January 2009 under revision: Comparison of mineral dust layers vertical structures modeled with CHIMERE-DUST and observed with the CALIOP lidar.

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Abstract.
The final budget of dust remaining in the atmosphere or deposited on the surface depends directly on the emissions, boundary layer turbulence, stability in the troposphere and clouds properties. The modeling of these processes remains uncertain and mineral dust long range transport constitutes a major unknown. To improve this transport, it is crucial to improve modeling of altitudes and thicknesses of mineral dust layers. The space born lidar CALIOP aboard CALIPSO collects new information about the aerosol vertical distribution. Here we diagnose the lidar profile from the outputs of the transport model CHIMERE-DUST and we compare those with their observed counterparts. During the periods June to September 2006 and January to March 2007, the occurrences and structures of dust layers are estimated from the observed and modeled lidar signals. Accounting for the daytime and nighttime periods, the seasonal variability and Calipso flight-tracks, it is showed that the presence/absence of dust is correctly reproduced by the model in 70% of the 170.000 vertical profiles studied. The mineral dust horizontal distribution is quite correctly reproduced by the model, while the vertical one shows a vertical over-spread which is more pronounced during winter (+100% compared to observations) than summer (+50% ) The maximum value of the modeled lidar signal is underestimated with respect to the measured one by typically 30%. Multi-layered dust situations are more frequent in the observations (30% of the total dataset) than in the model (10%) Despite these errors, the model is able to catch the seasonal variations of the dust layers: the increases of the dust load and of the dust altitudes during summer, and the northward shift of the maximum dust occurrence.

1. Introduction

Mineral dust is one of the most abundant aerosol type on the Earth surface, its global emission being estimated between 60 and 3000 Mt/yr (Duce [1995]). It is produced in arid and semi-arid areas and then travels in the free troposphere on intercontinental scales of distance. The huge amount of mineral dust in the atmosphere leads up to a significative impact on radiative balance, both directly (through their interaction with solar and Earth radiation) and undirectly (through their influence on clouds formation and optical properties) (e.g. Sokolik et al. [2001]). One of the major world dust source is the Saharan region and a large amount of Saharan emitted dust is transported over Mediterranean sea and Europe, at a rate of about 80-120 Mt/yr (d’Almeida [1986]). It is also transported by the trade winds over the Atlantic up to Caribbean Sea, at a rate that is estimated to be around 10 Mt/yr (Prospero et al. [1996]). This phenomenon accounts for most of Atlantic sedimentation, brings a large amount of nutrients to phytoplankton and other marine organisms, but is also responsible of the wrack of coral reefs, as it acts as
In order to refine our knowledge of the relative amount of dust emitted, transported and deposited near or far from the sources, three-dimensional emissions and transport models are necessary. Dust transport has been widely studied at global scale (i.e. Mikami et al. [2006], Zhu et al. [2007], Guelle et al. [2000], Ginoux et al. [2004], Duve [1995], and regional scales (i.e. Grini et al. [2006], Bouet et al. [2007], Menut et al. [2006], Mona et al. [2006], Ansmann et al. [2003], Kalashnikova and Kahn [2008]). The ability of the models to reproduce the vertical structure of the dust plumes (altitude and thickness) during their transport remains a key problem which impacts the final budget of dust in the atmosphere. Various studies (i.e. Kishcha et al. [2005] Colette et al. [2006], Amiridis et al. [2007], Barnaba et al. [2007], Heinold et al. [2007]) used ground based lidar observations to evaluate the dust layers predicted by transport models. They showed that these latters are not always able to catch fine vertical structures, but also that the presence of such thin layers have an impact on the surface aerosol budget over remote areas like Europe.

Lidars in space collect valuable information on the aerosol vertical distribution, that can be used to evaluate atmospheric transport models (see for example Karyampudi et al. [1999]). The lidar CALIOP, launched in April 2006 during the CALIPSO mission, measures the profiles of light backscattered by aerosols with a high vertical resolution (Winker et al. [2007]). It documents the aerosol vertical distribution, composition and optical characteristics (Liu et al. [2008b], Liu et al. [2008a]), that can be used to evaluated dust transport models. CALIPSO observations have been analysed in several studies jointly to other kind of measurements (Kim et al. [2008]; Liu et al. [2008c]) or in comparison with modeled dust profiles, for models validation/evaluation (Uno et al. [2008]; Hara et al. [2008]).

This study aims at evaluating the capability of CHIMERE-DUST model to simulate the mineral dust vertical distribution and transport in the atmosphere. The main characteristics of the model and the CALIOP observations are described in (§2) and (§3). The methodology that is used to compare consistently the model outputs with the observations is defined in (§4) together with the different characteristics of the dust layers (dust occurrence, dust load, altitudes of the upper and lower dust layers). Statistics of the observed and modeled dust characteristics are examined independently in (§5). The comparison between model and observation datasets are performed in two steps. In a first step, the two datasets are compared globally to evaluate the ability of the model to reproduce the mineral dust occurrence, and their vertical and horizontal distributions (§6). In a second step, the dust vertical structure is evaluated in using the sub-datasets where dust layers are identified at the same time and location in model and observations (§7). Conclusions of this study are given in §9.

