was used to release the submicron particles was given. The values of the binding energy of the aggregates and of the fine particles were computed by fitting modeled size distributions of the aerosol to the experimental results and this for three available wind speeds. The value of e for the submicron particles was estimated by determining at what wind speed (or corresponding kinetic energy of the sand grains) submicron particles were observed on Nuclepore filters used to collect samples of the aerosol. It was observed that for particles in a pure kaolin clay target, e decreased exponentially with particle size, d:

$$e(d) = 14.9 \exp(-0.53d) \qquad (1)$$

where e is in $g.cm^2.s^{-2}$ when d is in µm.

Extending the model to the submicron mode requires an estimation of the proportion p_{sub}. Exactly as it was done for the computation of p_{fine} in Alfaro et al. (1998), we shall assume that the fraction of kinetic energy of the saltators used to release submicron particles is given by:

$$\text{for } e_c \text{ ó } e_{sub}, \quad p_{sub} = 0 \qquad (2a)$$

$$\text{for } e_c > e_{sub}, \quad p_{sub} = (e_c - e_{sub})/(e_c - e_{ag}) \qquad (2b)$$

In the last case mentioned above the energy $p_{sub}e_c$ is no longer available for the release of fine particles or aggregates, we shall then weight the fractions p_{fine} and p_{ag}, by $(1-p_{sub})$ in order to ensure that $p_{ag} + p_{fine} + p_{sub}$ is still equal to 1. Expressions of the various p_i fractions valid for the different ranges of e_c are summarized in Table 1.

e_c	$0 < e_c < e_{ag}$	$e_{ag} < e_c < e_{fine}$	$e_{fine} < e_c < e_{sub}$	$e_{sub} < e_c$
p_{ag}	0	1	$1- p_{fine}$	$1 - p_{fine} - p_{sub}$
p_{fine}	0	0	$(e_c-e_{fine})/(e_c-e_{ag})$	$(1- p_{sub})(e_c-e_{fine})/(e_c-e_{ag})$
p_{sub}	0	0	0	$(e_c-e_{sub})/(e_c-e_{ag})$

Table 1: Fractions of the kinetic energy of a saltating soil-aggregate that are used for the release of the three types of dust particles present in the soil (see text for details)

Model input parameters

Determining the size distribution of an aerosol produced by sandblasting of soil aggregates of mass diameter D_p, requires the following parameters: on one hand kinetic energy of the soil aggregates when they hit the ground, with speed V_0, at the end of their saltation trajectory, and on the other hand, sizes and binding energies of the dust particles liable to be released from the aggregates during the impact.

The kinetic energy of the sand grains is proportional to their mass, M_p, and to V_0^2. Our choice of M_p values was guided by the fact that mass size distributions (obtained by dry sieving) of the wind erodible fraction of uncrusted soil samples characteristic of arid areas can be considered as mixtures of 2 or 3, among 4, lognormally distributed populations (Chatenet et al., 1996). The particles constituting these modes and their mass mean diameters and standard deviations are the following: aggregates of fine clayey particles (d = 125 µm, σ = 1.6), quartz grains coated with clay particles (d = 210 µm, σ = 1.8), salty aggregates (d = 510 µm, σ = 1.6) and coarse quartz grains or aggregates of sand grains cemented by clay particles (d = 690 µm, σ = 1.6). These four sizes will be used successively in the computations. As for V_0, it is generally admitted that V_0 is almost equal to the wind velocity at the center of the test section in wind tunnel studies (White, 1986). For open air saltation, V_0 will be considered to be of the order of magnitude of the wind speed at the highest point (of elevation h above the ground) reached by the particle on its trajectory. Considering that the von Karman log linear wind profile observed above the saltation layer is still valid at its top, one can write:

$$V_0 = (u^*/k).\ln(h/z_0) \qquad (3)$$

where k is the von Karman constant (= 0.4) and z_0 the roughness length of the soil in presence of saltation. Both h (White, 1986) and z_0 (Rasmussen and Mikkelsen, 1991) can be scaled by the ballistic height $u^{*2}/2g$. Consequently V_0 is proportional to u*. The order of magnitude of the proportionality constant estimated from typical saltation conditions (a few tens of cm for h and a few tenths of mm for z_0) is of about 17. An approximate value of 20 will be retained for the computations.

