Estimation of PM20 emissions by wind erosion: main sources of uncertainties

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Abstract

The physics of the two processes (saltation and sandblasting) leading to fine mineral dust emissions by wind erosion in arid or semi-arid areas has been detailed and modeled. The combination of these two models has led to a physically explicit Dust Production Model (DPM). In this work, sensitivity tests are performed with the DPM to determine the nature of the main soil parameters that control dust emissions by sandblasting. It is found that the soil roughness length and the dry size distribution of the soil aggregates constituting the loose wind erodible fraction of the topsoil have the greatest influence on the soil potential for mineral dust production. Contrary to what is often assumed, soil texture is not a relevant parameter.

In the light of these new findings, results of vertical flux measurements performed over a wide variety of sources in Niger and the US south west (14 soils) have been reanalyzed. Results show (1) that for the tested soils the DPM, and hence sandblasting, explain all dust emissions, and (2) that 13 of the 14 soils that had been selected a priori for their high potential for dust emissions contained a fine soil-aggregate component. This is consistent with the sensitivity tests indicating that the presence of such a component could enhance dust emissions by one order of magnitude. Finally, it can be concluded that most of the apparent scatter in the experimental results was in large part due to an inappropriate choice of soil parameters to interpret them.

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1. Introduction

Particles that can be observed a few centimeters above a surface undergoing wind erosion cover a wide range of diameters—from about 0.1 \( \mu \text{m} \) to several hundreds of \( \mu \text{m} \). After they have been lifted from the surface, their fate mostly depends on their weight. In usual conditions, turbulence can maintain particles larger than 20 \( \mu \text{m} \) in suspension only for a short time (less than a few hours) and they rapidly fall in the vicinity of the place they originated from. In consequence, the corresponding mass redistribution is significant at local scale only. On the contrary, particles finer than 20 \( \mu \text{m} \) (PM20) can be transported over long distances—hundreds or thousands of kilometers in the case of the smallest whose residence time in the lower
troposphere can reach a week. This has several effects: (1) the departure of fine particles that are also the richest in soil-nutrient can further deplete stocks of already poor soils encountered in semi-arid areas, (2) fine particles that are easily inhaled in the respiratory tract may have an impact on human or animal health, and (3) PM20 suspended in the atmosphere affect transfer of solar and terrestrial radiation. This presently constitutes one of the major sources of uncertainties in climate modeling.

However different, these effects have in common that their quantification requires determination of, at least, fine dust concentrations at any point of the atmosphere. These concentration fields can only be obtained by coupling transport models to dust emission ones that should be able to reproduce the time and space variability of source locations, of source intensities, and of other mineral aerosol initial characteristics (e.g., size distribution and composition) that condition their aptitude for transport as well as their optical properties. Thus, because they are the first link in a chain of models, dust emission models must be the most accurate possible in order to reduce the uncertainties attached to the final outputs of the whole chain. In summary, the more realistic the dust production model, the better the assessment of dust effects at large scale. The problem is that sophisticated models usually require such a complex set of input data that it becomes unrealistic to even think of using them at the spatial scale of natural source regions, that is to say at regional scale. The best way of solving this problem is to develop, in a first step, models that are initially accurate enough to account realistically for the physics of the processes involved in dust production. The second step consists in performing sensitivity tests with these models to determine to what extent their input data can be simplified without completely distorting the outputs. Though it may not be completely satisfactory, it is at the price of this simplification that one can hope to reproduce the characteristics of dust emissions at a scale somewhat larger than the one of a necessarily very small ideal plot that would be perfectly homogeneous in terms of model input data.

The aim of this paper is to apply this methodology to the estimation of PM20 mass fluxes that is a prerequisite to quantifying the three effects mentioned above. Indeed, though relatively numerous field studies have been dedicated to this problem, their results have not yet allowed to ascertain which parameters among the numerous ones apparently involved (soil texture, soil composition, soil-aggregate size distribution, soil roughness, wind friction velocity, humidity, etc.) are the more relevant to predict fine dust emissions from a source area. In its first part, this paper presents a brief summary of the physical bases of a dust production model (DPM) that is based on an explicit parameterization of the aeolian processes leading to fine dust emissions. In the second part of the paper, sensitivity tests are performed with the DPM to (1) identify parameters that have the main influence on dust emissions, and (2) determine the range of values encompassed by these parameters in natural conditions. Then, the DPM is used with simplified sets of key parameters to show that it can explain the large variability of field measurements available in the literature. Finally, the shortcomings of the DPM in its present state are discussed and indications as to what experimental efforts should be undertaken to improve it are given.

