SAHARAN DESERT DUST SOURCES: NEW INSIGHTS BASED ON AEROSOL VERTICAL PROFILES RETRIEVED FROM THERMAL INFRARED MEASUREMENTS BY IASI

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ABSTRACT

Desert dust is a major actor in the climate and one of the least characterized with respect to its radiative forcing, both direct and indirect. Studies of dust atmospheric load and sources are therefore of great scientific interest. In the last years, we have developed and improved a retrieval strategy to obtain desert dust aerosols vertical profiles, from thermal infrared measurements by IASI. This strategy has been used to process significant amount of IASI data above North Africa. This dataset allows a new insight in the study of Saharan desert dust sources: it provides twice a day, at interesting times considering the dust emission diurnal cycle, vertical profiles of desert dust (not only optical depth), making possible to distinguish local emissions from transported dust.

Key words: aerosol; desert dust; sources; thermal infrared; IASI .

1. INTRODUCTION

Desert dust is the most important aerosol in annual mass burden, mainly present in the Tropics but reaching Europe from time to time. Dust aerosols are a major actor in the climate: they absorb, scatter and re-emit radiation, impacting the Earth energetic balance along the solar and terrestrial spectrum. Their presence in the atmosphere may lead to surface warming or cooling, and to atmospheric warming in the dusty layers, with possible impacts on the atmospheric circulation. Furthermore, dust aerosols are efficient cloud/ice condensation nuclei, therefore impacting the lifetime and physical properties of clouds, and the amount or location of rainfalls. For all these reasons, studies of dust atmospheric load and sources are of great scientific interest.

Dust emissions in the atmosphere from the deserts are due abrasion, caused by wind sheer on erodible soil. Two major classes of dust emission mechanisms have been identified in the literature. The first one is called the Nocturnal Low Level Jets (NLLJ) breakdown, occurring at sunrise and continuing for a large part of the morning. NLLJs are wind speed maxima in the low troposphere (here especially the boundary layer) during the night. At sunrise, the vertical profile of temperature changes, causing a turbulent mix-down of those NLLJs and a momentum perpendicular to the surface, which causes erosion and dust emission. This mechanism is responsible for most of the desert dust emissions in the Sahara and Sahel in the mid-morning. Detailed explanations about this phenomenon and its role in the dust cycle can be found, for example, in Fiedler et al. [3]. The second class of mechanisms leading to dust emissions is convection, and in particular large systems called cold pools outflows or haboobs. They seem to occur mainly in the afternoon and evening (and also to a smaller extent at night), due to the meteorological conditions that drive them. Detailed explanations about those can be found for example in Knippertz et al. [6]. Very localized dust emissions may also occur in the form of extremely small scale tornadoes, called dust devils. Those are probably very hard to see with a satellite instrument.

Due to these two major types of mechanisms and their predominant time of occurrence, a clear cycle exists in dust emissions, with two major peaks as documented for example by Heinold et al. [5] or Kocha et al. [7]. The first one in the morning (about 6 to 12h local solar time) is mainly due to NLLJ breakdown, while the second one in the afternoon (starting at about 15h local solar time) and evening is mainly linked to convective events. Most of the dust sources studies are based on measurements by MODIS aboard Aqua, with the DeepBlue algorithm providing data above bright surfaces as deserts. Other instruments as OMI or AIRS have also been used in that purpose. Those three instruments make their measurements in the early afternoon, when the dust sources are at their minimum. Therefore they allow to catch the early transported plumes from the mid-morning emissions mainly, but will probably lead to a source map displaced with respect to the real source areas and fail to represent afternoon/evening sources. The geostationary instrument SEVIRI offers measurements along the whole day, but mostly provides a dust flag with very limited quantitative information. When adding IASI to the picture, we gain a very nice glance at dust sources with an overpass slightly after the mid-morning maximum emissions, and an evening overpass during the afternoon/evening emis-

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sions.

