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Seasonal cycle of desertic aerosols in West Africa : Analysis of the Coastal transition with passive and active sensors

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Abstract. The impact of desertic aerosols on climate, atmospheric processes and the environment is still debated in the scientific community. The extent of their influence remains to be determined and particularly requires a better understanding of the variability of their distribution. In this work, we studied the variability of these aerosols in West Africa using different types of satellite observations. SeaWiFS and OMI data have been used to characterize the spatial distribution of mineral aerosols from their optical and physical properties over the period 2005-2010. In particular, we focused on the variability of the transition between the West African continent and the Eastern Atlantic Ocean. Data provided by the Lidar scrolling CALIOP onboard the satellite CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations) for the period 2007-2013 were then used to assess the seasonal variability of the vertical distribution of desertic aerosols. We first obtained a good representation of Aerosol Optical Depth (AOD) and Single Scattering Albedo (SSA) by satellites (SeaWiFS and OMI, respectively) in comparison with AERONET estimates, both above the continent and the ocean. Dust occurrence frequency is higher in spring and boreal summer. In spring, the highest occurrences are located between the surface and 3 km above sea level, while in summer the highest occurrences are between 2 and 5 km altitude. The vertical distribution given by CALIOP also highlights an abrupt change at the coast from spring to fall with a layer of desertic aerosols confined in an atmospheric layer uplifted from the surface of the ocean. This uplift of the aerosol layer above the ocean contrasts with the winter season during which mineral aerosols are confined in the atmospheric boundary layer. Radiosondes at Dakar Weather Station (17.5°W, 14.74°N) provide basic thermodynamic variables which partially give causal relationship between the layering of the atmospheric circulation over West Africa and their aerosol contents throughout the year. A SSA increase is observed in winter and spring at the transition between the continent and the ocean. The analysis of mean NCEP winds at 925 hPa between 2000 and 2012 suggest a significant contribution of coastal sand sources from Mauritania in winter which would increase SSA over the ocean.

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1 Introduction

The Sahara is the largest source of mineral aerosols in the world, with a contribution of almost 40% compared to the overall emissions from natural sources (Ramanathan et al., 2001; Tanaka et al., 2005). These minerals and desert aerosols are emitted in arid and semi-arid North Africa and transported across the Atlantic Ocean to the American continent, the Caribbean islands, Florida (Chiapello et al., 1995; Dunion and Marron, 2008), South America (Prospero et al., 1981; Liu et al., 2008, 2012) and North America (Tsamalis et al., 2013). They play a very important role on the climate and the various processes involved in the climate system (Kaufman et al., 2005; Teller and Levin, 2006; Stith et al., 2009) through their direct impact in the visibility, in the infrared (Sokolik and Toon, 1999) or the earth radiation budget (Andreae et al., 1996; Solomon, 2007) which is still poorly known. The difficulty of understanding the impact of aerosols on the Earth's radiation balance is due to the large spatial and temporal variability of their concentration and composition in the atmosphere. The mineral particles suspended in the atmosphere come from different sources and have a nature similar to the nature of the soil from which they arise (Claquin et al., 1999; Formenti et al., 2008) with a broad spectrum of particle sizes ranging between 0.01 and 100 micrometers (Wagener, 2008). Their impact on the marine ecosystem and particularly on oceanic primary production (Duce and Tindale, 1991; Baker et al., 2003; Mills et al., 2004; Jickells et al., 2005; Mahowald et al., 2009) remains still uncertain and difficult to assess because of the composition of these particles and of physico-chemical processes affecting them (e.g., Friese et al., 2016). Mineral dust deposition also have a negative impact on human health and are responsible for meningitis epidemics or cardiac deseases (Thomson et al., 2006; Martiny and Chiapello, 2013; Diokhane et al., 2016; Prospero et al., 2005; Griffin, 2007).

The desert aerosols and their large-scale transport began to be studied in the 90s from satellite observations (Husar et al., 1997; Moulin, 1997). Passive sensors have the advantage of providing daily data on the state of the atmosphere with good spatial and temporal coverage. The satellite products have improved our knowledge of the source regions and dust transport pathways in recent years (Engelstaedter et al., 2006). However, studies of their spatial and temporal variability are mainly based on indices such as the Aerosol Optical Depth (AOD) or the Aerosol Index (AI) which provide vertically integrated information on the Atmospheric aerosol contents (passive space derived observations: (Cakmur et al., 2001; Chiapello and Moulin, 2002; Kaufman et al., 2005; Engelstaedter et al., 2006; Schepanski et al., 2009b). These satellite products also present some limitations since they are unable to differentiate aerosols and particularly those from desertic origin. Moreover AOD estimated by satellite integrates the contribution of every kind of particles and this latter estimation also depends on the altitude at which aerosols are located. In other words the signal changes with the height of the aerosol plume for a given aerosol content (Chiapello et al., 1999).

Recently, the vertical structure of the SAL has been analyzed from CALIPSO satellite observations. The vertical disconnection of dust layers between land and ocean strongly impacts the atmospheric deposition rates of mineral matters (Schepanski et al., 2009a) and dust concentration at the oceanic surface which has important consequences on the primary biological productivity of surface waters (Martin, 1992; Arístegui et al., 2009).

In boreal summer, the Saharan Air Layer (SAL) is characterized by hot, dry air, very dust-laden and is located between 10°N and 25°N (Dunion and Marron, 2008; Tsamalis et al., 2013). This SAL is marked by very strong potential temperatures up to

40°C and a radon presence (radon-222) indicating the desert origin of air masses (Carlson and Prospero, 1972). In winter, the SAL is characterized by the transport of chemical elements such as aliminum (Al), silicon (Si), iron (Fe), titanium (Ti) and manganese (Mn) (e.g., Ben-Ami et al., 2010) and is located between 5°N and 10°N (e.g., Tsamalis et al., 2013). The studies relating aerosols to their transport are generally a simple description of the vertical distribution of aerosols in the SAL (Generoso et al., 2008; Liu et al., 2008; Ben-Ami et al., 2009; Braun, 2010; Yu et al., 2010; Adams et al., 2012; Ridley et al., 2012; Yang et al., 2012) or a description of the seasonality of the SAL in connection with large-scale dynamics (Liu et al., 2012; Tsamalis et al., 2013). The effects of small-scale dynamics and thermodynamics for controlling the vertical structure of desert aerosols in coastal West Africa remain unknown, and efforts made in this direction are restricted to very sporadic case studies (Gamo, 1996; Reid et al., 2002; Petzold et al., 2011).

In this study, in-situ and satellite observations are used to describe the seasonal time-scale of mineral dust distribution. We first used complementary information, provided by Sea-viewing Wide Field Sensor (SeaWiFS) and Ozone Monitoring Instrument (OMI) which deliver optical (AOD: Aerosol Optical Depth; SSA: Single Scattering Albedo) and physical (AE: Angstrom Exponent) properties of desertic aerosols, to analyse the spatial variability of the desertic aerosol dust. Then we used CALIOP lidar on board CALIPSO to investigate the vertical distribution of these desertic aerosols.

We finally analyze meteorological data to explain the impact of the atmospheric variables on the seasonal cycle of the vertical distribution of desertic aerosols at the transition zone between the continent and the ocean. We conclude the present work by summarizing all the results which are reflecting our common knowledge on mineral dust discrimination and spatio-temporal distribution.

2 Methodology and Data

2.1 AErosol RObotic NETwork (AERONET)

We first used data of AOD from AERONET between January 2005 and December 2010. AERONET is a global network of in-situ observations developed by the NASA Earth Observing System (NASA's EOS) (Dubovik et al., 2000). AERONET consists of solar photometers Cimel providing measures of AOD every 15 minutes, refractive index and also allows inversions such as particle size distribution of aerosols and single scattering albedo (SSA) at 440nm, 670nm, 870nm and 1020nm wavelengths (Holben et al., 1998) with an accuracy of ± 0.01 (Slutsker and Kinne, 1999; Dubovik et al., 2000; Holben et al., 2001). AERONET's SSA are computed for favorable atmospheric conditions (AOD 440 nm > 0.4 and solar zenith angle >45°) using an algorithm which performs almucantar inversions (Jethva et al., 2014). These data are used to validate remotely sensed AOD and SSA measurements.

2.2 Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

We then used DeepBlue-SeaWiFS monthly mean AOD at 550 nm and AE products derived from SeaWiFS developed by NASA to study ocean color. SeaWiFS measures the solar radiation reflected at the top of the atmosphere in the wavelengths 412 nm, 443 nm, 490 nm, 510 nm, 555 nm, 670 nm, 765 nm and 865 nm. Satellite measurements carried out between October 1997 and December 2010 (Jamet et al., 2004; Hsu et al., 2012) have a value of signal-to-noise and uncertainty of 2%-3% for the different spectral bands (for details see (Eplee et al., 2007; Franz et al., 2007; Eplee Jr et al., 2011)). In this paper, we use the Level 3 version 4 products (Bettenhausen and Team, 2013) for years 2005 to 2010. The SeaWiFS AOD provided at 550 nm is available both over the land and over the ocean (Hsu et al., 2004; Sayer et al., 2012). The products used here are land-ocean estimates generated and made available to the scientific community by NASA (Wang et al., 2000).