2. Aeolian processes and their modeling

2.1. Saltation, splashing and sandblasting processes

By sieving, in dry conditions, the loose wind-erodible fraction of 26 arid and semi-arid soils, Chatenet et al. (1996) have shown that this fraction can usually be considered as a mixture of at most three, among four, log normally distributed soil-aggregate populations. The differences in geometric mean diameter (gmd) and geometric standard deviation (gsd) of these populations (Table 1) may be linked to their differences in composition revealed by elemental

<table>
<thead>
<tr>
<th></th>
<th>FFS</th>
<th>FS</th>
<th>MS</th>
<th>CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>gmd (μm)</td>
<td>125</td>
<td>210</td>
<td>520</td>
<td>690</td>
</tr>
<tr>
<td>gsd</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

FFS stands for very fine sans, FS for fine sand, MS for medium sand, and CS for coarse sand.
analysis: very fine sand (FFS) is essentially made of aluminosilicate silt, fine sand (FS) of fine quartz sand, medium sand (MS) of salt, and coarse sand (CS) of coarse quartz grains.

The gmd (125 μm) and gsd (1.6) of the smallest of these modes (FFS) show that the mass of PM20 present in arid soils in a free state is usually insignificant. These fine particles that indeed exist within the soil may be incorporated into two types of aggregates: They can either be glued to the surface of sand-sized grains, or imbedded in aggregates of fine material. When aggregates are set into motion by wind, their movement (saltation) remains essentially horizontal because of their weight. At the downwind end of their trajectories, their kinetic energy is partly transformed into heat in inelastic shocks, partly used to eject other aggregates from the soil (splashing), and the rest is used to release PM20 from the aggregates themselves or from the soil surface on which they impact (sandblasting). There is much experimental evidence (e.g., Gillette, 1977; Shao et al., 1993; Houser and Nickling, 2001) to prove that direct mobilization by aerodynamic forces plays a minimal role in PM20 emissions. Thus, from a formal point a view, it is natural to think of studying separately saltation on the one hand, and its direct consequence that is PM20 emissions by sandblasting on the other hand. This idea was first developed by Gillette (1977) who wanted to compare the ability of various natural soils in the southwestern part of the USA to release fine particles. For this, he defined a parameter (z) as the ratio of the measured PM20 vertical flux to the measured horizontal salination flux \( F_h \). This parameter presents the advantage of normalizing fine particle emissions to the horizontal flux and is expected to be a good representation of a soil’s intrinsic aptitude for sandblasting. As detailed below, the same idea of uncoupling saltation and sandblasting processes has been used in modeling activities.

### 2.2. Physics of saltation

After Bagnold (1941), the basic knowledge of the saltation process was derived from wind tunnel simulations performed in ideal conditions. Indeed, experiments were carried out in dry conditions and at controlled wind speeds over sand beds made of grains having all the same size and deprived of non-erodible elements. Various expressions accounting for the dependence of the horizontal salination flux to the wind friction velocity were proposed (see Greeley and Iversen, 1985, for a review). These expressions involve a parameter of crucial importance for salination, the threshold friction velocity \( u_{\ast t} \) under which wind stress is too low to set aggregates into motion. Well above this threshold, the horizontal flux becomes proportional to \( u_{\ast t}^3 \). In the case of loose beds, that is to say when all inter-particle bonds but electrical ones can be neglected, \( u_{\ast t} \) depends on particle characteristics such as size \( D \) and density \( \rho \), but it also depends on the degree of protection brought to the soil by non-erodible elements (pebbles, boulders, vegetation, etc.). The effect of these non-erodible elements is to increase the soil roughness length \( Z_0 \), and consequently \( u_{\ast t} \) for each soil aggregate size class. \( Z_0 \) can be used as a proxy to model the influence of non-erodible elements on \( u_{\ast t} \) (Marticorena and Bergametti, 1995; Alfaro and Gomes, 1995). Two other factors must be taken into account: soil surface humidity and soil surface crusting. Soil surface humidity can enhance the strength of inter-particle bonds by promoting development of a humid film between grains (Fécan et al., 1999). Soil crusting due to rainfall can limit the availability of soil aggregates for saltation in the case of fine-textured soils. Indeed, the strong crusts that form on clayey or loamy soils are efficient at limiting the availability of soil-aggregates for saltation (Gillette, 1988; Sterk et al., 1999; Gomes et al., 2003a), while the type of physical crust that develops on soils with a very low content in fine particles (sandy soils) does not affect saltation (Rajot et al., 2003).