In this contribution, we want to show how our retrievals of desert dust vertical profiles from IASI thermal infrared measurements can add to the study of desert dust sources. In addition to providing information at very interesting times of the day (and when the "usual" sensors don't provide information), using vertical profile information allows to separate dust close to the surface, more prone to be due to local sources, from dust higher up, more prone to be transported. This proceedings formalizes what has been presented during the ATMOS 2015 conference, with some additional technical details. The interested reader is invited to look at the slides of the presentation in parallel to have all the graphic material available.

2. THE RETRIEVAL STRATEGY

The data processed and presented here are the IASI datasets above North Africa for March, June, September and December 2013. We use level 1c IASI data in the principal component scores version (allowing huge data compression, together with interesting spectral noise reduction).

The retrieval strategy is based on the work published in Vandenbussche et al. [12], with the following main modifications:

- Surface temperature (Ts) has been added to the state vector; this has been done very recently after reaching the clear conclusion that no database of surface temperature was close enough to the real surface temperature for our retrievals to work properly; because of this, we currently only have 4 months of data instead of a whole year as was originally planned.
- The retrieval is now undertaken in one step thanks to the reduced noise in the principal component level1 data
- A climatology has been added for the a priori, since recently a pure dust vertical profile climatology has been made available by Amiridis et al. [1]
- Many technical improvements have been done to reduce the computational time and make the processing "chain" almost operational
- Some ancillary data needed for the retrievals have been updated to newer/improved versions

The next paragraphs describe more precisely the strategy.

Prior to the retrieval, the spectra are filtered to screen out clouds (using the IASI level 2 cloud product version 5). In that step, we have discovered an issue which is currently being solved. Without details, there are cases where one flag mentions a clear sky, while the cloud fraction is higher than 100%. As the cloud fraction was used to filter the data (maximum 10%), we rejected those spectra, which are clearly dusty and not cloudy (clear spectral signature of dust). We are now investigating another cloud filtering method to avoid such issues.

Retrievals are only undertaken when a clear spectral signature of desert dust is detected. The test remains the same as in Vandenbussche et al [12]. The retrievals would also work for spectra without that signature (leading to optical depths of zero), but this filtering allows to gain significant computation time.

The retrieval scheme, named MAPIR (Mineral Aerosol Profiling from Thermal Infrared Radiances), is based on Rodgers Optimal Estimation scheme [9], implemented within the ASIMUT package [11] that was developed at BIRA-IASB. The radiative transfer computations (including the jacobians) are undertaken with the Lidort package [10], which includes multiple scattering. The state vector contains the vertical profile of desert dust (0 to 6km altitude, by 1km steps) and the surface temperature. We obtain averaging kernels (showing about 2 degrees of freedom for the dust retrievals), and the vertical profiles of desert dust which can be integrated to the optical depth (usually computed at 10μm). Three spectral windows are used for the retrieval:

- 830-834 cm^{-1}: Ts and dust
- 905-927 cm^{-1}: dust
- 1098-1123 cm^{-1}: dust

Dust is represented by a spherical model, a monomodal log-normal particle size distribution (mean radius of 0.6μm, geometric standard deviation of 2, effective size of 2μm), and the GEISA-HITRAN dust-like refractive index. The optical parameters are computed using a standard Mie code.

The a priori for the dust vertical profile comes from the LIVAS monthly climatology of pure desert dust from CALIOP measurements, an updated version of Amiridis et al [1]. This climatology is provided as 550nm extinction (and standard deviation), and converted to particle concentration using the dust model described here above and a simple Mie code. Then this concentration is multiplied by a factor of 3 because the variance of the dust aerosol load is very high, and the retrievals work better when starting from a load too high than too low (i.e. a 100 % variance as most often reported in the climatology will cover a factor of 3 lower than the a priori but not a factor of 3 higher). A Gaussian correlation along 1km in the vertical dimension is used.

