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RESEARCH PAPER

Daily and Seasonal Variation of Aerosol Optical Depth and Angstrom Exponent over Ethiopia using MODIS Data

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ABSTRACT
Aerosols are tiny particles (liquid or solid) suspended in the atmosphere. They play a significant role in climate dynamics directly or indirectly. Aerosol Optical Depth (AOD) and Angstrom Exponent (AE) are significant parameters to study the concentration and size or type of aerosol over an area, respectively. In this article, we utilized three years of AOD and AE parameters derived from moderate resolution imaging spectroradiometer (MODIS) satellite during the period January, 2013 to December, 2015 over Ethiopia. In order to study the spatiotemporal pattern of aerosols, we choose three areas (Debretabour, Gojjam and Addis Ababa) over Ethiopian highlands, which are representative of non-industrial, agricultural and industrial areas respectively. Further we compare continental aerosols with marine aerosols from Djibouti. Our results clearly depicts the aerosol distribution over Ethiopia is highly variable spatially and temporally. The results indicates that the urban and biomass aerosols are dominate over Addis Ababa, and Gojjam respectively, whereas dust and biomass aerosols are present over Debretabour, while Djibouti is loaded by sea spray aerosols. The seasonal variability of AOD is found to be maximum during the kiremt (summer) and minimum during bega (winter) over all areas (continental and marine).
Keywords: MODIS; Aerosol optical depth; Angstrom exponent

INTRODUCTION

Atmospheric aerosols are tiny liquid or solid particulate matters suspended in the air, mainly in the lower atmosphere (troposphere) where they are densely populated. The sources of aerosols include both natural and anthropogenic phenomenon. In small amount, they can be found in stratosphere when they are ejected by strong volcanic eruptions and dispersed through the atmosphere due to turbulence and global circulation (Zipeng et al., 2013). Aerosols can be either, absorbing the short wave range of the spectrum and cause the heating of the atmosphere and the cooling of the underlying surface or non-absorbing which increase the albedo of the atmosphere and reduce the amount of solar radiation reaching the surface (Tzanis and Varotsos, 2008). The density and distribution of aerosols in the atmosphere spatio-temporally fluctuating with geographic location, seasons, atmospheric conditions, and the availability of local sources (Balarabe et al., 2016, Lv and Mao, 2020). Aerosols play crucial role in the dynamics of the climate of Earth and radiation budget. Studying spatio-

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temporal pattern of aerosols either by ground based remote sensing or satellite has significant practical applications like in traffic control, managing energy budget, mitigating climate change and to know the quality of air (Fahed, 2015). Aerosol optical depth (AOD) and Angstrom exponent (AE) are the parameters often used for studying aerosols. AOD is the aerosol extinction coefficient integrated over the whole atmosphere, which is significant parameter in the study of aerosol forcing on climate system (Devara et al., 1995). The parameter AE represents the relationship between the size of aerosol particles and the wavelength dependence of the extinction coefficient (Angstrom, 1929). Hence, AE is important to characterize the aerosol particle size whereas AOD gives information about the aerosol density (Kaufman et al., 2000). AOD can be measured by ground-based monitoring instruments such as Aerosol Robotic Network (AERONET). Even if these instruments provide fine spectral and high-precision aerosol information at point locations, they lack good spatial resolution. Satellite remote sensing, on the other hand, can provide much more information about an aerosol's spatial distribution and provide global coverage (Tian et al., 2018). Among different satellites, Moderate Resolution Imaging Spectro radiometer (MODIS), launched by NASA Earth Observing System (EOS) program, can provides AOD and AE data. MODIS has Aqua and Terra sensors, and they measure reflected and emitted radiance from the Earth and the atmosphere at day and night time, respectively. The day- time Aqua overpasses has been chosen around 13:30 (local standard time) since clouds are more likely to be developed in the afternoon than in the morning (Kloog et al., 2011, Lv and Mao, 2020). Numerous studies on Aerosols have been reported globally using MODIS data. For example, Xiaoyan and Fangqun, (2015) studied the seasonal and spatial variations of global AOD. Kang et al. (2015) carried out the correlation analysis between AOD and cloud parameters and to study their relationship over China province using ten years MODIS data. Makokha et al. (2017) presented the trend analysis of AOD and AE anomaly over East Africa based on MODIS and AERONET data. Recently Antuña-Marrero et al. (2018) made the comparison between the AOD and AE parameters using MODIS data (both Terra and Aqua) with ground based sun photometer (AOD) from 2008 to 2014 at Camagüey, Cuba. Filonchyk et al., 2020 investigated the spatio–temporal evolution of aerosols and their optical properties using 19 years of MODIS Terra data in the Eastern European countries and their tendencies. They found there was a gradual decrease in aerosol load in all countries with maximum AOD values in summer and minimum values in winter. Very recently Shaw and Gorai, 2020 performed single and multiple linear regression model analysis on MODIS-based AOD with meteorological parameters like temperature, relative humidity, wind speed, solar radiation, and precipitation over Indian continent. They found a weak correlation when they applied simple linear regression, whereas regression coefficients are improved for multiple linear regression. Moreover, they studies annual, seasonal, and diurnal trend of AOD over India.

Regarding to Ethiopia, Milkessa et al. (2017) studied stratospheric aerosol climatology over Ethiopia using Stratospheric Aerosols and Gas Experiment II (SAGEII) satellite data. Except one or two case studies, no reports have been undertaken on aerosol over Ethiopia; hence we are motivated to classify aerosols based on MODIS data over land and marine locations along with their seasonal distributions.

