Relative impact of roughness and soil texture on mineral dust emission fluxes modeling

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Abstract. Dust production models are widely used to estimate vertical fluxes of mineral aerosols over arid regions. Mineral dust fluxes emitted over western Africa represent one of the largest amount of aerosols in the atmosphere but the emission calculation remains highly uncertain. Several parameters are involved in the emissions calculations: among others, the surface and soil description is crucial. In atmospheric modeling, depending on the modelled area and the horizontal resolution, several surface and soil datasets are available and used. Some datasets are built merging satellite data and field campaigns specifically dedicated to this aerosol type: they are generally area limited. Some other datasets are less fine but available for the whole Earth, used for several model applications, including trends and climate studies. In this paper, different surface and soil databases are used to force the same dust production model. Mineral dust fluxes are calculated and compared in term of intensity and spatialization. It is shown that a combination of ERS satellite derived roughness length, of the USGS surface dataset and of the STATSGO-FAO the soil dataset, used with an explicit calculation of drag efficiency enables to estimates realistic mineral dust fluxes when compared to the LISA dataset, used as a reference and built with local measurements and analysis but restricted to the Saharan and Sahel regions.

1. Introduction

Dust aerosol particles are produced by wind erosion, in arid and semi-arid surfaces. From the local to the global scale, modeling of mineral dust remains a challenge. While dust distribution and dust effects are important at global scales, they strongly depend on dust emission, which is a threshold, sporadic and spatially heterogeneous phenomenon, locally controlled on small spatial and temporal scales. Since dust plays a key role in regional to global climate and air quality because of its effects upon radiation, ocean biogeochemistry, and human health, it is necessary to accurately represent its emission, transport and deposition at different spatial and temporal scales. During the last years, many efforts have been devoted to the reduction of emission uncertainties. Current theoretical knowledge would allow a satisfactory calculation of the vertical dust flux in models if the required input parameters-surface, soil and meteorological features-were accurately determined. However, the application of complex emission schemes in global and to a lesser extent regional models is mainly hampered by the lack or the strong uncertainties of the required input data at the pertinent scales and the inaccuracies of the driving meteorological model mainly with respect to surface wind velocities, turbulence and stability.

In order to partly overcome these limitations, current global models (e.g. [Chin et al., 2000], [Tegen et al., 2002], [Zender et al., 2003], [Mahowald et al., 2003], [Miller et al., 2006]) have assumed varying degrees of simplification in the dust emission scheme as a function of the availability and accuracy of the input data and in most cases several parameters are tuned to match quantitative dust observations that are mainly available far away from sources.

Regional mineral dust models have been also developed and used for particular regions such as for example DREAM ([Nichovic et al., 2003], [Perez et al., 2006]) and CHIMERE ([Menut et al., 2007]) in Northern Africa. Although simplifications also apply to regional models, some of them include specific surface and soil datasets developed for the most well-known source regions (e.g. [Chatenet et al., 1996], [Callot et al., 2000]). Numerous sensitivity experiments have been performed to better understand and quantify strengths and weaknesses of different formulations and datasets. The sensitivity to various dust production models and meteorology was quantified in [Todd et al., 2008] over the Bodele region and [Menut, 2008], [Cheng et al., 2008] and [Zhao et al., 2010], among others.

In dust model intercomparison exercises ([Textor et al., 2006], [Textor et al., 2007], [Todd et al., 2008], [Huneeus et al., 2011]) surface, soil, meteorology and dust production models (DPMs) vary from one model configuration to the other. It is therefore difficult to attribute model differences to a specific parameter or forcing, and error compensations are always possible. In an interesting effort, [Darmenova

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Marticorena and Bergametti different physically based schemes which were originally developed by [Marticorena and Bergametti, 1995] and [Shao et al., 1995]. The relative importance of the input parameters was assessed and some recommendations were provided on the selection of input parameters, including land and meteorological variables, to achieve an improved modeling of dust emission in Central and East Asia. A more recent study implemented three dust schemes in WRF-Chem and compared the vertical dust fluxes, highlighting large differences for the same meteorological conditions, surface and soil data, [Kang et al., 2011].

In this paper, the sensitivity of mineral dust fluxes to surface and soil features is studied over Northern Africa and the Middle East. Our goal is to understand and quantify, under idealized meteorology, the spatial distribution of emissions in the region when using different formulations and datasets describing the soil and surface conditions in the region.

Concerning the soil, the fractions of clay, silt and sand from global soil datasets (e.g., [Zobler, 1986]) are generally mapped according to the well-known textural triangle which is based on measurements using wet sedimentation techniques that may strongly overestimate the amount of clay particles [Laurent et al., 2008]. In this paper we will compare this approach against an alternative approach using dry techniques [Chatenet et al., 1996].

Another very important parameter is the aerodynamic roughness length that controls the threshold wind friction velocity above which saltation starts. The estimates of roughness length used in meteorological models do not apply to the scales needed for describing the dust emission process. Only recently, new encouraging approaches based on satellites ([Prigent et al., 2005] and [Laurent et al., 2008]) were proposed for providing the information on aerodynamic roughness lengths appropriate for global and regional dust models. We test and compare the spatial distribution of emissions using a drag partition scheme that includes estimates of roughness lengths from satellite estimates ([Prigent et al., 2005]).