2.3 Ozone Monitoring Instrument (OMI)

OMI is a passive sensor on board the Aura satellite launched on 15 July 2004 by NASA's EOS Aura space-craft which released its first observations in October 2004. Like all satellites in the A-Train constellation, OMI scans the entire Earth in 14 to 15 orbits with a nadir ground pixel spatial resolution of 13 × 24 km^2 (Jethva et al., 2014). In addition to the ozone content in the atmosphere OMI provides information on aerosols, clouds, gases (NO2, SO2, HCHO, BrO, and OClO) and irradiance in the ultraviolet (Levelt et al., 2006). We use Aura/OMI SSA at 500 nm taken from the OMAERUV Level 3 Collection 003 aerosol product processed in March 2012 with a spatial resolution of 1° x 1° to quantify the scattering of the aerosol types with passive sensors. The OMAERUV algorithm assigns flag to each pixel which carries information on the quality of the retrieval (Jethva et al., 2014).

The SSA represents the ratio (ranging between 0 and 1) of scattering coefficient to extinction coefficient and provides information about the absorbing properties of the aerosols. SSA of 0.9 indicates that 90% of the total extinction of solar light is caused by scattering and 10% by absorption effects (Jethva et al., 2014). This parameter depends on the wavelength, size and the complex refractive index of particles (Léon et al., 2009). The closer this value is to one the more desert aerosols dominate (Johnson et al., 2008; Léon et al., 2009; Ialongo et al., 2010; Malavelle, 2011).

OMI data were interpolated on the grid of SeaWiFS data to superimpose the products (AOD and SSA).

2.4 Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)

The first polarization lidar in space so-called CALIPSO is a sun-synchronous satellite developed by NASA as part of the Earth System Science Pathfinder program (ESSP) and launched on April 28, 2006 (Winker et al., 2007; Hunt et al., 2009) in order to provide a global coverage of the vertical distribution of the properties of clouds and aerosols (Winker, 2003). The lidar (LIght Detection and Ranging) Cloud-Aerosol Backscatter Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO acquires vertical profiles of the atmosphere at 30 m resolution in the lower layers (from the two orthogonal components that result from depolarization of a signal backscattered laser at 532 nm and vertical profiles of a total laser at 1064 nm signal backscattered at nadir). The final level-2 product is reduced to a uniform resolution calculated from averaging and/or interpolating different resolutions for generating intermediate products (Winker et al., 2006). We use the Vertical Feature Mask (VFM; stage 1 Version 3) for which the processing algorithm is described in CALIOP Algorithm Theoretical Basis, Part 3: Scene Algorithms Classification (Liu et al., 2005). VFM allows to separate aerosols from clouds but also the desert aerosols from other types of aerosols (Omar et al., 2009). This methodology of discrimination by CALIOP of aerosol types gives results

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close to another method of distinction between mineral dust made from inversions (SSA and AE) of AERONET level 2 products (Mielonen et al., 2009). The mix of layers of desert aerosol and other types of aerosols (i.e. biomass burning) is very rare (Chou et al., 2008; Heese and Wiegner, 2008) in our region of interest. During the dry season, mineral aerosols are observed in the atmospheric surface layer ranging 0.5 to 1 km while the aerosol emitted through biomass burning are carried to higher levels up to 5 km altitude (Cavalieri et al., 2010). Nevertheless, classification errors are possible for low values of the Mineral Dust Occurrence Frequency (MDOF) and at frontal zones between layers of different substances (Adams et al., 2012). For this reason we only consider here the values of MDOF above 10%. Our method for determining the mineral dust by a calculation of the MDOF is equivalent to (Adams et al., 2012) expressed by the following equation:

$$p(x,y,z) = \frac{\sum_{n=0}^{N} p(x+n,y,z)}{\sum_{n=0}^{N} s(x+n,y,z)} \qquad \forall \quad x,y,z \tag{1}$$

where p is the probability of occurrence of dust at a grid point, s the total number of valid satellite passing the same grid point and N the total number of grid points. Data were gridded with a near-uniform horizontal resolution of 0.5° x 0.5° and a vertical resolution of 30 m for 290 vertical levels between 0.5 and 8.2 km above sea level. The CALIOP lidar on CALIPSO (also in the A-train) has a 90 m instantaneous footprint which is smeared to 333 m in the along track direction by orbital motion over the lidar pulse duration. All satellites of the A-train constellation, such as CALIPSO, fly in a sun-synchronous orbit with a 16 days coverage cycle consisting of 233 orbits separated by 1.54 degrees longitude or about 172 km at the equator. Each satellite completes 14.55 orbits per day with a separation of 24.7 degrees longitude between each successive orbit at the equator. These CALIPSO orbits are controlled to cover the same ground with cross-track errors of less than ±10 km (Winker et al., 2007). This drastically reduces the spatial coverage of the satellite. Consequently, we use a mesh of 0.5° longitude to cover the area between 10°W-24°W and 12°N-21°N. The choice of this band of latitude is driven by one of the objectives of the paper which is to study the transition of aerosol distribution between the continent and the ocean. Dust occurrences are averaged over latitudes 12°N to 21°N and are then smoothed over 30 points longitudinal running mean and 50 points vertical running mean.

3 Results

3.1 Horizontal dust distribution

SeaWiFS AOD (estimated at wavelength 550 nm) represents an average value of the optical Depth of the atmosphere. It has first been compared to the monthly AOD given by AERONET photometers (given at the wavelength 675 nm) by calculating the correlation between the two measurements at different selected stations (Fig. 1). Our choice focused on the stations Banizoumbou (2.665°E-13.541°N), Agoufou (1.479°W-15.345°N), M'bour (16.959°W-14.394°N) and Capo Verde (22.935°W-16.733°N) to assess the quality of satellite information obtained accross the land-ocean continuum. A very good correlation is calculated between SeaWiFS and in-situ measurement given by the photometer at Banizoumbou (R=0.95; Fig. 1a). The photometer Cimel at Agoufou (Mali) also shows a very good correlation with SeaWiFS (R=0.92; Fig. 1b). The correlation between the two measures is equal to 0.81 at the shore in M'bour (Fig. 1c). It is close to the one in Capo Verde (R=0.83; Fig. 1d). All these correlation values of AOD are significant at 95% using a student statistical test. We also studied the structure of the cloud of points between the two datasets to assess the quality of the satellite measurements as a function of the aerosol concentration. The regression line obtained by the least squares method shows a linear relationship between satellite and in-situ monthly mean measurements of AOD at the selected stations.

The horizontal transport of desert aerosols can be followed by considering the key and complementary parameters that distinguish them. To better characterize the desertic aerosols, we combined AOD (SeaWiFS) with SSA (OMI) to specify the contribution of the latter compared to other types of aerosols in the atmosphere. A threshold of 0.90 in monthly averaged SSA is used to define regions dominated by desert aerosols. This value is chosen in agreement with the threshold value given in previous studies (Léon et al., 2009; Malavelle, 2011; Jethva et al., 2014). This method allowed us to define the Sahelo-Saharan region as the one which is the most influenced by dust plumes composed of desert aerosols throughout the year (between 12°N and 21°N; Fig. 3).

The comparison of the daily SSA of Aura/OMI versus AERONET is achieved to validate satellite SSA which provides a better spatio-temporal coverage of our region of interest. OMI SSA retrievals are taken between 10 and 15 am https://ozoneaq.gsfc.nasa.gov/data/lance-browse/, time range which cover AERONET measurements. As emphasized by Jethva et al. (2014), this comparison is done at the original wavelengths of each independent measurement (388 nm for OMI and 438 nm for AERONET) in order to avoid uncertainties induced by the interpolation at other wavelengths. Good correlations are retrieved between the two datasets at the different ground stations in West Africa for the period 2005-2010 within root mean square (RMS) difference of 0.03 in the selected region (Fig. 2). Globally, the OMAERUV SSA is well correlated with ground measurements. The correlation at all selected sites for this study is significant. The agreement between the two inversions is better at the shore of West Africa (M'bour station: r=0.66) and over the ocean (Capo Verde station: r=0.30) than over the continent (Banizoumbou station, r=0.47 and Agoufou station: r=0.50).

Figure 3 and Figure 4 show that horizontal monthly average of AOD is stronger above the continent than over the ocean throughout the year. The weakest AOD is given for winter months (DJF for December-January-February) with a mean value of 0.33 ± 0.07 (standard deviation). At this season, the SSA values are higher in the northeast tropical Atlantic than on the West African continent with a SSA maximum reaching 0.95. This indicates a stronger contribution of dust over the ocean than over the continent in the latitude range 12°N-21°N. Note that sources of dust aerosols are also indicated by high SSA values north of 21°N.

In spring (MAM for March-April-May), the increase of the monthly mean AOD compared to winter is indicated by a stronger mean value (0.50 ± 0.08). The mean optical depth indicates that the dust sources are becoming more active with an atmosphere more charged than in winter. The coarse mode dominates in the mixed atmosphere boundary layer over the continent with lower values of AE less than 0.7 (not shown). Nevertheless, the reflectance properties of aerosols (given by the SSA) is higher over the ocean than over the continent and vary weakly compared to winter.