2. Description of the model

The model consists of three elements: (i) the meteorological platform with the MM5 model forced by the NCEP global meteorological fields, (ii) the dust emissions model, (iii) the CHIMERE-DUST transport model. These elements are used together and in the same manner both in analysis or forecast mode. CHIMERE-DUST is a transport model dedicated to mineral dust only. It was developed on the basis of the chemistry-transport model CHIMERE (Vautard et al. [2001], Bessagnet et al. [2004]) currently used for boundary-layer regional air pollution studies and forecast. The complete model characteristics are explained in Menut et al. [2006].

2.1. The meteorological forcing

Since CHIMERE-DUST is an off-line model, meteorological fields are required: for this study, the

Figure 1. CHIMERE-DUST model domain. For all following results, the emissions area is denoted as 'EMI' and the surface in the model domain but not in the emissions area as 'noEMI'.
NCEP/GFS meteorological fields are used to force the regional mesoscale model MM5 (Dudhia [1993]). The outputs of MM5 have an horizontal resolution of 1° × 1°, with 32 vertical levels, from surface to 200hPa. The horizontal domain, 'Atlantic' frame in Figure 1, covers the whole North Atlantic ocean, including a large part of the Northern Africa and of the Western Europe. The results of the MM5 simulations (the wind components, the temperature, the specific humidity, the pressure fields, the 2m temperature and the sensible and latent surface heat fluxes) are used to diagnose additional turbulent parameters such as the boundary layer height $\overline{h}$, the friction velocity $u_*$ using a bulk Richardson profile approach as described in Menut [2003], the water liquid content (for the wet deposition). From all these parameters, vertically averaged meteorological profiles are estimated for the CHIMERE-DUST configuration, switching from 32 to 15 vertical levels.

2.2. The transport model CHIMERE-DUST

The CHIMERE-DUST is driven by MM5 meteorological fields at an hourly time-step and over the same horizontal domain, with 1°×1° resolution. Boundary conditions for the dust are not taken into account, considering the domain sufficiently large to include all the major dust sources. The dust concentration is initialized to zero at the first time-step, but we consider a long spin-up time in order to study realistic dust concentrations: in this study, the model ran 15 days before the first date of interest. The horizontal transport is computed using the Van Leer scheme (Van Leer [1979]). The dust simulations are performed with a 7'30" time-step and the dust concentrations are extracted every hour for analysis.

2.3. The dust emissions calculation

The emissions scheme used in the model is first based on the Marticorena and Bergametti [1995] dust production model. This models is used to compute horizontal fluxes from wind velocities and surface features for the emissions area (the 'EMISSIONS' area in the Figure 1). Then, the dust vertical fluxes is derived from the horizontal fluxes by using the Alfaro and Gomes [2001] parameterization, numerically optimized following Menut et al. [2005]. The vertical fluxes are computed corresponding to three dust size modes, then redistributed into the model size bins using the following mass partition scheme:

$$m_i = \sum_n \frac{m_n}{2} \left( \frac{\ln d_{n,i} / D_{p_n}}{\sqrt{2 \ln \sigma_n}} - \frac{\ln d_{n,u} / D_{p_n}}{\sqrt{2 \ln \sigma_n}} \right)$$

where $m_i$ and $m_n$ are the emitted masses in the model bins and in the three emitted modes, respectively. $D_{p_n}$ and $\sigma_n$ are the emitted mass diameters and associated standard deviations (as described in Menut et al. [2005]); $d_{n,i}$ and $d_{n,u}$, the diameter of the lower and upper limits of each dust size bin, respectively. The vertical deposition scheme is that described in Loosmore and Cederwall [2004]. The dry deposition velocity is parameterized following Venkatram and Pleim [1999].

3. Description of CALIOP observations

The CALIOP lidar is composed of a laser which emits two beams of linearly polarized light at 532nm and 1064nm, and a telescope that collects the laser light backscattered by molecules and particles at each level of altitude (Winker et al. [2007]). The intensity of the backscattered attenuated signal (ATB) depends on the aerosol vertical distribution while the depolarization ratio is related to their shape. At $\lambda = 532$ nm, CALIOP horizontal resolution is 333m below 8 km altitude and 1 km above.

CALIPSO platform follows a sun synchronized orbit with an equatorial crossing time of about 01:30 and 13:30 LST. The current study uses the CALIOP Version 2.01 Level 1 dataset at 532 nm collected within the CHIMERE-DUST domain in summer 2006 (June to September) and winter 2007 (January-February-March) during day and night time. Figure 2 shows an example of trajectory and corresponding data for January 23, 2007.

The ATB$_{mol}$ profile which represents the signal that would be measured by the lidar in absence of aerosols and clouds comes out CALIOP level1 files ; it is computed with local values of pressure and temperature profiles from GMAO (Global Modelling and Assimilation Office, Bey [2001]). The measured ATB and the computed ATB$_{mol}$ profiles are averaged over CHIMERE-DUST horizontal and vertical grid which increases significantly the signal to noise ratio (about 240 to 300 level 1 Caliop profiles are averaged in each model grid box). The averaged measured ATB profile is scaled to the averaged molecular one (ATB$_{mol}$) in the stratosphere (30-34 km) where the atmosphere is generally free of aerosols. To highlight the contribution of the particles to the lidar signal, the li-
Figure 2. [top] the CALIOP lidar trajectory aboard CALIPSO for January 23, 2007 and [bottom] the corresponding measured ATB (W.km$^{-1}$.sr$^{-1}$).