The a priori for the surface temperature, and the vertical profiles of temperature and water vapor come from the IASI level2 product version 6 (PWLR retrievals - the first guess without the optimal estimation step). This was not the operational product for the 2013 data but we obtained it through collaboration with EUMETSAT (T. Hultberg and T. August). This product is significantly better than the version 5 which was the operational product for the 2013 data. Other atmospheric data come from the AFGL 1986 Tropical atmosphere [2]. The gas line parameters are extracted from HITRAN 2012 [8].

3. QUICK INTER-COMPARISON OF THE VERTICAL PROFILES

The validation of the product used in this study is undergoing within the CCI aerosols phase 2 program (baseline for the optical depth and within an option for the vertical profiles) and is not the purpose of this contribution. However, as we intend to look at dust sources, we need to at least show by one example comparison with CALIOP that our profiles are able to capture dust at different altitudes.

Figure 1 shows the MAPIR retrieval results in terms of optical depth for the 9 June 2013 mid-morning overpass, and vertical profile comparisons with one CALIOP overpass about 3 hours later. Both MAPIR and CALIOP detect dust at the same geographical places, except for the last part of the transect where nothing is seen in the MAPIR results. This is not due to retrieval problems, but to the technical issue with the cloud mask. When following the transect from North to South, it is very clear that both CALIOP and MAPIR first detect dust in the lower layers only, then in the higher layers only, then some not well defined low load dust layer. This comparison shows that indeed our retrievals are capable to distinguish between dust close to the surface and higher up in the atmosphere. They are therefore suitable for the purpose of this contribution about dust source studies.

4. DESERT DUST SOURCE STUDY

4.1. Methodology

To detect dust sources, we look at the number of detections per day of dust with an optical depth (OD) of at least 0.2 in the lower atmospheric layer (within the retrieval vertical grid). This takes into account the topographic mean pixel altitude. To compare with the usual methods that consider the total column, we also look at the number of detections of desert dust with a total column optical depth of 0.2. These numbers are considered in a level3 gridded dataset (1° x 1°), as yearly or monthly datasets. At this point, the yearly average consists of the average of one month per season. The whole year 2013 is currently under processing. The number of detections per grid cell per day may be higher than one, as one grid cell contains about 9 IASI pixels (depending on their exact geolocation). An average of one detection per grid cell per day does not necessarily mean that every day dust is detected in that grid cell. When literature data is displayed on the MAPIR dust detection results, they consist in our reading of the hot spots from the dust source maps shown in the cited literature. It is therefore a personal discretization of the published source maps.

4.2. Yearly averages

Figure 2 shows the yearly average of mid-morning dust detections using the MAPIR algorithm. The right side shows the detections if considering the threshold of 0.2 OD in the total column. It would seem that the whole North Africa is a "hot spot" (which does not mean that every area is dusty during the whole year, as will be seen later with the monthly averages). On the other hand when looking at dust detections only close to the surface (left panel), clear and distinct dust hot spots are detected. Those match reasonably the different literature data also displayed, considering that there are also large differences between the different literature sources / instruments used. Our detected source area can also be compared with the figure 7 of Ginoux et al. [4]. That particular work was done in the goal to attribute dust sources to natural and anthropogenic mechanisms, but also has the advantage of extensively listing dust source area within North Africa. To compare this map to our left panel of Figure 2, it seems easier to look at the places where dust seems to never be detected at the surface. Those places indeed match the no-source area from Ginoux et al. [4]. There are however two area which are reported as natural sources about 50% of the time in Ginoux et al. [4] but not detected using our method. Those area are circled in red in Figure 2, and require more investigation to understand the reason for this discrepancy. It could be a side issue linked to the cloud mask technical problem, because less retrievals were undertaken in those area, probably meaning that more spectra are rejected by the cloud filter (some of them for wrong reasons). It could also be that those places are actually erroneous dust source detections because of the use of total columns for the dust detection. It seems important to highlight that the Eastern of those area where we do not detect dust close to the surface is not the Bodele depression, although it is close to it. Finally, our method seems to detect dust at the surface south of the Sahel (red rectangle), mainly in Nigeria, where, to the current (probably incomplete) knowledge of the authors, no other reference observe major dust sources. This requires further investigation to determine whether it is a new source area (new in time as we used data from 2013 while the other studies are based on more ancient data, or newly detected because of the different method), a deposition area, a place where dust is transported very low in the atmosphere, or an artifact of the method. One clue supporting the possibility of a new dust source is the presence of numerous reports about desertification in North Nigeria, exactly where we see dust in the surface layers. This hypothesis could be confirmed by the study of the complete time series of IASI measurements.