In summer (JJA for June-Jully-August), the maximum mean AOD is 0.52 ± 0.05. AOD values are associated with higher SSA above 0.96. It indicates that aerosols are clearly dominated by desert dust in boreal summer. At this season, the largest dust particles are mobilized and raised above the continent by convective systems (e.g., Rajot, 2001, Fig. 4c).

In autumn (SON for September-October-November), the monthly mean AOD is 0.34 ± 0.05. AOD is decreased compared to spring but the SSA values are much higher than in spring despite the fact that uplift occurrences are larger in spring than in fall in west Africa (Marticorena et al., 2010; Diokhane et al., 2016).

Changes of AOD and SSA are seen at the transition between the continent and the ocean (Fig. 4). Understanding these changes requires a thorough analysis of the vertical distribution of dust during transportation from east to west in North Africa.

3.2 Vertical dust distribution

The vertical distribution of desert aerosol indicates a strong presence of dust concentrations between the surface and 6 km in agreement with the results of Léon et al. (2009) who studied the vertical distribution of dust in the North-East Tropical Atlantic (Fig. 5).

In DJF, desert aerosols are mainly concentrated in the atmospheric boundary layer (ABL) between the surface and 2 km (Fig. 5a) both over the continent and the ocean. At this season, we also noted a homogeneous dust aerosol transition between Western Africa and the Eastern part of the Atlantic Ocean.

In MAM, there is an elevation of the SAL with a maximum altitude of 5 km on the continent and between 4 and 5 km above the ocean (Fig. 5b). The MDOF over 50% above the continent shows that dust emissions are much greater than in winter. ABL develops vertically to reach the level of the SAL. It results in an atmospheric layer well mixed between the surface and 5 km of altitude above the continent (10°W-15°W). Above the Ocean we see a detachment of the SAL from the ocean surface which occurs at the coast (around 18°W).

JJA is the busiest season of the year in terms of dust rising in the northern hemisphere of Africa. It is characterized by the development of density currents that intensify the mobilization of terrigenous aerosols (e.g., Bou Karam et al., 2008; Schepanski et al., 2009b, Fig. 5c).

Unlike DJF, we note a clear separation of the dust layer above the Eastern Atlantic Ocean where dusts are confined between 1 and 6 km altitude.

In SON, dust emissions decrease in intensity compared to JJA but the detachment from the surface of the ocean remains clear at the coast although less marked than in JJA (Fig. 5d). According to Adams et al. (2012), the heart of the SAL is located about 5 km above sea level in SON, whereas Liu et al. (2012) shows a maximum altitude of 4 km.

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4 Discussion

4.1 Seasonal variability

The desert aerosols in the band of latitude 12°N-21°N are mainly emitted in the Saharan and Sahelian regions. Emissions and transport processes are mainly controlled by meteorological variables (Brooks and Legrand, 2000; Joseph, 1999).

In the Sahara, the sources of dust emissions are less active in winter than during the other seasons and the vertical distribution of aerosols is not supported by a favorable wind regime ascending particles. The maximum altitude of this distribution is 3 km above the continent and 2 km at the West African coast in agreement with the studies of (Léon et al., 2009) and (Vuolo et al., 2009). Compared to other seasons, DJF show an important role played by the shallower atmospheric layers on the dust transported from source regions located in the Northwestern part of Mauritania and more generaly in the West African coastal region (Fig. 6a). These West African emission zones participate actively to the transport of mineral aerosols in the near Atlantic Ocean. This high occurrence is shown by the inter-seasonal variability derived from NCEP Reanalysis. Figure. 6 highlights that the Northwest region of Mauritania has the highest standard deviation of horizontal wind intensity between 18°N-24°N and that wind is very intense in winter compared to the other seasons (Fig. 6a). Hence this region represents an important sand source in winter as mentioned by previous studies (Bertrand et al., 1979; Ozer, 2000; Tulet et al., 2008; Laurent et al., 2008; Mokhtari, 2012; Hourdin et al., 2015). During this period, the studies of Dubovik et al. (2002); Schepanski et al. (2009b) or Tegen et al. (2013) suggested that the coarse mode fraction of mineral dust dominates the atmospheric mixture as AE values are below 0.7 (not shown) and are associated with AOD values greater than or equal to 0.3. Here, we have considered thresholds of 0.7 for AE and 0.2 for AOD to monitor the evolution of coarse (upper and lower bounds respectively) and fine (lower and upper bounds) modes of mineral aerosols.

Unlike winter, summer dust emissions are more concentrated in the higher layers of the ABL up to 6 km (Gamo, 1996) in response to intense convective mechanisms that are more common in the region at this season (Cuesta et al., 2009). Indeed, the convergence of hot, dry air (Harmatan) from the Sahara and fresh, moist air (monsoon) from the ocean causes the raising and maintenance of aerosol layers between 1 and 6 km at the thermal front area of the inter-tropical discontinuity (ITD) for which the northern edge is located around 16°N (Fig. 6c). Transport is also growing between 3 and 4 km above the ocean with a MDOF greater than 70%, i.e. more than 30% higher than that observed in DJF. This sharp increase of MDOF from DJF to JJA is in agreement with the results of (Schepanski et al., 2009b) who estimated an increase of more than 20% of the activity of dust sources in summer compared to winter in West Africa in the observations of Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). In summer, atmospheric dynamics raise large dust particles that are subject to the law of universal gravitation of Newton, thus settle much faster on the continent than the rest of the year. However, their reflectivity of solar radiation becomes larger and reaches a maximum value indicated by a SSA of 0.97 (Fig. 4c).

In autumn, SSA values are comparable to spring values but these high values are not due to high reflectance of desert aerosols like in spring because the southern migration of the Inter-Tropical Convergence Zone (ITCZ) reduces the activity of convective systems and causes a reduction of dust emissions shown by a decreasing of the AOD (Fig. 4d). These high SSA values can be

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attributed to atmospheric conditions seen through the relative humidity which is much higher than in spring (Fig. 7d). Indeed, OMI measures the atmospheric properties of the aerosols which are know to be hygroscopic (Jethva et al., 2014).

4.2 Continent-Ocean transition

To better understand the factors responsible for the high variability of the vertical transition of desert aerosols from the continent to the ocean, we placed ourselves at a coastal point (Dakar) to study the variation of meteorological variables and their potential influence on the distribution of aerosols. Seasonality of vertical distributions of winds, relative humidity and potential temperature from radiosounding conducted at the weather station (GOOY) of Dakar (at West African shore) are shown in Figure. 7.

In DJF, continental winds are very strong at the surface with a maximum of 22 m/s at 500 m (Fig. 7a). The north-east direction of the winds in the first thousand meters explains the homogeneity of the vertical distribution of dust from the continent towards the ocean. Their intensity also explain the strong values of MDOF (up to 50%) observed by CALIOP in wintertime above the continent. Between 1 and 2 km height, winds weaken and change direction (south to south-east) while MDOF observed by satellite decreases (Fig. 5a). Between 2 and 5 km height, the winds turn to the southwest and west. These dust-depleted air masses of oceanic origin are wetter than from the land, and limit the development of the ABL. The air masses of continental origin are located between the surface and 2000 m height (Fig. 7a). In Figure. 7a, the relative humidity is around 20% (between 500 and 2000 m) and it corresponds to a very dry air mass of Saharan origin. Between 2 and 5 km the potential temperature indicates a stable atmospheric layer.

Compared to the DJF situation, MAM surface winds (Fig. 7b) are intensifying to 25 m/s at 500 m height and are from the east. They are associated with MDOF above 50% in the ABL around 14°W. There is an inversion of easterly winds between 1 and 3 km and a second southerly wind peak (15 m/s) appears between 3 and 4 km. It corresponds to the dust layer (SAL) detected by CALIOP. The vertical profile of potential temperature indicates a stable thick layer, well mixed between the surface and 3 km (Fig. 7b). Beyond this altitude there is a stable stratification of the atmosphere indicated also by the potential temperature. Between 3 and 5 km height, the air masses coming from the South to the South-Southwest are also of oceanic origin and their interaction with a more consistent amount of dust than in winter could explain the better marked transition between the ocean and the continent in terms of SSA (increase) and AOD (decrease) for this season (Fig. 4b). Indeed, in general, increasing the relative humidity is likely to increase the SSA and size hygroscopic aerosols with dry to wet passage inducing a larger diameter even when humidity is below the saturation level (Hervo, 2013; Howell et al., 2006).