Lidar backscattering ratio profile $LBR = ATB/ATB_{mol}$ is computed from the two averaged profiles in each CHIMERE-DUST grid box along the satellite orbit track (Figure 3a). This LBR acronym is also commonly called Scattering Ratio $SR$ in the literature.

The ATB has two components: the first one is linearly polarized in the same direction as the incident laser light, and other one is polarized perpendicularly. The ratio between the intensities of these two components gives the lidar depolarization ratio, that is commonly used to distinguish dust from other aerosol types (Liu et al. [2008c]). Figure 4 shows a statistical comparison between the aerosol depolarization measured within the whole CHIMERE-DUST domain and a sub-dataset corresponding to the region centered on emission regions. Both the dust detection (detailed in §4) and depolarization ratio are computed over the model grid boxes. The depolarization is computed after averaging independently each component (parallel and perpendicular). It shows that at this resolution and in this region, the Saharan dust mostly correspond to depolarization ratio higher than 10%.

Figure 3. Analysis of the 23 January 2007 (01:00 UTC) lidar data. [top] Observed LBR backscattering ratio (ad.) averaged on CHIMERE grid but not filtered. [middle] same as top but filtered. [Bottom] modeled LBR backscattering ratio (ad.).
Figure 4. Distribution of measured depolarization values for the period June to September 2006. Only nighttime data are used. Occurrences are displayed for the whole domain and a sub-region called ‘Saharan’ and defined as -15<longitude<30; 13<latitude<32.

4. Methodology

4.1. Simulation of lidar signal from model outputs

To make a fully consistent statistical comparison between model and observations, we adapted a method used to evaluate aerosols in CHIMERE (Hodzic et al. [2004]) and clouds in MM5 (Chiriaco et al. [2006], Chepfer et al. [2007]). It consists in diagnosing the LBR as an output of the model in using pressure, temperature and dust mass concentrations fields from CHIMERE-DUST (see Annex A).

The molecular component of the LBR at $\lambda=532$ nm is simulated using the MM5 local values of pressure and temperature. The particle component of LBR requires the computation of their number concentration and of their optical properties (scattering and extinction cross sections). Those latters are computed with the Mie theory (Mie [1908]) for 400 values of aerosols diameters ranging between 0.01 to 40 $\mu$m. The spherical assumption (Mie theory) can produce errors when applied to mineral dust aerosol due to their non-sphericity. The mineral dust mass concentration is simulated by the model in 12 different size bins ranging between 0.1 and 50 $\mu$m (Forêt et al. [2006]). The mineral dust number concentration in each bin is then computed assuming the particles are spherical and their density is 2.65 g.cm$^{-3}$. A linear interpolation within the 12 bins allows deriving the dust number concentration for each of the 400 particle sizes for which the scattering and extinction cross sections have been tabulated previously.

The values of molecules and particles scattering and extinction coefficients are used to compute local values of LBR within the model cells located along the satellite orbit track at the time of the CALIPSO overpass (see Annex A for the detailed computation of LBR).

4.2. Mineral dust characteristics diagnostics

Various mineral dust characteristics are diagnosed consistently in observations and simulations. One observed or simulated LBR profile contains 30 successive layers. The CALIOP observations data are projected on these vertical levels in order to have the same data set than with the model. First, each layer of each profile is labelled following Chepfer et al. [2008]. Second, the whole set of labels for one profile is used to infer the ”dust occurrence” (§4.2.2), the ”profile classification” (§4.2.3), and the ”vertical structure”(§4.2.4).

4.2.1. Layer classification

The first step is to label independently each layer of each profile, both for model and observations. For the observations, each layer may be classified as ”clear” or ”cloudy” or ”dust”. These three classes will be used for statistics on the observations only (for the model, only ”clear” and ”dust” are defined and used).

For the observations profiles, the starting point is to exclude not useful layers. This class is called ”cloudy” and contains all layers with clouds and/or dust not relevant for the comparisons with the model results. Three criteria are applied: (i) a minimum in temperature to avoid cirrus clouds ($temp_{obs}$ must be greater than -30°C), (ii) a minimum in depolarization ratio to avoid aerosols than those modelled by CHIMERE-DUST ($depol_{obs}$ must be greater than 0.1) and (iii) a maximum of LBR to avoid water clouds ($LBR_{obs}$ must be lower than 4).

For all other layers, a sub classification is done: ”clear” or ”dust”. The ”clear” layers are defined for $LBR_{obs} \leq 1.2$ and the ”dust” for $1.2 < LBR_{obs} \leq 4$. The LBR threshold values used here can lead to classify some optically thick dust plume as cloudy, but ensures the rejection of all water clouds (Figure 3b).
The threshold on $\text{depol}_{\text{obs}}$ can lead to underestimate the total dust load (up to 20% based on §4) but ensures the rejection of non dust layers (not predicted by the model). On the other hand, the term “clear” is not really a clear atmosphere but define dust-free layers.

Finally, the same criteria are used on modeled dust concentrations outputs and only for model cells corresponding to CALIOP measurements.

4.2.2. Dust occurrence

For each observed and simulated grid box, we define the dust occurrence $N_{a,\text{obs/\text{mod}}}=1$ if the layer is "dust" and 0 if not. The seasonal dust occurrences are thus defined as the sum of all $N_{a,\text{obs/\text{mod}}}$ within a latitude band and during a season (Figure 5).