Partly due to the lack of aerodynamic roughness length datasets at a global scale, a very common approach has been the prescription of an erodibility factor that accounts for the spatial distribution of dust source intensities. [Prospero et al., 2002] showed that enclosed basins containing former lake beds or riverine sediment deposits are preferential sources dominating global dust emission. Several model representations of preferential sources have been used based on topographic ([Ginoux et al., 2001]), hydrological ([Tegen et al., 2002]) or geomorphological ([Zender et al., 2003]) approximations. Also surface reflectance retrieved from MODIS ([Gros et al., 2005]), the frequency of high Aerosol Index values ([Westphal et al., 2009]) and the UV-visible surface albedo ([Morcrette et al., 2009]) have been used to identify preferential sources. The results of sensitivity experiments with different preferential source formulations at a global scale ([Zender et al., 2003]; [Cakmur et al., 2006]) are rather inconclusive since they are dependent on the model and evaluation data as well as on the optimization and evaluation methods. The most popular representation of sources in dust modeling which has shown significant improvements is the topographic approach of [Ginoux et al., 2001]. In this paper we also test and analyze this approach in comparison to the use of aerodynamic roughness lengths in a drag partition scheme.

The surface and soil properties are described in section 2. The Dust Production Model (DPM) used is described in section 3. The methodology used for the comparison is described in section 4. The calculated mineral dust fluxes are presented and discussed in section 5, along with an analysis of differences among the datasets and emission fluxes. Conclusions are synthesized in section 6.

2. The surface, soil type and texture data
2.1. The soil type and texture data

In this study, two different datasets are used, hereafter named LISA and STATSGO-FAO. The LISA soil dataset was developed by [Marticorena and Bergametti, 1995]. The

![Figure 1. The LISA and STATSGO-FAO soil types data regridded to 1' x 1' resolution. The values correspond to the surface types explained in the Table 1. For each cell, only the most important relative surface is displayed (on a total of five possible surface types in a cell).](image-url)

### Table 1. Characteristics of each model soil type. CS=Coarse sand; FMS=Fine medium sand.

<table>
<thead>
<tr>
<th>LISA data soiltypes</th>
<th>n²</th>
<th>%</th>
<th>Soiltype</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46</td>
<td>46</td>
<td>5 3 0</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>41</td>
<td>18 0 0</td>
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<td>29</td>
<td>29</td>
<td>32 10 0</td>
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<tr>
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<td>10</td>
<td>10</td>
<td>85 5 0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>31.25 31.25 37.5 0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>20 0 80</td>
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<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>40 0 0</td>
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</table>

<table>
<thead>
<tr>
<th>STATSGO-FAO data soiltypes</th>
<th>n²</th>
<th>%</th>
<th>Soiltype</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46</td>
<td>46</td>
<td>5 3 0</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
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<td>17</td>
<td>17</td>
<td>70 13 0</td>
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<td>0</td>
<td>0</td>
<td>43 39 18</td>
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<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>10 56 34</td>
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<td>8</td>
<td>0</td>
<td>0</td>
<td>32 34 0</td>
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<td>11</td>
<td>0</td>
<td>0</td>
<td>22 20 58</td>
</tr>
</tbody>
</table>
STATSGO-FAO is a global dataset used in meteorological modeling and which may be used for global and regional dust transport modelling. Both provide soil texture characteristics over longitude/latitude regular grids. The native resolution of the datasets are different: 1° × 1° for LISA-soil and 0.0083° × 0.0083° for STATSGO-FAO-soil. In order to have homogeneous datasets, the STATSGO-FAO-soil data are regridded into a regular 1° × 1° grid, retaining the dominant feature.

The soil types for the two datasets are listed in Table 1 together with their relative percentage of silt, salt, clay and sand (coarse and fine-medium). Note that STATSGO does not contain salts and that we use four soil populations distinguishing among fine-medium sand and coarse sand according to criteria detailed in [Tegen et al., 2002]. In this sense, clay loams are highly unlikely to contain coarse sand while sandy clay loams could contain both coarse and medium fine sand. The textural triangle is based on measurements performed by wet sedimentation techniques which break the soil aggregates leading to high amounts of loose clay particles that generally form aggregates of larger size and that may not be encountered in natural soils. Following [Tegen et al., 2002] we assume that clay is in the form of aggregate in loamy sands where it is reassigned to the silt fraction.

For each soil, characteristics are prescribed in terms of mean mass median diameter, \(D_p\) (\(\mu m\)) and the associated standard deviation \(\sigma\). An issue is that the two datasets do not use the same values of these soil characteristics: in this study, for the sake of comparison we use the same size distribution characteristics for each population in the soil as displayed in Table 2.

For each LISA-soil grid cell, five different soils are described. They correspond to the five most important soils of the cell as a function of the surface. For each soil type, a surface percentage is given. From the highly resolved STATSGO-FAO-soil data, we calculate the same type of data, counting the relative percentage of each soil type in a cell of 1° × 1°. The data are thus sorted to save the five most important contributions.