In JJA, surface winds (0-1 km) decrease and are from the West to the Southwest (West African Monsoon) (Fig. 7c). This corresponds to lower values of MDOF (Fig. 5c) but to relative humidity values well above DJF or MAM (Fig. 7). Reid et al. (2002) presented a conceptual model of Saharan dust transport in the middle troposphere describing an evolution of relative humidity profile in agreement with the observations made in Dakar. These authors describe a moistening of the surface layers due to monsoon flow which penetrates up to 1.5 km above this layer. Between 2 and 6 km, winds are from the East and above 15 m/s. These wind velocity maxima reach 25 m/s in the range 3.5-5 km and are associated to the African Easterly Jet (AEJ) (Wu et al., 2009; Lafore et al., 2011). The co-localization of the AEJ and the SAL between 2 and 5 km height (Fig. 5c and

Fig. 7c) causes the westward SAL transport by AEJ in summer (Karyampudi et al., 1999). These strong winds correspond to the layer of dust detected by satellite at this altitude (Fig. 5c). Above the continent, the mesoscale features associated with the convergence between Harmattan and the West African Monsoon at the ITCZ cause strong updrafts that allow lifting and transport of dust particles throughout the air column (Tulet et al., 2008). The dynamics of the monsoon described by the conceptual scheme of mechanisms controlling the dust vertical redistribution in Cuesta et al. (2009) explain the wide occurrence of dust found between 2 and 5 km rather than at the surface. During transport from North Africa to the Atlantic Ocean, very large amounts of coarse dust (Fig. 4c) are deposited along the path with a rapid change in the size distribution of aerosols near the west African coast (Ryder et al., 2013). The signing of the SAL is evidenced by relative dryness of the atmosphere (Dulac et al., 2001) between 1.5 and 5 km (Fig. 7c). At this altitude, the vertical profile of potential temperature indicates Saharan origin of air masses with temperatures between 35°C and 45°C (Carlson and Prospero, 1972). The wind direction (east) given in Figure. 7c between 1.5 and 5 km altitude confirms the origin of the Saharan air masses. The presence of dust in the SAL causes both warming and drying of the atmosphere between 1.5 and 5 km and a cooling below this layer (Tulet et al., 2008).

In SON, winds are weak and from the East at the surface (Fig. 7c). Between 1 and 5 km, it is increasing but is less intense than in JJA between 3 and 5 km and it is associated with a decrease of the MDOF (Fig. 5d). The moisture profile in SON (Fig. 7d) is close to that of JJA, but has a more humid atmosphere in the layer between 1.5 and 5 km where maximum relative humidity of the year occurs (60%; Fig. 7d). The analysis of the vertical distribution of thermodynamic variables like relative humidity, potential temperature and wind measured at the Dakar weather station shows that the thermodynamical conditions control the dust vertical distribution as well as the depth of the dust layer depending on the season. This analysis also explains the unintuitive differences between spring, when the low values of SSA are associated with a strong AOD, and autumn characterized by high values of SSA associated with comparable AOD.

5 Conclusions

Studies of processes involved in the vertical distribution of aerosols at the transition between continent and ocean are very rare. Here, we took advantage of a weather station ideally located on the main pathway of desert aerosols from Northern Africa (Léon et al., 2009; Marticorena et al., 2010; Mortier et al., 2016) to explain the effect of meteorological variables on this transition in a region of primary importance worldwide. The interaction of air masses of oceanic origin with dust aerosols are crucial for understanding their fate (e.g., Friese et al., 2016). This study constitutes the first attempt to relate the seasonal dynamic of the atmosphere and the vertical distribution of dust aerosol in this region and provides the first dynamical explanation of a counterintuitive deposition pattern over the Atlantic ocean. Indeed, it explains the role of the local atmospheric circulation in driving a higher AOD and dust content in summer over west Africa in phase with dust deposition in Barbades islands but in opposition with Cape Verde islands where deposition is more intense in winter (Chiapello et al., 1995).

We have studied the seasonal variability of the distribution of desert aerosols in West Africa (continental and oceanic) from their optical and physical properties. First of all we have been able to show a good estimate of physical properties (AOD and SSA) of aerosols by satellite when compared with AERONET ground measurements on the mainland, the coast and the ocean. Space observations then allowed us to show the predominant presence of Saharan dust in the atmosphere north of 12°N throughout the year and an additional significant contribution of sandy sources from the Mauritanian coast in winter. The MDOF indicates a change in the vertical distribution of dust at the transition between the continent and the ocean, the largest differences occurring in spring and summer seasons. In DJF, the ABL is shallow ($\sim$ 1km) and strong winds from North-East transport the dust in a dry atmosphere from the continent to the ocean continuously. This surface layer is superimposed by a stable atmospheric layer which inhibits the vertical development of this surface layer rich in dust aerosols. The decrease from east to west of the AOD requires material deposition during the transit. In summer, convection associated with structures that develop at the ITCZ distribute dust over 6 km height and create a thicker AOD. In the lower layers, the westward oceanic moistly entries which are opposite to the higher eastward winds generate very different distributions above the continent or the ocean. On the mainland, the dust is dominated by coarse mode and have a homogeneous vertical distribution while above the ocean, lower layers are poor in dust and are superimposed by the SAL which is highly enriched. The SSA remains constant at this transition. MAM and SON represent transition periods, MAM being closer to the summer situation.

Future modeling experiments should bring further insights into ocean-atmosphere processes involved in explaining this transition and the dust deposition along this pathway. It also seems that a more tailored approach to ocean-atmosphere interactions including higher frequencies of variability and notably the diurnal cycle is needed to make more apparent the role of local circulation on the vertical distribution of aerosols in coastal areas.

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References

Adams, A. M., Prospero, J. M., and Zhang, C.: CALIPSO-derived three-dimensional structure of aerosol over the Atlantic Basin and adjacent continents, Journal of Climate, 25, 6862–6879, 2012.

Andreae, M. O. et al.: Raising dust in the greenhouse, Nature, 380, 389–390, 1996.

Arístegui, J., Barton, E. D., Álvarez-Salgado, X. A., Santos, A. M. P., Figueiras, F. G., Kifani, S., Hernández-León, S., Mason, E., Machú, E., and Demarcq, H.: Sub-regional ecosystem variability in the Canary Current upwelling, Progress in Oceanography, 83, 33–48, 2009.

Baker, A., Kelly, S., Biswas, K., Witt, M., and Jickells, T.: Atmospheric deposition of nutrients to the Atlantic Ocean, Geophysical Research Letters, 30, 2003.

Ben-Ami, Y., Koren, I., and Altaratz, O.: Patterns of North African dust transport over the Atlantic: winter vs. summer, based on CALIPSO first year data, Atmospheric Chemistry and Physics, 9, 7867–7875, 2009.

Ben-Ami, Y., Koren, I., Rudich, Y., Artaxo, P., Martin, S., and Andreae, M.: Transport of North African dust from the Bodélé depression to the Amazon Basin: a case study, Atmospheric Chemistry and Physics, 10, 7533–7544, 2010.

Bertrand, J., Cerf, A., and Domergue, J.: Repartition in space and time of dust haze south of the Sahara, The Long-Range Transport of Pollutants and its Relation to Gen. Circulation Including Stratospheric/Tropospheric Exchange Processes p 409-415(SEE N 80-26888 17-45), 1979.

Bettenhausen, C. and Team, G. D. M.: Consistent Long-Term Aerosol Data Records over Land and Ocean from SeaWiFS, in: Goddard Space Flight Center Greenbelt, Maryland, pp. 1–19, http://disc.sci.gsfc.nasa.gov/dust/documentation/README.DeepBlueSeaWiFS.pdf, 2013.

Bou Karam, D., Flamant, C., Knippertz, P., Reitebuch, O., Pelon, J., Chong, M., and Dabas, A.: Dust emissions over the Sahel associated with the West African monsoon intertropical discontinuity region: A representative case-study, Quarterly Journal of the Royal Meteorological Society, 134, 621–634, 2008.

Braun, S. A.: Reevaluating the role of the Saharan air layer in Atlantic tropical cyclogenesis and evolution, Monthly Weather Review, 138, 2007–2037, 2010.

Brooks, N. and Legrand, M.: Dust variability over northern Africa and rainfall in the Sahel, in: Linking climate change to land surface change, pp. 1–25, Springer, 2000.

Cakmur, R. V., Miller, R. L., and Tegen, I.: A comparison of seasonal and interannual variability of soil dust aerosols over the Atlantic Ocean as inferred by the TOMS AI and AVHRR AOT retrievals, Journal of Geophysical Research: Atmospheres, 106, 18 287–18 303, 2001.

Carlson, T. N. and Prospero, J. M.: The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic, Journal of applied meteorology, 11, 283–297, 1972.

Cavalieri, O., Cairo, F., Fierli, F., Donfrancesco, G. D., Snels, M., Viterbini, M., Cardillo, F., Chatenet, B., Formenti, P., Marticorena, B., et al.: Variability of aerosol vertical distribution in the Sahel, Atmospheric Chemistry and Physics, 10, 12 005–12 023, 2010.

Chiapello, I. and Moulin, C.: TOMS and METEOSAT satellite records of the variability of Saharan dust transport over the Atlantic during the last two decades (1979–1997), Geophysical Research Letters, 29, 2002.

Chiapello, I., Bergametti, G., Gomes, L., Chatenet, B., Dulac, F., Pimenta, J., and Santos Suares, E.: An additional low layer transport of Sahelian and Saharan dust over the north-eastern tropical Atlantic, Geophysical Research Letters, 22, 3191–3194, 1995.