4.2.3. Profile classification

From all layers classes, some profiles classes are defined. For the comparisons between model and observations, only three classes are necessary: clear, dust and cloud. The "cloud" class will only be used for observations statistics. The "clear" class is defined when a profile has only "clear" layers. The "dust" class is defined when a profile has only one or several "dust" layers. An intermediate class "dust+cloud" is defined when a "dust" layer is observed above a "cloud" layer. This profile can be partly used for analysis: since the CALIOP instrument is a nadir lidar, a dust layer above a cloud layer may be accurately identified. This profile is used for the "dust occurrence" statistics. But, if a "cloud" layer is identified as "cloud" and not used for statistics. In this case, and even if dust are present under the cloud, a doubt exists due to the signal perturbation due to the cloud layer. A refinement is done using the "cloud" layer altitude. If the layer is up to 8km, the profile label is "high cloud". For all other cases, the label is "low cloud".

4.2.4. Vertical structure diagnostics

We also evaluate the integrated value of $LBR$ over the "dust" cells ($LBR_{\text{int,}}$ in km), the local maximum value of $LBR$ ($LBR_{\text{max}}$) and its corresponding altitude ($z_{\text{m}}$). The dust layer thickness is estimated as the sum of the layers with "dust" (no necessary successive) and is denoted $th$. In the same way, the heights of the lower and upper dust layers are estimated and noted $z_1$ and $z_2$, respectively. These quantities are computed in considering only the "dust" and "clear" layers in each profiles. $LBR_{\text{int}}$ and $LBR_{\text{max}}$ depend mostly on the dust concentration and optical properties (these latter being directly related to their size), whereas $z_{\text{m}}, th, z_1$ and $z_2$ are directly influenced by the vertical transport (advection and mixing).

5. Analysis of observed and modeled dust layers

The diagnostics presented are applied to all the observed and simulated profiles along the CALIPSO orbits crossing the CHIMERE-DUST domain during the ‘summer’ (June to September 2006) and the ‘winter’ periods (January to March 2007). In order to help the statistical analysis, the modeled and observed datasets are splitted into ‘EMI’ area (corresponding to the ‘emissions’ region in Figure 1) and the ‘noEMI’ area corresponding to all others domain grid cells.

5.1. Statistics on the observations

<table>
<thead>
<tr>
<th>Observations statistics</th>
<th>Total</th>
<th>cloud high</th>
<th>cloud low</th>
<th>dust</th>
<th>dust +cloud</th>
<th>clear</th>
</tr>
</thead>
<tbody>
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<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EMI</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>night</td>
<td>7877</td>
<td>5%</td>
<td>21%</td>
<td>35%</td>
<td>20%</td>
<td>19%</td>
</tr>
<tr>
<td>day</td>
<td>8116</td>
<td>5%</td>
<td>14%</td>
<td>38%</td>
<td>23%</td>
<td>20%</td>
</tr>
<tr>
<td>noEMI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>night</td>
<td>40964</td>
<td>14%</td>
<td>53%</td>
<td>7%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>day</td>
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<td>13%</td>
<td>39%</td>
<td>11%</td>
<td>22%</td>
<td>15%</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMI</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>night</td>
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<td>21%</td>
<td>29%</td>
<td>22%</td>
<td>10%</td>
</tr>
<tr>
<td>day</td>
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<td>15%</td>
<td>18%</td>
<td>32%</td>
<td>28%</td>
<td>8%</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>47%</td>
<td>10%</td>
<td>15%</td>
<td>14%</td>
</tr>
<tr>
<td>day</td>
<td>44641</td>
<td>13%</td>
<td>35%</td>
<td>13%</td>
<td>28%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 1. Statistics of presence of clouds and dust layers on observed profiles. The dust column refers to dust without clouds, and the low cloud column to profiles with low clouds only (no dust). The sum of the five categories is 100%
night times. Far from the sources (‘noEMI’ regions), they represent less than 30% of the profiles. The high altitude clouds contaminate 5 to 18% of the profiles. These clouds are more numerous in summer (than winter) because they are produced by deep convection along the ITCZ. Moreover, their seasonal variation is more pronounced over land (EMI regions) than over ocean (noEMI). Over ocean, neither the fraction of high clouds profiles neither the total fraction of cloudy profiles shows a seasonal variation. The low level oceanic clouds are numerous all along the year, and they contribute to contaminate a significant part of the profiles over noEMI regions.

The profiles not contaminated by clouds are classified as “dust” (col.4) and “clear” (col.6): they represent less than half of the full dataset over EMI and even less (<30%) over noEMI regions. When considering only these situations, the relative part of dust containing profiles [col.4/(col.4+col.6)] is larger in summer than winter consistently with Liu et al. [2008b]. The percentage of profiles containing only ”dust” (col.4) does not show significant day/night differences; moreover its seasonal variation over EMI regions is mostly governed by the cloud seasonal cycle.

5.2. Statistics on modeled dust layers

The modeled dust profiles classification is presented in Table 2. Dust occurs in 53% to 63% of profiles above EMI and 3.5 to 6 times less (12% to 16%) above noEMI. The day/night difference is negligible. More dust is produced by the model in summer than winter above emission regions (differences of 10-15%). Far from the sources, the tendency is not the same, and more dust is detected during winter than during summer (differences of less than 4%). This may be due to different dynamical processes in the free troposphere, reducing the main sinks such as the precipitations and thus the dust scavenging.

