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Annual variability of aerosol optical thickness and analysis of meteorological factors contribution over two urban sites in Côte d'Ivoire (Abidjan and Korhogo)

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***Abstract*:**

Continuous measurements of aerosol optical thickness (AOT) at two urban sites (Abidjan in south and Korhogo in north) are used to examine aerosols characteristics as part of the PASMU (Pollution de l'Air et Santé dans les Milieux Urbains de Côte d'Ivoire) project. The specific objective of this work is to provide an approach in determining the temporal variation of the aerosol optical thickness and Ångström exponent (Alpha) over a period of 1 year (from October 2018 to December 2019) using sun photometer data. Our results suggest that 58-75% of the measured AOTs are between 0 and 0.5 and 23-37% between 0.5 and 1.24-34%, 30-34% and 26-32% of the measured Alpha are respectively between 0 and 0.5, 0.5 and 1 and 1 and 1.5. The findings indicate that the local meteorological pattern over the two urban cities, mainly driven by the West African Monsoon, has a great effect on the concentration and size distribution of the aerosols. The monthly average AOT values are observed to be generally higher in dry season than in wet season with some high values during the onset of the monsoon season (March) and the rainy period (July) at Korhogo. In general, the Ångström exponent values are, higher when AOT values are low and lower when AOT values are high. Moreover, the results reveal significant month-to-month variability in both AOT (ranging from 0.22 (AOT540) to 0.86 (AOT465) and from 0.24 (AOT619) to 0.75 (AOT465) at Abidjan and Korhogo, respectively) and Alpha (ranging from 0.33 to 1.05 and from 0.55 to 1.51 at Abidjan and Korhogo, respectively).The later highlights the influence of varying aerosol types. A link was established between the back-trajectories and the aerosol optical thickness. The use of this approach reveals that the particles influencing the optical properties of the atmosphere above Abidjan and Korhogo are from both local sources and the long-range transport.

***Keywords*:** Aerosols; Optical thickness; Angstrom exponent; Climate factors; Back-trajectories.

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1. Introduction

Particles in the atmosphere are distributed at every level, from ground to high altitude, and the spatial and vertical variability of their properties is still poorly investigated. Their spatial distribution depends on various factors, such as geographical location, size, lifetime, etc. Over the Ocean and near coastal regions, the atmosphere is mostly charged with marine aerosols (sea salt) whilst areas near the Sahara Desert are often rich in desert dust particles [1]. Moreover, big cities produce harmful aerosols affecting human health [2-6], degrade air quality and impact the climate [7-9]. In addition, aerosols have been extensively investigated and are suggested to play an important role in climate change on regional and global scales, largely due to their significant but uncertain direct and indirect effects [10-12]. These properties can be modified when the particles travel a long distance by interacting with other types of aerosols and, more generally, with their environment. The size distribution of total suspended particles (TSPs) in the ambient air is trimodal, including coarse particles, fine particles, and ultrafine particles [13]. The lifetime of suspended particulate matter (PM) in the atmosphere ranges from a few hours to a few weeks. Indeed, the smaller a particle is, the longer it will stay in the air. Also, epidemiological studies worldwide have associated aerosol particles, especially particulate matter, both PM2.5 and PM10 with adverse health outcomes, including cardiovascular, respiratory diseases, and even premature death [13, 14-17]. Short-term exposure to PM has frequently been associated with increased human morbidity and mortality [13, 18]. Effects of long-term exposure to PM are much more uncertain than the short-term effects, but are believed to have a much greater effect on health loss [13, 19]. Climate and human health effects depend on the size, amount, and composition of atmospheric particles. Consequently, systematic ground and satellite measurements have been undertaken to obtain improved information on atmospheric PM composition at high temporal and spatial resolution [20]. Satellite observations offer a much wider spatial view than in situ observations, and several studies have shown that they have great potential for deriving worldwide indirect estimates of ground PM [21]. However, satellite observations are less precise than in situ measurements [20]. Aerosol optical depth (AOD), which is defined as the integral of the extinction coefficient of aerosol in the vertical direction, indicates the attenuation of the light induced by aerosols and the degree of atmospheric pollution [20, 22]. As such, AOD has been widely used in climate research, atmospheric environmental observations, and other applications [1, 12, 23, 24]. AOD is the single most comprehensive variable for the remote assessment of the aerosol load in the atmosphere and which is used to reflect aerosol column loading.

Ground-based observations networks such as the Aerosol Robotic Network (AERONET) can provide accurate time-series AOD observations at different sites around the world [25]. Recently, satellite remote sensing and ground-based observations have become widely used to monitor the spatial and temporal distributions of aerosols on global and local scales [26-28]. PM retrieval from space is still challenging due to the elusive relationship between PM and aerosol optical depth, which is further complicated by meteorological factors [28]. Indeed, the relation between PM and AOD depends on many factors and usually changes significantly, even for data obtained at the same site during the year due to variations in source impacts and meteorology [28, 29]. Meteorological variables such as temperature, humidity, wind speed and direction, and mixing height play important roles in determining patterns of air quality over multiple scales in time and space [29]. These linkages can operate through changes in air pollution emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants. Aerosol properties are often obtained through satellite remote sensing, surface remote sensing, simulation-based, surface and aircraft in situ observations [26, 30]. Remote sensing observation generally provides the aerosol optical properties such as AOD and aerosol extinction coefficient, but not the aerosol mass or number concentration. In contrast, in situ observation can provide direct measurements of aerosol concentration and PM2.5. However, the limited samples of aircraft observation and limited sites of ground-based in situ observation make it challenging to obtain the PM2.5 over many locations, particularly the spatial distribution [20, 30]. Therefore, the ability of getting accurate temporal and spatial distribution of ground-based PM2.5 becomes an increasingly key prerequisite for the effective reduction and prevention of aerosol pollution [26, 27, 31]. Although PM2.5 from AOD has no high temporal resolution and is not available during cloudy or much polluted conditions, these methods provide the spatial distribution of PM2.5 globally or regionally [32, 33]. Recently, more sophisticated methods used to estimate PM2.5 from space were developed by taking into account meteorological factors such as cloud cover, wind speed, the mixed layer height, and relative humidity [30, 34].

A more detailed understanding of the role of different sources that contribute to the aerosol extinction coefficient and spatial and temporal variations of aerosols properties is required in order to quantify the dynamic influence on the regional climatic conditions and air quality. In addition, there is a lack of air pollution monitoring networks, especially in the most urbanized cities where needed due to the high cost of acquiring and maintaining air quality measurement equipment. Though installing low and medium cost sensors or equipment offering simple and inexpensive alternative could overcome this problem, in our case study, an experimental existing methodology based on the use of Calitoo sun photometer measurements was used to assess aerosol optical thickness in two cities of Côte d'Ivoire. The Aerosol Optical Thickness (AOT) measurements performed several times during the day provide a unique opportunity for determining the temporal variability of aerosol characteristics. The 15-months measurements allow the characterization of seasonal pattern of aerosol properties, known to influence the environment, thus may have an impact at regional scale. This seasonal pattern is expected to be important because (1) Abidjan and Korhogo are areas where aerosols from different origins are mixed and in proportions that depend on the activity of their sources, (2) the seasonal variation of the Harmattan affecting the areas, and the specific seasonal meteorological pattern driven by the monsoon and the location of the Inter-Tropical Convergence Zone (ITCZ). Specifically, this work (1) analyzes the annual evolution of Calitoo sun photometer aerosol optical thickness measurement performed between 01 October 2018 and 31 December 2019 over two urban sites in Côte d'Ivoire (Abidjan and Korhogo), and (2) investigates the contribution of meteorological factors. For the best of our knowledge, this study is the first contribution within the two cities focusing on the seasonal pattern of aerosol optical thickness (AOT) and Ångström exponent, and aiming at associating them with local emissions, meteorology variables and long-range transport. Considering the localized difference in anthropogenic aerosol emissions and meteorological conditions in the two cities, a key question is whether these factors are responsible for the AOT trends or which main factors dominate the trends.

2. Data and methods

2.1. Site description

This study does not encompass the whole territory of the country, but two cities, Abidjan and Korhogo located in two different ecological zones, respectively a coastal area densely populated and industrialized and the other in the hinterland, under populated and not industrialized (Figure 1). These cities were selected considering two main source parameters of aerosol pollution in urban environments: (1) the presence of industries in the metropolitan area, and (2) road traffic.Abidjan in the south is the economic capital of Côte d'Ivoire. It is located between 5.10° and 5.40° N and 3.50° and 4.20° W. Abidjan experiences dense and congested traffic every day with high density of population, resulting in increase of various anthropogenic emissions. Also, Abidjan is experiencing continuous growth characterized by high industrialization and rapid urbanization. Abidjan has a warmer and humid tropical climate with four seasons: two wet seasons (April-July and October-November) and two dry seasons (August-September and December-March).

Precipitation is abundant with more than 1500 mm/year. The annual mean temperature is about 27 °C and the annual mean relative humidity is over 80%. Korhogo is the fourth largest city in Côte d'Ivoire in terms of population and economy. It is located in the north of Côte d'Ivoire, between 9.20° and 9.50° N and 5.30° and 5.50° W, and 565 km away from Abidjan. Korhogo is experiencing continuous growth characterized by rapid urbanization but is not industrialized. Relatively close to the Sahel, it is characterized by traditional sources of pollution, such as dust, introduced into the region by Harmattan and road traffic. Korhogo has a warmer and dry tropical climate characterized by two seasons: a long dry season (November-April) and a long rainy season (May-October). The monthly mean temperature ranges from 20° to 40° C. Moreover, the amount of rainfall depicts a decreasing gradient northwards with 1485.3 (1162.5) mm/year in the south (north).