Figure 3 shows the yearly average of mid-morning dust

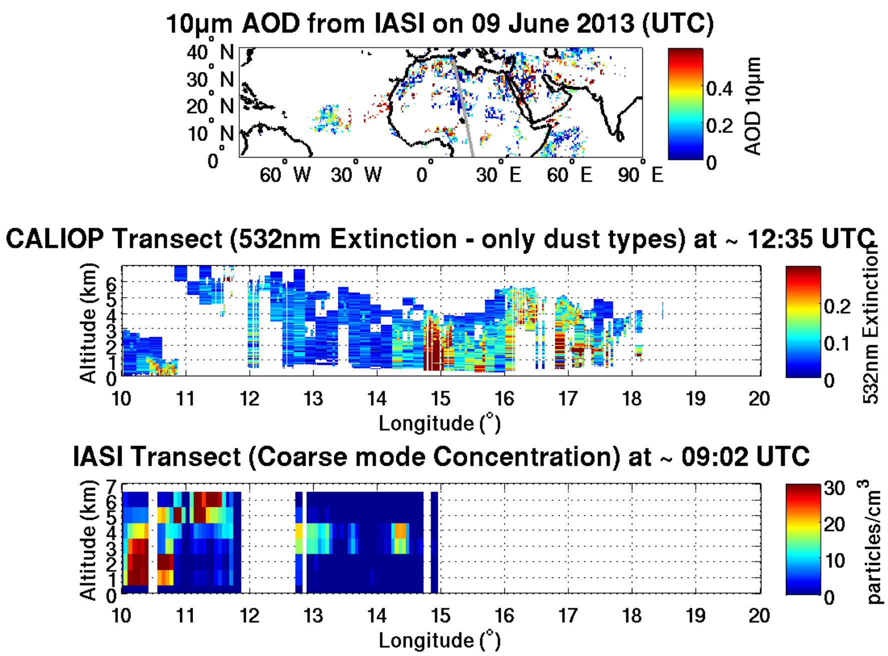

Figure 1. First panel: MAPIR dust optical depth for the mid morning overpass on 9 June 2013. Second and third panels: Comparison of the MAPIR dust profile retrievals and CALIOP extinction profiles (dust aerosol types only) for one CALIOP orbit crossing North Africa on 9 June 2013 (represented in the first panel as a gray line). Some data are missing for the IASI retrievals because of the cloud mask technical issue (see text for details).

detections using the MAPIR algorithm. There are a lot less dust detections than during mid-morning. This requires further investigation because, while it is possible that less dust is detected close to the surface (less sources) in the evening, it seems strange that the total column detections, which include transported dust, are that less frequent during the evening. The most plausible cause for this is an underestimation of the dust OD during the evening, or an overestimation of the dust OD during the morning, which could be due to respectively an over or underestimation of the surface temperature.

4.3. Monthly averages

Figure 4 shows the monthly average of dust detection when considering the total column optical depth. A clear seasonal cycle is detected but the hot spots do not seem to rely well on those listed in the literature. Furthermore, area as the Atlas mountains (NW of Africa) are particularly dusty during the summer and fall, while they are clearly not dust source area. When looking at Figure 5, which contains only the dust detections in the surface layer, those dusty but non source area disappear from the map, as expected. The hot spots of surface dust detections also match reasonably the dust source literature data. This therefore clearly supports the fact that, for desert dust studies using IASI data, the retrieval of vertical profiles (allowing to identify surface dust with respect to total columns) adds valuable information.