### 2.3. Physics of sandblasting

Wind tunnel simulations of wind erosion realized with different natural soils collected in source areas have shown that the PM20 that are ejected by sandblasting from the much coarser soil aggregates into which they were initially embedded can always be considered as a mixture, in various proportions, of only three log normally distributed populations (Alfaro et al., 1998). In first approximation, the size characteristics of these PM20 populations seem to be independent of the soil texture and mineral composition. Their gmds (and respective gsd) are the follow-
Marticorena and Bergametti (1995). Basical-
consequences on interparticle cohesion. 
only differ in size but also in composition with 
investigated is that the three PM20 populations not 
still unknown. A possibility that still has to be 
within the soil aggregates was a decreasing function 
between the three PM20 populations, 
ei values are 
least square routine meant to adjust aerosol size 
distributions computed in various wind conditions to 
those measured directly in the wind tunnel. 
Finally, a Dust Production Model (DPM) was 
obtained (Alfaro and Gomes, 2001) by combining 
the saltation and the sandblasting models. In the 
DPM, the energy partition scheme is applied to each 
size class of the saltation flux. Integration of the 
results over the full size range of saltating aggregates 
yields the vertical mass (and number) flux \( F_v \) of 
PM20 and its size distribution. Since the saltation 
part of the model computes the horizontal saltation 
flux, the DPM also provides the ratio of \( F_v \) to \( F_h \) that 
is to say \( z \). It has to be noted that, since the size 
characteristics of the three PM20 populations are 
 provisionally considered as fixed, the input data 
required to run the DPM in dry conditions are the 
fine particle binding energies \( (e_i) \) and the input 
necessary to run the saltation model, namely the 
wind friction velocity \( (u*) \), the parameters of the 
dry size distribution of the loose erodible soil aggreg-
egates (amplitudes, gmd, and gsd of the various 
populations), soil roughness length \( (Z_0) \), and soil 
aggregate mass density \( (\rho) \). 
In order to validate the DPM, predictions of its two 
sub-models (saltation and sandblasting) have been 
compared to direct measurements performed on a 
sandy soil in Niger and on a loamy soil in northeast 
Spain (Gomes et al., 2003b). In the Spanish case, the 
computed saltation flux overestimated the measured 
one because soil crusting limited the amount of soil 
aggregates available for saltation. In spite of this 
supply limitation, the measured sandblasting efficien-
cies \( (z) \) and the ones computed with the \( e_i \) deduced 
from the wind tunnel experiments were found to be in 
good agreement. On the contrary, the \( e_i \) had to be 
reduced by a factor 3 to retrieve the sandblasting 
efficiencies measured in Niger. This shows that a
certain dependence of $e_i$ to soil characteristics may exist in natural conditions.

3. Implications of the model: sensitivity of the PM20 flux to key variables

The impact of wind speed and of the various soil parameters on PM20 production can be tested by running the DPM with input parameters encompassing the usual range of values for natural conditions. In such conditions, $u^*$ generally varies between 0 and 100 cm/s, a value seldom observed in outdoor conditions. Based on Chatenet et al.’s (1996) results, the soil loose fraction will be considered as made of one of the four aggregate populations mentioned above, or as mixture of them. Except when explicitly mentioned, the soils will also be considered as smooth, that is to say deprived of non-erodible elements. In this case, $Z_0$ can be approximated by $Z_{0s} = D_{\text{max}}/30$, where $D_{\text{max}}$ is the gmd of the largest aggregate population (Greeley and Iversen, 1985). The binding energies used in the computations will be those determined for the sandy soil of Niger. For lack of other available data, the $e_i$ determined from wind-tunnel measurements will be considered as the binding energies upper limit. Finally, the soil aggregate mass density will be kept constant and equal to the one of quartz grains (2.65 g/cm$^3$).