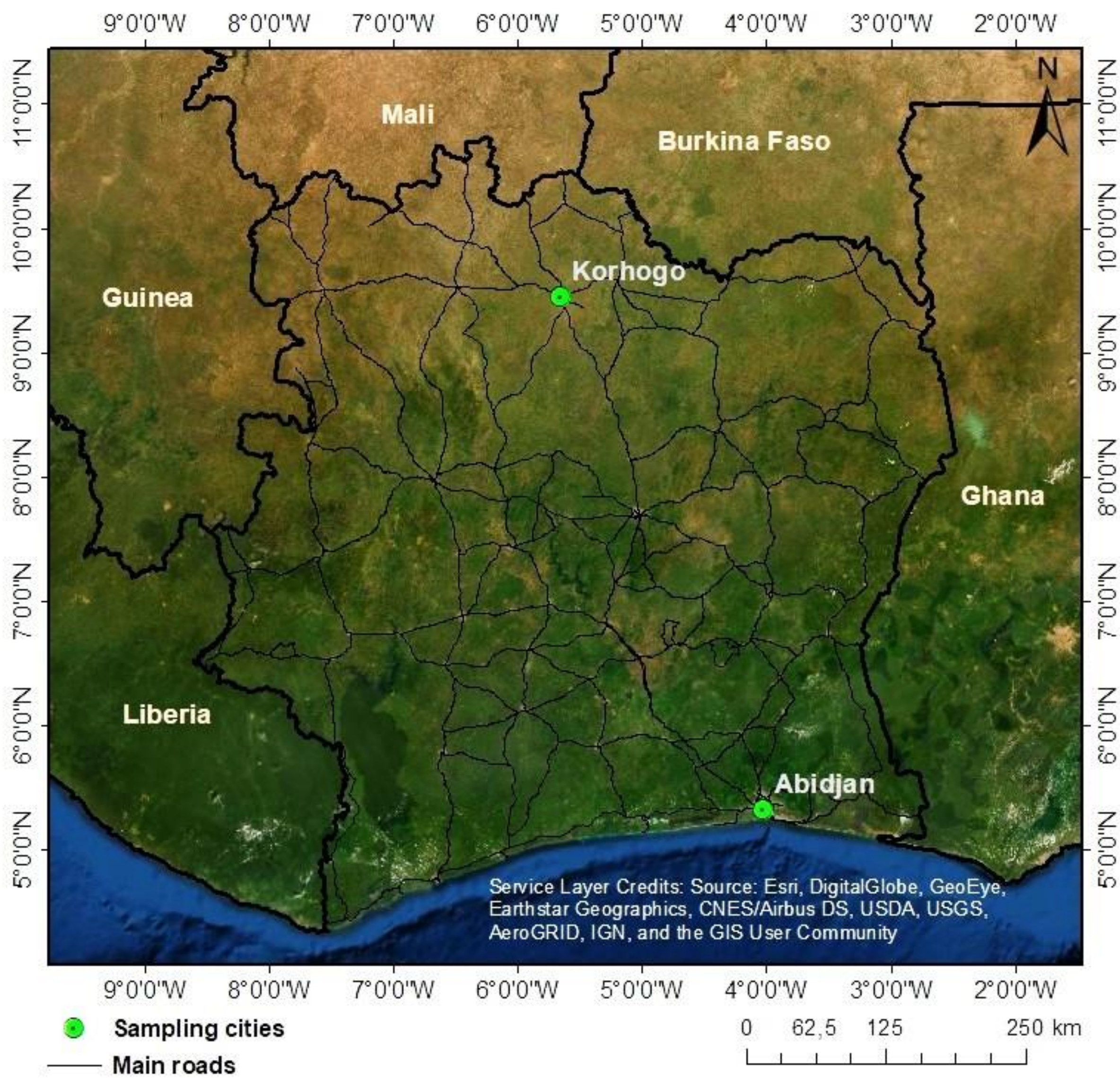
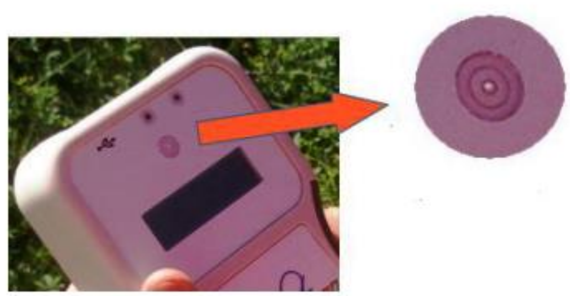


Fig. 1. Vegetation map of Côte d'Ivoire, the position of the two application cities in Côte d'Ivoire is shown by green dot.

2.2. Data Source and method

A handheld sun photometer is a well-known scientific instrument for measuring atmospheric transmission. In this study, we used a lightweight handheld sun photometer manufactured by TENUM (http://www.calitoo.fr). The sun photometer measures the Sun's irradiance at three wavelengths (blue (465 nm), green (540 nm) and red (619 nm)). The atmospheric optical depth is retrieved following the Beer–Lambert law knowing the calibration constant for each instrument and the relative air mass. The AOD is then retrieved after subtracting the Rayleigh and trace gases optical depth. Measurements are performed only for a cloud-free field of view. The operators performed the measurement at around 13:00 UTC. The operators were asked to take measurements only when the sun was not obscured by clouds and carried out with a sequence of five measurements within about 10 min. The principle of the measurement consists in pointing the sun to find the maximum sun irradiance. The photometer keeps only the maximum measured and then calculates the optical thickness. Pointing the sun is done manually. It is facilitated by the sighting device located above the display (Figure 2). The calculation of optical depth, detailed in the manual (http://www.calitoo.fr), use the raw brightness measurements, calibration coefficients, date and GPS latitude and atmospheric pressure. The Ångström exponent is computed between wavelengths 465 and 540 nm. Daily continuous measurements of aerosol optical depths have been made since October 2018. Measurements were obtained simultaneously at both sites (Abidjan and Korhogo). Very few measurements were collected in Abidjan compared to Korhogo due to the presence of the cloud cover which is almost permanent in Abidjan. Moreover, the measurement of Alpha by the sun photometer was considered from March 2019.



The Sun is in the center of the target when the photometer is pointed

Fig. 2. Calitoo Sun Photometer.

Meteorological observations provided by SODEXAM (Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique) has been used. The latter includes rainfall, temperature and relative humidity. Meteorological data are local measurements recorded at the airports of each city. The daily averages of aerosol optical depth were firstly calculated and then the monthly averages were calculated based on the daily averages. Time series of AOT were used for establishing the relationship between meteorological factors and the variation of AOT in both cities and investigate the influence of these factors on the seasonal variation of AOT. The relationship between the aerosol optical depth and the wavelength is given by the Angstrom exponent. It describes the spectral dependence of the aerosol optical depth and is an indicator of aerosol size. We use in this study the back-trajectories computed from HYSPLIT model. This model allows us to follow the spatial and temporal evolution of an air mass and to identify the source of the transported aerosol layers. The HYSPLIT model is a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations, which was developed by National Oceanic and Atmospheric Administration (NOAA) and Australia's Bureau of Meteorology [35].

3. Results and discussion

3.1. Temporal evolution of Aerosol Optical Thickness (AOT) and Ångström exponent (Alpha)

3.1.1. Frequency distribution of AOT and Ångström exponent (Alpha)

The frequency distribution for AOT465, 540 and 619 nm are presented in Figures 3 and 4 together with Ångström exponent (Alpha). The latter is obtained from the daily mean AOT and Alpha for the investigated period (October 2018 - December 2019) over Abidjan and Korhogo. The maximum relative frequency of AOT is found between 0–0.5 (>60%) and 0.5–1 (20<AOT<40%). The maximum relative frequency of Alpha is found in the Ranges 0–0.5, 0.5-1 and 1-1.5 (20<Alpha<40%). AOTs in the 1–1.5 range contribute for 0 to 1% in Abidjan and for 3 to 4% in Korhogo. AOTs higher than 1.5 contribute for 0% in Abidjan and only for 1 to 2% in Korhogo. The frequency distribution of the AOT shows that more than 60% of the year the aerosol are dust dominant particles (AOT < 1). Over Abidjan the Alpha values in the range 0-0.5, 0.5-1 and 1-1.5 contributions are 34, 34 and 32% respectively, while over Korhogo the contributions are 24, 30 and 26%, respectively.

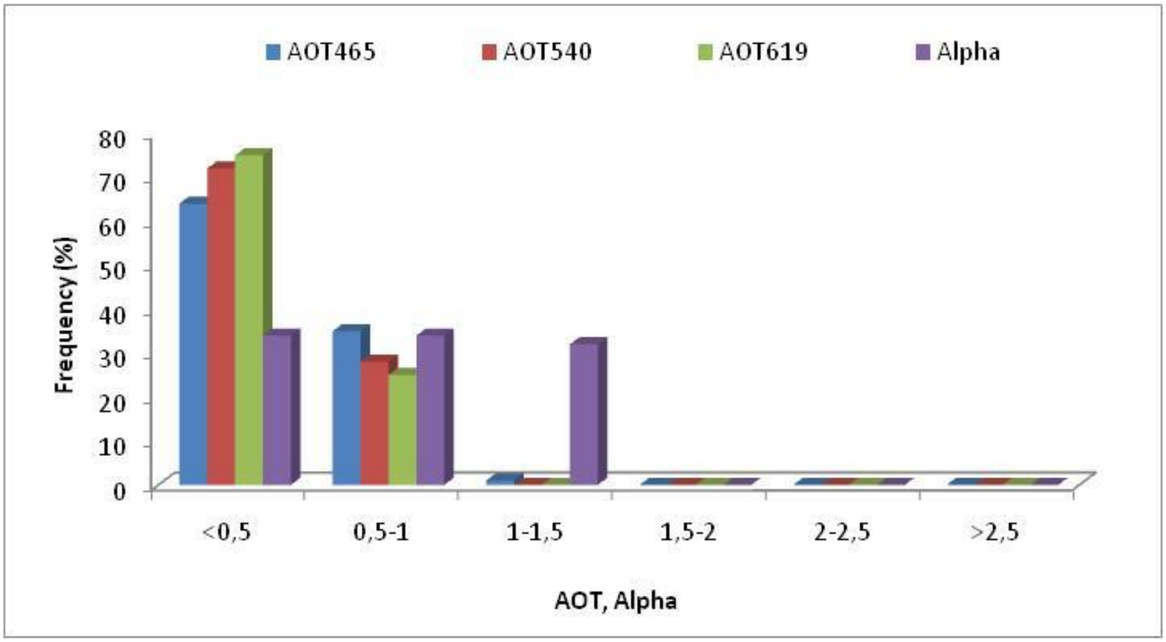


Fig. 3. Frequency distribution of Aerosol Optical Thickness (465, 540 and 619 nm) and Ångström exponent (Alpha) over Abidjan during the period of measurements.