The problem of the dust particle sizes and binding energies is more challenging. Size distributions of aerosols collected in the source regions during dust events present striking similarities. When observed carefully, the common mode distinguished by Patterson & Gillette (1977) in the 1-20µm range can generally be subdivided into an ubiquitous mode centered around

3 µm and another between 5 and 10 µm (Nickling and Gillies, 1983; Gomes and Gillette, 1993; Sviridenkov et al.; 1993). If not always, a submicron mode can also often be detected (d'Almeida and Schütz, 1983; Gomes et al., 1990; Reid et al., 1994; Kaufman et al.; 1994). Considering the great differences between them, it is notable that our wind tunnel experiments produced aerosols with size distributions so close to those observed in natural conditions. One possible explanation to this could be that, in spite of their mineralogical differences, the sizes of individual particles present in arid soils can be found either around 0.5 or around 3 µm, and that these particles tend to form relatively stable aggregates with diameters between 5 and 10 µm.. Though this assumption has not been otherwise checked, we will hereafter consider that the sizes of dust particles liable to be ejected from saltating aggregates are 0.5 µm, 3 µm and 7.5 µm (this assumption is not too bold if we bear in mind the fact that we only intend to determine the qualitative influence of u* and of the soil aggregate sizes on dust production by sandblasting). For the same reason we will assume that the binding energies of the dust particles in the soil aggregates are given by (1).

Computation of the sandblasting efficiency

The kinetic energy flux of particles hitting the ground in their downward movement is proportional to the integrated saltation mass flux, F_h. The proportionality constant, a, of about 16,300 $cm.s^{-2}$ for 250 µm grains (Gillette and Stockton, 1986; Alfaro et al., in press) will be supposed to remain valid for the various soil aggregate sizes used in the computations. Thus the kinetic energy flux will extract the following number of 7.5 µm aggregates

$$N_{ag} = p_{ag}.a\ F_h/e_{ag} \qquad (4)$$

with p_{ag} the proportion of e_c used for the release of aggregates.
This corresponds to the following vertical mass flux:

$$F_{ag} = (\pi/6)\rho_p a\ F_h(p_{ag}d_{ag}^3/e_{ag}) \qquad (5)$$

where ρ_p is the mass density of the clay particles (2.5 $g.cm^{-3}$), and d_{ag} their mean diameter
Similar expressions can be written for fine particles as well as for the submicron ones, which leads to the following expressions of the vertical mass flux of aerosol sized particles, and of the sandblasting efficiency, α:

$$F_{dust} = (\pi/6)\rho_p a\ F_h(p_{ag}d_{ag}^3/e_{ag} + p_{fine}d_{fine}^3/e_{fine} + p_{sub}d_{sub}^3/e_{sub}) \qquad (6)$$

$$\alpha = (\pi/6)\rho_p a(p_{ag}d_{ag}^3/e_{ag} + p_{fine}d_{fine}^3/e_{fine} + p_{sub}d_{sub}^3/e_{sub}) \qquad (7)$$

Results and comments

The sandblasting efficiency was computed from (7), for each one of the four sizes of aggregates that can be found in arid soils, and plotted versus u* (Fig. 1).

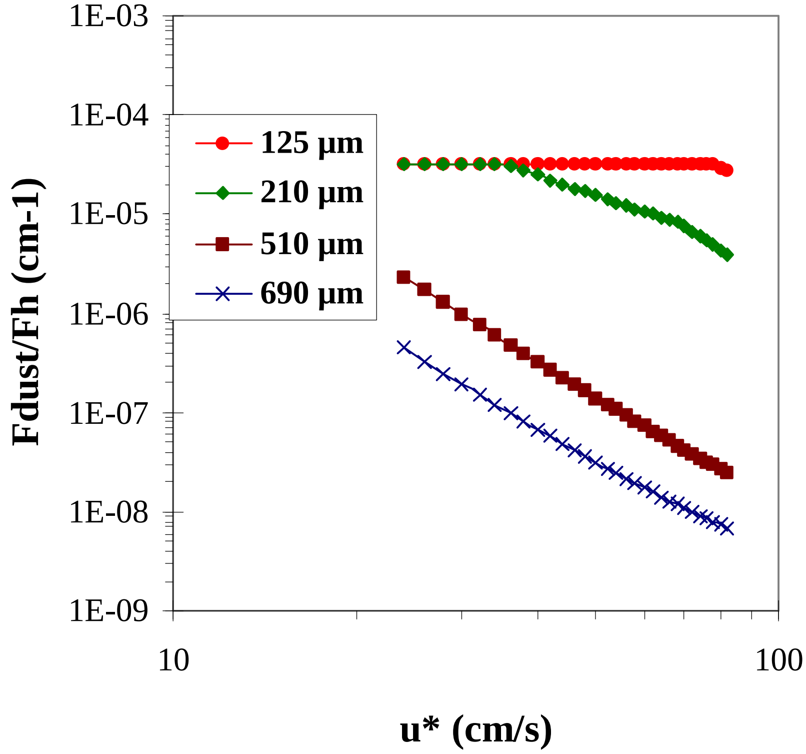
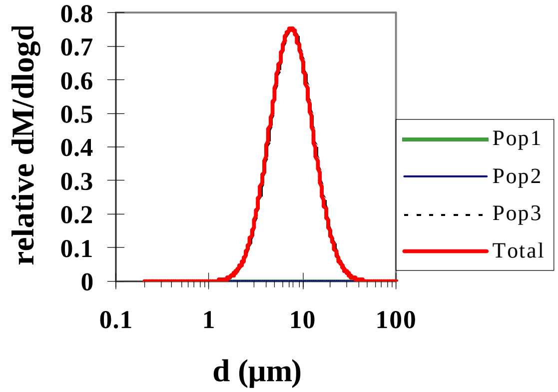


