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Contribution of Satellite Observations in the Optical and Microphysical Characterization of Aerosols in Burkina Faso, West Africa

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Abstract

In this work, we proceed to an optical and microphysical analysis of the observations reversed by the MODIS, SeaWiFS, MISR and OMI sensors with the aim of proposing the best-adapted airborne sensor for better monitoring of aerosols in Burkina Faso. To this end, a comparison of AOD between satellite observations and in situ measurements at the Ouagadougou site reveals an underestimation of AERONET AOD except for OMI which overestimates them. Also, an inter-comparison done based on the linear regression line representation shows the correlation between the aerosol models incorporated in the airborne sensor inversion algorithms and the aerosol population probed. This can be seen through the correlation coefficients R which are 0.84, 0.64, 0.55 and 0.054 for MODIS, SeaWiFS, MISR and OMI respectively. Furthermore, an optical analysis of aerosols in Burkina Faso by the MODIS sensor from 2001 to 2016 indicates a large spatial and temporal variability of particles strongly dominated by desert dust. This is corroborated by the annual and seasonal cycles of the AOD at 550 nm and the Angström coefficient measured in the spectral range between 412 nm and 470 nm. A zoom on a few sites chosen according to the three climatic zones confirms the majority presence of mineral aerosols in Burkina Faso, whose maxima are observed in spring and summer.

Keywords

AERONET, Airborne Sensors, Aerosol, Optical and Microphysical Properties

1. Introduction

Burkina Faso is a sub-Saharan African country in the heart of West Africa. Due to its geographical location, the country shares the same border with six states, including Mali and Niger in its northern and northeastern parts, which are largely affected by the Sahara desert [1]. This position makes Burkina Faso a country highly exposed to Saharan dust despite anthropogenic emissions from transport, household and agricultural activities and the density of some of its cities. In West Africa, aerosols are strongly dominated by mineral dust because this area is close to the Sahara which is recognized as the largest desert in the world and the first source of dust emission with a surface area of about 8.5 million km^2 [2] [3] [4] [5]. Mineral aerosols in Africa have their main sources of production located in the north of the continent between 18˚N and 25˚N of latitude and then concerns precisely the Sahara desert and the Sahel zone [6]. Indeed, the Saharan zone is responsible for more than 700 Mt/year on average of dust emitted, 88% of which is expelled towards the Atlantic Ocean [7] [8]. However, these annual emissions can vary from 130 Mt to 1600 Mt [9]. Thus, West Africa is marked by a permanent presence of dust throughout the year with a seasonal cycle characterized by peaks that are observed between October and March [1] [10] [11] [12]. During the summer (June-July-August), which is the winter period, the strong dust pulses are due to local emissions caused by convective systems responsible for the rains in the Sahel and the wet deposition of particles during this period [5]. Also, the African continent is strongly influenced by combustion products attributed to the numerous bushfires composed of fires and related to land use. These combustions are observed throughout the year with a strong spatial and temporal variability that indicates an activation of combustions in Central and Southern Africa from May with an intensification in summer while the fires in West Africa are intense in the winter period [5] [13] [14]. In this regard, the African continent participates in 40% of the production of combustion particles and is one of the most important areas in the world where different types of aerosols coexist in the atmosphere [3] [15]. In addition, there are anthropogenic emissions from the use of fossil fuels such as biofuels and biomass combustion. In addition, several studies based on in situ measurements of the AERONET network, satellite observations and climate models allow us to locate aerosols in West Africa during spring and summer [1] [2] [10]. Aerosols have multiple effects on the climate and the environment because of their optical and microphysical properties, which vary according to their emission sources, chemical nature and mode of formation. This justifies the complexity of their study, making them still very poorly known particles. To better understand the role of these particles in the climate system, several international efforts have been devoted to their study and the understanding of their interactions with the other components of the global climate system. These studies, which include measurement campaigns and monitoring networks, make it possible to characterize the physical and chemical properties of these particles and to assess their impact on the climate. Despite all these studies, the climatic role of aerosols is still known with large uncertainties [16]. In addition, there is a lack of ground measurement instruments covering all points of the globe, particularly in West Africa and more specifically in Burkina Faso. These major difficulties associated with deficiencies in global and regional climate models reflect a real problem in understanding the role of aerosols and climate prediction in West Africa. It is in this context that the objective of this work is to show the contribution of satellite observations in the optical and microphysical characterization of aerosols in Burkina Faso.

2. Data and Methodology

2.1. Instrumentation

2.1.1. AErosol RObotic NETwork (AERONET)

AERONET (AErosol RObotic NETwork) is a global network of CIMEL photometers installed in various geographical regions corresponding to multiple ecosystems: arid zones, tropical forests, temperate regions, oceanic and coastal zones, or mountains. The AERONET network was initially set up by NASA (National Aeronautics and Space Administration) in collaboration with the Laboratory of Atmospheric Optics of the National Center for Scientific Research. It allows archiving and public access to data on the optical, microphysical and radiative properties of aerosols in near-real time on a continuous and long-term basis [17]. These are the inversion results of various algorithms developed and improved over time by Dubovik *et al.* [18] [19] [20] [21]. AERONET aims to characterize aerosol properties by providing a permanently and continuously available database for aerosol climatology and validation of satellite observations [22].