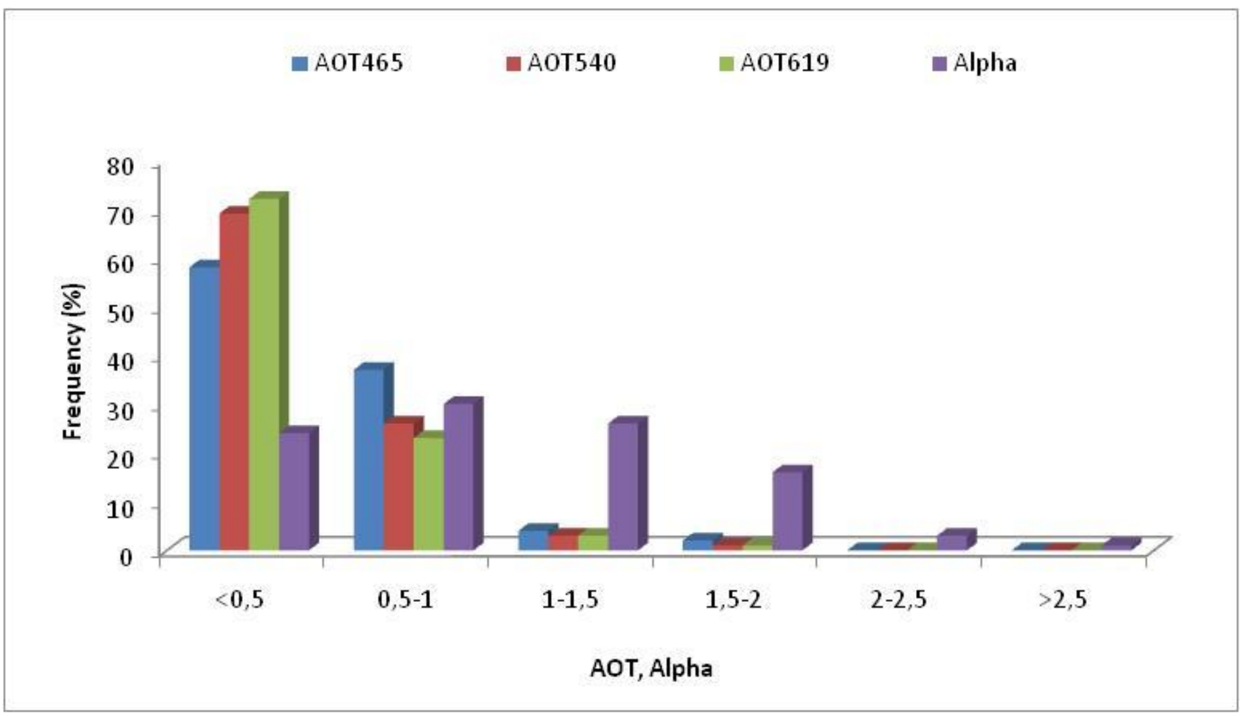


Fig. 4. Frequency distribution of Aerosol Optical Thickness (465, 540 and 619 nm) and Ångström exponent (Alpha) over Korhogo during the period of measurements.

Alpha values above 1.5 are found to contribute for 0% over Abidjan. Over Korhogo the Alpha values in the range 1.5-2, 2-2.5 and >2.5 contributions are 16, 3 and 1%, respectively. These frequency distribution histograms further bring out the distinct differences in variations in AOTs and Alphas over the two urban areas in Côte d'Ivoire. The frequencies of distribution of aerosol optical thickness and Ångström exponent (Alpha) over Abidjan and Korhogo show that the atmosphere over the two locations is characterized by a mixture of both predominant coarse and fine aerosols. Toledano et al. [36] found that over the El Arenosillo AERONET site (Huelva, Spain), up to 55% of the AOD(440 nm) observations are below 0.15, and 68% are below 0.2. The frequency of AOD (440 nm) above 0.3 is 15%. For the 870 nm band, up to 84% of data are below 0.15 and only 3% above 0.3. Verma et al. [37] showed that arid background and desert dust type aerosols are the most common at Jaipur (India) (34.7% and 13.6%, respectively), with a wide variability in both τ (aerosol optical thickness) and α (alpha). The two above-mentioned studies also found that the frequency histogram of α presents two modes around 1.2 and 0.5, the previous one related to the ordinary situation with mixed marine aerosols, whilst the latter is linked to the low α values during the desert dust events. Likewise, Diarra and Ba [38] found that over Agoufou and IER_Cinzana (Mali), the frequencies of distribution of aerosol optical parameters and the aerosol size distribution show that the atmosphere over the two locations is characterized by a mixture of both predominant coarse aerosols and fine aerosols.

3.1.2. Daily variation of AOT and Ångström exponent (Alpha)

Figures 5 and 6 illustrate the daily averaged aerosol optical thickness at 540 nm and Ångström exponent (Alpha) from October 2018 to December 2019 at Abidjan and Korhogo respectively, only for cloud-free days. The results reveal significant day-to-day variability in both AOT and alpha, underlying the influence of varying aerosol types. Moreover, it is worth noting that on the days of high AOT, alpha present very low values. While in Abidjan, the AOT peaks are depicted on certain days, at Korhogo, they occur more often in October-November, March-April and August-September periods. Similarly, the values of Alpha are, in general, higher in the September-December period, however they significantly drop during the rest of the year. In addition, during the September-December period, the increase in desert dust aerosols, advected by the Harmattan winds, would contribute to highly increase the concentration of coarse particle. The increase in fine mode particles loading due to long-range transport of aerosols from biomass burning can also be reflected in an increase of AOT and alpha [39].

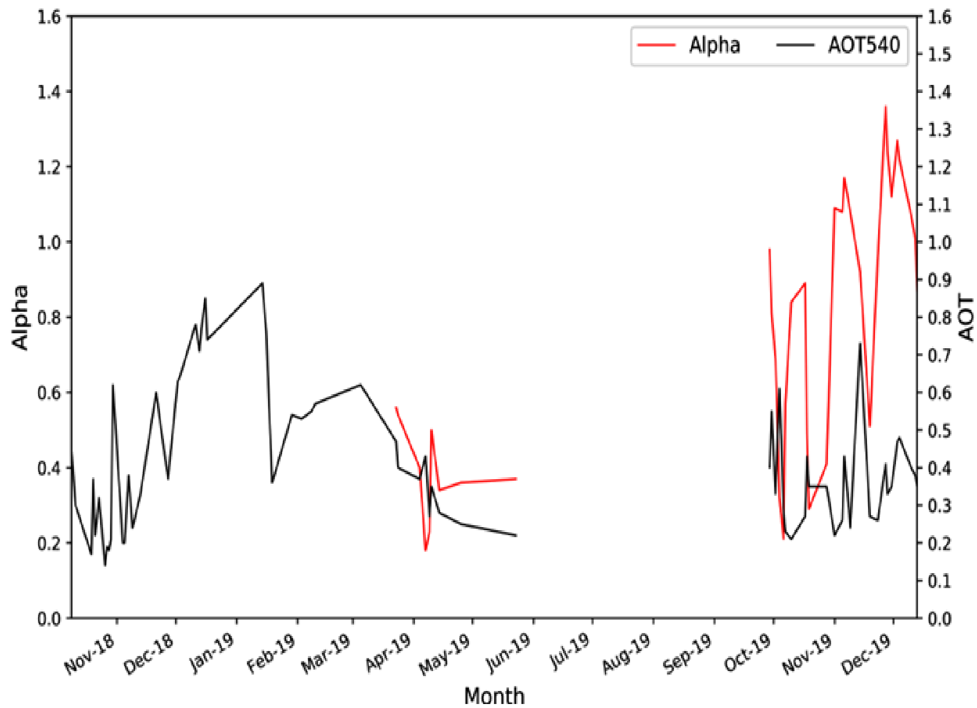


Fig. 5. Daily averaged Aerosol Optical Thickness at 540 nm and Alpha over Abidjan during the investigated period.