### Table 2. Mean characteristics of the soil textures used for the dust flux calculations with the mean mass median diameter \(D_p\) in \(\mu m\). L2008 refers to [Laurent et al., 2008], T2002 to [Tegen et al., 2002] and TS to 'this study'.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>L2008 (D_p)</th>
<th>L2008 (\sigma)</th>
<th>T2002 (D_p)</th>
<th>T2002 (\sigma)</th>
<th>TS (D_p)</th>
<th>TS (\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>690</td>
<td>1.6</td>
<td>710</td>
<td>2</td>
<td>690</td>
<td>1.6</td>
</tr>
<tr>
<td>Fine-medium sand</td>
<td>210</td>
<td>1.6</td>
<td>160</td>
<td>2</td>
<td>210</td>
<td>1.6</td>
</tr>
<tr>
<td>Silt</td>
<td>125</td>
<td>1.8</td>
<td>15</td>
<td>2</td>
<td>125</td>
<td>1.8</td>
</tr>
<tr>
<td>Clay</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Salts</td>
<td>520</td>
<td>1.5</td>
<td>-</td>
<td>2</td>
<td>520</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Figure 2. (top) the USGS landuse classes (from 1 to 23) over the domain. (bottom) The relative percentage of USGS class 19 surface (for barren soils). This class is used as a desert mask for the dust fluxes calculation when using the USGS data.

### Figure 3. The roughness length definitions as a function of its use in local to global meteorological and dust transport models.

### Figure 4. Comparison of the dynamical roughness lengths, \(z_0\) (cm), provided with the three surface data sets and for the most important relative surface fraction for each cell. Horizontal resolution is 1° × 1°. The colorscale is the same than in [Prigent et al., 2005] for LISA and OBS-P, but different for USGS, the values being one order of magnitude higher.
In this section, the landuse data are described in terms of their use for dust emissions fluxes calculations. The surface data are composed of landuse types. For each type, a dynamical (or aeolian) roughness length, \( z_0 \), is typically prescribed. As described in the next section, roughness lengths based on land use types are not appropriate for use in dust emission parameterizations. For mineral dust emission calculations, the landuse is typically used to estimate what surface is potentially erodible. For the LISA dataset, this information is contained in the percentage of erodibility of each grid cell: the desert mask is represented with values of the erodibility percentage null or not. Global or regional models typically consider arid and semiarid categories from a landuse database to identify potential dust source areas. Here, complementing the STATSGO-FAO, we use the USGS landuse dataset with a high horizontal resolution (0.0083° × 0.0083°) and averaged over the desired grid cell (here, to be the same than the LISA dataset). During the average, the five more important landuse types are sorted. For a specific grid cell, if a landuse class is 8 (shrubland) or 19 (barren soil), the relative part of the cell is considered as erodible. This constitutes the desert mask as presented in Figure 2.

2.3. The roughness length

Depending on the spatial scale of the model, the surface roughness varies widely. This is expressed by two parameters: the topography and the roughness length, \( z_0 \) and represent the same kind of process: the presence of solid obstacles able to slow the near-surface wind flow.

In meteorological modelling, the roughness length is mainly used to estimate the friction velocity, a turbulent parameter designed to estimate the wind speed near the surface. \( z_0 \) will be defined such that the modelled wind is realistic, compared to measurements. In this sense, the roughness length has no 'physical' and 'realistic' meaning: this is a parameter defined to integrate correctly the vertical wind.

In dust modelling, the roughness length may be used to estimate the threshold friction velocity. In meteorological and dust models, three roughness lengths at different scales may be used, as illustrated in Figure 3.

1. At the synoptic scale: This 'aerodynamic' roughness length is used mainly for the atmospheric part of the model to calculate the friction velocity to take into account the role of mountains or forests when slowing the mean wind fields at large scale. Values are often look-up tables or just constant over desert surfaces. The values are generally ranging from 1cm to one meter. This is the case of the USGS values presented in Figure 4. This dataset is not appropriate for the calculation of the threshold friction velocity in dust models since it does not represent the roughness at the scale needed for the emission process.

2. At the mesoscale: the roughness length accounts for vegetation and obstacles. Values are generally lower than the 'synoptic' roughness length and range from mm to cm. This is the case of the LISA dataset: \( z_0 \) is provided after the compilation by [Chatenet et al., 1996] and [Callot et al., 2000]. The values are representative of local effects and constitute a more realistic \( z_0 \) dataset for this study. Another available dataset, hereafter called OBS-P, is derived from ERS-1 satellite measurements (with a horizontal resolution of 0.25° × 0.25°). [Prigent et al., 2005]. The retrieval approach differs from the in-situ-based approach used for the LISA dataset and constitutes an interesting alternative for dust emission calculations at a global scale.

3. At the small (particle) scale: the smooth roughness length, \( z_{0s} \), accounts for mobile erodible sand particles. This length is generally tabulated or calculated using the mean mass median diameter of the erodible particles, \( D_p \), as \( z_{0s} = D_p / 30 \).

The roughness effect can be parameterized through a drag partition scheme which expresses the efficiency with which drag is partitioned between the roughness elements characterized by the aerodynamic roughness length \( z_0 \) and the erodible surface characterized by a smooth roughness length \( z_{0s} \). The different values of \( z_0 \) (cm) used in this study are presented in Figure 4. The LISA values show an important spatial variability and a large range of values (from \( z_0 = 10^{-4} \) to 10cm). The OBS-P values are spatially variable and close to the LISA values. The USGS values are homogeneous over the whole domain and are related to the most present landuse, barren soil. This leads to very high values (two orders of magnitude higher than LISA and OBS-P): in this case, a drag partition scheme is not usable ([MacKinnon et al., 2004]) and the USGS dataset will only be used for the calculation of the friction velocity and not for the threshold friction velocity.

