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Saltation Sandblasting behavior during mineral dust aerosol production

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[1] The dominant process in producing fine dust aerosols during saltation is thought to be sandblasting. Recent studies claim that due to competing physical processes, emission efficiencies of dust aerosols oscillate with increasing wind friction speed. These oscillations can result in order of magnitude changes in dust mass emissions. Our work shows that emission efficiencies, and hence emissions of dust aerosols are smooth functions of the wind friction speed for natural soil size distributions. This rules out oscillations as an explanation for scatter in experimental data. We show and explain the reasons for the oscillations. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801). **Citation:** Grini, A., C. S. Zender, and P. R. Colarco, Saltation Sandblasting behavior during mineral dust aerosol production, *Geophys. Res. Lett.*, *29*(18), 1868, doi:10.1029/2002GL015248, 2002.

1. Introduction

[2] Several modeling studies have shown the importance of mineral dust for the atmosphere's radiative balance [*Tegen and Fung*, 1994] and for its chemistry [*Dentener et al.*, 1996]. The size resolved emissions of dust is a key uncertainty in modeling dust transport [*Schulz et al.*, 1998] and radiative forcing [*Myhre and Stordal*, 2001]. A better understanding of dust emissions, both with respect to dust size distributions and total magnitude, is important to improve estimates of the climate impact of atmospheric dust.

[3] Saltation and sandblasting has been recognized as the most important mechanism for producing small dust aerosols [*Shao and Raupach*, 1993]. Saltation refers to a layer of soil moving with the wind just above the surface. Sandblasting refers to the release of dust aerosol during impacts by saltating particles. The dust aerosol may be remnants of disintegrating aggregate saltators or surface particles ejected by the saltator impact. Early dust production models [*Marticorena and Bergametti*, 1995; *Marticorena et al.*, 1997] have used this approach to model the flux of dust aerosols emitted into the atmosphere. These models did not model the size distribution of the emitted dust aerosols. Recent dust production models [*Shao and Raupach*, 1993; *Shao et al.*, 1996; *Alfaro et al.*, 1997, 1998; *Lu and Shao*, 1999; *Shao and Lu*, 2000; *Alfaro and Gomes*, 2001; *Shao*, 2001] use various physical approaches to model the sandblasting process to give equations for the size distributed flux of dust aerosols.

[4] The ratio of the vertical mass flux of dust aerosols to the saltating mass flux is called the sandblasting efficiency α [*Gillette*, 1979]. Defined in this manner, α largely reflects the size of particles emitted rather than their number or the energy consumed in the sandblasting process. We therefore use the term mass sandblasting efficiency to describe α. The early dust production models used an empirical relation to estimate α based on soil clay content [*Marticorena and Bergametti*, 1995]. *Alfaro and Gomes* [2001] use a physical model of the binding energy of dust and the kinetic energy of the saltation layer to calculate α. They argue that, even for a continuous soil size distribution, a combination of several competing effects results in a strongly oscillatory behavior of the mass sandblasting efficiency with increasing wind friction speed.

[5] Our results lead to a new interpretation of the physical processes governing saltation and sandblasting. The reported oscillatory behavior of α is an artifact caused by inadequacies in the numerical procedure used to evaluate α. The actual mass sandblasting efficiency is a smooth function of the wind friction speed for natural (i.e., continuous) soil size distributions.

2. Current Understanding

[6] Wind friction speeds of about 0.20 m s^{-1} can directly entrain soil grains of about 75 μm into the saltation layer. The threshold wind friction speed is larger both for smaller and larger soil grain sizes [*Iversen and White*, 1982]. Due to large binding energies, small dust aerosols need large wind friction speeds to be mobilized by direct entrainment [*Iversen and White*, 1982].

[7] Several works have pointed out sandblasting as the most important mechanism for releasing dust aerosols from a soil [*Shao and Raupach*, 1993; *Shao et al.*, 1996; *Marticorena and Bergametti*, 1995]. *Shao and Raupach* [1993] and *Shao et al.* [1996] proposed that the number of of dust particles dislodged from the surface per saltation impact is