Chiapello, I., Prospero, J., Herman, J., and Hsu, N.: Detection of mineral dust over the North Atlantic Ocean and Africa with the Nimbus 7 TOMS, Journal of Geophysical Research: Atmospheres, 104, 9277–9291, 1999.

Chou, C., Formenti, P., Maille, M., Ausset, P., Helas, G., Osborne, S., and Harrison, M.: Size distribution, shape and composition of dust aerosols collected during the AMMA SOP0 field campaign in the northeast of Niger, January 2006, J. Geophys. Res, 113, D00C10, 2008.

Claquin, T., Schulz, M., and Balkanski, Y.: Modeling the mineralogy of atmospheric dust sources, Journal of Geophysical Research: Atmospheres, 104, 22 243–22 256, 1999.

Cuesta, J., Marsham, J. H., Parker, D. J., and Flamant, C.: Dynamical mechanisms controlling the vertical redistribution of dust and the thermodynamic structure of the West Saharan atmospheric boundary layer during summer, Atmospheric Science Letters, 10, 34–42, 2009.

Diokhane, A. M., Jenkins, G. S., Manga, N., Drame, M. S., and Mbodji, B.: Linkages between observed, modeled Saharan dust loading and meningitis in Senegal during 2012 and 2013, International journal of biometeorology, 60, 557–575, 2016.

Dubovik, O., Smirnov, A., Holben, B., King, M., Kaufman, Y., Eck, T., and Slutsker, I.: Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) Sun and sky radiance measurements, Journal of Geophysical Research: Atmospheres, 105, 9791–9806, 2000.

Dubovik, O., Holben, B., Eck, T. F., Smirnov, A., Kaufman, Y. J., King, M. D., Tanré, D., and Slutsker, I.: Variability of absorption and optical properties of key aerosol types observed in worldwide locations, Journal of the atmospheric sciences, 59, 590–608, 2002.

Duce, R. A. and Tindale, N. W.: Atmospheric transport of iron and its deposition in the ocean, Limnology and Oceanography, 36, 1715–1726, 1991.

Dulac, F., Chazette, P., Gomes, L., Chatenet, B., Berger, H., and Dos Santos, J. V.: A method for aerosol profiling in the lower troposphere with coupled scatter and meteorological rawindsondes and first data from the tropical Atlantic off Sahara, Journal of aerosol science, 32, 1069–1086, 2001.

Dunion, J. P. and Marron, C. S.: A reexamination of the Jordan mean tropical sounding based on awareness of the Saharan air layer: Results from 2002, Journal of Climate, 21, 5242–5253, 2008.

Engelstaedter, S., Tegen, I., and Washington, R.: North African dust emissions and transport, Earth-Science Reviews, 79, 73–100, 2006.

Eplee, R. E., Patt, F. S., Barnes, R. A., and McClain, C. R.: SeaWiFS long-term solar diffuser reflectance and sensor noise analyses, Applied optics, 46, 762–773, 2007.

Eplee Jr, R. E., Sun, J.-Q., Meister, G., Patt, F. S., Xiong, X., and McClain, C. R.: Cross calibration of SeaWiFS and MODIS using on-orbit observations of the Moon, Applied Optics, 50, 120–133, 2011.

Formenti, P., Rajot, J. L., Desboeufs, K., Caquineau, S., Chevaillier, S., Nava, S., Gaudichet, A., Journet, E., Triquet, S., Alfaro, S., et al.: Regional variability of the composition of mineral dust from western Africa: Results from the AMMA SOP0/DABEX and DODO field campaigns, Journal of Geophysical Research: Atmospheres, 113, 2008.

Franz, B. A., Bailey, S. W., Werdell, P. J., and McClain, C. R.: Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry, Applied optics, 46, 5068–5082, 2007.

Friese, C. A., van der Does, M., Merkel, U., Iversen, M. H., Fischer, G., and Stuut, J.-B. W.: Environmental factors controlling the seasonal variability in particle size distribution of modern Saharan dust deposited off Cape Blanc, Aeolian Research, 22, 165–179, 2016.

Gamo, M.: Thickness of the dry convection and large-scale subsidence above deserts, Boundary-Layer Meteorology, 79, 265–278, 1996.

Generoso, S., Bey, I., Labonne, M., and Bréon, F.-M.: Aerosol vertical distribution in dust outflow over the Atlantic: Comparisons between GEOS-Chem and Cloud-aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Journal of Geophysical Research: Atmospheres, 113, 2008.

Griffin, D. W.: Atmospheric movement of microorganisms in clouds of desert dust and implications for human health, Clinical microbiology reviews, 20, 459–477, 2007.

Heese, B. and Wiegner, M.: Vertical aerosol profiles from Raman polarization lidar observations during the dry season AMMA field campaign, Journal of Geophysical Research: Atmospheres, 113, 2008.

Hervo, M.: Etude des propriétés optiques et radiatives des aérosols en atmosphère réelle: Impact de l'hygroscopicité, Ph.D. thesis, Université Blaise Pascal-Clermont-Ferrand II, 2013.

Holben, B., Tanre, D., Smirnov, A., Eck, T., Slutsker, I., Abuhassan, N., Newcomb, W., Schafer, J., Chatenet, B., Lavenu, F., et al.: An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET, Journal of Geophysical Research: Atmospheres, 106, 12 067–12 097, 2001.

Holben, B. N., Eck, T., Slutsker, I., Tanre, D., Buis, J., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y., Nakajima, T., et al.: AERONET—A federated instrument network and data archive for aerosol characterization, Remote sensing of environment, 66, 1–16, 1998.

Hourdin, F., Gueye, M., Diallo, B., Dufresne, J.-L., Escribano, J., Menut, L., Marticoréna, B., Siour, G., and Guichard, F.: Parameterization of convective transport in the boundary layer and its impact on the representation of the diurnal cycle of wind and dust emissions, Atmospheric Chemistry and Physics, 15, 6775–6788, 2015.

Howell, S., Clarke, A., Shinozuka, Y., Kapustin, V., McNaughton, C., Huebert, B., Doherty, S., and Anderson, T.: Influence of relative humidity upon pollution and dust during ACE-Asia: Size distributions and implications for optical properties, Journal of Geophysical Research: Atmospheres, 111, 2006.

Hsu, N., Gautam, R., Sayer, A., Bettenhausen, C., Li, C., Jeong, M., Tsay, S., and Holben, B.: Global and regional trends of aerosol optical depth over land and ocean using SeaWiFS measurements from 1997 to 2010, 2012.

Hsu, N. C., Tsay, S.-C., King, M. D., and Herman, J. R.: Aerosol properties over bright-reflecting source regions, IEEE Transactions on Geoscience and Remote Sensing, 42, 557–569, 2004.

Hunt, W. H., Winker, D. M., Vaughan, M. A., Powell, K. A., Lucker, P. L., and Weimer, C.: CALIPSO lidar description and performance assessment, Journal of Atmospheric and Oceanic Technology, 26, 1214–1228, 2009.

Husar, R. B., Prospero, J. M., and Stowe, L. L.: Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product, Journal of Geophysical Research: Atmospheres, 102, 16 889–16 909, 1997.

Ialongo, I., Buchard, V., Brogniez, C., Casale, G., and Siani, A.: Aerosol Single Scattering Albedo retrieval in the UV range: an application to OMI satellite validation, Atmospheric Chemistry and Physics, 10, 331–340, 2010.

Jamet, C., Moulin, C., and Thiria, S.: Monitoring aerosol optical properties over the Mediterranean from SeaWiFS images using a neural network inversion, Geophysical Research Letters, 31, 2004.

Jethva, H., Torres, O., and Ahn, C.: Global assessment of OMI aerosol single-scattering albedo using ground-based AERONET inversion, Journal of Geophysical Research: Atmospheres, 119, 9020–9040, 2014.

Jickells, T., An, Z., Andersen, K. K., Baker, A., Bergametti, G., Brooks, N., Cao, J., Boyd, P., Duce, R., Hunter, K., et al.: Global iron connections between desert dust, ocean biogeochemistry, and climate, science, 308, 67–71, 2005.

Johnson, B., Osborne, S., Haywood, J., and Harrison, M.: Aircraft measurements of biomass burning aerosol over West Africa during DABEX, Journal of Geophysical Research: Atmospheres, 113, 2008.

Joseph, M.: Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality, 1999.

Karyampudi, V. M., Palm, S. P., Reagen, J. A., Fang, H., et al.: Validation of the Saharan dust plume conceptual model using lidar, Meteosat, and ECMWF data, Bulletin of the American Meteorological Society, 80, 1045, 1999.

Kaufman, Y., Koren, I., Remer, L., Tanré, D., Ginoux, P., and Fan, S.: Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean, Journal of Geophysical Research: Atmospheres, 110, 2005.

Lafore, J.-P., Flamant, C., Guichard, F., Parker, D., Bouniol, D., Fink, A., Giraud, V., Gosset, M., Hall, N., Höller, H., et al.: Progress in understanding of weather systems in West Africa, Atmospheric Science Letters, 12, 7–12, 2011.