3. Dust production model design

The dust emission fluxes are calculated using the parameterization of [Marticorena and Bergametti, 1995] (hereafter denoted MB95) for saltation and the DPM proposed by [Alfaro and Gomes, 2001] (hereafter denoted AG01) for sandblasting. Before calculating the fluxes, the estimation of the friction velocity is required. All steps involved in the calculation are presented in this section.

3.1. The friction velocity

For this academic study, the friction velocity, \( u^* \), is estimated under neutral conditions, as:

\[
 u^* = \left[ \frac{k}{\ln(z/z_0)} \right] \left( \frac{\tau}{\rho} \right)
\]

with \( k=0.41 \), the Karman constant, \( z \) the height above ground level where the wind speed is estimated by the meteorological model, in this case \( z=10m \), and \( z_0 \) the roughness length. This roughness length is a key point for this study.

Figure 5. The drag efficiency calculated for a wide range of roughness length ad for specific values of the smooth roughness length, depending on the mean mass median diameter of the particles.
3.2. The threshold friction velocities and the drag efficiency

The saltation flux \( F_h \) is non-zero only if \( u_* > u_*^T(D_h) \) for a given soil particle diameter \( D_h \). \( u_*^T \) is the threshold friction velocity depending on \( D_h \), the soil particle diameter, \( z_0 \), the 'aeolian' roughness length and \( z_0^s \), the 'smooth' roughness length.

The 'smooth' threshold friction velocity \( u_*^{T,s} \) is estimated following [Shao and Lu, 2000]:

\[
u_*^{T,s}(D_h) = \left( a_n \cdot \frac{\rho_g D_h}{\rho_{air} + \gamma \cdot p_{air}(D_h)} \right)
\]

with the constant parameters \( a_n = 0.0123 \) and \( \gamma = 30^\circ F \). The particle density, \( \rho_p = 2.65 \times 10^3 \text{ kg.m}^{-3} \) is chosen to be representative of quartz grains clay minerals.

The threshold friction velocity, \( u_*^T \), is expressed as:

\[
u_*^T(D_h) = u_*^{T,s}(D_h) \cdot f_{\text{eff}}(z_0, z_0^s)
\]

with \( q \) a soil moisture correction. For this academic study, and in order to not add more variability to analysis, this correction is set to \( q=1 \).

\( f_{\text{eff}} \) represents the drag efficiency, i.e., a function depending on \( z_0 \), the 'aeolian' roughness length and \( z_0^s \), the 'smooth' roughness length which is expressed as, [Marticorena et al., 1997]:

\[
f_{\text{eff}} = \left[ 1 - \frac{\ln(z_0/z_0^s)}{\ln(0.35([0.1z_0^s]/z_0))} \right]^2
\]

This function takes into account the non erodible elements dissipating a part of the wind momentum that will not be available for saltation.

The evolution of this parameter as a function of the roughness length values is displayed in Figure 5. The drag efficiency is limited to have values between 0 and 1. For \( f_{\text{eff}}=1 \), the threshold friction velocity \( u_*^T \) is equal to the smooth threshold friction velocity \( u_*^{T,s} \); the surface is smooth and there are no non-erodible elements. On the other hand, for an increasing roughness length \( z_0 \), non-erodible elements are present: \( f_{\text{eff}} \) tends to zero, increasing the value of \( u_*^T \) and thus limiting the potential erodibility of the considered surface.

3.3. The wind speed distribution

Even if the current study uses academic wind speed over the whole domain, the goal is to evaluate the mineral dust fluxes under realistic conditions. The model grid resolution is \( 1^\circ \times 1^\circ \), thus larger than the subgrid scale variability of observed winds.

If the use of a mean wind speed value may have a limited impact on the model results, this is not the case for saltation process being a wind dependent threshold process. In order to take into account this spatial subgrid scale wind variability, a Weibull distribution is implemented, following [Cakmur et al., 2004] and [Pyror et al., 2005]. The probability density function is expressed as:

\[
p(U) = \frac{k}{A} \left( \frac{U}{A} \right)^{k-1} \exp \left[ -\left( \frac{U}{A} \right)^k \right]
\]

where \( k \) is a dimensionless shape parameter (in our case, \( k = 4 \), a value commonly used to represent the wind variability over larger surfaces). \( A \) is a scale parameter related to the mean of the distribution: in our case the modelled wind speed for each cell and each modelled hour.

3.4. The horizontal saltation fluxes

The parameterization of [Marticorena and Bergametti, 1995] estimates saltation fluxes using wind speed values and a complete description of the soil characteristics (dry size-distribution of the loose erodible soil aggregates, soil humidity, vegetation cover, presence of non-erodible elements such as rocks on the surface). The calculation of the vertically integrated saltation flux is based on [White, 1986]’s equation:

\[
F_h(D_h) = K \frac{D_h}{\rho_p u_*^3} \left( 1 - \frac{u_*}{u_*^T} \right) \left( 1 + \frac{u_*}{u_*^T} \right)^2
\]

Following the recommendation of [Gomes et al., 2003], we set \( K=1 \) in our calculations. The air density is also considered as constant (\( \rho_{air}=1.227 \text{ kg.m}^{-3} \)) for this academic study.