The surface dust detections south of the Sahel, in Nigeria, that we discussed in the previous section, are here observed only in December. It therefore reduces the probability of it being an artifact: there is no obvious reason why something particularly wrong would occur with the retrievals only during the winter and in that particular area. An analysis of the winds could help understand why the surface dust detections in North Nigeria occur only in the winter.

5. CONCLUSIONS

The thermal infrared measurements by IASI are successfully used to retrieve vertical profiles of desert dust. In this work, IASI data is used for the first time to study desert dust sources. Using vertical profiles instead of total columns allows to better distinguish between surface dust, more prone to be locally emitted, from transported dust higher up in the atmosphere. The time of the IASI measurements are particularly interesting for studying dust sources, as IASI overpasses occur closely after the two daily maxima of dust emissions.

Some technical issue remains with the pre-filtering of the data, that will be quickly solved. This issue could lead to underestimation of the dust occurrences in particular in the Sahel, possibly explaining the two missing dust hot spots in our dataset with respect to the literature, in particular the work of Ginoux et al [4]. The large difference between the morning and evening dust occurrence detections in the total column are an indication that there is probably either an overestimation of the morning dust concentration, or an underestimation of the evening dust concentration (or both), most probably respectively linked to an under or overestimation of the surface temperature.

The detected source area mainly match geographically the source area reported in the literature, considering that even between different publications large differences are observed. Additionally, we may have discovered a new dust source area in North Nigeria, mainly active during the winter, but this requires thorough confirmation.

This short study confirms the great potential of the MAPIR algorithm for studying desert dust sources. One full year of data will be available very soon, and next year the complete time series of IASI data will be processed as part of the CCI Aerosols phase 2 project. These 10 years of data will allow the study of long-term changes in the desert dust sources. Furthermore, transport and deposition of desert dust can also be studied using the MAPIR algorithm and its results.

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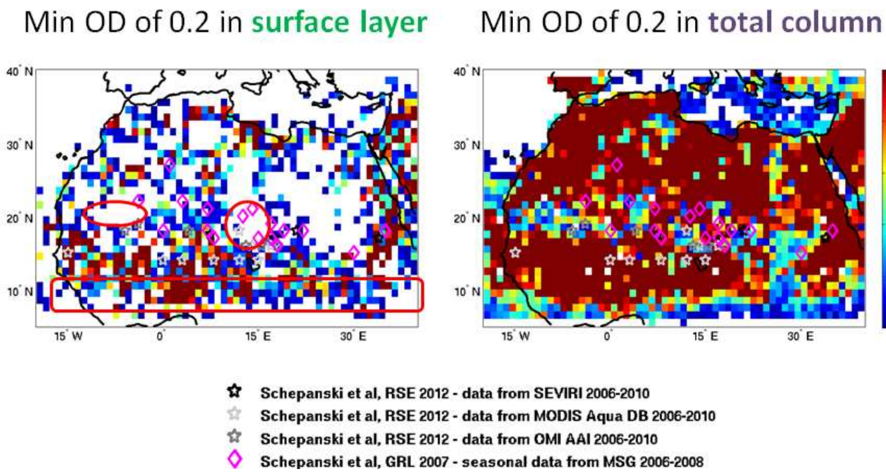

Figure 2. Yearly average of the mid-morning dust detections per day, on the left in the surface layer and on the right in the total column. Some literature dust sources are listed in the figure.