2.1.2. MODerate Resolution Imaging Spectroradiometer (MODIS)

MODIS is a sensor transported by the TERRA satellites since December 1999 and Aqua in April 2002. TERRA sweeps the Earth's surface from the North to the South around the equator in the morning around 10:30 am while Aqua occurs in the evening, around 10:30 am in an orbit oriented South-North of the Equator [23]. MODIS has 36 spectral bands that enable it to provide measurements on the atmosphere, the Earth and the ocean, 7 of which are used to study aerosols (466, 553, 644, 855, 1243, 1632 and 2119 nm). In addition, it uses different algorithms to invert aerosol properties on Earth [24] and on seas [25] where measurements are made with a spatial resolution ranging from 1 to 250 km and temporal from 1 to 2 days. For our study, we use MODIS-Terra Deep-Blue inversions at 550 nm available on NASA's Giovanni site (https://giovanni.gsfc.nasa.gov/giovanni/). Indeed, the Deep Blue algorithm takes into account cloud masks, the aerosol model and the reflection of shiny surfaces [23] [26]. This makes it possible to eliminate contaminations due to the reflection of the shiny surfaces and to improve the qualified observations in level 2 [27].

2.1.3. Sea-viewing Wide Fiel-of-View Sensor (SeaWiFS)

SeaWiFS is a sensor of the NASA observation system developed to study ocean color [28]. However, it makes measurements on the optical properties of aerosols, in particular the optical thickness and the Angström coefficient. In orbit since September 1997, SeaWiFS continues to perform measurements with very good sensor performance in different wavelengths (412, 443, 490, 510, 555, 670 and 865 nm) where the Angstrom coefficient is calculated in the spectral range 510 to 865 nm. In addition, aerosol products supplied by SeaWiFS are mainly applicable and valid for oceanic regions [29] [30] and are available on NASA's website (https://giovanni.gsfc.nasa.gov/giovanni/). All these details about the SeaWiFS sensor are clearly provided by Nébon *et al.* [12].

2.1.4. Ozone Monitoring Instrument (OMI)

OMI is a passive sensor placed in orbit onboard NASA's EOS-Aura satellite in July 2004 by the Netherlands Agency for Aerospace Programs in collaboration with the Finland Meteorological Institute. It provides aerosol information on a global scale and scans certain regions once or twice a day [31] [32]. The sensor performs two types of inversions, one in the ultraviolet between 354 and 388 nm and the other which is multispectral gives measurements at 19 wavelengths between 330 and 500 nm covering the UV and visible range [31]. However, measurements in the UV take into account the reflection, which is not the case in the visible where the surfaces appear very reflective and constitute a difficulty to calculate the data [33]. In fact, OMI was originally intended for measurements of gases such as ozone (O_3), nitrogen dioxide (NO_2) and sulfur (SO_2). However, it also provides measurements of atmospheric particles [28] [34].

2.1.5. Multi-angle Imaging Spectroradiometer (MISR)

MISR was launched in 1999 on the TERRA satellite in polar orbit at an altitude of 705 km [12]. It has a temporal resolution of 16 days and nominal spatial resolutions of 250 m, 275 m and 1 km with radiances measured at 1.1 km resolution for the inversion of aerosol properties qualified as level 2 with a pixel size of 17.6 km × 17.6 km. MISR provides continuous daily data over most regions of the world with a frequency that depends on altitude [34]. It can also provide aerosol data in very bright desert areas due to its ability to perform multi-spectral observations along forward or backward directions. In agreement with Kahn *et al.* [35], about 70% - 75% of MISR-reversed AODs yield values proportional to 5% or 20% of AERONET AODs and about 50% - 55% of MISR AODs correspond to 3% or 10% of AERONET measurements. On the other hand, errors can be high especially for sites heavily influenced by desert dust or mixed aerosols composed of combustion products and mineral particles [31].

2.2. Methodology for Analysis and Validation of Observations

The validation concerns the data from the MODIS-TERRA and SeaWiFS sensors measured at 550 nm, followed by data from the MISR and OMI sensors measured at 555 nm and 483.5 nm, respectively, at the Ouagadougou site. This is in order to determine the satellite model that best fits the Burkina Faso area for adequate monitoring of aerosols in this locality of the sahel characterized by an absence of ground measurement instruments such as photometers and lidars. Indeed, given the limitation of AERONET data in time at the Ouagadougou site, the measurement period concerned by the validation is between 1999 and 2006 for SeaWiFS, 2005 and 2006 for OMI, 2001 and 2006 for MODIS and MISR sensors. In addition, an interpolation was done in the spectral range of 440 to 870 nm in order to generate in situ measurements from the AERONET network $(\text{AOD}_{\text{AERONET}})$ at 550 nm corresponding to the measurements from the MODIS and SeaWiFS sensors, then at 555 nm and 483.5 nm in accordance with the data from the MISR and OMI sensors. This interpolation is performed on the basis of the photometric measurements from the AERONET network at 675 nm according to Equation (1) [36] [37] [38] [39].

$$\text{AOD}_{\text{a}} = \text{AOD}_{\text{b}} \left(\frac{a}{b}\right)^{-\alpha} \quad (1)$$

In this equation a and b denote wavelengths, the angstrom coefficient (α), AOD_{a} and AOD_{b} the optical thicknesses at wavelengths a and b respectively. Subsequently, a linear regression analysis is done based on Equation (2) where m is the slope of the line and C is the point of intersection between the line and the ordinate axis [34].

$$\text{AOD}_{\text{satellite}} = m \times \text{AOD}_{\text{AERONET}} + C \quad (2)$$

The quantities (m, C) and the correlation coefficient R from the intercomparison serve as an indication of the local and spatial characteristics of the AOD over time [40]. The slope m of the linear regression equation reveals how well the assumed aerosol model represents that of the observed area while the constant C relates the error caused by surface reflection [41] [42]. Thus, the regression equation gives information about the factor that affects the correlation [43] and in the case of a good correlation C must be zero and m must tend towards unity [41].