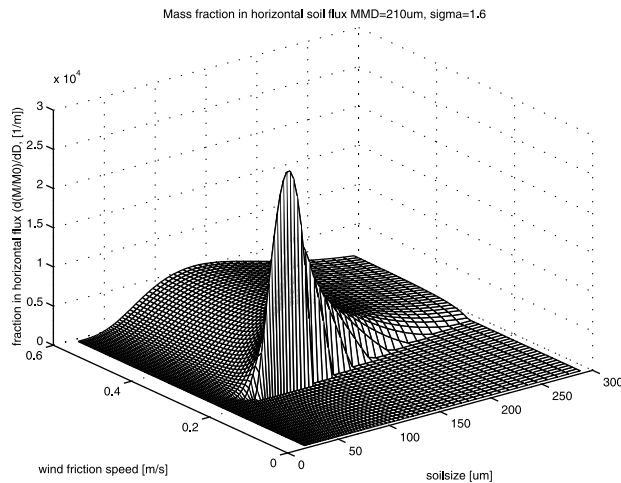Mass fraction in horizontal soil flux MMD=210um, sigma=1.6

Figure 1. Size distribution of the saltation layer over fine sand (FS) at different wind friction speeds. The size distribution is given in fraction of mass at a given size per unit size.

proportional to the ratio of the kinetic energy loss during a saltation impact to the typical binding potential energy holding a dust particle to the surface, Ψ, which is higher for small dust particles as they are bound by stronger cohesion forces. Thus the vertical, size distributed dust flux is sensitive to the mass and the speed of the saltating soil grains.

[8] Each soil size has its own mass sandblasting efficiency. Soil particles with low energy will release large particles, and those with high energy will be able to release small particles. It is thus important to know the size distribution of the particles in the saltation layer at any wind friction speed and to carefully integrate the mass sandblasting efficiency over this size distribution. The total, integrated mass sandblasting efficiency for a soil, is highly sensitive to its size distribution [*Shao and Raupach*, 1993; *Shao et al.*, 1996; *Shao and Lu*, 2000; *Alfaro and Gomes*, 2001]. Not all of the kinetic energy of the saltating particle is used to release fine dust. *Lu and Shao* [1999] and *Shao* [2001] emphasize that a large part of the kinetic energy of the saltating particle is actually used for plastic deformation of the soil, and that the emissions from a soil largely depend on the plastic pressure of the soil surface.

[9] *Alfaro and Gomes* [2001] developed a dust production model where the wind friction speed (u_*) together with the size distribution of the saltating soil particles determines the size distribution of the emitted dust aerosols. They propose that the emitted dust aerosols will be a composition of three lognormal modes with mass median diameters of d_1 = 1.5 μm, d_2 = 6.7 μm and d_3 = 14.2 μm. Each of the modes has a characteristic binding energy which must be exceeded before it is released. The binding energies were estimated in wind tunnel experiments [*Alfaro et al.*, 1998].

[10] Adopting the notation of *Alfaro and Gomes* [2001], the vertical number flux of aerosols from mode i from sandblasting by a given soil particle size is:

$$dN_i(D_p) = \beta dF_h(D_p)\frac{p_i(D_p)}{e_i} \tag{1}$$

where N is upward, vertical number flux of aerosols in mode i (m^{-2} s^{-1}), β is a constant (163 m s^{-2}), F_h is horizontal flux of aerosols (kg m^{-1} s^{-1}), p_i is fraction of energy used to release aerosols from mode i, e_i is binding energy of mode i (J) and D_p is diameter of saltating soil grains (m). The net vertical dust flux is the upward flux (1) minus the depositional fluxes (gravitation, turbulent mix-out, scavenging) with which this paper is not concerned.

[11] The vertical mass flux of aerosols from mode i is:

$$dF_{aeros,i}(D_p) = \frac{\pi}{6}\rho_p\beta dF_h(D_p)\frac{p_i(D_p)\bar{d}_i^3}{e_i} \tag{2}$$

where F_{aeros} is the upward, vertical mass flux of aerosols in mode i (kg m^{-2} s^{-1}), ρ_p is the density of aerosols (kg m^{-3}) and d_i is the mass mean diameter of the aerosol mode (m). *Alfaro and Gomes*, 2001 use mass median diameter instead of mass mean diameter in (2). Doing so overestimates mass flux by a factor of about 2.5.

[12] As noted by *Alfaro and Gomes* [2001], several effects compete in determining the vertical mass flux of dust aerosols from a soil with a lognormal size distribution. The change in mass sandblasting efficiency with increasing friction wind speed is influenced by the following factors: 1) Already saltating aggregates release finer and finer particles, decreasing α 2) A larger amount of coarse aggregates of poor mass sandblasting efficiency enter saltation, decreasing α and 3) Smaller aggregates already saltating but previously inefficient for sandblasting become productive, increasing α.