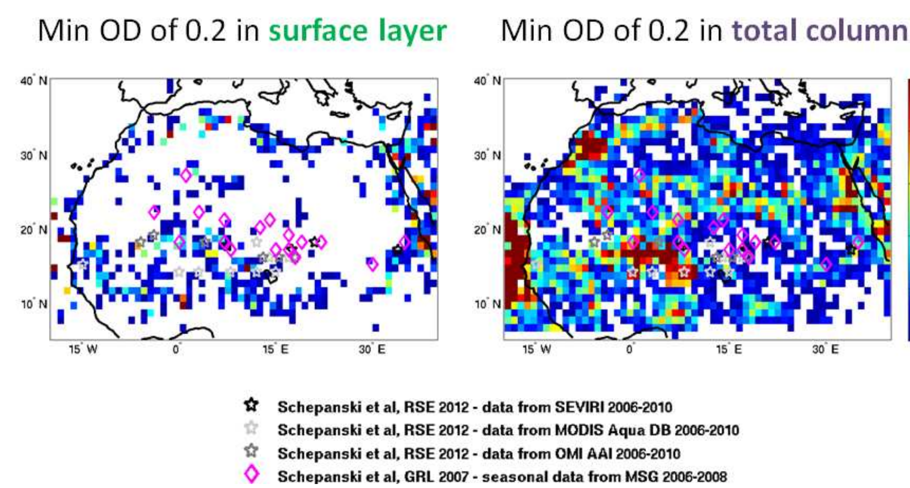

Figure 3. Same as Figure 2 for evening dust detections.

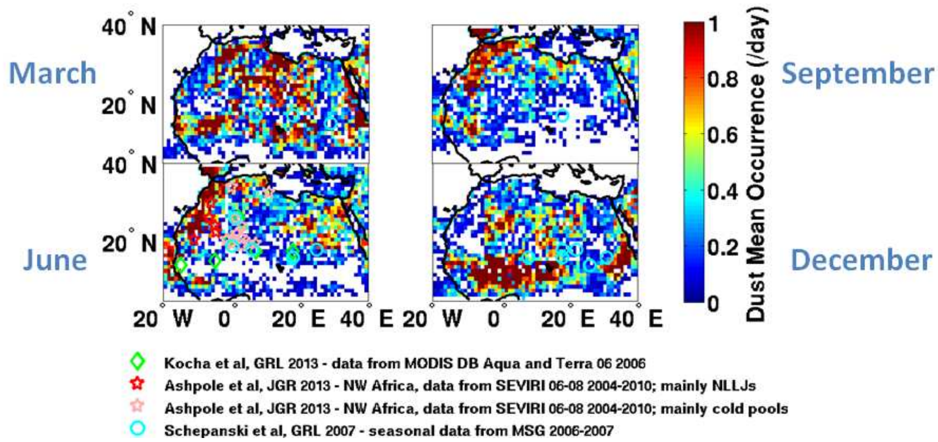

Figure 4. Monthly average of the mid-morning dust detections per day in the total column. Some literature dust sources are listed in the figure.

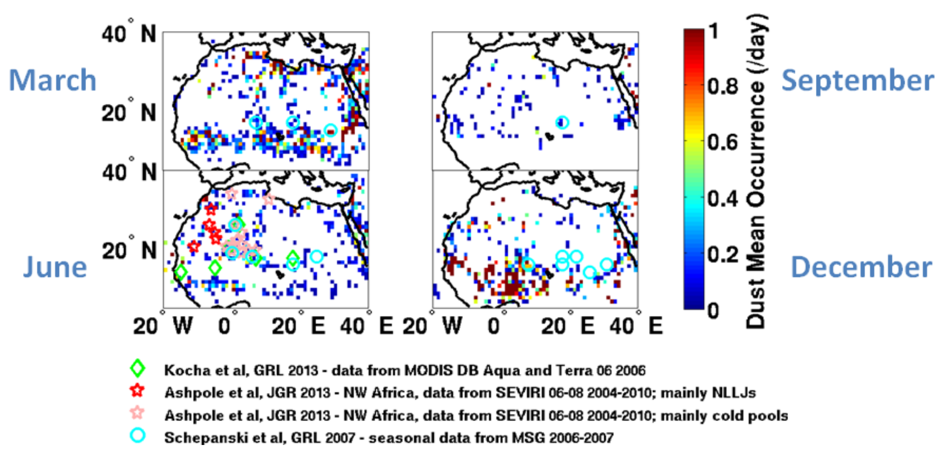

Figure 5. Same as Figure 4 for surface dust detections.

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