2.3. Site and Study Area Presentation

Burkina Faso is a Sahelian country located at the heart of West Africa between latitudes 9˚20 and 15˚ North and longitudes 5˚30 West and 2˚30 East. It has three climatic zones: the Sahelian zone, which covers the entire northern part, a larger Sudano-Sahelian zone extending from west to east, and a wetter Sudanian zone in the south [44]. To better situate aerosol seasonality in Burkina Faso, we zoomed in on a number of sites across the country and according to climatic zones. These include Dori (14.035˚N, −0.0345˚E) in the Sahel, Ouahigouya (13.58˚N, −2.42˚E) in the north, Ouagadougou (12.20˚N, −1.40˚E) in the center, Fada N'Gourma (12.06˚N, 0.358˚E) in the east, Pô (11.169˚N, −1.145˚E) in the southeast and Bobo-Dioulasso (11.177˚N, −4.297˚E) in the southwest.

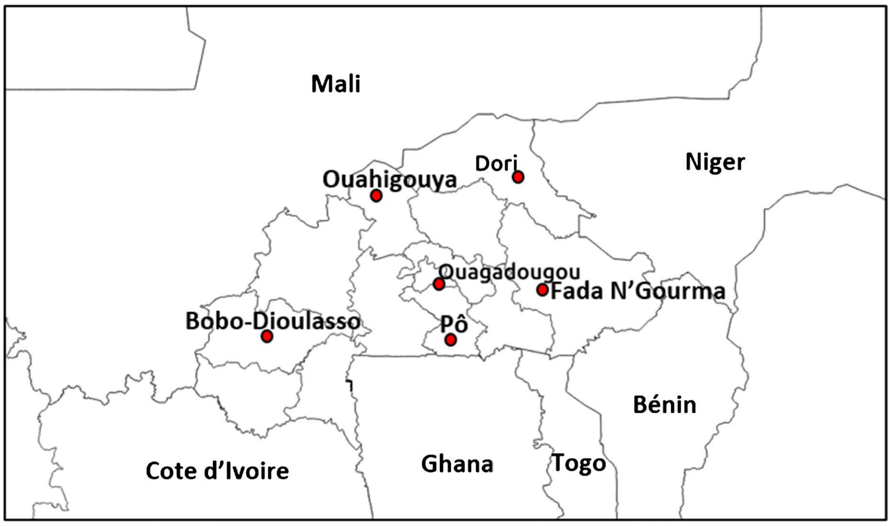

Figure 1. Study sites in Burkina Faso

3. Results and Discussion

3.1. Comparison of Monthly Averages of Optical Thickness

In this section, the focus is on a time series analysis of monthly AOD averages from the AERONET network and MODIS, SeaWiFS, MISR and OMI sensors. Figure 2 shows that the monthly averages of the AOD of satellite observations are between 0.12 - 1.57, 0.12 - 0.93, 0.13 - 1.37 and 0.35 - 1.22 respectively obtained by MODIS (Figure 2(a)), MISR (Figure 2(c)), SeaWiFS (Figure 2(b)) and OMI (Figure 2(d)) against AERONET measurements which are between 0.16 - 2.29 for the periods of 1999 to 2006, 2001 to 2006 and between 0.27 - 1.11 for the measurements of 2005 to 2006 at the site of Ouagadougou. In agreement with Bibi *et al.* [34], we can say that all these results show an underestimation of AERONET measurements by MODIS, MISR and SeaWiFS sensors while OMI overestimates them. Moreover, the maximum value of AOD measured by MODIS (1.57), SeaWiFS (1.37) and MISR (0.93) mentioned in brackets is observed in March 2004 by that measured by AERONET (2.29) which is also obtained in the same period. However, the maximum monthly average AOD calculated by the OMI sensor (1.22) is observed in August 2006 while that of the AERONET network (1.11) corresponds to March 2005. Thus, all the measurement systems indicate the peak of particulate suspensions in the dry season in March, except for OMI which places it in August, the winter period in Burkina Faso.

3.2. Intercomparison of Satellite and AERONET Measurements

The linear regression analysis shows well the correlation between the AOD measured by MODIS, SeaWiFS, MISR, OMI and AERONET sensors at 550 nm, 555 nm and 483.5 nm respectively illustrated in Figure 3. This representation indicates a better correlation between MODIS and AERONET measurements with a linear regression coefficient R = 0.84 (Figure 3(a)). Unlike the other sensors