MATERIALS AND METHODS

MODIS is a relatively good instrument abroad the Earth observing system (EOS) satellites and provides useful information on aerosols, clouds, moisture, and the ground surface. Its sensors are located on polar orbiting and sun-synchronous Terra and Aqua satellites. Both satellites perform measurements in the visible to thermal infrared spectrum region. MODIS sensor onboard Terra and Aqua earth observation system satellites provide multispectral data of 36 bands span visible, near infrared and far infrared portion of the spectrum. It has 1000m, 500m, and 250m multi-spatial resolution sensors with a temporal resolution of 1 to 2 days and covers the entire globe. Its revisit time is 12 hours and has a swath width of 705 km (Xue et al., 2011, Kloog et al., 2011, Filonchyk et al., 2019). Daily mean AOD and AE products at $1^o \times 1^o\ m$ resolution are used for this study (mean_MYD08_D3_6.1) at 550 nm wavelength onboard the Aqua satellite. Aerosol optical depth (AOD) is the degree to which aerosols prevent the transmission of light by absorption or scattering. It is defined as the integrated extinction coefficient over a vertical column of unit cross-section. Extinction coefficient is the fractional depletion (attenuation) of radiance per unit path length.

Aerosol Optical Depth (AOD) in a wavelength (λ) can be expressed as (Panagiotis, 2017);

$$AOD(\lambda) = \ln\left(\frac{\phi^{i}{}_{e,\lambda}}{\phi^{t}{}_{e,\lambda}}\right) = lnT_{\lambda} \quad (3.1)$$

Where:

$\phi^{t}{}_{e,\lambda}$ is the spectral radiant flux in wavelength transmitted;
$\phi^{i}{}_{e,\lambda}$ is the spectral radiant flux in wavelength received;
T_{λ} is the spectral transmittance in wavelength λ.

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ln
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AngExp ¼
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Angstrom exponent (AE) can be calculated from the AOD data of MODIS satellite as follows:

$$AOD(\lambda) = \beta\ \lambda^{-AE} \quad (3.2)$$

$$AE = \frac{\ln[AOD(\lambda)/\beta]}{ln(\lambda)} \quad (3.3)$$

Where β is the turbidity coefficient and varies from 0 to 0.5 (Thapa et al., 2016).

In order to study the variability of aerosol concentration over a region, coefficient of variation (CV) method has been adopted. A high value of CV indicates that aerosol concentration variability is more compared to other location and vice versa (Praseed et al., 2010). Percent coefficient of variation is the ratio of standard deviation to the mean.

$$CV\ (\%) = \frac{Sd}{\bar{x}} * 100\% \quad (3.4)$$

RESULTS & DISCUSSION

This section deals the daily and seasonal variations of AOD and AE parameters over land and marine areas of Ethiopia. To compare continental (land) aerosols with marine (sea) aerosols, data from three stations in Ethiopia treated as continental (Addis Ababa, Debretabour, Gojjam), and Djibouti concerned as marine area. The daily value of AOD parameter derived from MODIS satellite from 2013 to 2015 for Addis Ababa station is depicted in figure 1a.

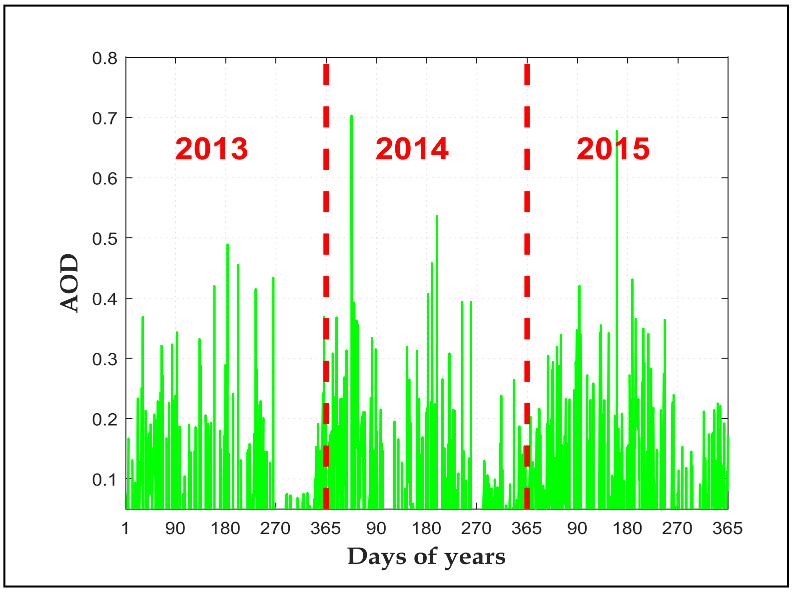

Fig. 1a. Daily variation of AOD over Addis Ababa from 2013 to 2015

The AOD values are fluctuating from 0.016 to 0.703 with a mean of 0.1495 and a coefficient of variation (CV) of 67.69%. The low value of AOD is found on December 3rd 2013, and the maximum value on February 15th 2014. The daily variation of AOD for Debretabour station is displayed in figure 1b. In this station AOD values ranges from 0.0150 to 1.1430 with a mean of 0.1623 and a CV of 94.21%. The minimum value occurred on January 20th 2014, and the maximum AOD value on April 5th 2015.