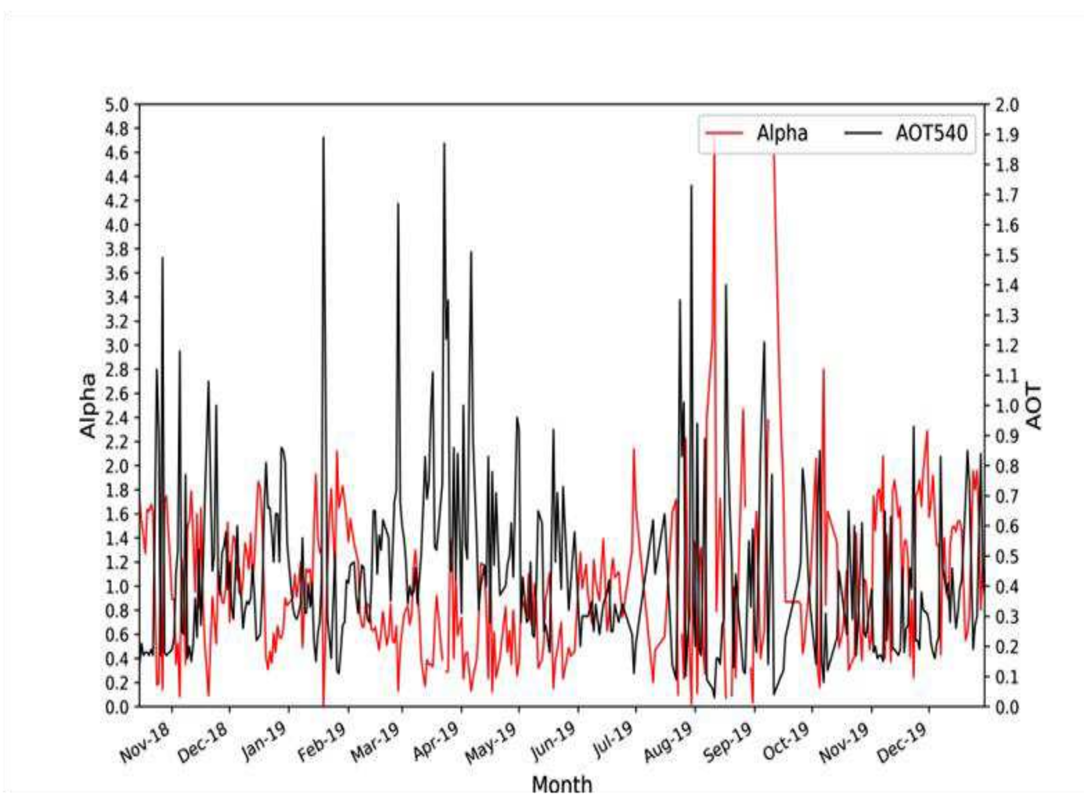
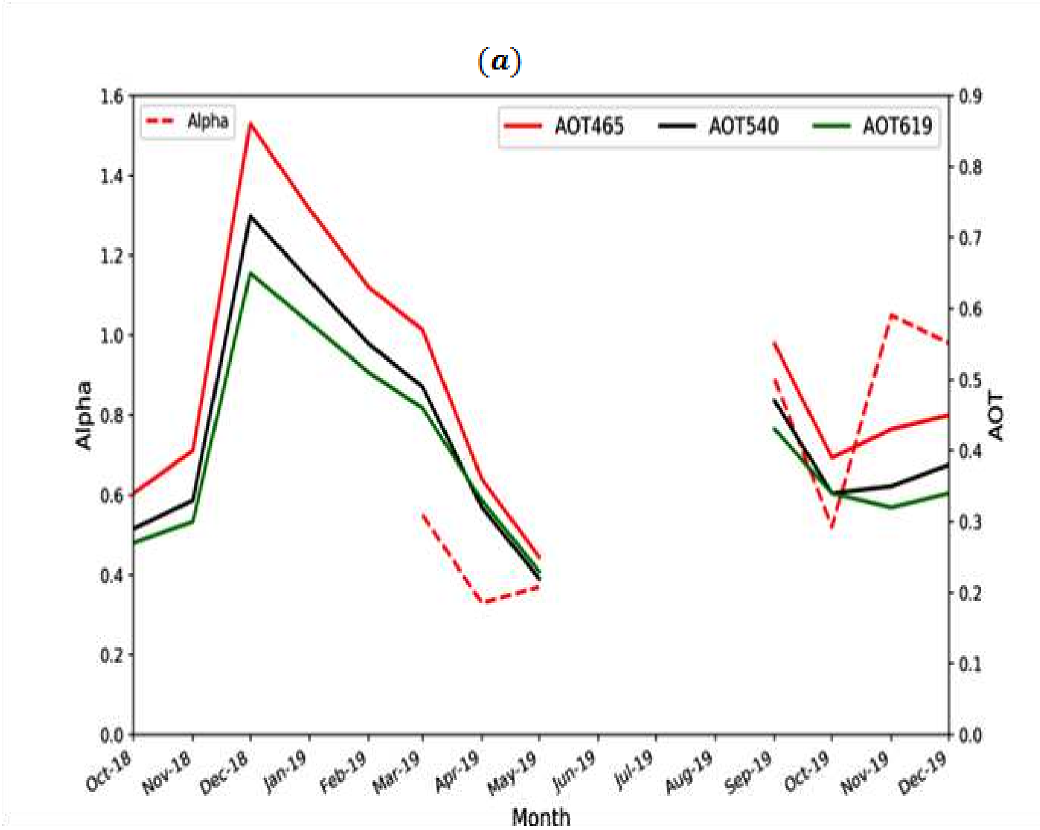


Fig. 6. Daily averaged Aerosol Optical Thickness at 540 nm and Ångström exponent (Alpha) over Korhogo during the investigated period.

3.1.3. Annual variation of Aerosols Optical Thickness (AOT)

The monthly variations in AOT at 619, 540 and 465 nm and Ångström exponent (Alpha) computed between wavelengths 465 and 540 nm, were analyzed. The monthly analysis is a reflection of the seasonality of aerosol, such that the AOT distributions demonstrate significantly different seasonal variation features between Abidjan and Korhogo. Figures 7a and 7b illustrate the fluctuation of all AOT and Alpha observed during the study period (October 2018-december 2019). The monthly average AOT values are observed to be generally higher in dry season than in wet season with some high values during the onset monsoon season (March) and the rainy period (July) at Korhogo. In sharp contrast, the Ångström exponent values are, in general, higher when AOT values are low and lower when AOT values are high. Moreover, the results reveal significant month-to-month variability in both AOT (ranging from 0.22 (AOT540) to 0.86 (AOT465) and from 0.24 (AOT619) to 0.75 (AOT465) at Abidjan and Korhogo, respectively) and Alpha (ranging from 0.33 to 1.05 and from 0.55 to 1.51 at Abidjan and Korhogo, respectively), underlying the influence of varying aerosol types. The aerosol optical thickness reached its maximum at Abidjan in December 2018 and January 2019, with values ranging between 0.65 (AOT619) and 0.86 (AOT465) and 0.58 (AOT619) and 0.74 (AOT465) respectively. Maximum value was reached in 2019 at Korhogo in March and April with values ranging between 0.65 (AOT619) and 0.75 (AOT465) and 0.57 (AOT619) and 0.64 (AOT465) respectively. The minimum value observed was obtained in May 2019 at Abidjan with a value of 0.22 (AOT540) whilst in November 2019 at Korhogo with a value of 0.24 (AOT619). These different cases will be analyzed in the following section. The AOT values show a pronounced decrease in the March-May period in both cities (Abidjan and Korhogo). This strong decrease in AOT values may partly be attributed to cloud cover. Also, from June to August, measurements have been impossible in Abidjan due to cloud cover. The largest monthly mean AOT are associated with weak Alpha values indicating a presence of several types of suspended particles in the atmosphere. These variations are probably the result of seasonal factors and the impact of local sources and long-range transport of aerosols. This indicates that under these conditions the aerosols are probably a mixture of several components differing in size and that the proportion of this mixture depends on season. Indeed, aerosols, responsible for high values of the aerosol optical thickness are from several sources because the AOT cannot reach very high values if those aerosols were only local. Moreover, Korhogo, the northern city is not characterized by industrial activities which may cause a high optical thickness.



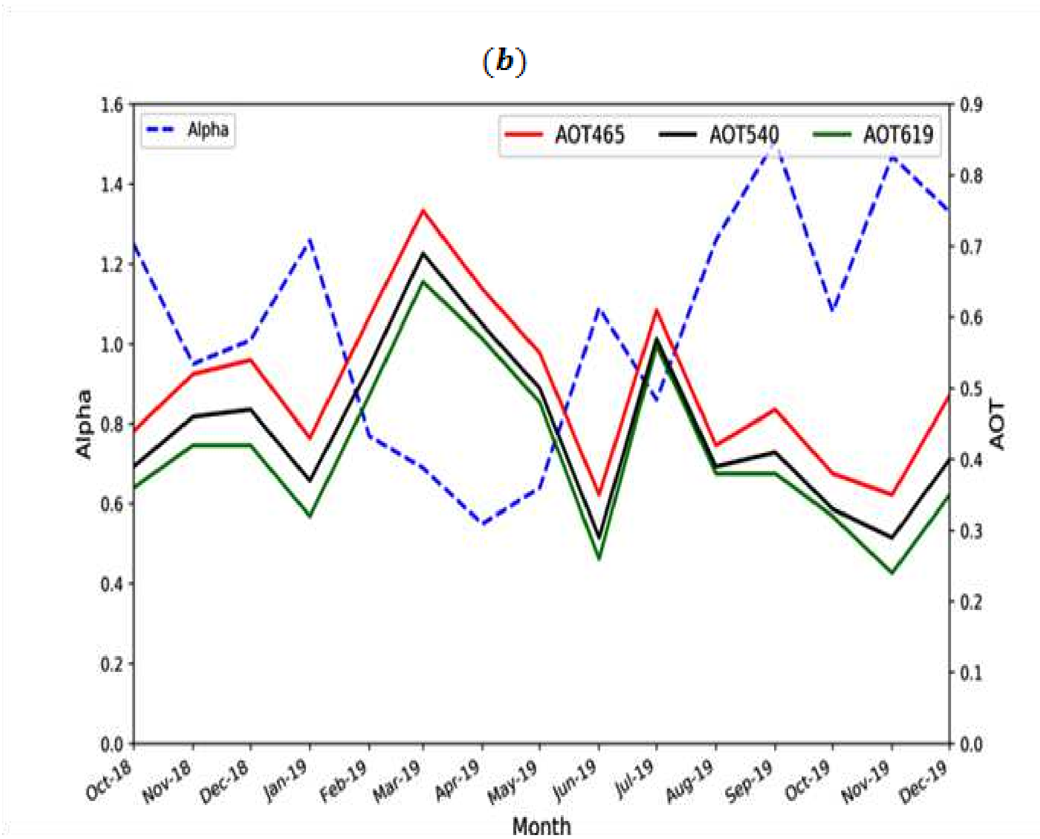


Fig. 7. Variation of monthly average AOT and Ångström exponent (Alpha) values over Abidjan (a) and Korhogo (b).