Laurent, B., Marticorena, B., Bergametti, G., Léon, J., and Mahowald, N.: Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database, Journal of Geophysical Research: Atmospheres, 113, 2008.

Léon, J.-F., Derimian, Y., Chiapello, I., Tanré, D., Podvin, T., Chatenet, B., Diallo, A., and Deroo, C.: Aerosol vertical distribution and optical properties over M'Bour (16.96 W; 14.39 N), Senegal from 2006 to 2008, Atmospheric Chemistry and Physics, 9, 9249–9261, 2009.

Levelt, P. F., van den Oord, G. H., Dobber, M. R., Malkki, A., Visser, H., de Vries, J., Stammes, P., Lundell, J. O., and Saari, H.: The ozone monitoring instrument, IEEE Transactions on geoscience and remote sensing, 44, 1093–1101, 2006.

Liu, D., Wang, Z., Liu, Z., Winker, D., and Trepte, C.: A height resolved global view of dust aerosols from the first year CALIPSO lidar measurements, Journal of Geophysical Research: Atmospheres, 113, 2008.

Liu, D., Wang, Y., Wang, Z., and Zhou, J.: The three-dimensional structure of transatlantic African dust transport: a new perspective from CALIPSO LIDAR measurements, Advances in Meteorology, 2012, 2012.

Liu, Z., Omar, A., Hu, Y., Vaughan, M., Winker, D., Poole, L., and Kovacs, T.: CALIOP algorithm theoretical basis document. Part 3: Scene classification algorithms, NASA-CNES document PC-SCI-203, 2005.

Mahowald, N. M., Engelstaedter, S., Luo, C., Sealy, A., Artaxo, P., Benitez-Nelson, C., Bonnet, S., Chen, Y., Chuang, P. Y., Cohen, D. D., et al.: Atmospheric Iron Deposition: Global Distribution, Variability, and Human Perturbations*, Annual Review of Marine Science, 1, 245–278, 2009.

Malavelle, F.: Effets direct et semi-direct des aérosols en Afrique de l'ouest pendant la saison sèche, Ph.D. thesis, Université Paul Sabatier-Toulouse III, 2011.

Marticorena, B., Chatenet, B., Rajot, J.-L., Traoré, S., Coulibaly, M., Diallo, A., Koné, I., Maman, A., NDiaye, T., and Zakou, A.: Temporal variability of mineral dust concentrations over West Africa: analyses of a pluriannual monitoring from the AMMA Sahelian Dust Transect, Atmospheric Chemistry and Physics, 10, 8899–8915, 2010.

Martin, J. H.: Iron as a limiting factor in oceanic productivity, in: Primary productivity and biogeochemical cycles in the sea, pp. 123–137, Springer, 1992.

Martiny, N. and Chiapello, I.: Assessments for the impact of mineral dust on the meningitis incidence in West Africa, Atmospheric Environment, 70, 245–253, 2013.

Mielonen, T., Arola, A., Komppula, M., Kukkonen, J., Koskinen, J., de Leeuw, G., and Lehtinen, K.: Comparison of CALIOP level 2 aerosol subtypes to aerosol types derived from AERONET inversion data, Geophysical Research Letters, 36, 2009.

Mills, M. M., Ridame, C., Davey, M., La Roche, J., and Geider, R. J.: Iron and phosphorus co-limit nitrogen fixation in the eastern tropical North Atlantic, Nature, 429, 292–294, 2004.

Mokhtari, M.: Amélioration de la prise en compte des aérosols terrigènes dans les modèles atmosphériques à moyenne échelle, Ph.D. thesis, Université de Toulouse, Université Toulouse III-Paul Sabatier, 2012.

Mortier, A., Goloub, P., Derimian, Y., Tanré, D., Podvin, T., Blarel, L., Deroo, C., Marticorena, B., Diallo, A., and Ndiaye, T.: Climatology of aerosol properties and clear-sky shortwave radiative effects using Lidar and Sun photometer observations in the Dakar site, Journal of Geophysical Research: Atmospheres, 2016.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-683, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 6 December 2016

Moulin, C.: Transport atmosphérique des poussières africaines sur la Méditerranée et l'Atlantique: climatologie satellitale à partir des images Météosat VIS(1983-1994) et relations avec le climat, Ph.D. thesis, 1997.

Omar, A. H., Winker, D. M., Vaughan, M. A., Hu, Y., Trepte, C. R., Ferrare, R. A., Lee, K.-P., Hostetler, C. A., Kittaka, C., Rogers, R. R., et al.: The CALIPSO automated aerosol classification and lidar ratio selection algorithm, Journal of Atmospheric and Oceanic Technology, 26, 1994–2014, 2009.

Ozer, P.: Les lithométéores en région sahélienne: un indicateur climatique de la désertification, Ph.D. thesis, Université de Liège Faculté des sciences Liège Belgique, Liège, Belgique, 2000.

Petzold, A., Veira, A., Mund, S., Esselborn, M., Kiemle, C., Weinzierl, B., Hamburger, T., Ehret, G., Lieke, K., and Kandler, K.: Mixing of mineral dust with urban pollution aerosol over Dakar (Senegal): impact on dust physico-chemical and radiative properties, Tellus B, 63, 619–634, 2011.

Prospero, J., Glaccum, R., and Nees, R.: Atmospheric transport of soil dust from Africa to South America, Nature, 289, 570–572, 1981.

Prospero, J. M., Blades, E., Mathison, G., and Naidu, R.: Interhemispheric transport of viable fungi and bacteria from Africa to the Caribbean with soil dust, Aerobiologia, 21, 1–19, 2005.

Rajot, J.-L.: Wind blown sediment mass budget of Sahelian village land units in Niger, Bulletin de la Société Géologique de France, 172, 523–531, 2001.

Ramanathan, V., Crutzen, P., Kiehl, J., and Rosenfeld, D.: Aerosols, climate, and the hydrological cycle, science, 294, 2119–2124, 2001.

Reid, J. S., Westphal, D. L., Livingston, J. M., Savoie, D. L., Maring, H. B., Jonsson, H. H., Eleuterio, D. P., Kinney, J. E., and Reid, E. A.: Dust vertical distribution in the Caribbean during the Puerto Rico Dust Experiment, Geophysical research letters, 29, 2002.

Ridley, D., Heald, C., and Ford, B.: North African dust export and deposition: A satellite and model perspective, Journal of Geophysical Research: Atmospheres, 117, 2012.

Ryder, C., Highwood, E., Lai, T., Sodemann, H., and Marsham, J.: Impact of atmospheric transport on the evolution of microphysical and optical properties of Saharan dust, Geophysical Research Letters, 40, 2433–2438, 2013.

Sayer, A., Hsu, N., Bettenhausen, C., Ahmad, Z., Holben, B., Smirnov, A., Thomas, G., and Zhang, J.: SeaWiFS Ocean Aerosol Retrieval (SOAR): Algorithm, validation, and comparison with other data sets, Journal of Geophysical Research: Atmospheres, 117, 2012.

Schepanski, K., Tegen, I., and Macke, A.: Saharan dust transport and deposition towards the tropical northern Atlantic, Atmos. Chem. Phys, 9, 1173–1189, 2009a.

Schepanski, K., Tegen, I., Todd, M., Heinold, B., Bönisch, G., Laurent, B., and Macke, A.: Meteorological processes forcing Saharan dust emission inferred from MSG-SEVIRI observations of subdaily dust source activation and numerical models, Journal of Geophysical Research: Atmospheres, 114, 2009b.

Slutsker, I. and Kinne, S.: Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols, J Geophys Res, 104, 00 093–5, 1999.

Sokolik, I. N. and Toon, O. B.: Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths, Journal of Geophysical Research, 104, 9423–9444, 1999.

Solomon, S.: Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, vol. 4, Cambridge University Press, 2007.

Stith, J., Ramanathan, V., Cooper, W., Roberts, G., DeMott, P., Carmichael, G., Hatch, C., Adhikary, B., Twohy, C., Rogers, D., et al.: An overview of aircraft observations from the Pacific Dust Experiment campaign, Journal of Geophysical Research: Atmospheres, 114, 2009.

Tanaka, T. Y., Kurosaki, Y., Chiba, M., Matsumura, T., Nagai, T., Yamazaki, A., Uchiyama, A., Tsunematsu, N., and Kai, K.: Possible transcontinental dust transport from North Africa and the Middle East to East Asia, Atmospheric Environment, 39, 3901–3909, 2005.

Tegen, I., Schepanski, K., and Heinold, B.: Comparing two years of Saharan dust source activation obtained by regional modelling and satellite observations, Atmospheric Chemistry and Physics, 13, 2381–2390, 2013.

Teller, A. and Levin, Z.: The effects of aerosols on precipitation and dimensions of subtropical clouds: a sensitivity study using a numerical cloud model, Atmospheric Chemistry and Physics, 6, 67–80, 2006.

Thomson, M. C., Molesworth, A. M., Djingarey, M. H., Yameogo, K., Belanger, F., and Cuevas, L. E.: Potential of environmental models to predict meningitis epidemics in Africa, Tropical Medicine & International Health, 11, 781–788, 2006.