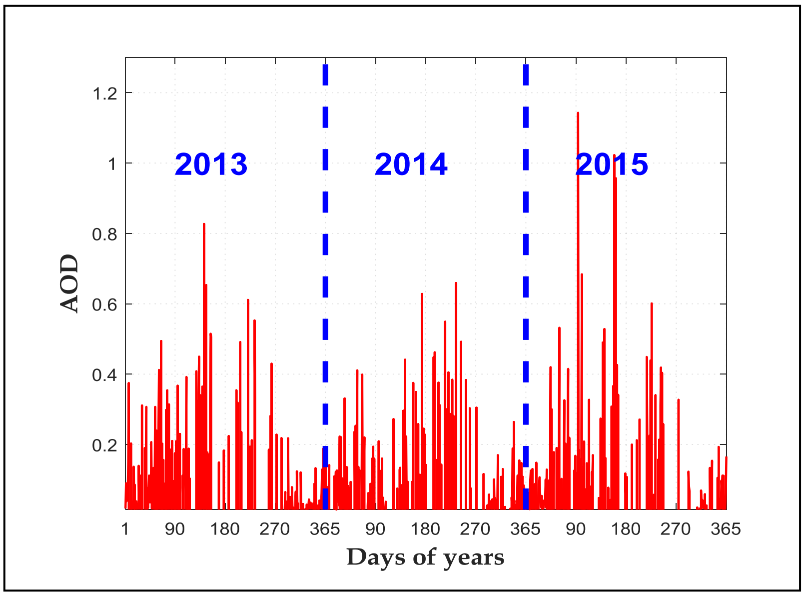

Fig .1b. Daily variation of AOD over Debretabour from 2013 to 2015

Similarly daily variation of AOD for Gojjam is depicted in figure 1c. It depicts high percent coefficient of variation (77.78%) of AOD values, since Gojjam is an Agricultural area and charcoal production is common practice in different parts of Gojjam, henceforth it produces soot (black carbon) in the atmosphere, that causes high value of AOD over Gojjam.

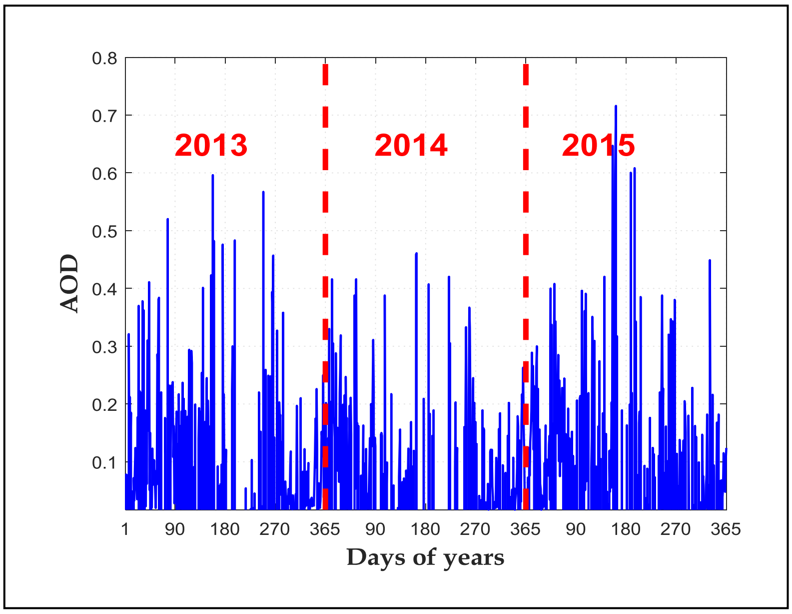

Fig. 1c. Daily variation of AOD over Gojjam from 2013 to 2015

Daily variation of AOD for Djibouti is displayed on figure 1d. The minimum and maximum AOD occurred on June 9th 2013 and March 5th 2015, respectively, with a coefficient of variation 57.16%. It reveals low variability of aerosols over Djibouti compared to other three stations.

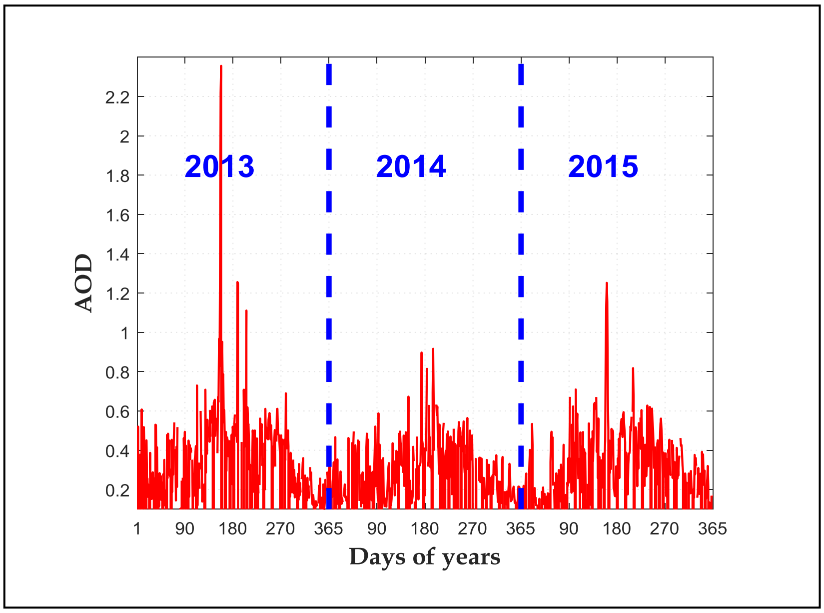

Fig. 1d. Daily variation of AOD for Djibouti from 2013 to 2015

Statistical descriptions of AOD values such as mean, standard deviation and CV for all stations are displayed in Table 1.