[13] During the interplay of complicated processes, several of which include threshold values, one might expect oscillations. *Alfaro and Gomes* [2001] explain that α oscillates with increasing wind friction speed because of this interplay. They compare the mass sandblasting efficiencies from their dust production model to measured mass sandblasting efficiencies of between 10^{-6} and 10^{-3} m^{-1} for varying soils and wind friction speeds. The oscillating nature of the calculated mass sandblasting efficiency seems
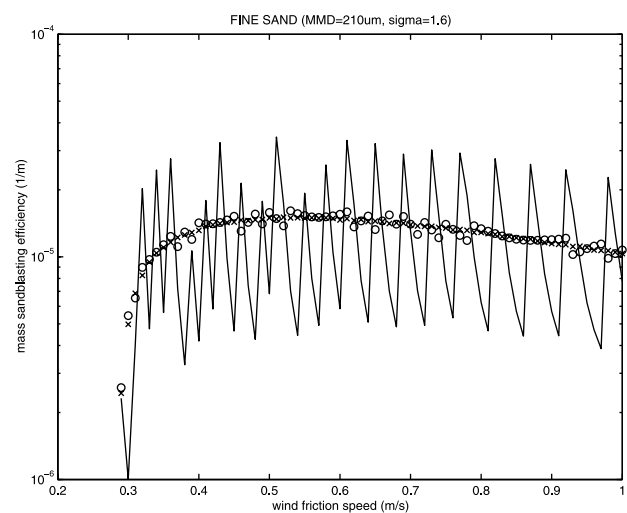

FINE SAND (MMD=210um, sigma=1.6)

Figure 2. Mass sandblasting efficiencies (m^{-1}) calculated by using 100 points (solid line), 1000 points (circles) and 10000 points (crosses) along the soil size distribution.
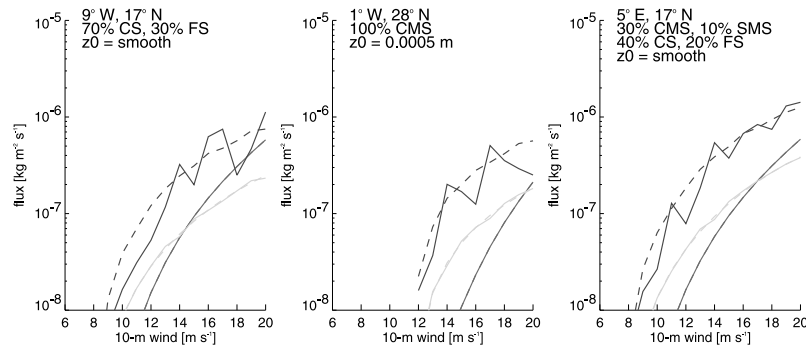
Figure 3. Total fluxes calculated at different locations in Africa. CS, FS, CMS, and SMS are different soil size distributions (see *Chatenet et al.* [1996] and *Marticorena et al.* [1997]). The lines show the flux of fine (light grey), medium (medium grey), and coarse (black) mode aerosols calculated with the dust production model. Solid lines use a coarse integration over the soil sizes (400 bins), and the dashed lines use a fine integration over soil sizes (4000 bins). The 10m wind speed is calculated from wind friction speed assuming neutral boundary layer.

consistent with the scatter in these observations. We find that, when using continuous soil size distributions, α is non-oscillatory and that the observed scatter in α is due to other causes.

3. Proposed New Interpretation

[14] We now show that the mass sandblasting efficiencies for a soil size distribution depend strongly on the numerical procedure employed to calculate them. Accurate integration, using small steps along the soil-diameter axis is important due to shift in size distributions.

[15] We calculated α using (2) for the soil type called fine sand (FS) by *Chatenet et al.* [1996]. This soil is lognormally distributed, it has a mass median diameter of 210 μm and a standard deviation (σ) of 1.6. In the following, we assume a smooth surface with no drag partitioning effects. Figure 1 shows how the size distribution of the saltating flux changes with the wind friction speed [*Iversen and White*, 1982]. At low wind friction speeds, only the 75 μm particles are available. At high wind friction speeds, all sizes in the soil size distribution are available for saltation.

[16] Figure 2 shows the mass sandblasting efficiency (α) calculated with the same numerical procedure using different size resolutions (N = 100, 1000, 10000 points) logarithmically evenly spaced along the soil-diameter axis. The oscillations occur in the low resolution (N = 100) calculations. Increasing the size resolution damps the oscillations (N = 1000) until they eventually disappear (N = 10000). It should be noted that the oscillations for the lowest resolution calculation are of an order of magnitude, consistent with *Alfaro and Gomes* [2001]. The mass sandblasting efficiency goes through a maximum at 0.54 m s^{-1} and then decreases. This maximum is not very distinct for FS, but it is more distinct for soils with larger mass median diameter (not shown), such as coarse sand (CS) and salts (SS) [*Chatenet et al.*, 1996]. We performed a large range of sensitivity studies to soil size distributions (using soil size distributions from *Chatenet et al.* [1996]) and friction speed (varying from 0 to 1 m s^{-1}) to verify that α does not oscillate under any conditions.