3.1. Sensitivity to soil aggregates size distribution

Vertical fluxes have been computed for the four individual populations defined by Chatenet et al. (1996). It can be seen (Fig. 1a) that when the gmd of the soil aggregate population decreases from 690 (CS) to 210 μm (FS) dust production increases by between one and two orders of magnitude, but that this increase is much less important when the gmd changes from 210 to 125 μm (FFS). The physical explanation for this is that the kinetic energy of saltating grains, being proportional to their mass, and hence to $D^3$, this energy is much larger for coarse grains than for fine ones. For example, assuming that their terminal velocities are approximately the same, 690-μm grains will have a kinetic energy exceeding 125-μm particles by more than two orders of magnitude. In consequence, impacts of coarse grains on the ground will be able to release proportionally more of the finest among the PM20 particles—that are also the hardest to dislodge—than impacts of finer soil aggregates. In other words, an important fraction of the kinetic energy of coarse grains (CS or MS) is used to release the lightest PM20 particles whereas the one of finer sand grains (FFS or FS) is essentially used to release heavier PM20 particles. Thus, from the point of view of PM20 mass production, coarse grains’ sandblasting efficiency is less than the one of finer grains. This can also be illustrated by the sandblasting efficiencies computed for the four populations (Fig. 1b). Indeed, except just above sandblasting threshold, $\alpha$ is about 10 times larger for the two finest modes (125 and 210 μm) than for the two coarsest (520 or 690 μm).
In order to test the aptitude of composite soils for dust production, $F_v$ and $\alpha$ have also been computed for a mixture, in equal parts, of fine (210 $\mu$m) and coarse (690 $\mu$m) populations. Fig. 2a and b shows that in this case the influence of the coarse populations can be neglected. Two reasons can explain this predominance of the fine sand grains regarding dust emissions: (1) They dominate the salination flux because they are more easily set into motion by wind action than coarse grains, and (2) their sandblasting efficiency is larger than that of coarse aggregates. This result is of the uttermost importance: It means that dust emissions by a soil will be in large part controlled by the finest aggregate population present in its dry size distribution regardless of the coarsest modes. The gmd of this finest population will hereinafter be referred to as $D_{\text{min}}$.

3.2. Sensitivity to fine particle binding energies

The effect of binding energy variations is tested for a smooth soil made of only one aggregate population (FS). Due to the threefold increase in $e_i$, the sandblasting threshold shifts from 25 to 27.5 cm/s, and the fine particle flux decreases (Fig. 3a). Naturally, this decrease is relatively more important close to threshold.

Fig. 2. Characteristics of dust production [vertical mass flux (a), and sandblasting efficiency (b)] computed by the DPM for a mixture in equal proportions of FS and CS (bold line). Results obtained for pure CS and pure FS have been plotted for the sake of comparison.

Fig. 3. Influence of the binding energies of the PM20 populations within soil aggregates on the characteristics of dust production [vertical mass flux (a), and sandblasting efficiency (b)]. Computations have been performed for an FS soil with binding energies corresponding to the Niger case (thick line), then with binding energies estimated from wind-tunnel measurements (thin line).
old than at higher wind speeds. The effect of $e_i$ modifications on $z$ is also more pronounced at low speeds (Fig. 3b).

3.3. Sensitivity to soil roughness length

The effect of roughness length is tested for a monodisperse soil (FS). The soil is first considered to be smooth and $Z_0 = Z_{0s} = 7 \mu m$. Then $Z_0$ is increased to 1 mm, a value usually considered as high enough to inhibit saltation over natural surfaces (Gillette, 1999). Fig. 4 shows that the main effect of $Z_0$ is to control the threshold of dust production. This can be explained by the increased protection of the soil surface by non-erodible elements, which results in saltation limitation. With wind speeds increasing above threshold, this protective effect becomes progressively less efficient at limiting saltation, and the influence of $Z_0$ is less strongly felt.