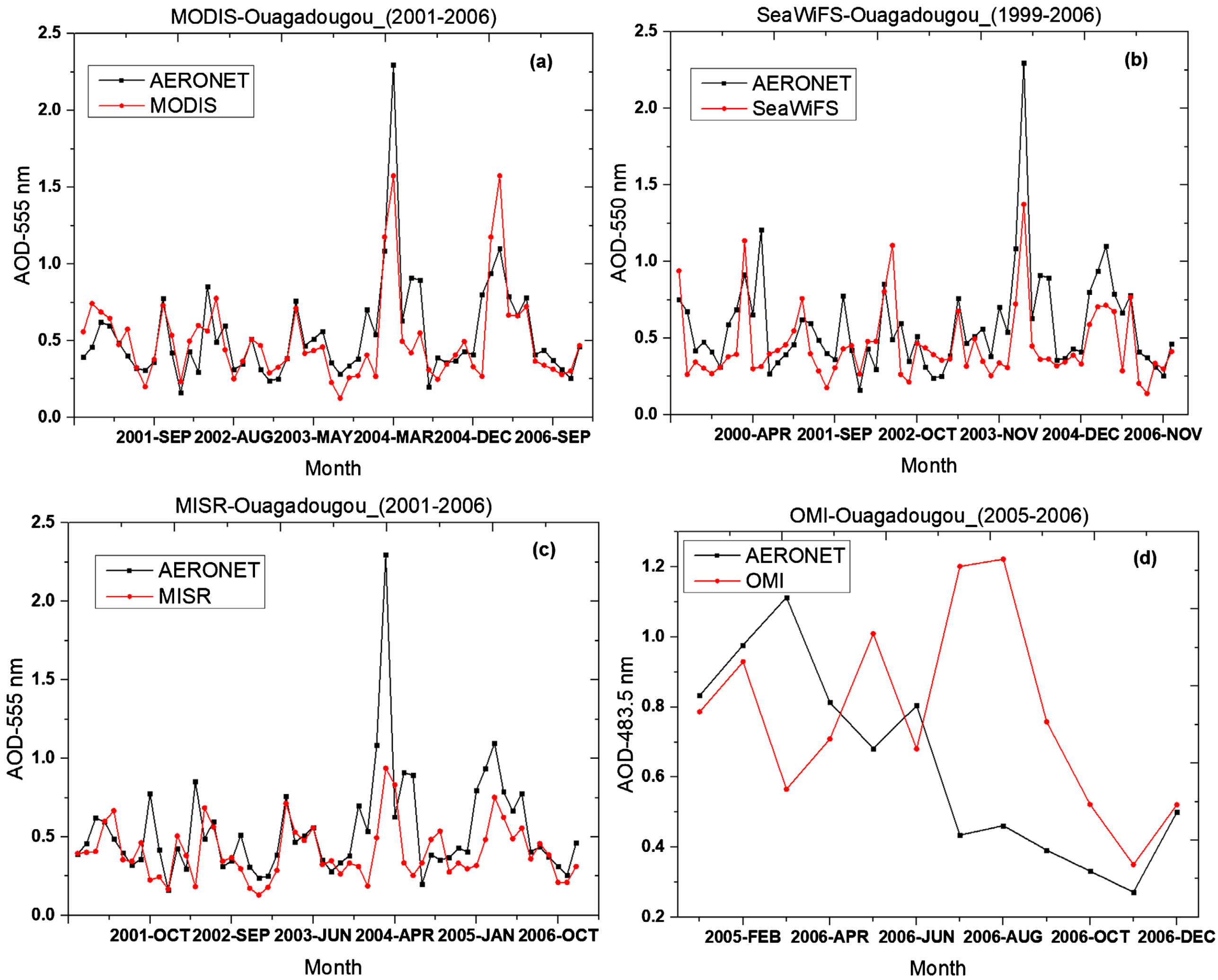

Figure 2. Time series of monthly averages of AOD measured by airborne and in situ sensors of the AERONET network at the Ouagadougou site

SeaWiFS (R = 0.64), MISR (R = 0.55) and OMI (R = 0.054), MODIS is the most representative satellite model for long-term aerosol characterization at the Ouagadougou site. This accuracy of the airborne sensors is also visible through the slopes of the regression lines which are 0.67, 0.48, 0.3 and 0.054 obtained between AERONET and MODIS (Figure 3(a)), SeaWiFS (Figure 3(b)), MISR (Figure 3(c)) and OMI (Figure 3(d)) respectively. However, the smallest point of intersection is given by the inter-comparison with MODIS and is 0.14. This shows the better accuracy of this sensor on board the TERRA satellite compared to the others. However, a very large inconsistency is observed in the measurements of the OMI sensor in addition to a correlation coefficient (R = 0.054) and a slope (m = 0.054) that are almost zero, a relatively large intersection constant (C = 0.74). Thus, the OMI model shows a very large discrepancy with the AERONET measurements justifying the overestimation of the measurements revealed by the time series of monthly AOD averages as well as the shift of the aerosol peak in summer precisely in August.