6. Comparison between simulated and observed dust ”without collocation constraint”

6.1. Global dust occurrence

The zonal dust occurrence (defined in §4.2.2) observed and simulated over the whole CHIMERE-DUST domain in both seasons (Figure 5) shows that the dust sources are quite well localized in the model, and that the increase of global dust occurrence in summer is also catched by the model.

The dust occurrence is larger in summer than in winter because of the higher activity of dust sources in this season (Prospero et al. [2002]). This variation is reproduced by the model, even if global dust occurrence seems slightly overestimated in winter and underestimated in summer. Nevertheless, the dust are not sufficiently transported to the Northern latitudes in winter, while in summer the occurrence is underestimated in the sources latitudes. Dust are injected significantly too high in altitude whatever the season.

The region of maximum dust occurrence is in the latitude belt 15-25°N and is shifted northward in summer being in the latitude belt 8-18°N. This is consistent with the observations of Liu et al. [2008a] and this shift follows the ITCZ position (Prospero et al. [1981]) as well as the location of the most active dust sources (Prospero et al. [2002]).

The observed meridional dust occurrence (Figure 6) also shows a significative increase in summer, especially in the longitude belt ~ 40-60°E. The model roughly reproduces this behavior, but with an underestimate of the summer dust occurrence over the latitude belt ~ 10°W-20°E. Compared to the Figure 5 results confirm a model underestimation for the region corresponding to the western Africa sources (with a mean latitude of 20°N and a mean longitude of 0 to 10°W).

6.2. Global dust vertical distribution

The characteristics of the dust vertical distribution (Table 3) are computed in considering only the profiles which contain dust (Table 1) (col4+col5) for the observations).

The dust load (proportional to \(LBR_{int}\)) shows an important variability: it is larger during summer than winter and larger over EMI than noEMI regions. Contrarily to \(LBR_{int}\), the value of \(LBR_{max}\) is
Figure 5. Zonally summed dust occurrence over the whole domain during the period January-march 2007 and June-September 2006 for all nighttime profiles observed and simulated.

Figure 6. As in Figure 5 but with meridional sum of the dust occurrence relatively constant in space and time, which means
that the maximum amount of dust within a layer at a given altitude does not depend on the season and the location. Thus, the variation of the dust load in the column \( LBR_{\text{int}} \) is associated to a variation of the vertical extent of the dust plume: \( th \) values increase (and decrease) with \( LBR_{\text{int}} \) values. The mean layer thickness reaches a maximum of 2.3km during summer and in EMI area, compared to about 1km for the other cases. The mean layer thickness increase is mainly due to an increased top level of these layers, when the lowest ones stay around 1 to 2km in altitude consistently with Carlson and Prospero [1972]. This is likely due to the enhanced boundary layer convection in summer that inject higher quantity of dust in the free troposphere (increasing \( LBR_{\text{int}} \)) and can be transported toward long distances (increasing \( z_t \)) and can be transported toward long distances (increasing \( Z_{\text{L}} \)).

The summer reduction of \( Z_t \) (Table 3) when passing from EMI to noEMI areas is reasonably due to the subsidence of the SAL in its westward pathway (Carlson and Prospero [1972]). This behaviour is not observed in winter, when an average increase of \( Z_t \) is observed when passing from EMI to noEMI areas. A possible explanation is the increased efficiency of northward dust transport during winter and spring with respect to the westward one (Dayan et al. [2008]). The major relative weight of mediterranean dust layers can be responsible of the lifting of \( Z_t \) as these aerosols are known to penetrate higher into the troposphere than the ones transported across the Atlantic (Hamonou et al. [1999]; Alpert et al. [2004]). Also this tendency of summer (winter) reduction (increase) of \( Z_t \) from EMI to noEMI regions is catched by the model, though significative discrepancies in the absolute values.

### Table 3. Mean characteristics of the nighttime observed and modeled dust layers. Values are presented separately for the emission regions (EMI) and the regions outside the emissions domain (noEMI) during winter (W) and summer (S). The scores are for \( LBR_{\text{int}} \) (km), \( LBR_{\text{max}} \) (adimensional) and for \( Z_m, Z_{\text{th}}, Z_t \) and \( Z_l \) in km.

<table>
<thead>
<tr>
<th></th>
<th>( LBR_{\text{int}} ) (km)</th>
<th>( LBR_{\text{max}} ) (ad.)</th>
<th>( Z_m ) (km)</th>
<th>( Z_{\text{th}} ) (km)</th>
<th>( Z_t ) (km)</th>
<th>( Z_l ) (km)</th>
</tr>
</thead>
<tbody>
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<td><strong>EMI</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>2.2</td>
<td>2.3</td>
<td>1.8</td>
<td>1.2</td>
<td>1.1</td>
<td>2.5</td>
</tr>
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<td>S</td>
<td>4.2</td>
<td>2.3</td>
<td>3.2</td>
<td>2.3</td>
<td>1.6</td>
<td>4.3</td>
</tr>
<tr>
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</tr>
<tr>
<td>W</td>
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</tbody>
</table>

In average (Table 3), the dust load \( LBR_{\text{int}} \) is larger in the model than in the observation and simultaneously \( LBR_{\text{max}} \) is underestimated in the model, suggesting that the dust vertical distribution is too spread in the model. This is confirmed by \( th \) which is overestimated by 50% to 100% whatever the season and the region.