Table 1: Statistical description of AOD for each station for three years

Station	Average (mean)	Standard deviation	Minimum value	Maximum value	CV%
Addis Ababa	0.1495	0.1012	0.0160	0.7030	67.69
Debretabour	0.1623	0.1592	0.0150	1.1430	94.21
Gojjam	0.1503	0.1169	0.0170	0.7160	77.78
Djibouti	0.3443	0.1968	0.0697	2.3560	57.16

High CV is observed at Debretabour compared to other three stations. The cause behind the observation of maximum AOD values might be due to local wind speed, temperatures fluctuations, contribution of biomass burning, influence of vehicular emissions, growing infrastructure like construction, industrial activities and large emissions of smoke, soot by biomass burning, and by the process of charcoal production. High wind speed can facilitate dust aerosol emission and high temperature increases evaporation, which leads to increase the concentration of aerosols (Alam et al., 2014). The influence of vehicular emissions and growing infrastructure like construction, industrial activities throughout the region may be the major source for the contribution of the high values of AOD at Addis Ababa because it is industrial area. In this section we studied the seasonal variations of AOD over land and marine areas for 3 years (from 2013 to 2015). Generally Ethiopian climate has four major seasons: summer (Kiremet) (June – August); autumn (Meher) (September-November); winter (Bega) (December – February) and spring (Belg) (March– May). A seasonal variation of AOD for each individual year from 2013 to 2015 for Addis Ababa station is displayed on Figure 2a.

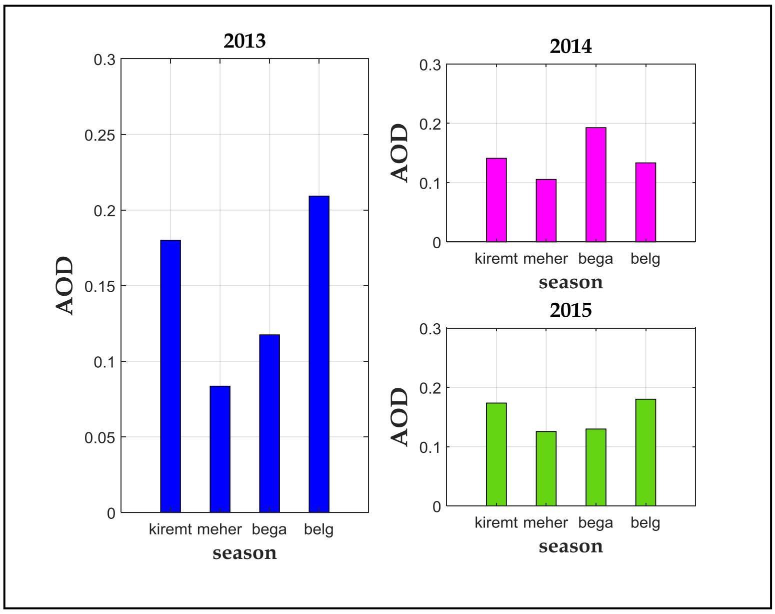

Fig. 2a. Seasonal variation of AOD over Addis Ababa from 2013 to 2015

The highest values of AOD occurred in belg (spring) for 2013 and 2015 due to rapidly rising temperatures and dry air that cause the evaporation of soil moisture, and this allows for the formation of dust events under intense wind conditions. In addition, spring (belg) is the most active season for cold fronts, since cold and dry air masses meets with tropical air masses during this season. The strong winds behind these cold fronts provide favorable dynamic conditions for dust weather; therefore, more frequent dust weather causes AOD to be increased in the spring (belg) (Kolhe et al., 2016, Zipeng et al., 2013). The second maximum AOD appeared in kiremt (summer) because the plentiful atmospheric water vapor in summer accelerate the hygroscopic growth of aerosols, which led to a significant increase in AOD (Li et al., 2015). Further, maximum AOD appeared in 2014 during the winter (bega), since large emissions of smoke and soot due to biomass burning are reported. Rapid industrial development and human activities increase aerosol emissions, especially sulphate aerosols (Wang et al., 2008), whereas Meher season shows low AOD values owing to most of the time cloud presence, so aerosols act as a cloud condensation nuclei along with wind speed is low, so the amount of dust aerosol reduction leads to low AOD values (Lei et al., 2013). The seasonal variations of AOD for each year from 2013 to 2014 over Debretabour are displayed on Figure 2b.