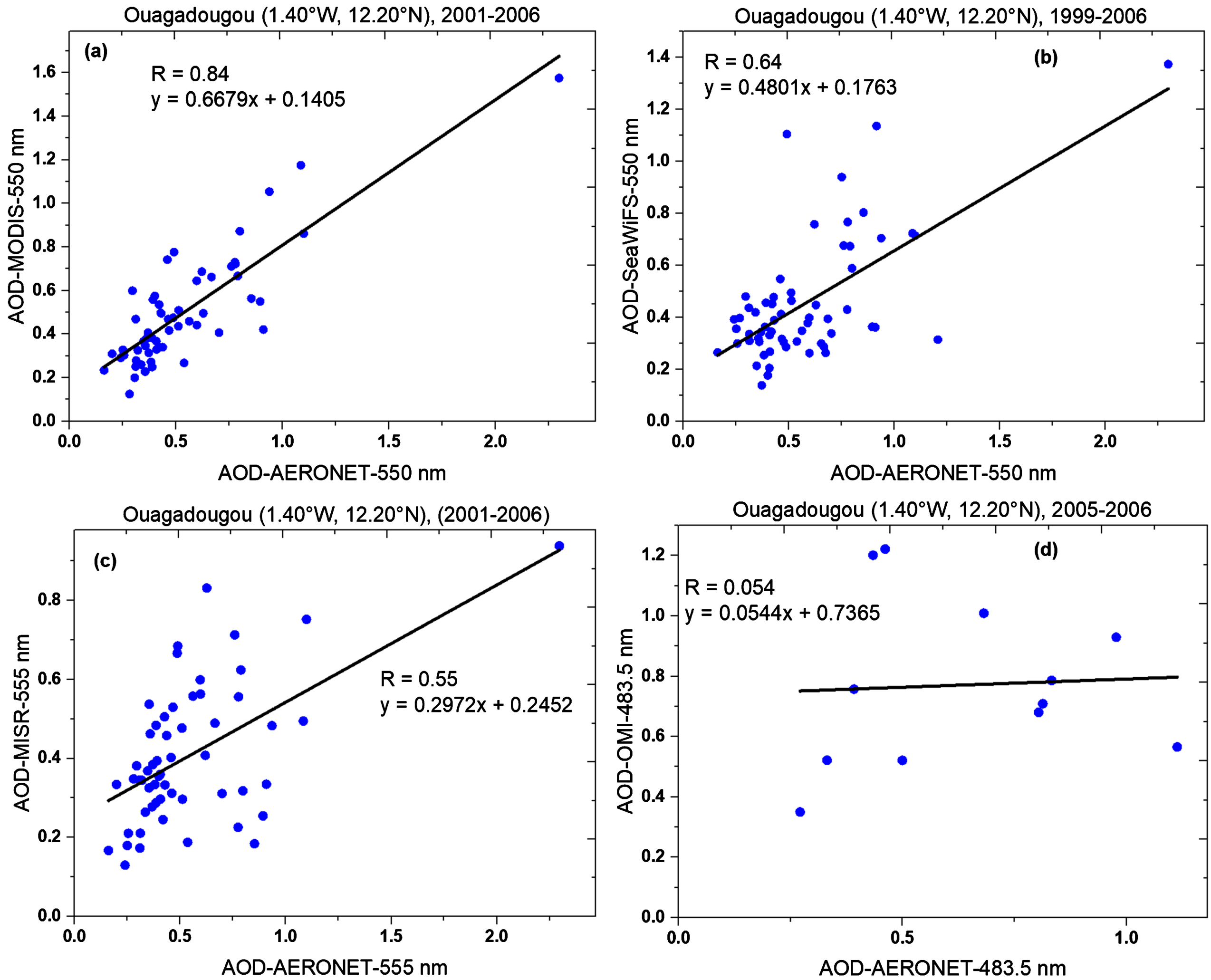

Figure 3. Illustration of the correlation by the regression lines.

3.3. Study of the Spatial Variability of Aerosols in Burkina Faso by MODIS

3.3.1. Annual Cycles of Aerosol Optical Thickness (AOD)

Burkina Faso is a Sahelian country close to the Sahara and is strongly influenced by dust emissions that vary in time and space. For a better understanding of the frequency of dust events in Burkina Faso, an interannual monthly climatology is shown in Figure 4 between 2001 and 2016. An analysis of this figure allows us to locate aerosols in Burkina Faso in March with a maximum in the eastern part and in June marked by a massive presence of aerosols on the northern side. All this illustrates the effect of aerosol emissions in the Sahara probably due to the proximity of this area containing the main sources of dust [12]. These are located in the northern part of the country, more precisely in the northwestern part of Mali, and on the eastern side towards Niger, including Bodélé in Chad, which is considered the largest source of dust emissions in the world [9]. In April and May, the effect of Saharan dust is still noticed in the northeast and this is also the case in July, August and September may be under the influence of