Finally, the total saltation flux is obtained by integrating \( F_h \) over the soil size distribution from \( D_{p_{min}}^{\text{max}}=10^{-6} \text{m} \) to \( D_{p_{max}}^{\text{max}}=2.10^{-3} \text{m} \). This interval is chosen in order to cover the whole range of possible soil sizes. The final saltation flux is expressed as:

\[
F_h = \int_{D_{p_{min}}^{\text{max}}}^{D_{p_{max}}^{\text{max}}} F_h(D_p) dS_{rel}(D_p) dD_p
\]

The relative surface distribution covered by particles with a mean median diameter \( D_p \) ([Marticorena and Bergametti, 1995]).

3.5. The vertical sandblasting fluxes

In order to estimate size resolved vertical dust fluxes, i.e sandblasting fluxes, the [Alfaro and Gomes, 2001] DPM is used with the numerical optimization described in [Menut et al., 2005]. The sandblasting flux is computed based on the partitioning of the kinetic energy of individual saltating aggregates and the cohesion energy of the populations of dust particles. This model assumes that dust emitted by sandblasting is characterized by three modes whose proportion depends on the wind friction velocity. From wind tunnel measurements performed on two natural soils from semi arid regions, [Alfaro et al., 1998] consider these three modes as independent of the soil types. They described the three modes using log-normal distributions with diameters \( d_1=1.5 \times 10^{-6} \text{m} \), \( d_2=6.7 \times 10^{-6} \text{m} \) and \( d_3=14.2 \times 10^{-6} \text{m} \) and their associated standard deviation, respectively \( \sigma_1=1.7 \), \( \sigma_2=1.6 \) and \( \sigma_3=1.5 \). Based on this model, as soil aggregate size or wind speed increases, kinetic energy becomes able to release first particles of the coarsest mode that are associated with the lowest cohesion energy, then particles from the intermediate population, and finally the finest particles. It also implies that for a specific wind speed and soil size distribution, the dust flux may be zero even if the saltation process occurs. In order to apportion the available kinetic energy between the three modes, a constant cohesion energy \( \epsilon_i \) is associated to each mode values. The numerical values of \( \epsilon_i \) were determined by adjusting the predicted aerosols size distribution to those measured in wind tunnel under different wind conditions, using an iterative least square routine. In this study, the values recommended by [Alfaro and Gomes, 2001] are used: \( \epsilon_1=0.376 \), \( \epsilon_2=0.366 \) and \( \epsilon_3=0.346 \text{ kg.m}^{-1}.s^{-2} \).

The kinetic energy is expressed as a function of the soil particle diameter after [Alfaro et al., 1997] and [Shao and Lu, 2000]:

\[
\epsilon_i = \rho_p \frac{100\pi r_i^3}{3} D_p^3 (u_*)^2
\]

It is compared to the cohesion energy of the three aerosol modes in order to compute the proportion \( \rho_i(D_p) \) of these three modes in the total dust size-distribution. Summing equation 9 over the three aerosols modes, the total sandblasting flux may be written:

\[
F_{\text{vert},i}(D_p) = \int_{D_{p_{min}}^{\text{max}}}^{D_{p_{max}}^{\text{max}}} \frac{\rho_i(D_p)}{6} \rho_p \frac{100\pi r_i^3}{3} D_p^3 dD_p
\]
the whole modelled domain and over some specific areas. These areas are displayed in the Figure 6 (top) where the map represents the Aerosol Optical Depth at 555 nm measured by MISR and averaged from February 2000 to December 2010, with a 0.5° × 0.5° resolution. The MISR AOD represents both sources and dust load in the atmosphere, after transport. But, we consider that the strongest regional AOD coincide roughly with the main dust sources. Among the sources, we highlight the Bodele and eastern Niger, the Mali/Mauritania border source, the Chotts, the Lybian desert and the Ariabian desert. In Figure 6 (top), the rectangles define restricted areas where results will be presented. Results will be also presented for a larger domain encompassing the whole Saharan-Sahel region. This spatial limitation corresponds to the availability of the LISA data. Names and coordinates of the areas are given in the Table 3.

4.2. Sensitivity to input parameters

The main goal is to estimate the variability of dust vertical fluxes emissions when using different soil and surface descriptions, and the use of drag efficiency or not. The horizontal resolution was chosen to be the same for all calculations, 1° × 1°. For each of these configurations, the [Alfaro and Gomes, 2001] DPM is used, after its numerical optimization described in [Menut et al., 2005].