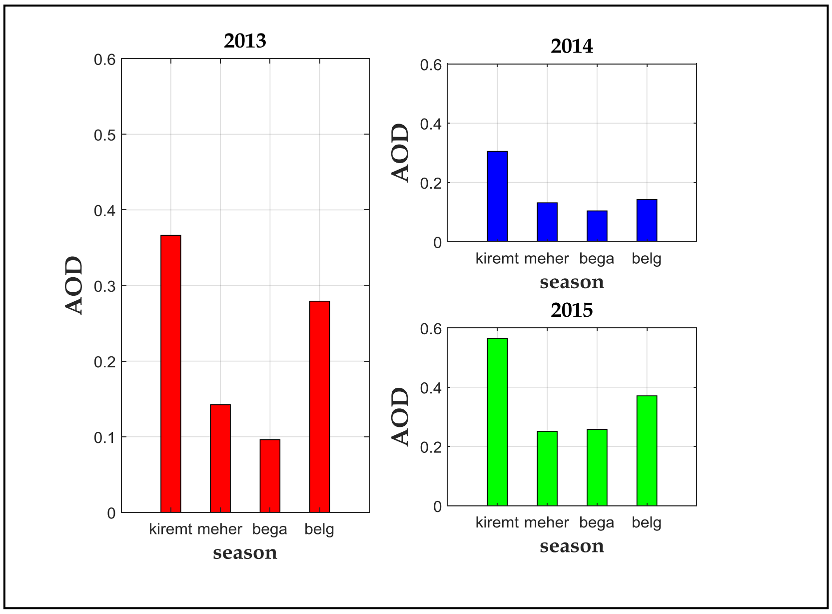

Fig. 2b. Seasonal variation of AOD over Debretabour from 2013 to 2015

From the figure it is observed that higher AOD values were recorded during kiremt and this is due to the increase in convective activities that enhance wind speed and surface temperature. The speed of wind initiated and facilitated the movement of copious amounts of soil dust aerosols into the atmosphere from the surface of dry ground of the arid and semiarid regions. In addition to this, in kiremt due to higher temperature, soil moistures are evaporated and heated up from soil due to high wind velocities which can increase AOD values and higher concentration of water vapors leads to a higher AOD (Alam et al., 2014, Filonchyk et al., 2019). High temperature and humidity are favorable to the gas to particle conversion process and the hygroscopic growth of aerosol; whereas, the low value of AOD in bega was caused by the low surface temperature, which results in the weak production of mineral dust derived from the soil surface (Li et al., 2015). In addition, dry weather and lower humidity in bega result in lower AOD values (Alam et al., 2011). Seasonal variations of AOD for each year from 2013 to 2015 over Gojjam are displayed in Figure 2c.

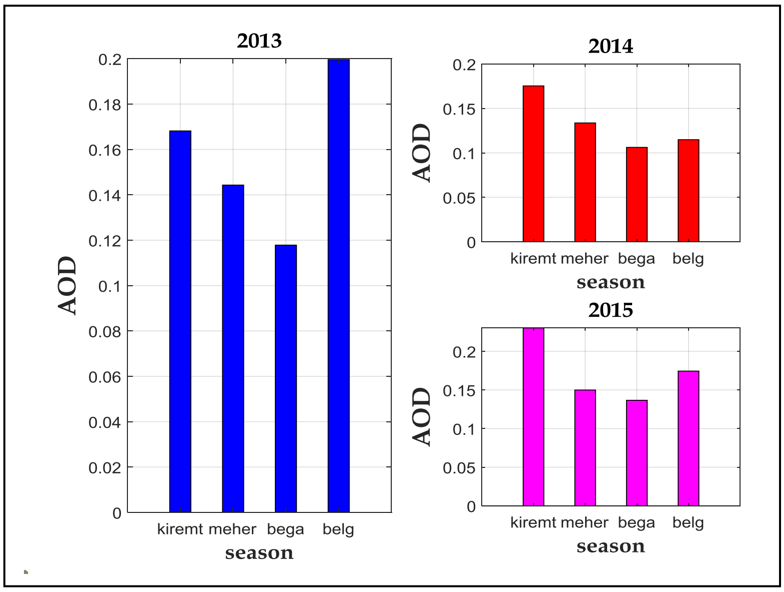

Fig. 2c. Seasonal variation of AOD over Gojjam from 2013 to 2015

As shown in Figure 2c, AOD was high during the belg season in 2013, probably due to heavy smoke from seasonal forest fires and crop residue burning. During this season, farmers produce huge biomass burning for preparation of farm land as this zone is an agricultural area. This causes high concentration of smoke (black carbon) aerosols and leads to high AOD values. Biomass burning is a frequent source of atmospheric pollution and poor air quality (Li et al., 2015). The high value of AOD in 2014 and 2015 are occurred during the kiremt (summer) because of high temperature and humidity which are significant factors for the formation of fine particle by gas particle conversion process and hygroscopic growth of aerosol. In addition, strong convective motion in this season contributes to the upward transport of aerosols near surface (Li et al., 2015). In contrast to this, low value of AOD occurred during the bega season due to low temperature, leads to decreasing evaporation and hence decreasing aerosol concentration. Seasonal variations of AOD for each year from 2013 to 2015 over Djibouti are presented in figure 2d.