Figure 7 shows that multi-layers dust situations are frequently observed (typically 2 or 3 dust layers separated by clear layers) consistently with (Hamonou et al. [1999]). The model produces more single layers than observed and is able to reproduce half of the complex multi-layers structures.

### 6.3. Global dust horizontal pattern

The spatial distribution of the dust plume during summer is illustrated in Figure 8. Both the observations and model reproduces the Saharan dust plume over the Atlantic ocean and its spatial extent. The top altitude, \( Z_t \), westward decrease illustrating the subsidence of the Saharan air layer (Carlson and
Table 4. Profiles classification for model and observations. From the left to the right: number of considered profiles (without high clouds or undefined values on the top), percentage of profiles where model and observations agree on the presence/absence of dust, of profiles with both observed and modeled dust, of profiles where model and observations disagree on the presence/absence of dust, and of profiles with measured dust and not modeled ones.

Prospero [1972]) far from the sources: Larger than 5km above the main emission regions, $z_t$ displayed a maximum of 3km above the Atlantic Ocean. With a lowest variability of $z_t$ ($\approx$ 1km both for model and observations), this induces a regular decrease of the layer thicknesses, $th$.

7. Comparison between model and observations when mineral dust are collocated

7.1. Dust occurrence for the collocated datasets

The model versus observations agreement on the presence or absence of dust within a same profile is about 60 to 80% (Table 4), with higher values far from the sources. Nevertheless the main part of the sub-dataset ”agreement” is due to clear profiles (absence of dust). Consequently, this agreement is slightly higher in winter when there are less mineral dust than in summer. The sub-dataset where both model and observation agree on the presence of dust somewhere within the same atmospheric column at the same time represents typically 35-47% of the profiles above emission regions and 7% above non-emissions (Table 4). It means that they are emitted at the good time and location half of the time, the first part of the transport is correct (inland) but their transport over seas is not well reproduced by the model. The modeled and observed dust vertical structure for the sub-dataset of profiles where model and observations agree on the presence of dust is studied here after.

7.2. Dust vertical distribution for the collocated datasets

<table>
<thead>
<tr>
<th></th>
<th>$\Delta int$</th>
<th>$\Delta LBR_{max}$</th>
<th>$\Delta z_t$</th>
<th>$\Delta th$</th>
<th>$\Delta z_l$</th>
<th>$\Delta z_m$</th>
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</thead>
<tbody>
<tr>
<td><strong>EMI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>57%</td>
<td>-24%</td>
<td>12%</td>
<td>90%</td>
<td>41%</td>
<td>-10%</td>
</tr>
<tr>
<td>S</td>
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<td>-27%</td>
<td>34%</td>
<td>40%</td>
<td>36%</td>
<td>47%</td>
</tr>
<tr>
<td><strong>noEMI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
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<td>-37%</td>
<td>37%</td>
<td>123%</td>
<td>57%</td>
<td>21%</td>
</tr>
<tr>
<td>S</td>
<td>14%</td>
<td>-38%</td>
<td>24%</td>
<td>52%</td>
<td>30%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Table 5. Model versus observations mean errors estimated for the periods January-March 2007 and June-September 2006 and for the nighttime data: The mean relative errors are displayed in % and are splittet into the EMI and noEMI regions.

7.2.1. Mean values The differences between model and dust vertical structures are reported in Figure 9 as histograms and Table 5 as synthetized scores. Figure 9 shows a relatively good agreement between model and observations despite some
Figure 8. Maps of [top] $LBR_{int}$, [middle] "th" Dust layer thickness (km) and $z_t$ (km) [bottom] for the period 1 to 15 July 2006. Only nighttime data are used and comparisons are presented for [left] the CALIOP data and [right] the CHIMERE-DUST outputs.

large spreads around the mean zero value, and some differences between EMI and noEMI regions. The largest differences are denoted for the $LBR_{max}$, between model and observations. The model exhibits lowest values than observations, with a more pronounced tendency over noEMI area. This is quantified by a histogram peak value of $LBR_{max}(model) – LBR_{max}(obs)=-1$ in Figure 9 and a relative difference of -24/-27% over EMI and -37/-38% over noEMI areas. These latter percentages are very similar to those obtained for the complete dataset without collocation constraint (Table 3). The $z_t$ and th overestimates by the model are also of the same order of magnitude for the "collocated dataset” and "non-collocated one”, meaning that the modeled vertical distribution is not very sensitive to the profile location. This may be due to the large majority of studied profiles in the noEMI area are located over the Atlantic Ocean and in the free troposphere. This is a part of the atmosphere where layers are strongly stratified and when the vertical mesh used in the model is never able to reproduce the fine physics of thin dust layers long range transport. Thus, due to the nature of the algorithm used to described vertical transport, the concentrations fields are systematically more diffused in the model compared to the accurate measurements delivered by lidar measurements.