4. Reanalyzing published field data in the light of the DPM

4.1. Methodology

As seen above, the DPM predicts that, apart from $u^*$, the main parameters controlling dust emission from a non-crusted surface are mainly $Z_0$ and the soil aggregate size distribution, and to a lesser extent the $e_i$. When the soil erodible fraction is not made of a neatly dominant coarse component mixed with a minor fine aggregate one, the overall soil aggregate size distribution can be reduced to its finest population (of size $D_{min}$) for PM20 computation purposes. If we provisionally assume that this criterion is met for a majority of arid or semi-arid surfaces, and that the Niger $e_i$ are representative of most arid soil values, it should then be possible to retrieve the characteristics of dust emissions from most uncrusted arid surfaces provided their $Z_0$ and $D_{min}$ values are known. To our knowledge, the results of field measurements performed in Niger by Rajot et al. (2003) constitute the only data set meeting this requirement. A brief summary of the experimental conditions and comparison of the DPM outputs with field measurements are presented below.

Less complete data sets have also been published in the literature. For example, Gillette (1977), and later Nickling and Gillies (1989) have measured fine particle emissions and sandblasting efficiencies over a series of surfaces in the southwestern part of the United States. In both cases, the experimental sites had been chosen for being representative of the various potential sources encountered in the area. In the description of his experiments, Gillette mentioned that the various soils differed in texture as well as in surface state but neither $Z_0$ nor dry aggregate size-distributions were measured. On the contrary, Nickling and Gillies provided the roughness lengths associated with each of the 13 surfaces they tested. In these experiments, a transportable wind tunnel was used, and $Z_0$ and the wind friction velocities were determined from wind profile measurements. The
corresponding data set will be hereinafter named NG89. The $Z_0$ values and the range of silt and clay content of each soil are reported in Table 3. Since the dry size distribution of the wind erodible soil aggregates had not been measured, assumptions will have to be made regarding $D_{\text{min}}$ in order to perform the DPM computations. Theoretically, Chatenet et al.’s (1996) results allow four possibilities for $D_{\text{min}}$ (125, 210, 520, and 690 $\mu$m), but Fig. 1a and b shows that, on the one hand 125 and 210 $\mu$m aggregates, and on the other hand 520 and 690 $\mu$m aggregates, have relatively similar potential for dust production. This means that, in first approximation, we are left with two possible choices for $D_{\text{min}}$: a fine sand possibility (e.g., FS) and a coarse one (e.g., CS). Comparison of the measured $\alpha$ and PM20 fluxes with the two corresponding DPM computations will at the same time provide an estimation of $D_{\text{min}}$ and a test of the accuracy of the DPM predictions. Results of these comparisons are presented below.

4.2. Results

4.2.1. Niger experiment

The experiment that took place in Niger from February to June 1998 has been fully described by Rajot et al. (2003). The measurements were conducted

<table>
<thead>
<tr>
<th>Period no.</th>
<th>$Z_0$ (mm)</th>
<th>Amplitude (%)</th>
<th>$g_{\text{md}}$ ($\mu$m)</th>
<th>$g_{\text{sd}}$</th>
<th>$\rho$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop 1</td>
<td>0.19</td>
<td>44</td>
<td>56</td>
<td>160</td>
<td>1.9</td>
</tr>
<tr>
<td>Pop 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pop 1</td>
<td>1.16</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Pop 2</td>
<td></td>
<td></td>
<td></td>
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</table>

Fig. 5. Comparison of vertical mass flux (a), and sandblasting efficiencies (b) measured over a bare field in Niger with the DPM predictions. The effect of the roughness length increase between the first (squares) and second (open circles) periods of the measurements is well reproduced by the DPM. For the sake of comparison, predictions of the DPM for a smooth case have also been plotted.