Thus, the only local aerosols that could increase the optical depth in the region are aerosols caused by traffic and biomass burning. Therefore if the optical thickness increases instantaneously in this region, it means that particles are coming from other regions, specially the Sahel. Abidjan is characterized by rapidly growing economy with the largest urban and industrial agglomerations and the highest density of population, with a great amount of emissions from industrial and traffic as well as daily living needs (domestic activities), resulting in high aerosol load. Indeed, industrialization and urbanization processes are characterized by consumption of enormous amount of fossil fuel (coal, oil), which results in emission of a significant amount of anthropogenic secondary aerosols. Thus, Alpert et al. [40], highlighted that the effects of urbanization on AOD are related to a high level of anthropogenic aerosol emissions in megacities, in which most of the world population resides and most of the anthropogenic pollution emitted. It is important to emphasize that seasonal variability in the total AOT values for the two cities (Abidjan and Korhogo) is due to a complex mixture of aerosols from different sources. On one hand, the lowest value of AOT indicating the dominance of fine anthropogenic particles could result from traffic, industry and residential emissions. On the other hand, the highest values of AOT highlighting a relatively higher concentration of coarse mode aerosols originated from local, regional, continental sources and maritime aerosols. Our results agree with those obtained by previous studies in other regions. According to Kaskaoutis et al. [39] analysing aerosols pattern in India, indicated that the three individual components of differing origin, composition and optical characteristics are (1) an urban/industrial aerosol type composed of aerosols produced locally and throughout the year by combustion activities in the city or long-range transported (mainly in spring) biomass burning aerosols, (2) an aerosol type of mineral origin raised by the wind in the deserts (mainly during pre-monsoon season) or constituting coarse-mode aerosols under high relative humidity conditions mainly in the monsoon period, and (3) an aerosol type with a marine influence under background conditions occurring in monsoon and post-monsoon periods. Verma et al. [41] showed that in Northwestern India, the seasonal variation of AOT500 nm depicts high values (0.51±0.18) during pre-monsoon (dust dominant) season while low values (0.36±0.14) are exhibited during winter. The Ångström wavelength exponent has been found to exhibit low value (<0.25) indicating relative dominance of coarse-mode particles during pre-monsoon season. Balarabe et al. [42] analyzed the monthly mean aerosol index (AI) obtained from the Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) in comparison with the available ground observations in Nigeria during 1984-2013. Their results revealed a strong seasonal pattern of the monthly distribution and variability of absorbing aerosols along a north-south gradient. The monthly mean AI showed higher values during the dry months (Harmattan) and lower values during the wet months (summer) in all zones. Djossou et al. [43] performed measurements in two southern West Africa cities Cotonou (Benin) and Abidjan (Côte d'Ivoire). their results showed that the seasonal cycle is dominated by the large increase in surface mass concentration and AOD during the main dry season (December-February) as expected due to mineral dust advection and biomass burning activities. The lowest concentrations are observed during the minor dry season (August-September) due to an increase in surface wind speed leading to a better ventilation. Furthermore, Ayanlade et al. [44] examined the influence of intertropical discontinuity movement on seasonality and distribution of atmospheric aerosols over Nigeria, using remote sensing approach. The results highlighted significant variations in monthly mean distributions of aerosol, but the variation is much more extraordinary during Harmattan season than Wet and Dry seasons. Indeed, their results showed that the observed seasonal cycle could reflect the impact of mineral dust on the atmospheric column during the Harmattan as mineral dust transport is associated with high AOD and a low Ångström exponent.

3.2. Influences of local meteorological factors

In this section, we investigate the influence of local meteorological factors such as temperature, relative humidity and precipitation on AOT variability. This analysis was conducted to assess the role of meteorological factors on the variability of AOT.

3.2.1. Relationship between AOT and precipitation

During the Harmattan and dry seasons (Figures 8a and 8b), AOT increases in Abidjan $(0.30 \leq AOT \leq 0.86)$ as well as in Korhogo $(0.42 \leq AOT \leq 0.75)$. These values reach their maximum in January and March for Abidjan and Korhogo respectively. Throughout the wet season, the values of AOT were relatively lower than in dry season. Moreover, from June to August, measurements have been impossible in Abidjan due to cloud cover. During the dry season, the observed high values of aerosols optical thickness could be explained by the weakness of the atmospheric washout due to rainfall and by transported desert dust. Indeed, during the Harmattan months, the dusty atmosphere in many parts of Côte d'Ivoire, with less precipitation is due to the prevalent flow of the tropical continental air mass from the Sahara Desert to the Atlantic Ocean. During these months, most of atmospheric dusts result from windblown dust from the Sahara Desert which covers the entire country.

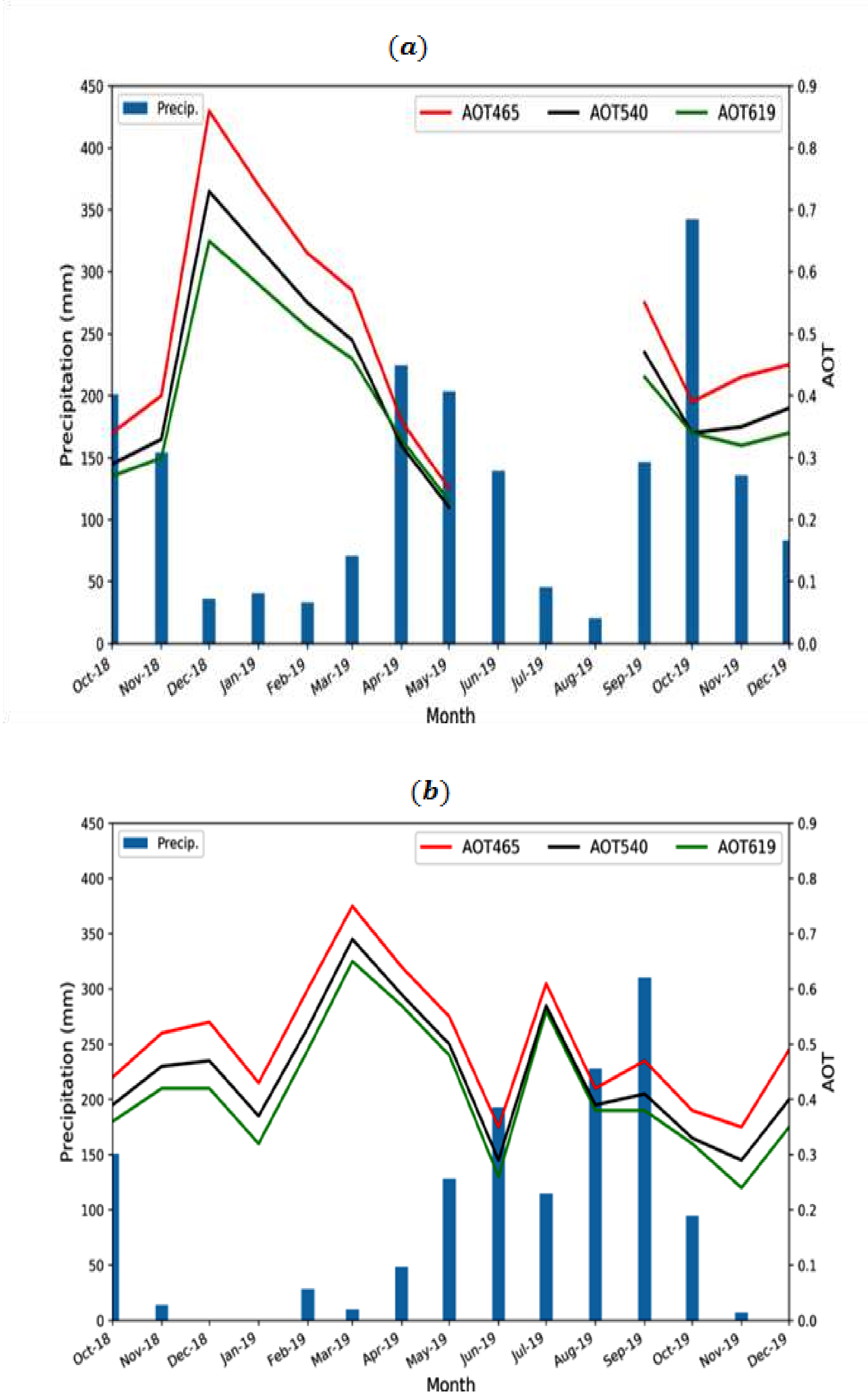


Fig. 8. Variation of monthly average values of AOT and rainfall at Abidjan (a) and Korhogo (b).