7.2.2. Diurnal variation
Summer (June-September 2006) mineral dust observations and simulations are compared to evaluate the diurnal variation of the vertical dynamics of the Saharan dust Layer [Figure 10]. Normalized occurrences for each $LBRI_{int}$ are displayed separately for the EMI and noEMI regions. Over the noEMI regions, the differences between day and night are lower than over EMI. This is due to the transport: far from the sources, the dust plumes are transported into the free troposphere and the diurnal cycle has no important impact on the dust vertical structure. In this case, the integrated $LBRI$ values are often low with an occurrence peak of 20-25% of values with $LBRI_{int} \approx 1$. Over the EMI area, the differences between night and day are much more pronounced: the maximum number of observed $LBR$ values is for $LBRI_{int} \approx 1$ during the day and $LBRI_{int} \approx 6$ during the night. This differences show directly the impact of the wind speed diurnal cycle on dust emissions ([Menut [2008]]).

### 7.2.3. Seasonal variation

[Figure 11] shows the $LBR$ seasonal variability between winter and summer and highlights whether the model ability to reproduce observed events is strongly dependent on the season or not. For the two seasons, the dust amount distribution, $LBRI_{int}$, is well estimated by the model. During summer, the model catches better this general evolution than during winter: with a very peakly value of $LBRI_{int} \approx 1$ for the observations, the model shows a more spreaded distribution where a large part of wintertime modeled $LBRI_{int}$ are be-
8. Possible sources of errors

Some problems were identified and quantified with the model: (i) a tendency to overestimate plume thickness and top height, (ii) an underestimation of the LBR maximum value, (iii) the difficulty to reproduce some complex multi-layered structures. These lacks are first of all related to the model vertical resolution. Due to computer limitations, the model is not able to run over a large domain and during a long period with a vertical resolution close to the real thin layers observed in the free troposphere. Thus, the modeled dust layers are vertically averaged layers and more able to be diffused vertically. Since the differences between $\theta_{\text{obs}}$ and $\theta_{\text{mod}}$ may be larger than the model resolution, the discrepancies may also be attributed to the vertical diffusion parameterization themselves. As for many transport models used for air quality or long-range transport and climate, improvements on the vertical subgrid turbulence parameterizations is one of the most important challenge for the next years. In case of this paper, results showed that the model simulates too strong vertical mixing, raising the simulated dust higher than the observed ones, missing multi-layered structures, and smoothing the peaks of LBR. It has already pointed out (Noh et al. [2003]) that one of the major shortcomings of the Troen and Mahrt [1986] parameterization of mixing is the fact that the eddy diffusivity depends only on surface stability and remains constant along the atmospheric column. So, a crucial phenomenon that could be taken into account is the stabilizing effect in altitude of the warmed dust lay-

The same tendency is observed in winter and summer without significant impact of the season for $LBR_{\text{max}}$. The most important variability is denoted for the altitude of the $LBR_{\text{max}}$ as already discussed with the [Table 5]: the differences between model and observations are large and depend on the period of the year. As a consequence of the dynamic processes occurring in the boundary layer (after the emissions and over land) and the free troposphere (mainly during dust long range transport and over the Ocean), the model has difficulties to represents thin and highly concentrated dust layers of altitude less than 3km. This certainly highlights the needs to better represent vertical structure of thin layers in model as well as the transition between boundary layer and free troposphere when dust are trapped in more stratified layers at the end of each day.

Figure 10. Diurnal variability of $LBR_{\text{int}}$ over [top] the EMI area and [bottom] the noEMI area for the period June to September 2006.

Figure 11. Analysis of the lidar backscattering ratio seasonal variability with nighttime data and model (over the noEMI region).

between 1 and 4. An opposite behaviour is estimated for $LBR_{\text{max}}$: when the model calculated the largest part of $LBR_{\text{max}}$ with values less than 2, observations are more equally distributed between 1 and 4.
ers, with the subsequent reduction of mixing. It is known indeed that the temperature of the SAL is warmer than the normal tropical temperature by 5-10°C (Carlson and Prospero [1972]). This latter effect is not taken into account actually in models. The horizontal pattern of the dust plumes can be considered instead quite well reproduced by the model. Besides, this pattern is mainly driven by the modeled horizontal wind fields, previously validated by many other studies (White et al. [1999]; Hanna and Yang [2001]; Menut [2008] among others). Errors may also be due to the transport scheme itself: a recent study, Vuolo et al. [2009], showed this can be at the origin of some more or less diffused modeled horizontal dust plumes.

9. Conclusion

Six months of CALIOP lidar data and CHIMERE-DUST modeled mineral dust concentrations fields are analyzed and compared. In order to have an homogeneous dataset, lidar signal and dust concentrations values are processed to get the Lidar Scattering Ratio ($LBR$). For the observations and the model, data are over the same horizontal and vertical grid as the model, at the time of the satellite overpass along its trajectory.

Criteria on $LBR$ values are defined to discriminate the lidar profiles containing dust, clouds (or none or both) as a function of the time (night or day), the location (over the western Africa, near sources or over the Atlantic Ocean, far from the mineral dust sources), and the season (winter and summer). It was first showed that about 60% and 30% of the 170,000 observed profiles contained mineral dust (sometimes mixed with clouds), over the emissions and non-emissions regions, respectively. For the same dataset, the model diagnosed 60% and 15% over the same regions. The difference between the two scores may be due to model data which can not be contaminated by clouds contrarily to the observations.

The vertical distribution and nature of the mineral dust layers was analyzed and compared: the thickest layers are observed during summer and over the emissions areas. The same tendency is calculated with the model even if this latter estimates highest absolute values. But the time and locations of the major events are well modeled compared to the measurements.