As previously described, the threshold friction velocity may depend on a drag efficiency parameter. In order to test the sensitivity of our calculations, we define three different experiments:

1. NOeff: without any drag efficiency calculation and thus with $f_{eff}$ set to 1.
2. Feff: with the drag efficiency as described in equation 4.
3. GOpref: with a preferential source function. This latter was proposed partly due to the historical lack of roughness length for dust models a preferential source erodibility map such as the one proposed by [Ginoux et al., 2001] for the GOCART model has been widely used to specify the most erodible areas in models. In Figure 6 (bottom), the values represent a multiplicative factor, $\alpha$, with an horizontal resolution of 1° × 1°, ranging from 0 to 1 and built to enhance the representation of the most erodible surfaces. In this case, the vertical dust fluxes are calculated using $f_{eff} = 1$ and $F_{v,GMpref} = \alpha \times F_v$.

In addition to these configurations about the drag efficiency, we define three different use of the roughness length and the soil types, as described in Figure 7. The different combinations lead to the calculation of three different mineral dust fluxes:

1. z0LISA-soilLISA: represents the flux with the use of the LISA dataset for the soil texture and the roughness length in the drag partition scheme.
2. z0OBS-P-soilLISA: represents the flux using the LISA soil texture and the OBS-P $z_0$ in the drag partition scheme.
3. z0OBS-P-soilSGF: represents the flux using the STATSGO-FAO for the soil texture and the OBS-P $z_0$ in the drag partition scheme.

Note that the soil texture affects the threshold friction velocity through $z_0$. For each of these configurations, the threshold friction velocity affects the threshold friction velocity through $z_0$, which depends on the coarser soil particle population, the saltation flux through the relative surface area of the soil particles and the kinetic energy in the vertical flux though the soil particle diameter.

These nine configurations will make it possible to evaluate the relative sensitivities of the fluxes to the soil datasets and the way to prescribe the roughness over erodible surfaces. The comparisons between z0LISA-soilLISA and z0OBS-P-soilLISA are used to estimate the impact of the roughness length on the flux calculations. The comparisons between z0OBS-P-soilLISA and z0OBS-P-soilSGF are used to quantify the impact of the soil texture database on the flux calculations.

4. Methodology

4.1. Main dust Saharan dust sources

The relative impact of roughness length and soil texture on mineral dust fluxes modeling will be estimated over
5. Results and discussion

5.1. Horizontal maps

Maps of surface fluxes are displayed in Figure 8. For the three configurations (z0LISA-soilLISA, z0OBS-P-soilLISA, and z0OBS-P-soilSGF, Figure 7), with the use of the drag efficiency, noted \( f_{eff} \), the GOCART preferential sources noted GOpref, and without representation of erodibility noted NOfg. The wind speed is academic and corresponds to a constant value of 12m/s over the whole modelled domain.

Note that all results are presented as a function of the wind speed values and not as a function of the friction velocity, as usually done in articles discussing on mineral dust emissions calculations (from Marticorena and Bergametti 1995 to Darmenova et al. 2009, for example). This choice is linked to the present study focus: we study the impact of the roughness length, used to recalculate the friction velocity. If the results were presented in terms of friction velocity, the analysis would be more difficult because it would mask the variability of results due to the roughness and to the deduced friction velocity.

For the ‘NOfg’ configuration, the fluxes are higher than with Feff or GOpref. The spatial variability is rather low over the whole continent, being diagnosed over areas where no sources are detected by MISR. The worst situation is certainly z0LISA-soilLISA. Using the OBS-P roughness length, the results are more realistic with the LISA or STASGO-FAO soils, in particular there is no unrealistic fluxes over Sahel.

For the ‘Feff’ configuration, the z0LISA-soilLISA dataset represents well the spatial variability of the dust sources observed in Africa. When using the OBS-P z0 with the LISA soil (z0OBS-P-soilLISA), the major sources are conserved, but the lowest fluxes become negligible. Using the OBS-P z0 with the STASGO-FAO soil data (z0OBS-P-soilSGF) the spatial variability is very close to z0OBS-P-soilLISA, due to the roughness length but the flux magnitudes are higher, due to the soil texture, which is smoother with USGS than with LISA.

For the ‘GOpref’ configuration, the three cases exhibit close spatial variability, the fluxes being mostly driven by the \( \alpha \) factor. The highest fluxes are estimated using z0LISA-soilLISA, as in the model cases using the \( f_{eff} \) drag efficiency. In contrast to the Feff experiments, the preferential source enhances the fluxes in the border of Algeria with Mauritania and Mali, and emits to a large extent the Mali/Mauritania border source.

By comparing the z0LISA-soilLISA fluxes, with \( f_{eff} \), GOpref, NOfg one has the direct effect of the use of a drag partition scheme, the preferential source or without any of the previous. It is noticeable that the use of a drag efficiency scheme completely changes the spatial distribution of fluxes. The fluxes are always lower than with the NOfg configuration, by a factor of 2 or 3, showing the high sensitivity of fluxes calculations to those attenuation factors.

Spatially, the use of Feff with z0LISA-soilLISA tends to suppress fluxes in the Sahelian area, for latitudes under 17°N. Using NOfg or GOpref \( \alpha \) factor, fluxes are important under this latitude.

By comparing z0LISA-soilLISA and z0OBS-P-soilLISA, one has the direct effect of changing the roughness length value while using the same soil data. The differences are important and show that fluxes are highly sensitive to the roughness. Even if the z0 are close between LISA and OBS-P, the calculated fluxes are very different. This specific point will be discussed in more detail in the next section.