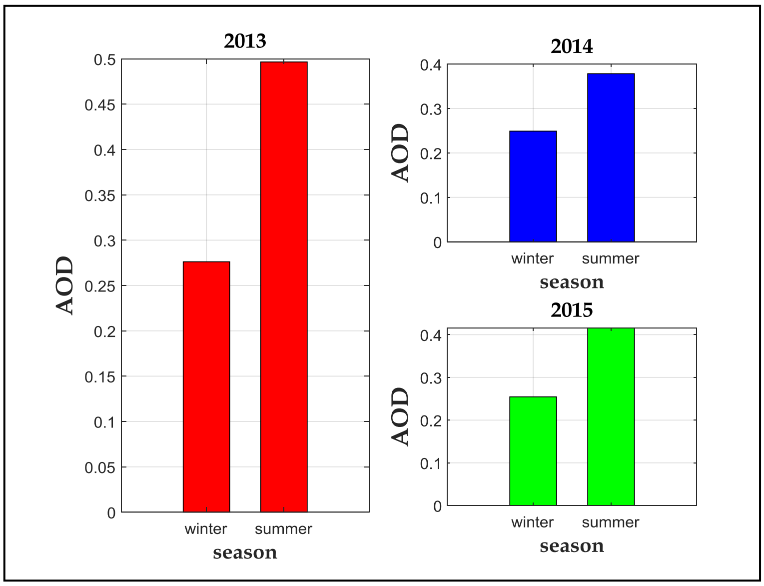

Fig. 2d. Seasonal variation of AOD over Djibouti from 2013 to 2015

In contrast to four seasons in Ethiopia, Djibouti had two well-known seasons, which are winter and summer. Winter season is considered as the monthly average AOD values in November, December, January, February, March and April, whereas, for summer May, June, July, August, September and October are considered. During winter season, Djibouti experiences sparse rainfall, cool breezes, and temperatures near 20^{o}C, while summer season begins in May and ends in October with, temperatures greater than 49^{o}C. The khamsin is a strong, hot, sand-loaded wind that blows in Djibouti during the summer season. Occasionally, the khamsin begins in the morning and lasts for three to four days. There is another strong wind in Djibouti called the Saba and it is a fall or gravity wind (the winds that flow downhill under the pull of gravity) is always cool. Sometimes Saba is accompanied by light rain and, it disturbs less dust than other winds. It occurs only in the morning hours during the summer, begins and ends abruptly (Djibouti-climate, 2015). From figure 2d we observed that, AOD in summer is higher than winter due to high temperature that leads high evaporation from red sea and Gulf of Aden with high concentration of sea salt aerosols. In addition, due to higher temperature, moistures are evaporated and heated up from soil, because of high wind velocities that cause high AOD values in summer season. Higher concentration of water vapors in summer leads to a higher AOD. Furthermore, during summer season, prevailing khamsin and Saba winds could facilitate dust aerosols and increase AOD. Conversely, minimum AOD values are recorded in winter, compared to summer, because low temperatures usually decrease the evaporation, leading to a decrease in AOD. Dry weather and lower humidity in winter are responsible for lower AOD values (Alam et al., 2011, 2014). Aerosol particle sizes are characterized by Angstrom exponent parameter. Large AE value shows the presence of fine particle aerosols, whereas small AE values signify coarse particle aerosols (Angstrom, 1929). Different authors proposed classification of aerosol size based on AE parameter. For example, Kaufman et al. (2000), classified aerosols as dust aerosols (with large size), mixed aerosols (with medium size) and smoke aerosols (with small size) based on the following AE values: AE < 0.7, 0.7 < AE < 1.8, and AE > 1.8, respectively. According to Yunfeng et al. (2001) when AE is approaches to 0, it signifies coarse-mode or larger particles such as dust particles, and when it is greater than or approaching to 2, it indicates smaller particles such as smoke from biomass burning**.** Evgenieva et al. (2015) also suggest that values of AE ≤ 1 indicates coarse mode aerosols of effective radius usually greater than 0.5 μm (mainly dust or sea-spray aerosols) and values of AE≥1 indicate a size distribution dominated by fine-mode aerosols of effective radius smaller than 0.5μm (urban pollution and biomass burning). Moreover, Ntwali and Chen, (2018) classify aerosols based on AE values as dust dominated, mixed aerosols and fine anthropogenic aerosols when AE≤0.75, 0.75 < AE < 1.2 and AE > 1.2, respectively. Mixed type aerosols are a result of mixing between different size particles from different sources. Among the above mentioned classification from different researchers, we followed recent classification of AE parameter by Ntwali and Chen, (2018).

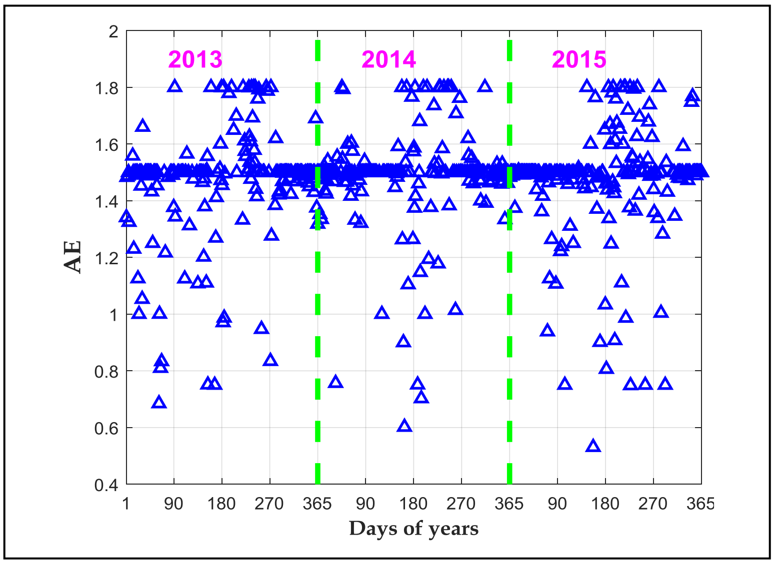

Fig. 3a. Daily variation of AE over Addis Ababa from 2013 to 2015

Thus, the size of aerosols over Addis Ababa, Debretabour, Gojjam, and Djibouti from 2013 to 2015 is classified according to the AE variations, based on Ntwali and Chen, (2018) and the results are displayed on figure 3(a) – (d). The daily values of AE parameters over Addis Ababa from 2013 to 2015 are plotted in Figure 3a. About 3.03% of AE values are below 0.75, about 1.76% are between 0.75 and 1.2 and about 91.21% are greater than 1.2. So we conclude that, dust and mixed aerosols are present in very little amount, but fine anthropogenic aerosols (which are urban aerosols) are dominate (91.21%) over this region. Addis Ababa is a heavy industrialized area; hence the probability of urban pollution is high in this area. The daily values of AE parameters over Debretabour are depicted on Figure 3b. About 21.93% of AE are less than 0.75 which indicates that dust aerosols are available, 13.19% of AE values are between 0.75 and 1.2, shows mixed aerosols, and about 64.87% are greater than 1.2, is dominated by fine anthropogenic aerosols. Hence we conclude that Aerosols due to biomass burning are dominate over this region, moreover during farming period more dusts produces by wind and hence accumulate anthropogenic aerosols.