Similar seasonal variations in AOD values have been found by previous studies in different regions. For instance, Belaidi et al. [1] found that in Tizi Ouzou (Algerie), the aerosol optical depth at 500 nm and the Angstrom exponent respectively having the values $\tau > 0.5$ and $\alpha < 0.25$ indicate the high presence of desert dust particles from Saharan origin. This type of particles is frequently observed for α ranging between 0.25 and 0.35. Over the tropical urban site of Hyderabad (India), the AOD_{500} presented a rather insignificant monthly variation with larger values in March-April and June (~ 0.7) and lower in November and January (~ 0.5). In contrast, the $\alpha_{380-870}$ exhibited a pronounced annual pattern with low values in the monsoon period and high in winter and pre-monsoon [39]. Over Jaipur in Northwestern India, the seasonal variation of AOT_{500} nm shows high values (0.51±0.18) during pre-monsoon (dust dominant) season while low values (0.36±0.14) are exhibited during winter. The Ångström wavelength exponent has been found to exhibit low value (<0.25) indicating relative dominance of coarse mode particles during pre-monsoon season [41]. During a field campaign, Djossou et al. [43] observe that in the major southern West African cities of Cotonou (Benin) and Abidjan (Côte d'Ivoire), the seasonal cycle is dominated by the large increase in surface mass concentration and AOD during the long dry season (December-February) as expected due to mineral dust advection and biomass burning activities. The lowest concentrations are observed during the short dry season (August-September) due to an increase in surface wind speed leading to better ventilation. Furthermore, Ayanlade et al. [44] examined the seasonal distribution of atmospheric aerosols over Nigeria over the period of 2001–2017, using Dark Target MODIS AOD data. Their results showed significant variations in monthly mean distributions of aerosol, but the variation is much more extraordinary during Harmattan season than Wet and Dry seasons. The major findings of their study are that seasonal shifts in the location of the ITD considerably affect not only rainfall distribution, resulting in the Wet and Dry seasons in the study area, but also have significant impacts on atmospheric aerosol distributions. TOMS, MODIS, MISR and AERONET aerosol measurements have been used to assess the variability of aerosol concentrations over various cities in Pakistan. An assessment of seasonal variability in AOD for industrial, urban, semi-urban, rural, and semi-arid areas revealed maximum AOD values during the summer over all the areas investigated [45]. The aerosol optical and radiative properties changed from pre-monsoon to post-monsoon season [46]. The monthly average AOD values over Lahore were generally greater than 0.47. The maximum monthly average AOD occurred in July (1.02) and minimum in the month of February (0.47) [47]. According to a study of Ma and Guan [48], the AOD seasonal variation features and the influence of monsoon circulation patterns on the AOD distribution over East China and India have been investigated and compared. The results indicate some similarities and differences in the features of AOD changes associated with East Asian and Indian monsoon circulations. In East China, the AOD is higher in spring and summer but lower in autumn and winter, whereas in India, the highest AOD is observed during summer and lower AOD values are observed in spring, autumn, and winter. According to these authors, these variations in AOD may be related to the monsoon circulation changes; the AOD in East China is under the control of the East Asian monsoon system, whereas the AOD in India is under the control of the Indian monsoon system. Ali et al. [49] investigate trends in AOD using long-term data derived from moderate resolution imaging spectro-radiometer (MODIS) over twelve regions in Pakistan. All the selected regions experience increasing AOD trends during the winter season with six being statistically significant while during the summer season seven regions experience increasing AOD trends and the remaining five exhibit opposite trends with two being statistically significant. The changes in the sign and magnitude of AOD trends have been attributed to prevailing meteorological conditions.

The observation of relatively lower values in most of the studies was attributed to the impact of precipitation in modifying the aerosol concentrations, while the relatively higher AOD values were related to the heavy winds that drive dust particles.

3.2.2. Relationship between AOT, temperature and relative humidity (RH)

In this section, the possible relation between AOT evolution and atmospheric parameters (mainly relative humidity (RH) and temperature) is examined during the investigated period.

The meteorological parameters (temperature and relative humidity) are presented in Figures 9a and 9b and Figures 10a and 10b, respectively. It is established that in all the seasons (throughout the year), the temperature is higher in Korhogo (the northern zone city) compared to Abidjan (the southern and coastal zone city). A similar and opposite pattern (higher in Abidjan compared to Korhogo) was observed for the relative humidity. However, RH variation clearly depends on the season in the north (Korhogo), which is high during the rainy season and low during the dry season. Indeed, during the timeframe under investigation, RH varies between 21.7 and 84.5% with a noticeable seasonal cycle in Korhogo.

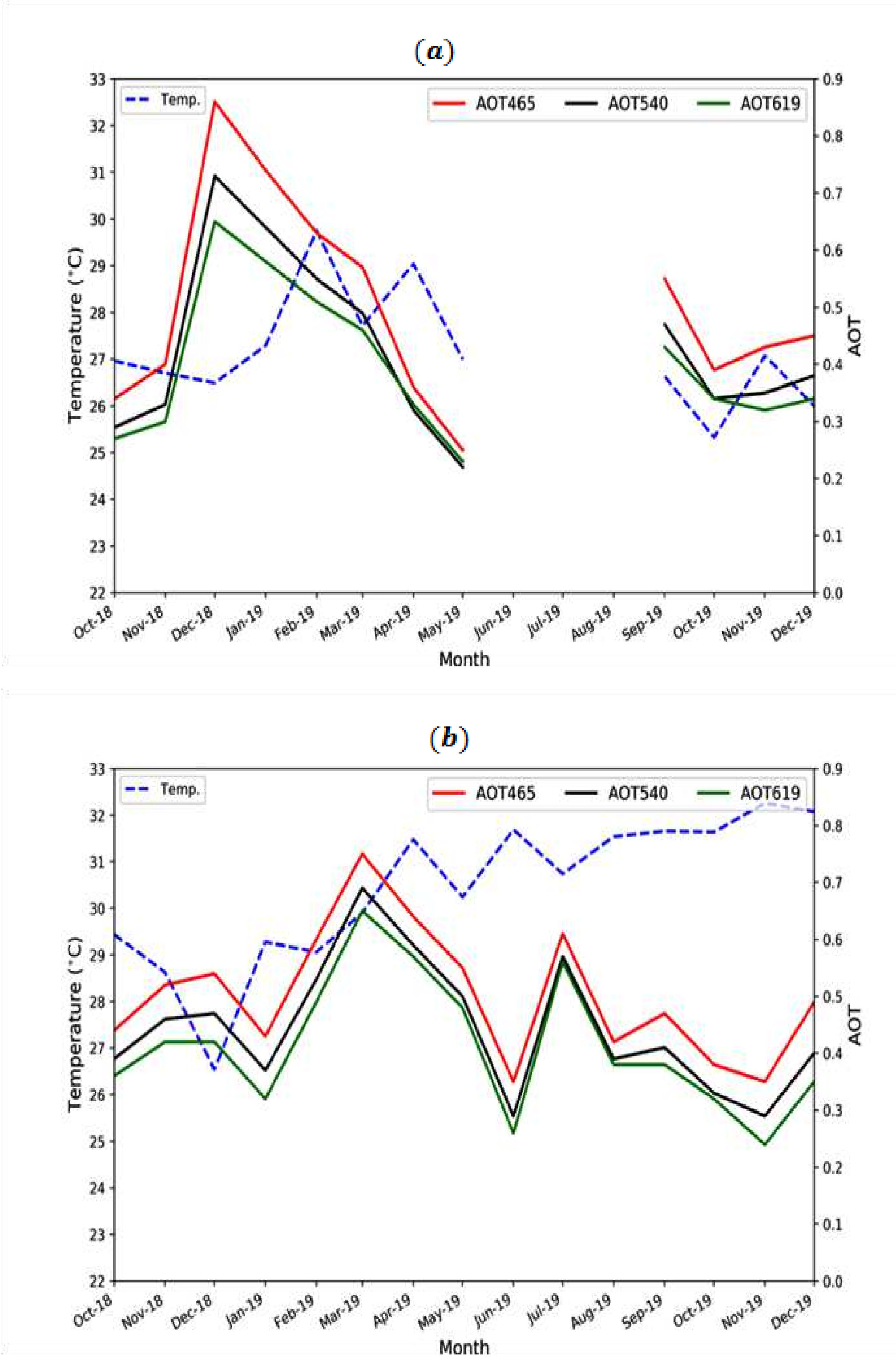


Fig. 9. Variation of monthly average values of AOT and temperature at Abidjan (a) and Korhogo (b).