Tsamalis, C., Chédin, A., Pelon, J., and Capelle, V.: The seasonal vertical distribution of the Saharan Air Layer and its modulation by the wind, Atmospheric Chemistry and Physics, 13, 11 235–11 257, 2013.

Tulet, P., Mallet, M., Pont, V., Pelon, J., and Boone, A.: The 7–13 March 2006 dust storm over West Africa: Generation, transport, and vertical stratification, Journal of Geophysical Research: Atmospheres, 113, 2008.

Vuolo, M. R., Chepfer, H., Menut, L., and Cesana, G.: Comparison of mineral dust layers vertical structures modeled with CHIMERE-DUST and observed with the CALIOP lidar, Journal of Geophysical Research: Atmospheres, 114, 2009.

Wagener, T.: Le fer à l'interface océan-atmosphère: Flux et processus de dissolution dans l'eau de mer., Ph.D. thesis, Université de la Méditerranée-Aix-Marseille II, 2008.

Wang, M., Bailey, S., Pietras, C., McClain, C., and Riley, T.: SeaWiFS aerosol optical thickness matchup analyses, The Sea-WiFS Postlaunch Technical Report Series, 10, 39–44, 2000.

Winker, D.: Accounting for multiple scattering in retrievals from space lidar, in: Proc. of SPIE Vol, vol. 5059, p. 129, 2003.

Winker, D. M., Hostetler, C., Vaughan, M., and Omar, A.: CALIOP Algorithm Theoretical Basis Document, Part 1: CALIOP Instrument, and Algorithms Overview, Release, 2, 29, 2006.

Winker, D. M., Hunt, W. H., and McGill, M. J.: Initial performance assessment of CALIOP, Geophysical Research Letters, 34, 2007.

Wu, M.-L. C., Reale, O., Schubert, S. D., Suarez, M. J., Koster, R. D., and Pegion, P. J.: African easterly jet: structure and maintenance, Journal of Climate, 22, 4459–4480, 2009.

Yang, W., Marshak, A., Várnai, T., Kalashnikova, O. V., and Kostinski, A. B.: CALIPSO observations of transatlantic dust: vertical stratification and effect of clouds, Atmospheric Chemistry and Physics, 12, 11 339–11 354, 2012.

Yu, H., Chin, M., Winker, D. M., Omar, A. H., Liu, Z., Kittaka, C., and Diehl, T.: Global view of aerosol vertical distributions from CALIPSO lidar measurements and GOCART simulations: Regional and seasonal variations, Journal of Geophysical Research: Atmospheres, 115, 2010.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-683, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 6 December 2016

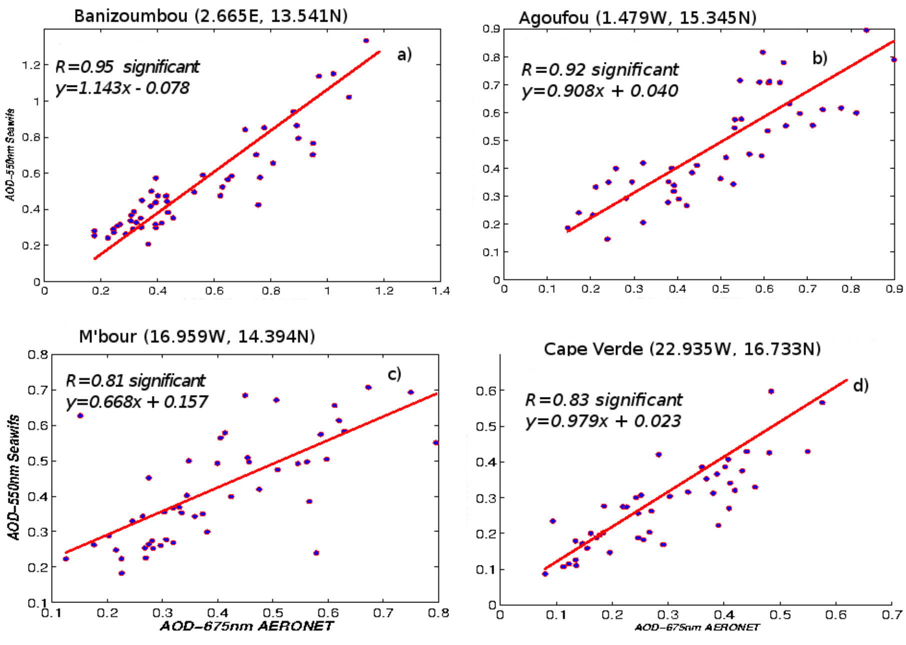

Figure 1. Comparison of monthly mean aerosol optical depth (AOD) between SeaWiFS (550 nm) and ground measurements from AERONET (675 nm) from January 2005 to December 2010. This comparison is done at the following stations : a) Banizoumbou (53 points), b) Agoufou (47 points), c) M'bour (50 points) and d) Cape verde (47 points). The red solid line represents the regression between both dataset

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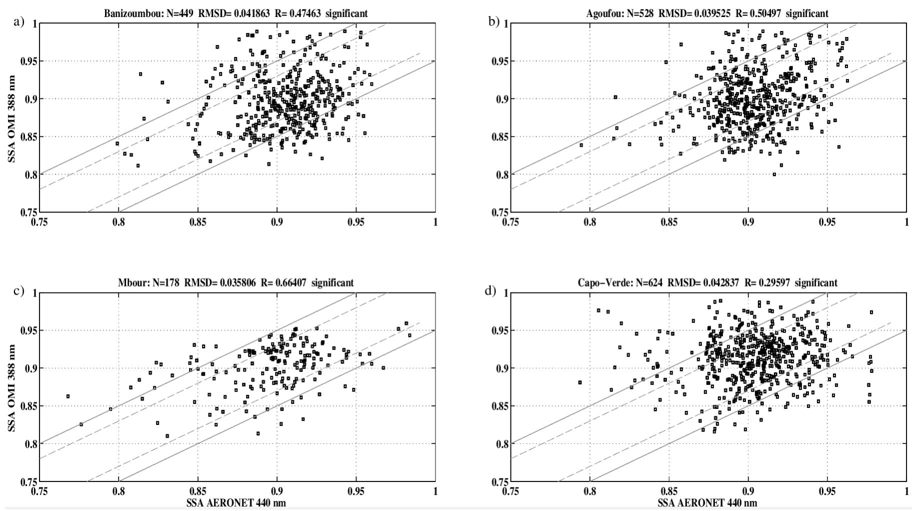

Figure 2. OMAERUV SSA at 440 nm wavelength as a function of AERONET SSA at 440 nm at a) Banizoumbou (lon=2.665,lat=13.541; a total of 449 retrievals are plotted, yielding a root mean square difference (RMSD) of 0.04); b) Agoufou (lon=-1.479, lat=15.345; 528 retrievals with a RMSD of 0.04); c) Mbour (lon=-16.959, lat=14.394; 178 retrievals with a RMSD of 0.04) and d) Capo Verde (lon=-22.935, lat=16.733; 624 retrievals with a RMSD of 0.04). The solid lines indicate the domain where the two retrievals agree with each other within 0.03 and the dashed lines indicate agreement within 0.05. The AERONET's data used here are Level 2, quality assured for Banizoumbou, Agoufou and M'bour sites. For Cape Verde Level 1.5, is used to get a significant number of retrievals.

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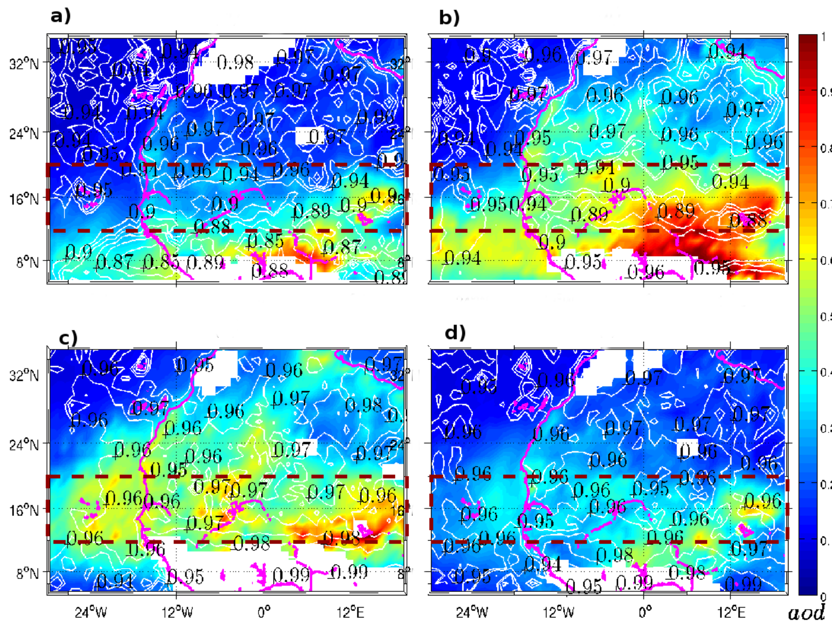

Figure 3. Seasonal distribution of aerosol optical depth (average between 2005 and 2010) at 550 nm wavelength (colours) from SeaWiFS for a) winter (DJF); b) spring (MAM); c) summer (JJA) and d) fall (SON). Single scattering albedo (SSA) from OMI is superimposed with white contour lines. The box delimited by brown dashed lines represent the band of latitude averaged in Fig. 4 (12°-21°N) where dust aerosols have the strongest contribution to AOD.

