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Spatial-Temporal Assessment of Changes in Aerosol Optical Properties Pre, during, and Post COVID-19 Lockdowns over Kenya, East Africa

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Abstract

In reference to the contribution of natural and anthropogenic activities to pollution levels over Kenya, investigation of the changes in aerosol optical properties during COVID-19 lockdowns was assessed. To achieve its objective the present study used aerosol Optical Depth (AOD), Angstrom exponent (AE) and Single Scattering Albedo (SSA) from Ozone Monitoring Instrument (OMI) and Moderate-resolution Imaging Spectroradiometer (MODIS) satellite sensors, to analyze the variations in aerosol properties for pre, during and post COVID-19 pandemic. This was achieved by doing a phase wise analysis of the spatial-temporal variation over Kenya during the lockdown phase. A comparison to reference period was done for the pre-lockdown, during lockdown and post lockdown phases. 24-hour mean value data retrieval over Kenya was obtained from the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) model from 1st April to 30th June 2019 - 2021. It was evident that the emissions into the atmosphere over Kenya did not reduce relatively during the COVID-19 lockdowns. The spatial-temporal variability of the pollutants (AOD, AE AND SSA) did not depict a significant deviation from the normal in the lockdown phase as compared to the same season in the previous one year and a year after lockdowns. This was because of the migration of aerosols from regional sources, dominance of natural sources such as geothermal activities and low stringent levels on lockdown protocols. However meteorological factors have had great influence on the variability and seasonality of the aerosol optical properties over the sampled region, with the March-April-May (wet season) recording lower values of AOD and June-July-August (dry season) registering the highest values of AOD. In summary lockdowns did not alter values of aerosol optical properties over Kenya due to limited control of anthropogenic emissions. The findings of this proposed study can be utilized by the scientific community and regulators to strengthen the emergency response to check on high pollution in Kenya until cleaner technologies are put in place.

Subject Areas

Atmospheric Sciences

Keywords

Aerosols, Pollution, Aerosol Optical Properties, COVID-19, Lockdowns

1. Introduction

Atmospheric aerosols are liquid and solid particles with varying diameters suspended in the atmosphere [1]. Their diameter may vary from a few nanometers to tens of micrometers. Aerosols play an important role in solar radiation budget, climate change, hydrological cycle, air quality and visibility through the process of scattering and absorption of incoming solar energy from the sun [2]. Aerosols may cause health-related issues such as asthma, premature death, lung cancer, cardiopulmonary mortality and pulmonary inflammation [3]. The knowledge on the concentration and chemical composition of these particles at different locations and spatial scales is a key as far as health is concerned [4].

In December 2019, there was an eruption of a pandemic of the severe acute respiratory syndrome (SARS) species of virus in Wuhan city of China [5] and later spread to the whole world [6]. The virus was named Corona Virus Disease 2019 (COVID-19) whose symptoms are related to the already witnessed SARS and Middle East Respiratory Syndrome (MERS) virus [7]. Lockdowns were therefore instituted to control the spread of the COVID-19 over various domains [8].

Scientists have investigated various domains on the effect of COVID-19 lockdown aerosol optical properties. For instance, [9] analyzed the effect of SARS COVID-19 lockdowns on AOD over urban and mining regions in India and reported a huge drop in AOD levels during the lockdown periods as compared to its AOD in 2019. In another related study, [10] conducted research on the effect of lockdowns on AOD over urban and mining regions in India and indicated that the lockdown reduced the air pollution levels and therefore decreased the AOD. Further, [11] used space-time machine learning models to analyze COVID-19 pandemic lockdown effects on AOD over Europe and reported AOD drop during the COVID-19 lockdown.

A number of studies have further ascertained the trend of optical properties over Kenya and how they are influenced by anthropogenic activities. [12] did a trend analysis of the AOD_{550} and $AE_{470\text{-}660nm}$ anomaly over the East Africa region using MODIS and recorded an increasing trend over Nairobi. [13], analyzed the changes in Absorption Angstrom Exponent (AAE) and Single Scattering Albedo (SSA) over Athens city in Greece during the pre-lockdown (1^{st} to 2^{nd} March 2020), lockdown (23^{rd} March to 3^{rd} May 2020) and post lockdown 4^{th} to 31^{st} May 2020) periods. The results revealed an increase in AAE during lockdown period due to reduced emissions from fossil fuel combustion, while a slight increase in SSA values was noted indicating that the dominant aerosol were scattering in nature.

These lockdowns provide a unique scientific opportunity to detect and understand the impact of anthropogenic emissions on Earth's atmosphere at all spatial scales -from region to global [14], hence forming a basis for research in air quality in a number of studies worldwide. Additionally, similar studies have attracted intense scientific research in 2020 at various domains with the view of understanding both regional and global aerosol variability. However, most of these studies have mainly focused on the variation of PM and aerosol optical properties and how they relate to the COVID-19 lockdowns and curfews.