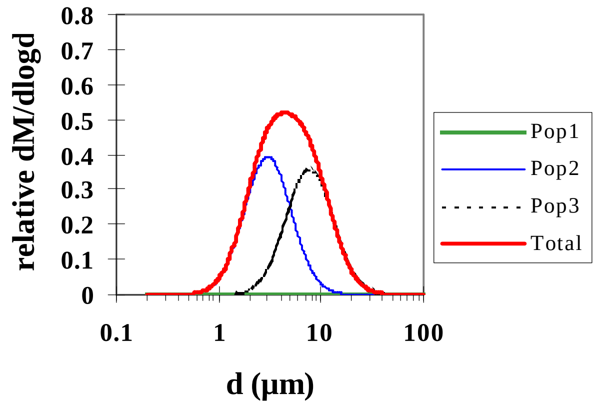
Figure 1: Computed ability of 4 soil-aggregates populations of different sizes to release dust during saltation events. This efficiency is characterized by the ratio, α, of the vertical dust flux, F_{dust} ($g.cm^{-2}.s^{-1}$), to the horizontal saltation flux, F_h ($g.cm^{-1}.s^{-1}$).

It can be seen on Figure 1 that for the 125 µm aggregates, α remains constant for u* values less than 80 cm/s. This means that for usual wind conditions, the vertical mass flux of dust is proportional to the horizontal flux. This is due to the fact that for u* less than 80 cm/s, the individual kinetic energy of the aggregates never reaches the binding energy value for the 3 µm fine dust particles. In other words, their kinetic energy, e_c, is only used to release 'heavy' 7.5 µm-aggregates rather than 'lighter' particles. This is better seen on the size distribution of the dust raised at 50 cm/s by the three smaller soil aggregate types (Figure 2). In terms of mass production, the sandblasting efficiency decreases above the 80 cm/s threshold as the fraction of kinetic energy 'wasted' to release fine particles grows higher.

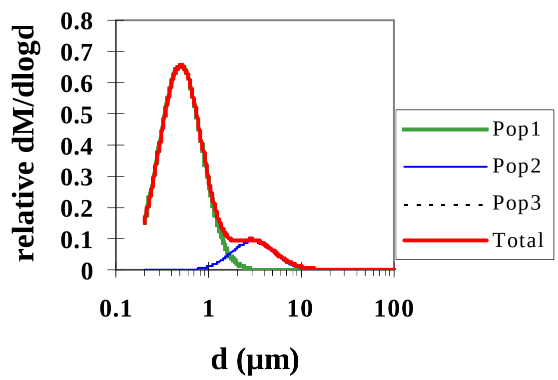
Because of their larger mass, this threshold effect corresponding to the binding energy of the fine particles can be observed at a lower u* value (35 cm/s) for the 210 µm soil aggregates. Figure 2b confirms that with these soil aggregates, fine particles are already produced at u* = 50 cm/s. A second threshold corresponding to the release of the submicron particles can be observed for u* = 75 cm/s. Above it, the saltation efficiency decreases dramatically (Fig.1). With the 510 and 690 µm aggregates, the projectiles' mass is so large that production of submicron particles is possible as soon as their saltation begins (Fig. 2c for the 510 µm particles), which implies small emission power in terms of mass.



a)



b)



c)

Figure 2: Computed size-distributions of the dust produced by sandblasting at constant friction velocity (u* = 50 cm/s) over three ideal monodisperse soils. The mean geometric mass sizes of the soil size distributions are 125, 210, and 590 µm, successively.