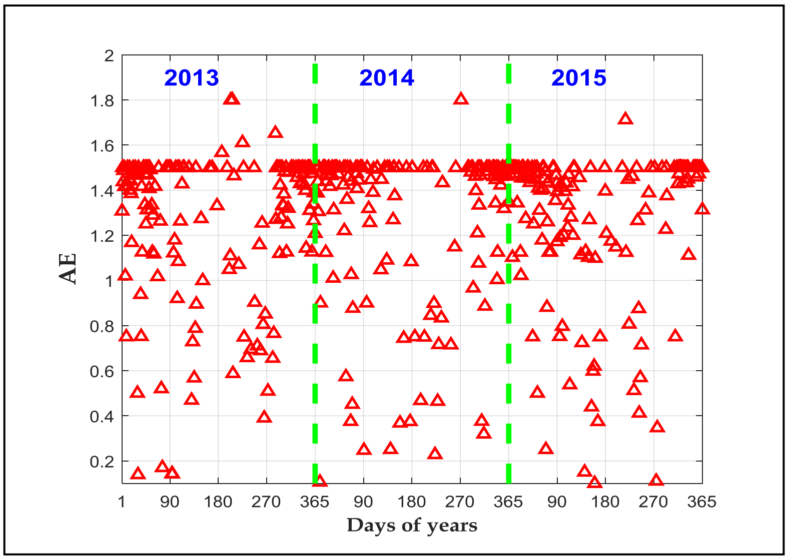

Fig. 3b. Daily variation of AE over Debretabour from 2013 to 2015

The daily values of AE parameters over Gojjam are plotted in Figure 3c. About 0.49% of AE values are less than 0.75, which indicates dust aerosols, and 1.13% of AE values are between 0.75 and 1.2, which represents mixed aerosols. The highest percentage of AE values, which is 98.38% are greater than 1.2, indicating that fine anthropogenic aerosols are dominant over the region due to biomass burning during the preparation of farmlands and production of charcoal, which produces large amount of smoke (black carbon).

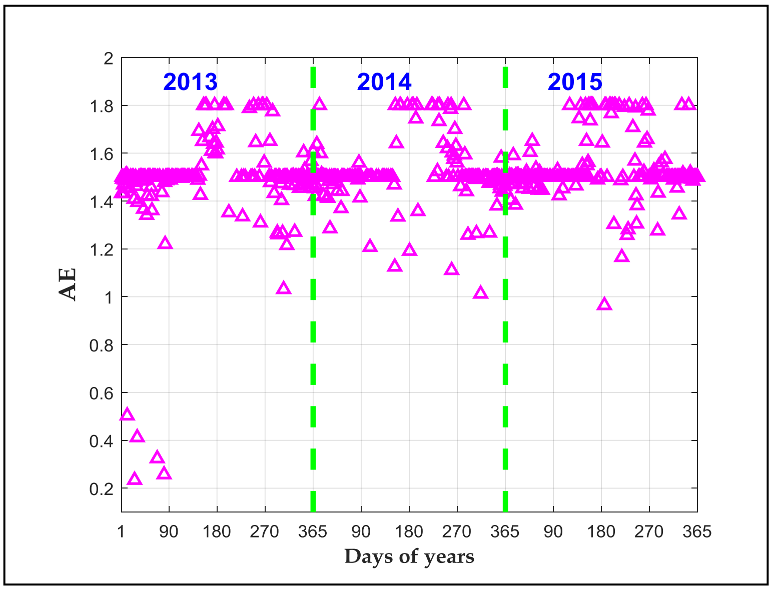

Fig. 3c. Daily variation of AE over Gojjam from 2013 to 2015

The daily values of AE parameters over Djibouti are displayed on Figure 3d. In Djibouti region, 48.70% of AE values are less than 0.75, which indicates that either dust or sea spray aerosols are more dominant over the region, because of its climatic condition as day time temperature is high, so evaporation is high and facilitate the sea salt aerosols from sea. About 21.88% of AE values found in between 0.75 and 1.2, which are mixed aerosols. Finally 29.42% of AE values are greater than 1.2, means fine anthropogenic aerosols. Djibouti is surrounded by oceanic regions such as Red Sea and Gulf of Aden, which are the major sources of natural marine aerosols. Marine aerosols are composed of primary aerosols, generated at the sea surface through wind driven processes, and secondary aerosols, through gas to particle conversion processes. Marine aerosols contribute to both fine and coarse particles, with dominant fractions of inorganic sea salt and organic particles in the super micron and submicron modes, respectively (Tesfaye et al., 2011). Statistical descriptions of AE values such as mean, standard deviation and CV for all stations from 203to2015 are displayed in Table 2 along with their percentage values provided in Table 3.

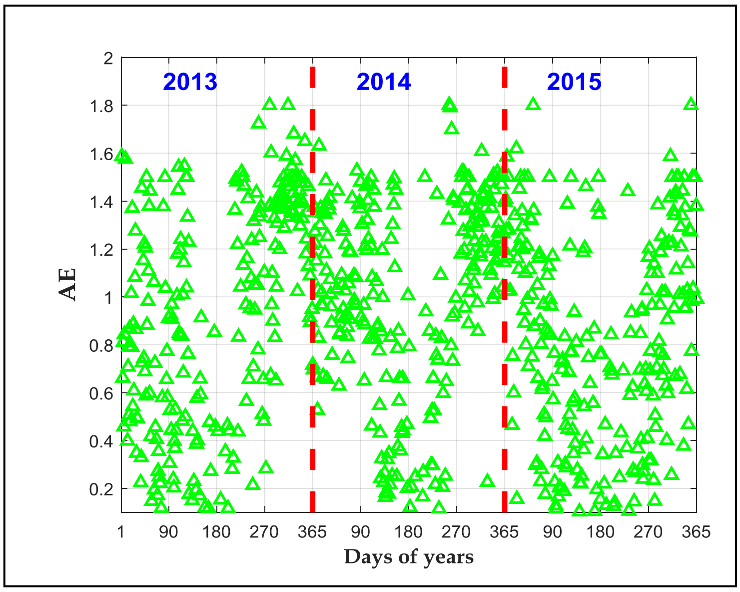

Fig. 3d. Daily variation of AE over Djibouti from 2013 to 2015

Table 2: Statistical description of AE for three years from 2013 to 2015 of each region