[17] In Figure 3, we show total emissions calculated from the dust production model calculated at different locations in Africa. The locations contain blends of four natural arid soil types which can be found in nature [*Chatenet et al.*, 1996]. The predicted mass fluxes at each location show spurious, order of magnitude oscillations unless adequate resolution is used to compute them. The noise is largest for the coarse mode aerosols which is consistent with the reason for the oscillations (see below).

[18] The oscillations occur because the parameter p_i in (1) and (2), and hence the number fraction of dust in each mode, is very sensitive to the saltator soil size. This is illustrated for a wind friction speed of 0.50 m s^{-1} in Figure 4. The fraction of coarse mode aerosols increase and decreases very rapidly with increasing saltator soil size indicating that a fine size resolution is needed to capture this behavior. The smallest soil sizes which contribute to sandblasting determine all flux from the coarsest mode.

[19] At saltator size resolutions which do not resolve the narrow emission peak of coarse mode aerosols, the pre-
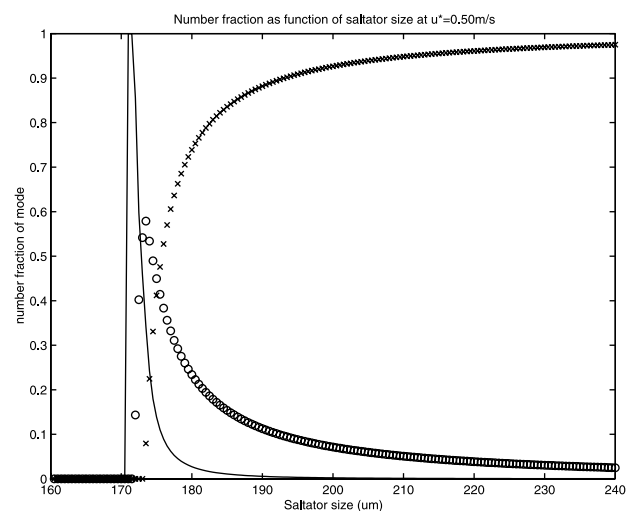

Figure 4. Fraction of number flux coming from each of the fine (crosses), medium (circles) and coarse (solid) mode aerosols for wind friction speed of 0.50 m s^{-1}. The fraction of coarse mode number flux increases and decreases rapidly with saltator size at constant wind friction speed.

dicted contribution from the coarse mode aerosols will be too high or too low. This random bias shows up as oscillations when calculating the mass sandblasting efficiency at low resolutions. The total mass flux is mostly dependent on the coarse mode aerosols due to weighting of the number flux from mode 3 by $\bar{d}_i^3$ in (2). It is therefore determined by the smallest sandblasting soil sizes. A similar behavior (not shown) occurs at other wind friction speed, but the peak for the coarse dust particles occurs at lower (higher) soil sizes for higher (lower) wind friction speed.

[20] Interestingly, as this phenomenon leads to oscillations in total mass fluxes at low resolutions (because of changes in the size distribution of the dust flux), the total number flux can be calculated accurately with low resolution. The total number flux of dust is quite insensitive to $p_i(1)$. p_i being inaccurate only means that the number flux will come from another mode. The total number flux can thus be approximately correct even though the p_i (and hence the size distribution) is wrong.

[21] Our results rule out oscillations as explanation to scatter in observed mass sandblasting efficiencies. The scatter is more likely due to differences in soil properties or measurement techniques.

[22] Our results alter the conceptual understanding that activation of progressively finer aerosol modes by progressively higher kinetic energy leads to oscillatory behavior in α. This is important to keep in mind if the dust production model is to be used in transport models of mineral dust aerosols since total emissions is a key output from such models.

4. Summary

[23] It has been argued that, even for continuous soil size distributions, competing threshold processes interact to yield an oscillatory behavior in the mass sandblasting efficiency of a soil. We find that these oscillations only occur if one does not use high enough resolution when integrating the mass sandblasting efficiency over the soil size distribution.

[24] Our results change the conceptual understanding proposed earlier that activation of progressively finer aerosol modes by progressively higher kinetic energy leads to oscillatory behavior in the mass sandblasting efficiency, α.

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