Discussion

Most of the available data are related to vertical mass flux and result from field experiments. Contrary to what was assumed in our computations, wind stress partition by non-erodible elements has generally to be taken into account under natural conditions. By increasing the soil threshold friction velocity this stress partition affects the horizontal flux F_h and, consequently, the vertical flux F_{dust}, but not the efficiency ratio F_{dust}/F_h, and this is the main interest of α.

Figure 1 shows that for very fine sand, α should be independent of u*, which is in good agreement with Shao et al. (1993). In their theory these authors assumed that the dust particles were all of the same sizes and binding energies. In the case of the 125 µm soil aggregates these assumptions are practically valid because the largest dust particles only, can be released at reasonable wind speeds. With the coarsest soil-aggregates, particles of different sizes and binding energies can be released and the α ratio is found to decrease by 1 to 2 orders of magnitude when u* varied over the span of friction velocities generally observed in natural conditions (30 to 80 cm/s). This is not in contradiction with Gillette's field results (1981) that are reproduced on Fig.3.

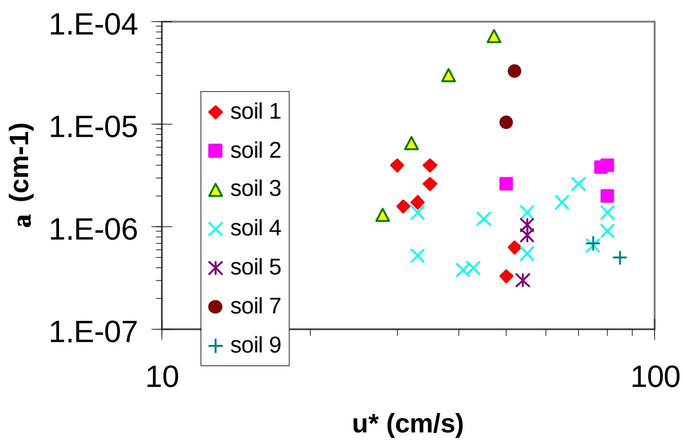


Figure 3: Field measured efficiency ratios for 7 different soils (Gillette, 1977). Soils 1, 2, 4, 5 are sandy, 3, 7 are loamy, and 9 clayey.

He indeed stated that the α ratio for sandy soils was approximately constant, but the highly scattered experimental results could as well be coherent with our theory. Furthermore, if we take a closer look at soil 1, it appears that a decreasing behaviour might become acceptable. It was also noted that the efficiency ratio seems to be an increasing function of the soil clay content (Marticorena and Bergametti, 1995), but since the size of the wind erobible soil aggregates decreases when the soil clay content rises (Chatenet et al. 1996), this is tantamount to the saltator size effect previously mentioned.

Our model predictions can also be compared to field experiment results that are presented in this volume (Sabre et al.). Contrarily to what is often assumed, α is never found to be independent of u*. When only one soil aggregate size is responsible for sandblasting, which was the case in our theoretical computations, it is observed that α decreases with u*, as predicted by the model. But the case of loamy soils for which the efficiency ratio increases as fast as a 5^{th} to 7^{th} degree power function of u* (Gillette, 1977; Nickling and Gillies, 1989) remains unexplained.

Conclusion

With the exception of the loamy soils case, a good quantitative agreement was found between the computed sandblasting efficiency ratio and field data obtained for different soil types. This seems to indicate 1) that, in terms of mass, saltation of the finest mode of soil aggregates present in a soil conditions its ability for dust production 2) that saltation of the coarser soil particles tends to inject finer (3 µm or submicron) particles into the atmosphere. As a result, dust emissions by the coarser soil modes cannot be neglected when matters of interest are health hazards or optical effects of dust.

Because of experimental difficulties, most of the field data correspond to vertical mass flux measurements in which the smaller (d < 1µm) dust modes are lost. The importance of the finest dust particles could justify more experimental work aiming at the determination of the aerosol size distribution as a function of wind speed. Such experiments performed with various natural soils would allow determination of the sizes of dust particles liable to be released by each soil. At the same time, one could determine the binding energies of these particles in the soil-aggregates by fitting the size distributions computed by the sandblasting model to the experimental ones. Real values for the dust particle sizes and binding energies are indeed necessary in order to turn the qualitative predictions of the model into quantitative ones.

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