By comparing z0OBS-P-soilLISA and z0OBS-P-soilSGF, one has the direct effect of replacing the soil database. The spatial distributions of fluxes are close, but there are considerable changes in magnitude, particularly over the Bodele and the Arabian and Libyan deserts.

Finally, it appears that the spatial distribution of fluxes is mainly driven by the values of roughness length, \( z_0 \). The flux magnitude is mainly sensitive to the soil description and to whether a drag partition scheme is used or not.

5.2. Distributions of fluxes

Figure 11 presents the distribution of the values presented in Figure 8, for NOfg, Feff and GOpref configurations. The flux values are represented with a step of 0.5 \( g.cm^{-2}.s^{-1} \times 10^8 \). The occurrence is normalized and represents a percentage (from 0 to 100%). The values represent
the percente number of grid cells where the dust flux value is estimated.

For NOfg, Feff and GOpref, it is remarkable that \( z_{0\text{LISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \) distributions observed in \( z_{0\text{OBS-P-soilLISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \). This is a direct effect of the way distributions observed with \( z_{0\text{LISA}} \) and \( z_{0\text{OBS-P-soilLISA}} \). For NOfg, Feff and GOpref, it clearly appears that Feff and GOpref act on the low flux values by decreasing the mean average value of \( 10^{-15.10^{-8}} \) to \( 1-3\times10^{-8} \) g.cm\(^{-2}\)s\(^{-1}\) for the data sets with \( z_{0\text{LISA}} \) and \( z_{0\text{OBS-P-soilLISA}} \). The different model configurations show large discrepancies. With \( z_{0\text{OBS-P-soilLISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \) versions diagnosed vertical fluxes lower than with \( z_{0\text{LISA}} \) for some specific land types and thus, only "discrete" values are prescribed.

5.3. Fluxes over specific areas

For all configurations, the dust production model was ran with spatially constant wind speed values, from 0 to 24m/s (with a step of 1m/s). Results are spatially integrated over the specific source regions and results are displayed in Figure 9 and Figure 10. An integration of fluxes over the whole domain simulation is added in figures as 'ALL' in the title.

The choice of the specific areas is linked to their main characteristics in terms of sources and also to the differences diagnosed between the roughness length maps and the preferential source locations. It is noticeable, by comparing the roughness length maps, Figure 4, and the GOCART preferential sources, Figure 6, that a large part of the mineral dust sources are coincident. Some specific sources differ, the roughness maps emphasize the Mali-Mauritania border source while the preferential source emphasizes sources in the north of Mauritania and Mali and southern Algeria.

These differences are important for the next results in the paper and are logically due to the data themselves.

The fluxes with the configuration \( z_{0\text{LISA-soilLISA}} \) are generally higher than when the OBS-P roughness length is used (with \( z_{0\text{OBS-P-soilLISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \)). This is observed for the whole domain (ALL) but also for some specific regions, even if this tendency is lower over Bodélé, the Lybian and Arabian deserts. Another general tendency is that the fluxes without the drag efficiency, Feff, are important for very low wind speed. For desert areas and their associated mineralogy, it is often observed than fluxes are close to zero up to 7 or 8m/s, for the 10m wind speed. This is not the case for the configurations of NOfg and GOpref, for which some non negligible values are observed for low wind speed, between 2 and 6m/s. This effect is important with the \( z_{0\text{LISA-soilLISA}} \) dataset and is certainly unrealistic. The same applies for \( z_{0\text{OBS-P-soilLISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \), but to a lesser extent. Globally, this means that the use of no drag efficiency at all (NOfg) or GOpref gives unrealistic emissions fluxes for wind speeds between 4 and 8m/s. For wind speed values up to 8m/s, the configurations NOfg and GOpref produces more important fluxes that Feff for all regions.

5.4. Relative impact of \( z_0 \) distributions

The different model configurations show large discrepancies. With Figure 9 and Figure 10, it appears that the \( z_{0\text{OBS-P-soilLISA}} \) and \( z_{0\text{OBS-P-soilSGF}} \) versions diagnosed vertical fluxes lower than with \( z_{0\text{LISA-soilLISA}} \). This result is not dependent on the use of the drag efficiency or GOpref. This is thus a direct effect of the way to prescribe the roughness length. To understand this behaviour, Figure 12 presents distributions of aeolian roughness length, \( z_0 \), over the whole African domain and for the two datasets, LISA and OBS-P.

Since the LISA dataset is based on geomorphological considerations and measurement data, \( z_0 \) values are prescribed for some specific land types and thus, only "discrete" values are available. On the other hand, the OBS-P \( z_0 \) values are
estimated from satellite measurements and exhibit a continuous spectra of values. It is obvious that, to describe physical characteristics, a continuous spectra is more realistic that some few discrete values and in the case of mineral dust flux calculations, this may lead to large differences since the parameterizations used are based on threshold principles.