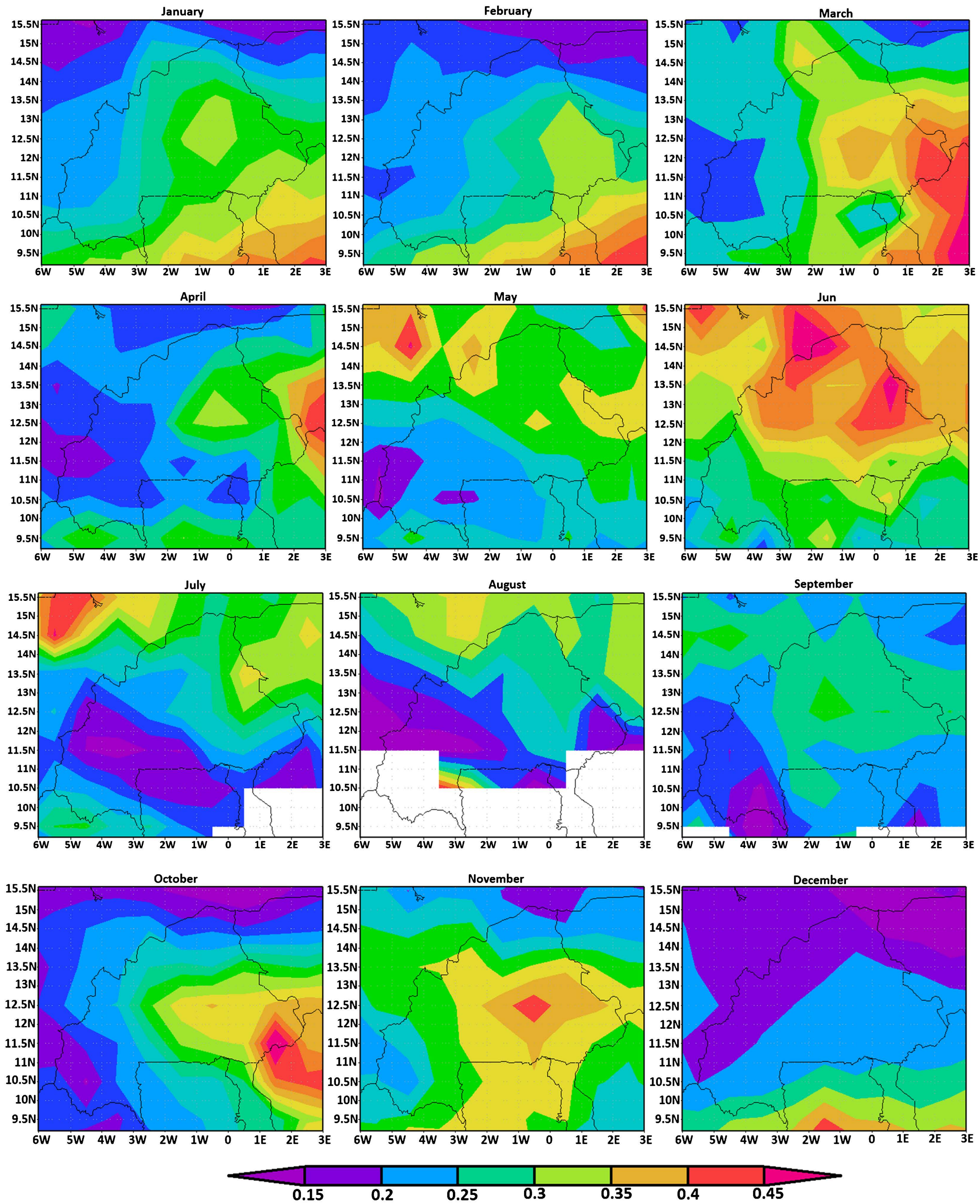

Figure 4. Interannual monthly averages of MODIS sensor optical thicknesses between 2001 and 2016 in Burkina Faso.

convective systems in this rainy season. The month of October is mainly marked by dust in the southeast while in November the maximums of AOD can be noticed between 11.5˚N and 14˚N which can be associated with the meridional wind from north to south because of the retreat of the monsoon responsible for the rains in summer (June-July-August) and with the easterly wind that can cause the aerosols in this period of autumn (September-October-November) characterized by a transition between the flow of the monsoon and harmattan. In addition, from October onwards combustion sources are active in West Africa [16] and this could contribute to the increase in particulate suspensions during the autumn. In January and February, the particles are rather on the southeast side as well as in December which may be due to biomass burning which is intense in the Gulf of Guinea in this winter period [13]. Indeed, during winter (December-January-February) the harmattan flow which is a north-east wind remains very intense in West Africa because of the position of the ITCZ (inter-tropical convergence zone) located around the equator below 10˚N. This could also be the source of a southwesterly wind carrying combustion particles from the Gulf of Guinea to the rest of the sub-region. These combustion products then mix with desert dust carried by easterly winds creating a mixed aerosol layer.

3.3.2. Interannual Spatial Distribution of Aerosol Size

The Angström coefficient is a very revealing parameter of the nature (origin and size) of aerosols and atmospheric disorder. Thus, coarse particles are associated with Angstrom coefficient values below 1 while fine pollution particles correspond to the highest values (Angstrom coefficient above 1). **Figure 5** shows the presence of coarse and fine particles in all periods but in varying proportions depending on the seasonality of the AOD illustrated previously in **Figure 4**. It shows that coarse particles associated with mineral aerosols are noticeable in spring and summer, especially in the northern part confirming the influence of dust sources in the Sahara. However, the southwest is more influenced by fine particles that may be related to combustion in the Gulf of Guinea and to dust from the north and northeast. The fall (SON) is shown to be under the influence of desert particles strongly present in the southeast in agreement with the AOD maxima represented by **Figure 3**. Indeed, most of the mineral aerosols observed in autumn are most often related to the transition period between the monsoon and harmattan flow characterized by the southward shift of the ITCZ [2] [45] [46]. In addition, there are sediments mobilized by water erosion and exposed to the mechanical action of the wind. The winter period (DJF) is marked by fine particles more present in the north, probably due to the north and northeast atmospheric circulation. Coarse particles appear to be more important in the southwest reflecting the effect of strong southwest winds tearing away freshly dewatered sediments and additionally promoting the northward spread of biomass combustion products.