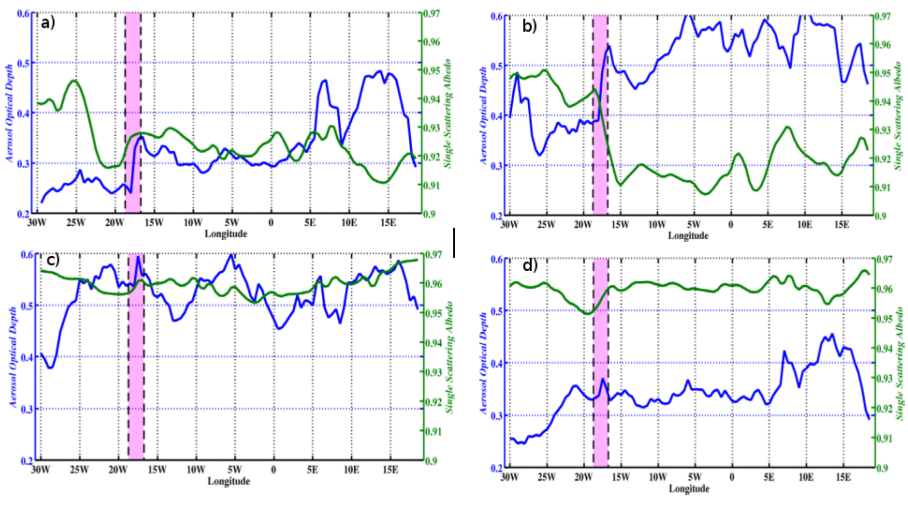

Figure 4. Seasonal SeaWiFS AOD at 550 nm (bleu), Aura/OMI SSA (green) zonally averaged between 12° and 21°N and from 2005 to 2010: a) DJF; b) MAM; c) JJA; and d) SON. The black dashed lines indicate the continent-ocean transition for the latitude range 12°-21°N.

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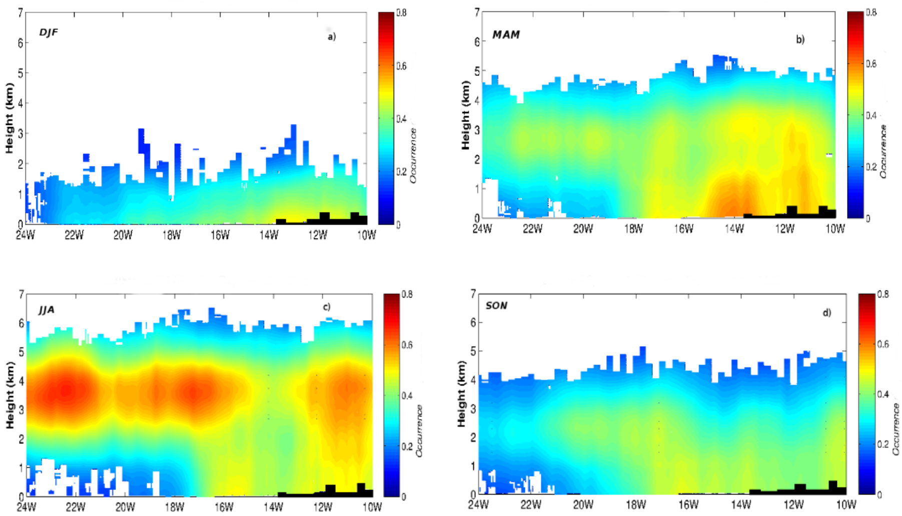

Figure 5. CALIOP daytime seasonal vertical distribution of the frequency of mineral dust aerosol occurrence zonally averaged between 12° and 21°N over the period 2007-2013: a) winter; b) spring; c) summer; and d) fall.

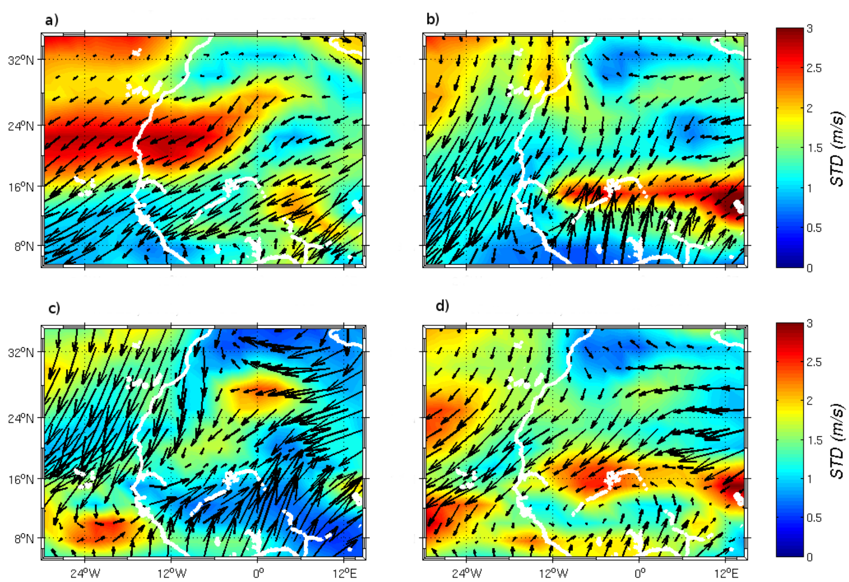

Figure 6. Seasonal mean zonal wind field at 925 hPa over West Africa from NCEP Reanalysis between 2000 and 2012: a) winter (DJF); b) spring (MAM); c) summer (JJA); and d) fall (SON). The vectors show wind direction while colors indicate the standard deviation of wind velocity (m.s^{-}1).

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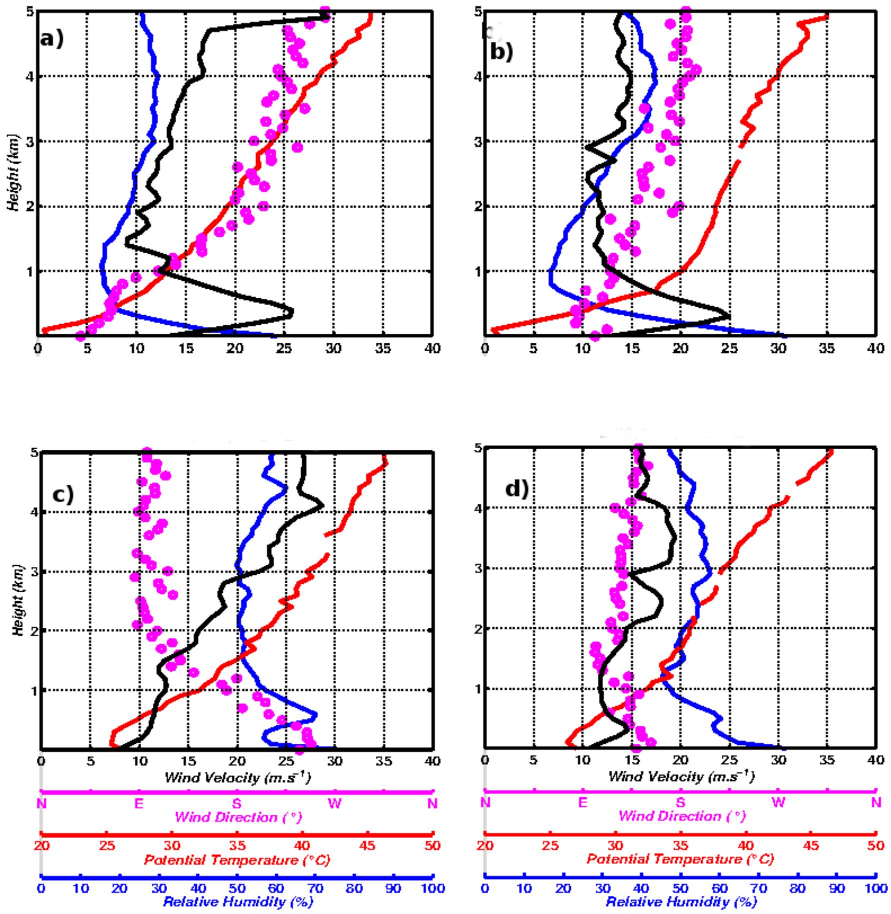

Figure 7. Mean seasonal vertical profiles of wind velocity (black line), wind direction (pink dots), potential temperature (red line) and relative humidity (blue line) at Dakar weather station (14.73°N, 17.51°W) for a) winter; b) spring; c) summer; and d) fall. Observations correspond to weather balloon launched daily at 12UTC for years 2012 to 2014.