Fig. 6. Comparison of model predictions with $D_{\text{min}} = 210 \mu$m (thin line), and $D_{\text{min}} = 690 \mu$m (bold line) with Nickling and Gillies (1989) measurements at the Glendale (squares) and Mesa agricultural (circles) sites.
over a sandy cultivated field that had been bared of all vegetation in order to promote wind erosion. During the first part of the experiment, the wind blew from the east (Harmattan regime) and the soil aerodynamic roughness determined from wind profiles was found to be $Z_{0,1} = 0.19 \text{ mm}$. Due to the onset of the monsoon season, the wind turned to southwest during the second part of the experiment. Assumedly because of an anisotropy in the arrangement of non-erodible elements, a significant increase in roughness length accompanied this shift in wind direction. The new average $Z_0$ value was $Z_{0,2} = 1.16 \text{ mm}$. The size distribution of the loose soil aggregates determined by dry sieving remained the same during the two periods. The parameters of this size distribution are given in Table 2.

During wind erosion events, instantaneous values of $F_h$ were determined by evaluating time integrated BSNE sand catcher measurements with the help of high frequency saltiphone measurements. $F_v$ was measured by the classical gradient method (Gillette, 1977). The sandblasting efficiency can thus be determined from these measurements.

Comparison of DPM outputs with measurements (Fig. 5a and b) shows that the shift in saltation threshold resulting from the $Z_0$ increase between the two periods of the experiment is well reproduced by the model.

<table>
<thead>
<tr>
<th>Site</th>
<th>$Z_0$ (μm)</th>
<th>Silt and clay content</th>
<th>$D_{\text{min}}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesa (agricultural)</td>
<td>331</td>
<td>ib</td>
<td>690</td>
</tr>
<tr>
<td>Yuma (agricultural)</td>
<td>224</td>
<td>&lt;15%</td>
<td>210</td>
</tr>
<tr>
<td>Casa Grande</td>
<td>67</td>
<td>&gt;25%</td>
<td>210</td>
</tr>
<tr>
<td>Glendale</td>
<td>301</td>
<td>&gt;25%</td>
<td>210</td>
</tr>
<tr>
<td>Tucson</td>
<td>191</td>
<td>&lt;15%</td>
<td>210</td>
</tr>
<tr>
<td>Ajo</td>
<td>176</td>
<td>&lt;15%</td>
<td>210</td>
</tr>
<tr>
<td>Hayden</td>
<td>141</td>
<td>&gt;25%</td>
<td>210</td>
</tr>
<tr>
<td>Sta. Cruz</td>
<td>204</td>
<td>ib</td>
<td>210</td>
</tr>
<tr>
<td>Mesa (Salt River)</td>
<td>100</td>
<td>&gt;25%</td>
<td>210</td>
</tr>
<tr>
<td>Yuma (scrub desert)</td>
<td>163</td>
<td>ib</td>
<td>210</td>
</tr>
<tr>
<td>Yuma (disturbed scrub desert)</td>
<td>731</td>
<td>&lt;15%</td>
<td>210</td>
</tr>
<tr>
<td>Maricopa</td>
<td>1255</td>
<td>&lt;15%</td>
<td>210</td>
</tr>
<tr>
<td>Algodones</td>
<td>166</td>
<td>ib</td>
<td>210/690</td>
</tr>
</tbody>
</table>

The ib indication means that the silt and clay content is in between 15% and 25%. $D_{\text{min}}$ is the gmd of the soil aggregate population dominating dust emissions (see text for details).

Fig. 7. Results of the reanalysis of the data of Nickling and Gillies (1989). Ten sites (out of 13) have a dust production potential similar to the one predicted by the model for FS-dominated soils, and 1 (Mesa ag.) is clearly dominated by a CS component.
Moreover, in spite of a relatively large scatter in experimental values the computed $F_v$ and $z$ are of the same order of magnitude as the measured ones. It can also be noted that the parallel increase in $u^*$ and $Z_0$ values during the second period of the measurements did not result in any significant alteration of fine dust emissions as compared to the first period.