3.3.3. Combined Analysis between AERONET and MODIS

Figure 6 presents the time series of monthly interannual averages of MODIS-Terra

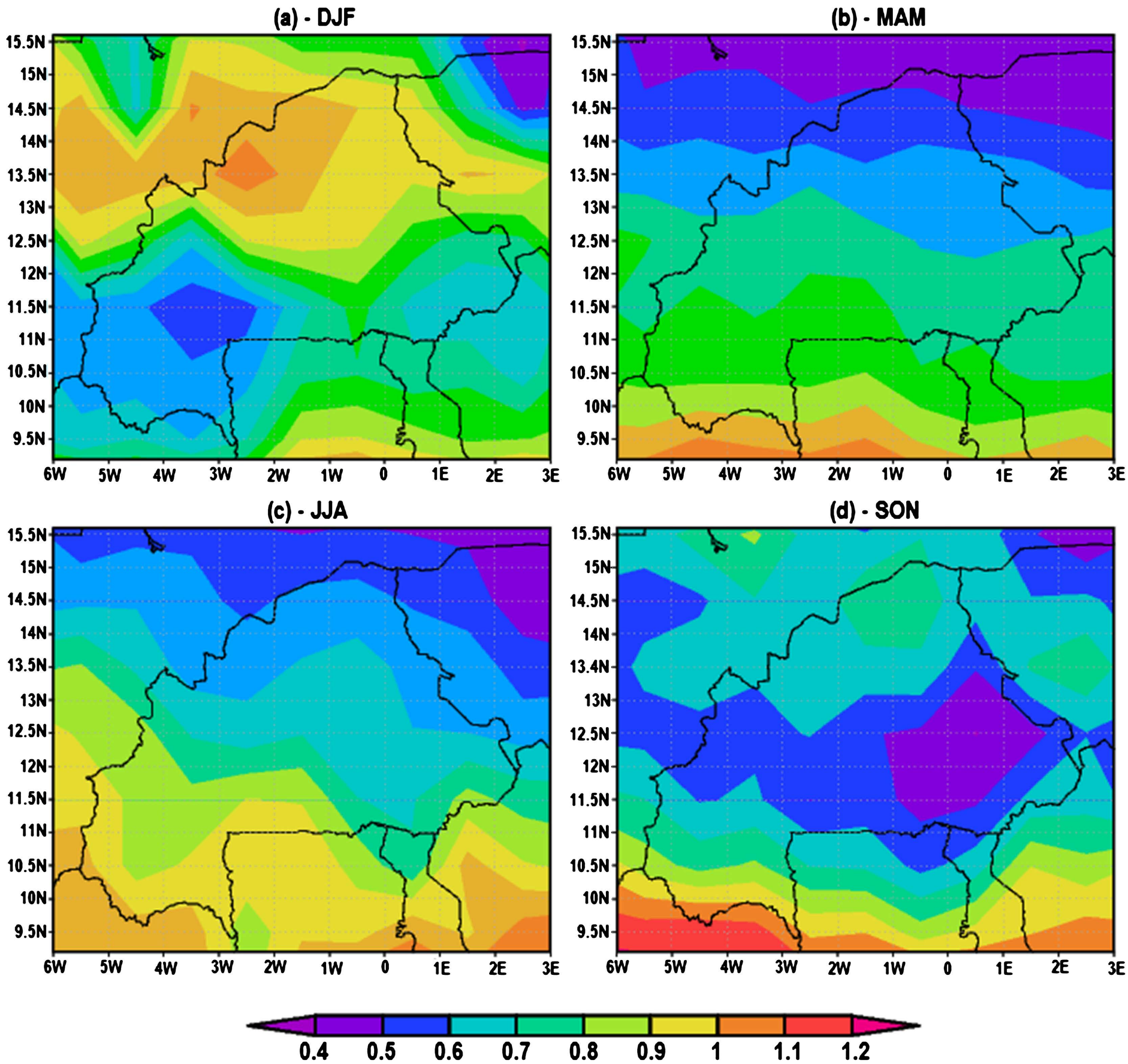

Figure 5. Seasonal cycle of the angstrom coefficient between 2001 and 2016 in Burkina Faso

inverted AOD between 2001 and 2016 over the entire Burkina Faso area and the Ouagadougou site. These time series are compared with those produced by AERONET measurements at the Ouagadougou site. Indeed, the ground measurements (blue curve) of the AERONET network indicate the aerosol maximum in spring clearly shown by the AOD peaks in March and May. At the same time, MODIS observations (black and red curves) are in good agreement with the AOD maxima in spring. However, in addition to spring, MODIS reproduces the summer peak of AOD in June. This evolution of atmospheric particles is corroborated by the seasonality of aerosols shown in Figure 5 and Figure 6. However, we recall that studies conducted by several authors on the vertical distribution of aerosols allow us to locate the aerosol layer in summer between 3

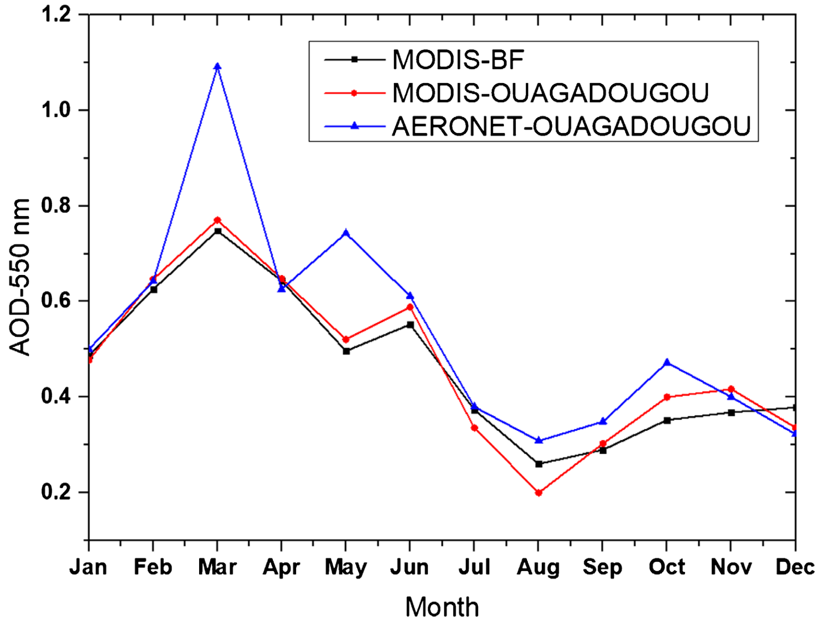

Figure 6. Representation of the annual cycle of aerosol optical thickness over Burkina Faso (black) and Ouagadougou by AERONET (blue) and MODIS (red) measurements.

and 6 km in West Africa [5] [28]. Thus, this presence of particles in the upper troposphere may well explain the observation of the AOD peak in summer by the MODIS sensor which has a much wider field of view compared to the photometer which may be limited by precipitation and cloudy passages. Thus, the particles observed in summer are mostly mineral dust from the distant transport of aerosols contained in the Saharan air layer and also due to convective systems. On the other hand, the AOD minima in August are probably due to particle removal by sedimentation following water uptake or by atmospheric leaching due to heavy rainfall. However, the aerosol maxima in autumn observed in October and November are probably related to the transition between the monsoon and harmattan flow which is very turbulent [5].