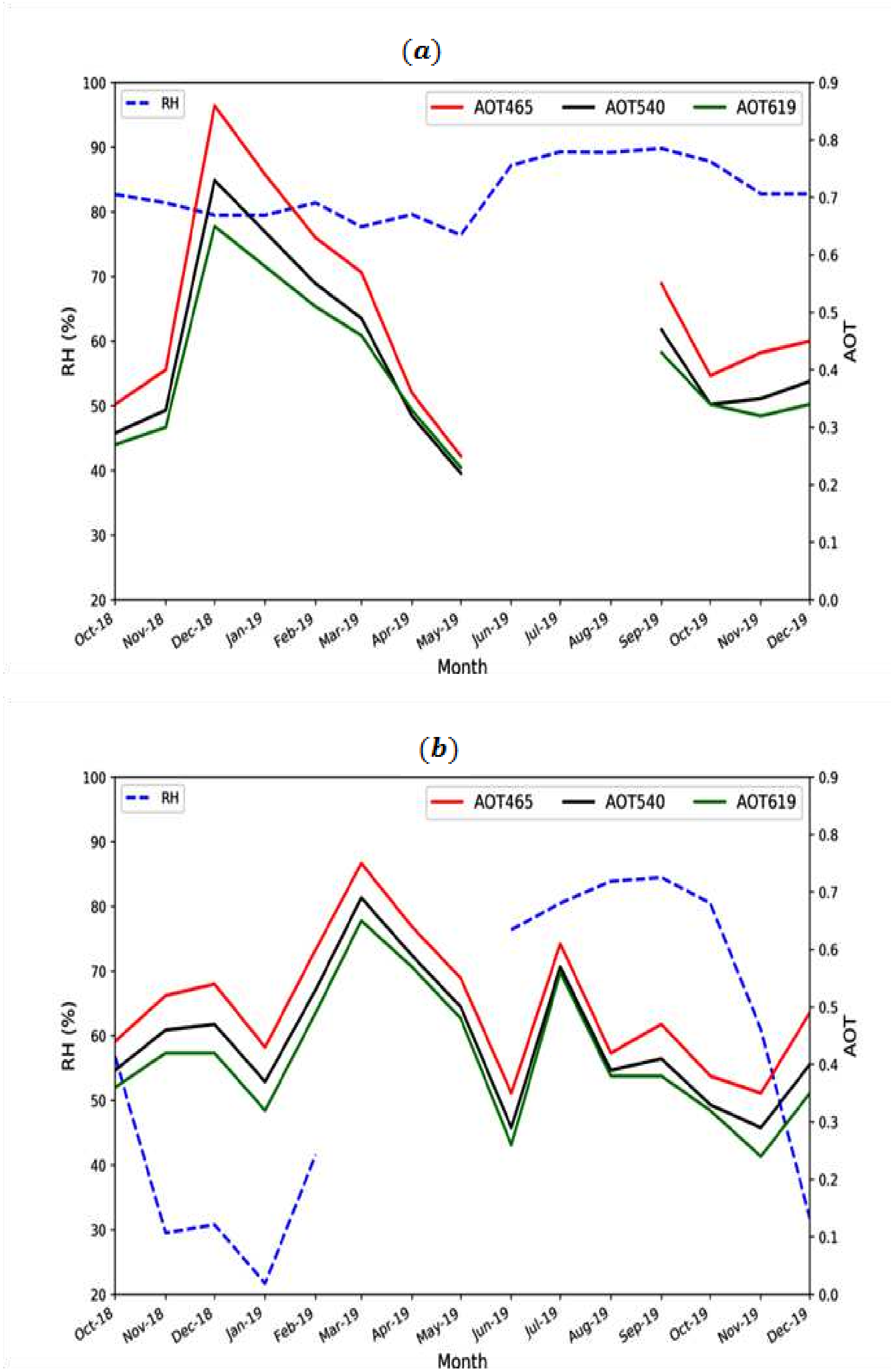


Fig. 10. Variation of monthly average values of AOT and relative humidity at Abidjan (a) and Korhogo (b).

Lowest values of RH are observed during Harmattan (November-February), ranging from 21.7% to 61% in Korhogo, while highest values occur in Abidjan during monsoon (July-October), ranging from 87.2% to 89.8%. In the south (Abidjan), we observed a weak variation of the RH values throughout the year, ranging from 21.7% to 61%. Also, for the two cities, a weak variation of the temperature is seen throughout the year, ranging from 26.54˚C to 32.26˚C in Korhogo, from 25.33˚C to 29.75˚C in Abidjan. The decreasing rainfall and RH and increasing temperature trends mostly support the increasing AOT trend over Korhogo in the north region. Moreover, the season of low (high) rainfall as well as low (high) relative humidity correspond to the season of high (low) AOT values. The increasing AOT is also found to correspond to a period of increasing temperature in the southern and coastal region (Abidjan).The reduced air temperature and RH during the Harmattan months (November-February) reduces the likelihood of hygroscopic growth of ambient aerosols. In addition, the dry season is characterized by low relative humidity and predominance of mineral dust, while during rainy season anthropogenic aerosols (traffic and residential emissions) and sea salt are dominant. Likewise, higher relative humidity during the rainy season may cause notable hygroscopic growth of atmospheric aerosols.

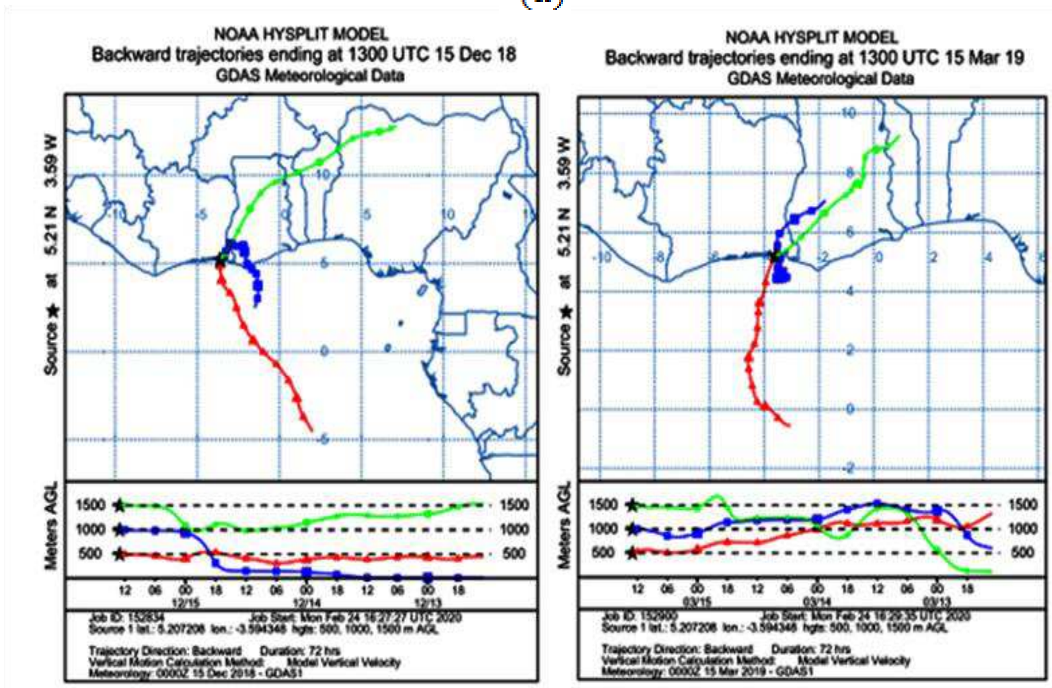
As far as our study is concerned, the hydrophobic nature of aerosols can be clearly seen by the coupling of the optical thickness with relative humidity (Figure 9). We clearly see the decrease of the monthly average of the optical thickness with increasing relative humidity between months of July and October and the increase of the monthly average of AOT with decreasing relative humidity between the months of November and January.

It has been reported that the regional meteorology and seasonal variation in particle source strength could be the primary causes of spatial inconsistencies in the distribution of aerosol types as well as their concentration [49]. The work of Ali et al. [49] attributed the changes in the sign and magnitude of AOD trends over twelve regions in Pakistan to prevailing meteorological conditions. Indeed, the trends in AOD over selected locations are fairly supported by trends in rainfall and temperature over these regions. The decreasing rainfall and increasing temperature trends during winter season over most regions support the increasing AOD trends. The decreasing rainfall trend reduces the likelihood of the rainfall washout processes of atmospheric aerosols whereas the increasing temperature trend supports the generation/growth of secondary aerosols as well as strengthening the convection process responsible for vertical distribution of atmospheric aerosols. Moreover, the high/low AOD phases during the study period may be ascribed to the anomalies in mid-tropospheric relative humidity and wind fields. The natural activities related to atmospheric dynamics may also act as precursors for aerosol generation/growth, and consequently increasing AOD concentration over an area. Thus, the high (low) concentration of water vapor in the atmosphere as well as high (low) temperature may be the cause of higher (lower) AOD levels [50]. Previous works [51] also reported that higher relative humidity aided by high temperature may intensify the hygroscopic growth of aerosols and gas-to-particle conversion process, producing more secondary aerosols and resulting in higher AOD. Indeed, relative humidity, by affecting the water uptake process of aerosol, can cause a pronounced change to the aerosol size distribution, chemical composition, and the extinction characteristics [34].

3.2.3. Influence of air masses on AOT using back trajectory analysis

We use in this section the back-trajectories computed from NOAA-HYSPLIT (National Oceanic and Atmospheric Administration Hybrid Single-Particle Lagrangian Integrated Trajectory) model. This model allows us to follow the spatial and temporal evolution of an air mass and identify sources of the transported aerosol layers which influence AOT over Abidjan or Korhogo for each season. In order to understand origins of the air masses arriving over the investigated area, we performed three-day back trajectory analyses. The 3-day time period is consistent with the residence time of aerosols. The air masses are computed at three altitudes (500, 1000 and 1500 m) on each day at 13:00 UTC. The choice of these heights is because they allow study the air motion in the atmospheric boundary layer, known as the seat of atmospheric turbulence that strongly influence the meteorology and dispersion [52]. During the investigated year, the Ångström exponent has exhibited different values each time aerosol optical thickness increased or decreased. It has reached weak values in December and March and high values in June and September. We have performed an analysis of air mass trajectories for dry season (15 December and 15 March) and for rainy season (15 Jun and 15 September) to point out for the selected days the origins of the detected aerosols. During the dry season (15 December and 15 March), there is a well-established difference between the trajectories of air masses at each altitude in Abidjan (Figure 11). At 500 m the air masses come from southern direction originating mainly from the ocean. At 1500 m the air masses are of continental origin, mainly from north of Nigeria, traversing Benin, Togo and Ghana. At 1000 m, air masses have travelled shorter distances. Thus, in Abidjan, the air masses from different source regions lead to the formation of different aerosol types.