4.2.2. NG89 results

The method described above is applied to each soil of the NG89 data set. More precisely, the DPM is run with the experimental $Z_0$ and with two possible values of $D_{\text{min}}$ (210 and 690 μm). Results are then compared to the measurements. Fig. 6a and b presents examples of such comparisons for the Glendale and Mesa (agricultural) soils. It can be seen that Glendale measurements are better reproduced with $D_{\text{min}} = 210$ μm indicating that an aggregate population of the FS type dominates dust emissions by this soil. On the contrary, a CS aggregate population explains emissions by the Mesa agricultural site. This shows that the loose erodible fraction of this soil does not contain fine sand populations that else would dominate dust production. The same method applied to the various soils directly provides a $D_{\text{min}}$ value for 11 out of the 13 soils of the NG89 data set. These $D_{\text{min}}$ are reported in Table 3. Fig. 7 compares $F_v$ measured over these 11 soils to computations by the DPM with the average of

![Graphs showing $F_v$ and $\alpha$ as functions of $u^*$ for NG89 results.](image)

**Fig. 8.** Results of the reanalysis of the data of Nickling and Gillies (1989) for the Algodones site. Measured sandblasting efficiencies and vertical fluxes are in between those predicted for pure FS (thin line) and pure CS (bold line) components, indicating that a small proportion of FS must be mixed with a larger proportion of CS soil aggregates.

![Graphs showing $\alpha$ as functions of $u^*$ for NG89 results.](image)

**Fig. 9.** Results of the reanalysis of the data of Nickling and Gillies (1989) for the Maricopa site. Measured sandblasting efficiencies (b) are consistent with a FS component (bold line), but measured vertical fluxes (a) are lower than predicted for such a component.
the 11 experimental $Z_0$ values. Of the 11 soils, only one (Mesa ag.) is undoubtedly of the CS type. Between the two remaining cases, the Algodones site probably carries a mixture of FS and CS with a large proportion of the latter type of aggregates. Indeed, in spite of a large experimental scatter, $F_v$ and $x$ values are comprised between those predicted for FS and CS soils (Fig. 8a,b). For Maricopa (Fig. 9a,b), the $x$ value is that of an FS component, but $F_v$ is lower than predicted for such a soil. This may result from the particular surface roughness condition of this plot. Nickling and Gillies report that the field had been ploughed a little before the wind tunnel measurements and that the surface carried well-defined ridges 15–20 cm in height. Moreover, large 10-cm clods brought out by the ploughing process were present. In such conditions, there is a possibility that the parameterization used in the DPM for assessing the protective effect of non-erodible elements might become less effective. The ensuing overestimation of the saltation flux could thus explain the overestimation of $F_v$ by the DPM but, as demonstrated by Gomes et al. (2003a), this does not prevent a correct computation of the sandblasting efficiency by the DPM.

5. Summary and conclusion

The DPM has managed to reproduce the vertical fluxes measured by Rajot et al. (2003) over a bare field in Niger, and by Nickling and Gillies (1989) over 13 different sites in Arizona and California. For this, the binding energies of the three PM20 populations that can be released by sandblasting from the soil aggregates have been fixed to their value previously determined for Niger soils. This indicates that these energies must only weakly depend on soil composition, and that in all the tested cases sandblasting is probably the driving mechanism explaining dust production.

The sensitivity tests performed with the DPM, and the subsequent comparisons with extensive field measurements have demonstrated that PM20 emissions from a given surface are a multivariate phenomenon. Apart from the wind friction velocity that is a measure of the constraint exerted by wind on the surface, soil aerodynamic roughness is an important parameter. Indeed, it conditions the threshold above which saltation and sandblasting can occur. In addition to this parameter, the one that has the main influence on dust production is the dry size-distribution of the soil aggregates present in the loose, wind-erodible fraction of the soil. More precisely, the aptitude of a soil for dust emission is, in most tested cases, conditioned by the size (gmd) of the finest soil-aggregate population it contains. For example, our results show that 12 out of the 13 natural soils selected by Nickling and Gillies for their high potential for dust emissions contained a fine soil aggregate population. The fact that these soils were characterized by quite different contents in silt and clay (Table 3) shows that, contrary to what is often assumed, texture is not directly a relevant parameter to predict the aptitude of a soil for dust emissions. Nonetheless, texture may play an indirect role because crusts able to limit saltation, and hence dust production, are more liable to form on fine textured soils than on coarse-textured ones. The influence of crusting is not yet taken into account in the DPM.

Finally, this study shows that when reanalyzed with the appropriate soil parameters the apparent scatter of field measurements is much less important than it previously seemed to be. Though it will not suppress the sometimes-important uncertainties inherent to field measurements, these new findings should be taken into account in the preparation of field experiments to come.

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