The seasonal variability is weak compared to the sensitivity to the dust plume location. This is correctly reproduced by the model, clearly showing that the diurnal cycle is also moderated compared to the variability due to the range from the source.

The seasonal variation of the dust as deduced by the observations is in agreement with previous studies: there is a summer northward shift of the regions of maximum dust occurrence (as the one described in Liu et al. [2008a]), and a summer increase of dust load (as in Husar et al. [1997]; Kaufman et al. [2005]) and of the height reached by the dust (as in Kishcha et al. [2005]; Papayannis et al. [2008]; Liu et al. [2008a]). The model catches these behaviours even if the summer/winter ratio of integrated LBR (proportional to the dust load) is smaller in the model than in the observations (1.3 against 1.9 above the emission regions, 1.1 against 1.3 away from emission regions).

The model is generally in better agreement with the observations in winter than summer. But the model always underestimates the maximum value of $LBR$ within the profile and in average overestimates the vertical extension of the mineral dust in the column; this means that in the model most of the atmospheric layers contain a small amount of dust, whereas in the observations a few layers at a given altitude contain a large amount of mineral dust particles. Hence the model is not able to reproduce vertically confined layers of aerosols, and mostly produces small amount of dust spread within a too large vertical extent.

Errors on the thickness of the mineral dust layers are of the order of 100% in winter and 50% in summer, while the maximum value of the lidar signal on a vertical profile is typically underestimated by 30%. Also, multi-layered dust structures are typically missed by the model. All these discrepancies suggest that the model simulates an excessive mixing, probably in conditions where it should be suppressed by the presence of the dust layers themselves (the model at present does not take into account the radiative effect of aerosols and their eventual suppression of convective mixing).

Finally, the model behaves quite well far from the emission regions. There is no noticeable disagreement with the observations there, except those which have already been identified above the emission regions and are slightly more pronounced far from the sources after dust long range transport.
Evaluation of CHIMERE-DUST model against CALIOP level-1 lidar signals

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Appendix A: Annex: The lidar signal

The power of light backscattered by air molecules and aerosol particles at a distance \( z \) from the lidar depends on their number concentration \( n_{\text{mol/part}} \text{[m}^{-3}\text{]} \) and on their scattering and absorption cross sections \( C_{\text{sca,mol/part}}, C_{\text{ext,mol/part}} \text{[m}^2\text{]} \). The Attenuated Lidar Backscattering Profile, \( ATB \text{[Wm}^{-2}\text{sr}^{-1}] \), is given by the lidar equation:

\[
ATB(z) = [\beta_{\text{mol}}(z) + \beta_{\text{part}}(z)] \times 
\exp \left\{ -2 \int_0^z [\alpha_{\text{ext,mol}}(z) + \alpha_{\text{ext,part}}(z)] \, dz \right\} \tag{A1}
\]

where \( \beta_{\text{mol/part}} \text{[m}^{-1}\text{sr}^{-1}] \) are molecules (particles) backscattering coefficients, expressed as:

\[
\beta_{\text{mol/part}} = \frac{P_{\pi,\text{mol/part}}}{\pi} n_{\text{mol/part}} C_{\text{sca,mol/part}} \tag{A2}
\]

where \( P_{\pi,\text{mol/part}} \text{[sr}^{-1}] \) are the phase functions in backscattering.

The attenuation extinction (scattering+absorption) coefficients \( \alpha_{\text{ext,mol/part}} \text{[m}^{-1}] \) are given by:

\[
\alpha_{\text{ext,mol/part}} = n_{\text{mol/part}} C_{\text{ext,mol/part}} \tag{A3}
\]

with:

\[
C_{\text{ext,mol/part}} = C_{\text{sca,mol/part}} + C_{\text{abs,mol/part}} \tag{A4}
\]

The absorption cross section \( C_{\text{abs,mol}} \) is negligible for air molecules at 532 and 1064 nm.

Following Collis and Russell [1976] scattering and attenuation coefficients for molecules \( \beta_{\text{mol}}, \alpha_{\text{mol}} \) can be expressed as:

\[
\beta_{\text{mol}} = \frac{P}{kT} (5.45 \cdot 10^{-32}) \left( \frac{\lambda}{0.55} \right)^{-4.09} \tag{A5}
\]

\[
\alpha_{\text{mol}} = \frac{\beta_{\text{mol}}}{0.119} \tag{A6}
\]

Where \( \lambda \) is the wavelength of the incident light, \( P \) and \( T \) are pressure and temperature, \( k \) is the Boltzmann constant.

To highlight the contribution of aerosols, the lidar signal is normalised to the molecular one, leading to the (adimensional) Lidar Backscattering Ratio:

\[
LBR = \frac{ATB}{ATB_{\text{mol}}} \tag{A7}
\]

where:

\[
ATB_{\text{mol}}(z) = \beta_{\text{mol}}(z) \exp \left\{ -2 \int_0^z \alpha_{\text{ext,mol}}(z) \, dz \right\} \tag{A8}
\]

By definition, \( LBR \equiv 1 \) in clear-sky conditions (\( \beta_{\text{part}} = \alpha_{\text{part}} = 0 \)).

References


evaluation of CHIMERE-DUST model against CALIOP level-1 lidar signals

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