To better quantify this ‘discrete values’ effect, Figure 13 presents the distribution of the drag efficiency, $f_{\text{eff}}$, calculated for $z_{\text{LISA-soil}}$, $z_{\text{OBS-P-soil}}$ and $z_{\text{GRIP-soil}}$ for an academic wind speed of 12 m/s. This representation explains the main differences diagnosed in the fluxes calculations. Since the LISA $z_0$ dataset used only few different values of $z_0$, the corresponding $f_{\text{eff}}$ also exhibit a few discrete values. This means that the dust fluxes calculated with the complete dataset of LISA is less physical, being very dependent on the available tabulated values. On the other hand, when $f_{\text{eff}}$ is estimated with the $z_0$ of OBS-P, this latter having a more continuous spectra, the $f_{\text{eff}}$ is more continuous and more physically realistic. This means that for threshold friction velocity (dependent on the mean mass median diameter and thus the soil texture), the LISA dataset would provide more cells with a roughness length able to produce a flux than the other dataset, where the roughness length is more distributed. The LISA dataset would produce more mineral fluxes for a same wind, and more with the same magnitude.

The validation problem is there is no dust emissions fluxes measurements. The accuracy of estimated fluxes is only possible using a transport model, and comparisons between AOD of dust concentrations in the troposphere. It is thus not possible to state what is the more realistic emission schemes and database. But it is clear that there is an edge equation between the surface and soil datasets on the one side, and the parameterisation on the other side: the LISA dataset and scheme were developed together and the physics is adapted to the availability of discrete and not continuous $z_0$ values. Used as it with other surface and soil data, the saltation and sandblasting schemes are producing more important fluxes than expected.

6. Conclusion

In this paper, mineral dust emissions fluxes modelled over the Western Africa region are compared when using different roughness and soil texture datasets.

For dust modeling, several datasets are presently available. Some of them are issued from field campaigns and geomorphological analysis: they are generally spatially limited and thus useful for local or meso-scale modeling only. Some others are global, with a low horizontal resolution and some lacks may be present in the fine description of the soil texture and landuses. But the chemistry-transport modeling future, including mineral dust, is to have high resolution global datasets. It is therefore important to compare accurate but area-limited datasets with those available over the whole Earth.

For the specific study of mineral dust, numerous modeling studies already exist over the western Africa and the Sahel regions. One of the most known and widely used soil and surface dataset is the one proposed by the LISA and described in [Marticorena and Bergametti, 1995], with $1^\circ \times 1^\circ$ horizontal resolution. Information are deduced after field campaigns and geomorphological analyses, providing one of the more realistic dataset. On the other hand, global model also use such kind of dataset, but informations are more smooth and were not deduced after fine local studies. In particular, the roughness length is often more related to large scale dynamics than to the real need for mineral dust emissions. This is the case of the STATSGO-FAO and USGS datasets for which zooms over specific areas, such as western Africa, presents some lacks in the real variability of this region.

The main goal of this paper is to compare calculated mineral dust fluxes using these two datasets: LISA, STATSGO-FAO and USGS. In order to better compare and understand the fluxes variability, we present some changes in the way to take into account some surface properties. First, we replace the provided roughness length in LISA by the one proposed by [Prigent et al., 2005] (OBS-P), after ERS satellite analysis. We also used this roughness length to complete the
USGA dataset. Second, we implement the concept of the dust preferential sources, developed and used in the global GOCART model, [Ginoux et al., 2004], to replace the drag efficiency calculations. In addition, all estimations are also done without any drag efficiency use.

For all configurations, the dust production model of [Alfaro and Gomes, 2001] is used in all cases and academic wind speed is prescribed over the whole domain. Having no direct emissions measurements, comparisons are done model versus model, and we consider the full LISA dataset as the more realistic (being done with local measurements and geomorphological data) and thus the reference in this study. First, it is shown that the use of the OBS-P roughness length, \( z_0 \), dataset is completely able to replace prescribed LISA \( z_0 \). Second, even if the soil properties seems to be less spatially variable defined, the STATSGO-FAO soil dataset is realistic enough to make possible fluxes calculations over the whole domain. Sensitivity tests were also done for the use or not of the drag efficiency. It was shown that without this ponderation factor, fluxes are unrealistic, leading to huge values over the Sahelian region, among others. The use of the GOCART preferential sources is able to match the most important sources areas, but leads to more important fluxes than the drag efficiency direct calculation. It was highlighted that the LISA dust fluxes are, in average, more important than the other model configurations, due to the distribution of \( z_0 \) values. Being tabulated, values are more discrete and thus less realistic than those provided by satellite analysis such as the OBS-P data. Finally, in order to have realistic mineral dust fluxes calculations without spatial limitations, we showed that the use of the OBS-P \( z_0 \), combined to the USGS landuse, the STATSGO-FAO soil data and the use of the explicit drag efficiency calculation enables to calculates the same kind of fluxes than with LISA. In addition, this new combination of dataset opens the door to calculate mineral fluxes emissions over areas larger than the Sahara Sahel region, the limited area of the LISA dataset.

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Figure 11. Distribution of vertical dust fluxes calculated with the several model configurations and for an academic and constant wind speed of 12m/s. The calculations are done with a step of 0.1 g.cm\(^{-2}\).s\(^{-1}\) \times 10\(^8\) for the dust flux. The occurrence represents the number of grid cell where each dust flux value was estimated.

Figure 12. Distribution of eolian roughness lengths, \( z_0 \) (in cm), over the whole African domain, for the LISA and ERS datasets.

Figure 13. Distribution of the drag efficiency \( f_{\text{eff}} \) calculated for the three models configurations and an academic wind speed of 12m/s.
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