(a)



(b)

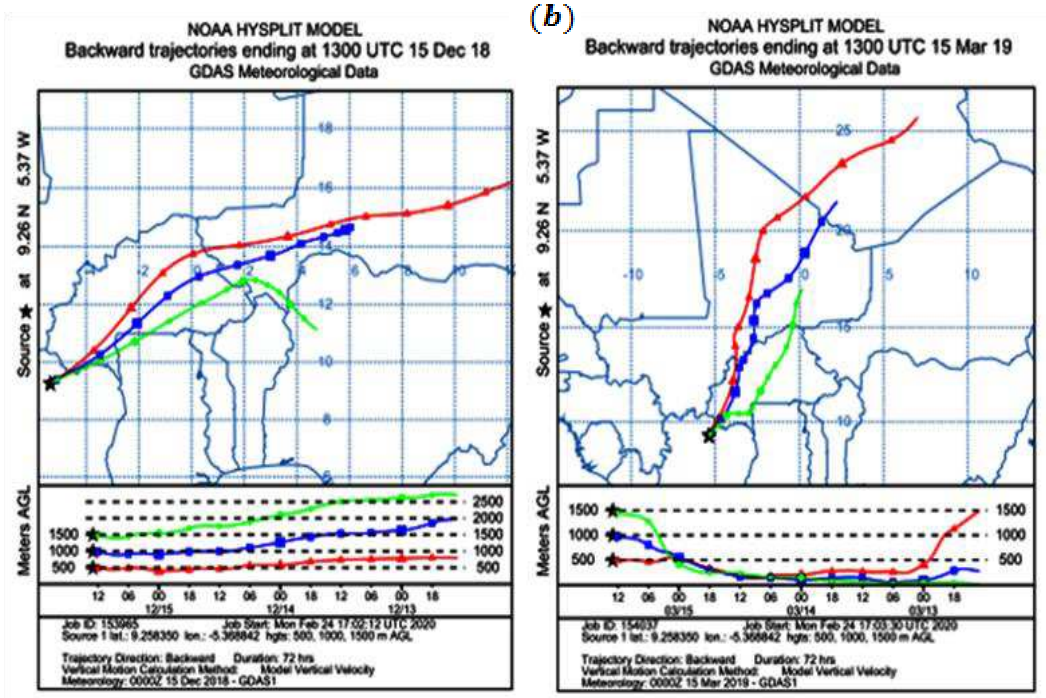


Fig. 11. Three-day back trajectories for Abidjan (a) and Korhogo (b), for 15th December 2018 and 15th March 2019.

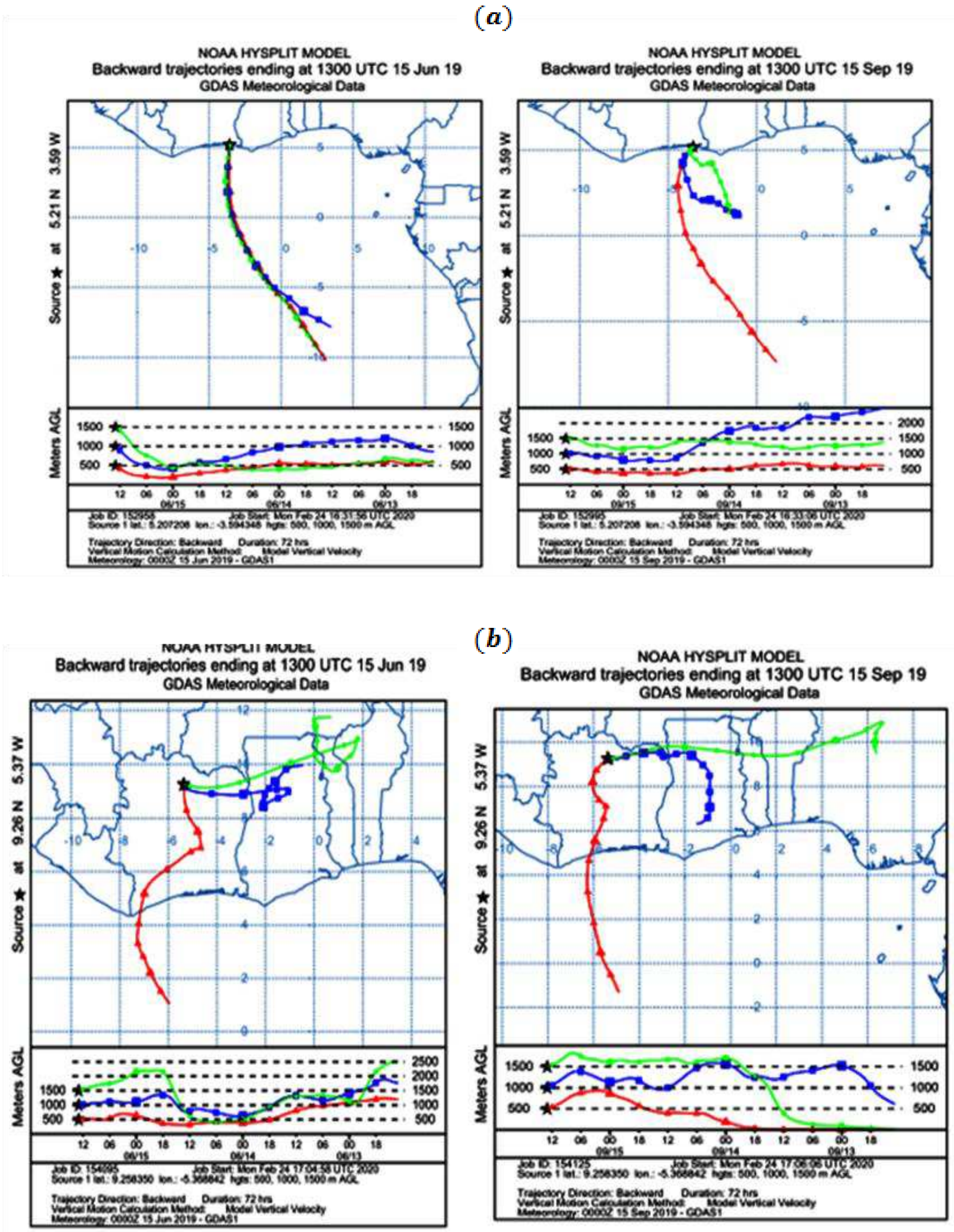


Fig. 12. Three-day back trajectories for Abidjan (a) and Korhogo (b), for 15th June 2019 and 15th September 2019.

Contrary to Abidjan, in Korhogo, the air masses come from Northeast Africa, mainly from Chad (December) and Algeria (March), in dry season whatever the altitude. During this period, Korgo et al. [52] also found that over Ouagadougou, the winds generally come from the Mediterranean, describing curves through either southern Libya, northern Chad and crossing an important part of Niger, or by Algeria and northern Mali and eastern Niger. They also shown that the high values of AOT are recorded in the period of predominance of harmattan winds, with annual peaks observed almost regularly between the months of February and March. In the wet season (15 Jun and 15 September) (Figure 12), it is shown that the transport routes and the direction of trajectories are dominated by air masses coming from south and east. Indeed, in Abidjan, the pathways of the air masses come from the southern direction originating from ocean independent to the altitude. Over Korhogo, at 500 m, the air masses trajectories come from the Gulf of Guinea. The 1000 m and 1500 m air masses trajectories generally come from the northeast, crossing northern Ghana, Togo, Benin and Nigeria. The low values of AOT recorded during the monsoon season highlight the hydrophobic nature of aerosols and suggest the dominance of desert aerosols that are difficult to mobilize in that period due to soil moisture or leached by rainfall [52].

4. Conclusion

Monthly mean variations in aerosol optical Thickness (AOT) and Ångström exponent (Alpha) along with variations in rainfall, temperature and relative humidity (RH) for two urban areas in Côte d'Ivoire, Abidjan in the south and Korhogo in the north, have been analyzed and discussed. The AOT and Alpha at these locations varies with season and are mainly influenced by the prevailing meteorology, air mass trajectories. The monthly average AOT values are observed to be generally higher in dry season than in wet season with some high values during the onset of monsoon season (March) and the rainy period (July) at Korhogo. In sharp contrast, the Ångström exponent values are, in general, higher when AOT values are low and lower when AOT values are high. Indeed, during the Harmattan and dry seasons, AOT increases at Abidjan $(0.30 \leq \text{AOT} \leq 0.86)$ as well as Korhogo $(0.42 \leq \text{AOT} \leq 0.75)$. On one hand, these values reach their maximum in January and March respectively for Abidjan and Korhogo. On the other hand, throughout the wet season, the values of AOT were relatively lower compared to those measured during the dry season. The decreasing rainfall and RH and increasing temperature trends mostly support the increasing AOT trend over Korhogo in the north region. Moreover, the season of low (high) rainfall as well as low (high) relative humidity correspond to the season of high (low) AOT values.

In the dry season (15 December and 15 March), there is a well-established difference between the trajectories of air masses at each altitude in Abidjan. In contrast, focusing on Korhogo, the air masses come from Northeast Africa, mainly from Chad (December) and Algeria (March), independent to the altitude. During the wet season (15 Jun and 15 September), it is observed that the transport routes and the direction of trajectories are dominated by air masses coming from south and east. The results presented in the paper are an initial stage of research examining the temporal variation of AOT on the basis of ground-based measurements. Obtaining continuous aerosol optical depth (AOT) measurements is a difficult task due to the cloud cover related issues. With the main motivation of overcoming this problem, an AOD predicting model and satellite measurements are proposed.

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