3.3.4. Optical Analysis of Aerosols at Sites Representative of Climatic Zones

Figure 7(a) shows the aerosol maxima in spring with peaks in March except for the Dori site where the AOD peak is displayed in April and in summer in June. This is consistent with the spatial and temporal variability of aerosols in Burkina Faso and West Africa in general. Thus, the maximum values of AOD found in the north at Dori (0.72) and Ouahigouya (0.71) are simply due to the effect of Saharan dust which is frequent in spring. This is also the case for Fada N'Gourma (0.88) in the east and Po (0.77) in the south, which in addition to the dust coming from eastern Niger because of the Bodélé depression in Chad are affected by combustion sources that are very active in the Gulf of Guinea from October to May [13] [16]. This influence of combustions can also be noticed in the southwest at the Bobo-Dioulasso site defined by an interannual mean value of AOD equal to 0.64. However, the average AOD value found at the Ouagadougou

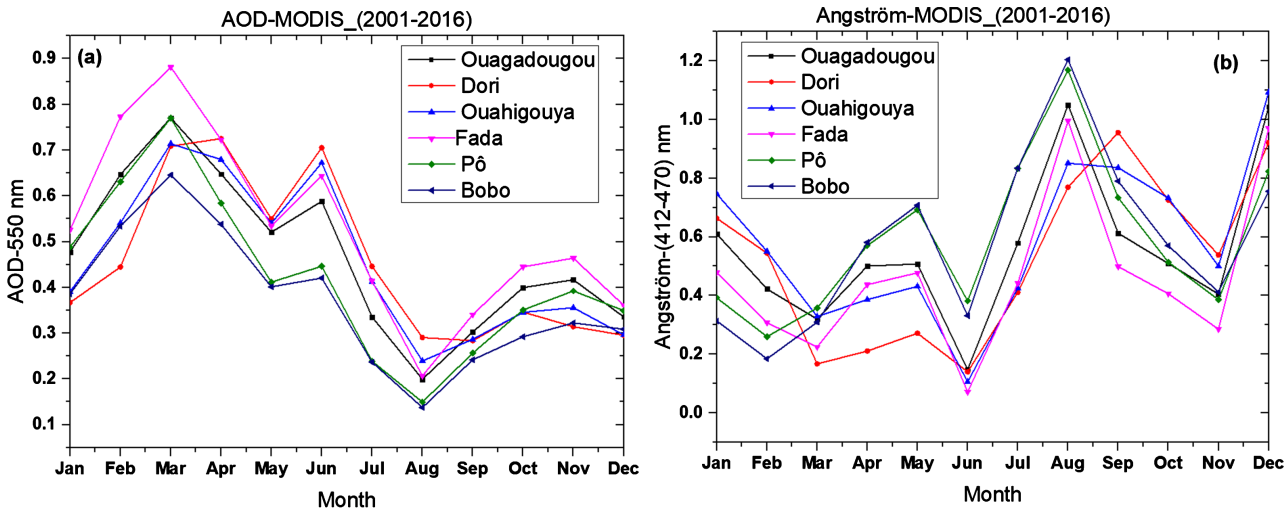

Figure 7. Interannual monthly averages of optical thickness (a) and angstrom coefficient (b) were observed at Ouagadougou (blue), Dori (red), Ouahigouya (black), Fada (green), PO (pink) and Bobo (yellow).

site (0.64) may be due to local particulate matter emissions from socio-economic activities, road traffic and distant transport of aerosols contained in the Saharan air layer.

Figure 7(b) confirms the dominance of dust in spring and summer with the Angström coefficient minima observed in March and June respectively. However, for Bobo-Dioulasso and Po, the Angström minima in winter (February) shows the effect of sediments blown by southwest winds. The month of August always indicates the importance of fine desert particles related to distant transportation. This phenomenon is also illustrated by the peak in September at the Dori site. Furthermore, autumn is marked by mineral aerosols because of the transition between the monsoon and harmattan flow in this period. This transition is characterized by very turbulent convective systems and easterly winds responsible for local dust emissions.

4. Conclusion

This work is an optical and microphysical study of aerosols in Burkina Faso based on data from satellite airborne sensors. This is, in order to show the contribution of MODIS, SeaWiFS, MISR and OMI sensors in the characterization of atmospheric particles in this part of West Africa marked by a deficit of ground measurement instruments for a better monitoring of aerosols. After validation of the satellite observations by the measurements of the CIMEL photometer of the AERONET network at the Ouagadougou site, we obtained a better accuracy with the MODIS sensor which best reflects the AERONET inversions with a relatively high R correlation coefficient. However, the OMI sensor is less representative with a large discrepancy between the aerosol model integrated into the sensor algorithm and the aerosol population probed. Furthermore, an optical analysis of aerosols by the MODIS sensor shows a very high variability of particles in time and space in Burkina Faso. These particles are strongly dominated by desert dust with maxima observed in spring and summer. However, it is necessary to continue this study through a characterization of the pollution particles PM_10 and PM_2.5 in particular the fine desert particles at the local and regional scale in order to contribute in addition to a better understanding of the climatic, environmental and sanitary role of aerosols in West Africa.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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