Station	Average (mean)	Standard deviation	Minimum value	Maximum value	CV%
Addis Ababa	1.4414	0.2838	0	1.8000	19.96
Debretabour	1.1209	0.1623	0.015	1.1430	14.47
Gojjam	1.5113	0.1577	0	1.8000	10.43
Djibouti	0.8025	0.5172	0	1.8000	19.59

Table 3: Percentage values of AE over Addis Ababa, Debretabour Gojjam and Djibouti for three years.

Station	AE<0.75	0.75<AE<1.2	AE>1.2
Addis Ababa	3.03%	1.76%	91.21%
Debretabour	21.93%	13.19%	64.87%
Gojjam	0.49%	1.13%	98.38%
Djibouti	48.70%	29.42%	21.88%

In this section, we analyze the monthly mean variation of AE values for three years (from 2013 to 2015) over four stations and results are displayed on Figure 4 (a) – (d). Figure 4 (a) depicts 94.44% of AE values over Addis Ababa, are greater than 1.2, and about 5.55% lies between 0.75 and 1.2, which indicates that fine mode aerosols from urban pollution are dominant. However, about 22.22% of AE is less than 0.75 in Debretabour (Figure 4b) which indicates dust aerosol, and about 20.88% of AE lies between 0.75 and 1.2, which indicates mixed type of aerosol, whereas 56.88% of AE indicates the presence of biomass burning aerosol. Similarly from Figure 4 (c), we observe AE values in Gojjam are greater than 1.2 for all years, which indicates that fine mode aerosol due to biomass burning from farm lands are dominant. For Djibouti (Fig 4 (d)) about 49.66% of AE is less than 0.75, showing that sea spray aerosols are dominant over the region, and about 23.8% of AE is greater than 1.2, which indicates biomass burning and urban pollution, and the remaining 26.44% of AE lies between 0.75 and 1.2, which indicates the presence of mixed aerosols.

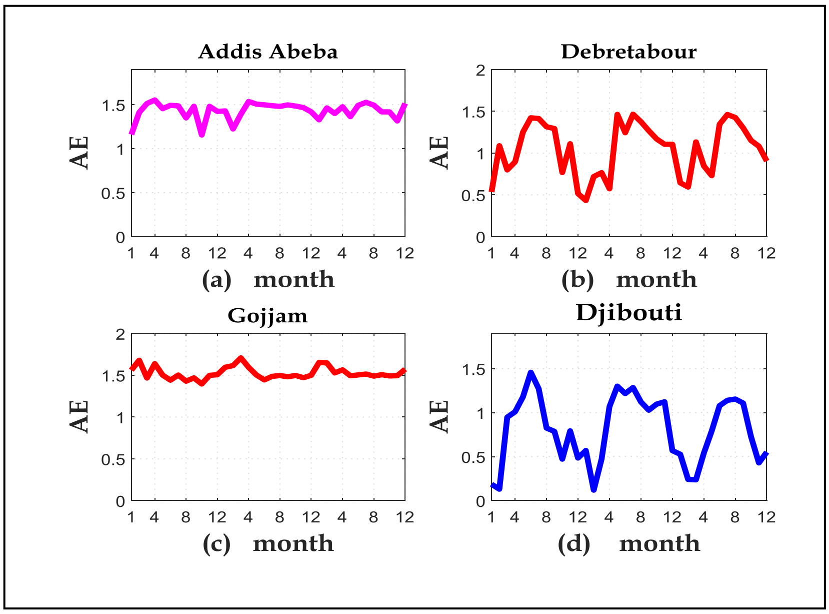

Fig. 4(a) - (d). Monthly variation of AE from 2013 to 2015

CONCLUSION

In this article we explored, daily and seasonal variations of AOD and AE parameters derived from MODIS satellite over three distinct locations in Ethiopia and marine location of Djibouti from 2013 to 2015. It reveals a significant difference in aerosol concentration and size distribution over all stations. From the 3 year mean AOD values for Addis Ababa (0.149), Gojjam (0.15), Debretabour (0.16) and Djibouti (0.3443) indicates that aerosols are more concentrated over Djibouti. Consequently coefficient of variation (CV) analysis reveals aerosol variability is observed in all stations, but it is highly variable in Debretabour (94.21%). Monthly mean seasonal variations of AOD shows a maximum value in kiremt (summer) and a minimum value in bega (winter) at all stations except Addis Ababa. Angstrom exponent parameter is used to characterize the aerosol particle sizes. The observed AE values between 0 and 1.8 in all stations indicates the presence of different type of aerosols from different sources. Mean monthly AE values show that, Addis Ababa is dominated by fine anthropogenic aerosols **(**urban pollution) due to heavy industrialization and Debretabour is distributed by biomass aerosol due to more dust. Gojjam, being an agricultural area loaded with biomass burning aerosols (mostly from coal related smoke).Djibouti is dominated by sea spray aerosols as it is surrounded by oceanic regions.

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This research did not receive any financial support

CONFLICT OF INTERSET

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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