Air quality studies have not been adequately done in Kenya because of limited ground-based date on pollutant concentration and trends.

Since there is a justified link between COVID-19 lockdowns, air quality and associated aerosol optical properties (AOD, AE and SSA) reported by previous researchers over various domains [15] [16], little knowledge has been documented over the same in East Africa especially Kenya. As a result, the study sought to assess the impact of the lockdowns and curfews on aerosol optical properties over the current study domain.

1.1. Study Area and Meteorology

Kenya is a country in East Africa region located between the longitudes 32˚ East and 42˚ East and latitudes 5˚ South and 5˚ North. It is bordered by Ethiopia to the north, Tanzania to the south, South Sudan to the Northwest, Uganda to the west and Somalia to the east.

The country is populous with a population of 47,564,296 (Kenya 2019 census). Kenya has a land area of about 569,374 km^2 with varying topography and which includes glaciated mountain peaks with permanent snow cover, plateaus and coastal plain [12]. The long-term annual average values of temperature over the Kenyan territory are 25˚C to 34˚C while the relative humidity ranges between 24.0% and 69.0% respectively [17]. Climatologically, the seasons are, MAM, JJA, SON and DJF. MAM and SON are the local wet sessions whereas DJF and JJA are local dry seasons.

1.2. Data

To ascertain the impact of lockdown on air quality, selected aerosol properties and pollutant concentrations were studied in three phases as designed by [18].

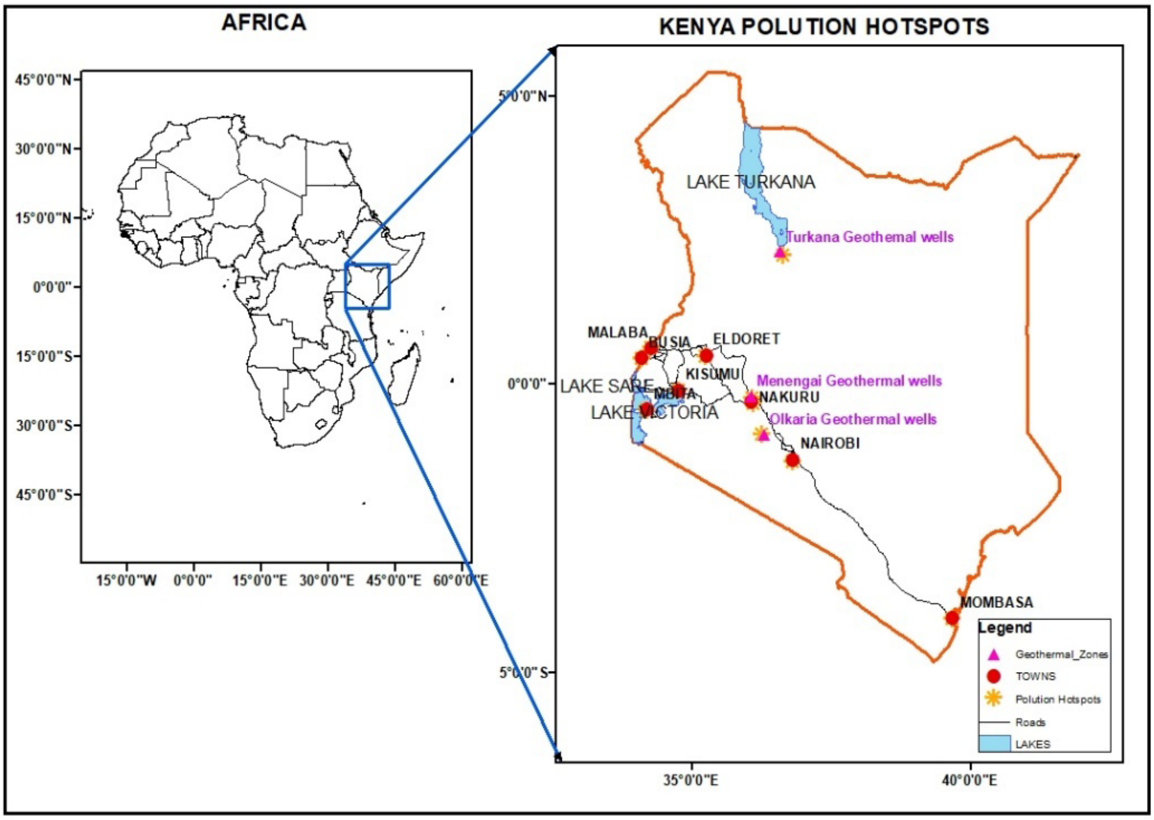

Figure 1. Map of Kenya. The inset shows the map of Africa the area shaded blue represents the water bodies while the wording in purple and the red coloured spots are pollution hot spots.

First was the Pre-lockdown period. This period ran from April 1st to June 30th 2018. The second period during the study was during the lockdown period over the study domain from April 1st to June 30th 2019 while the last period of study was the Post Lockdown which spans from April 1st to June 30th 2020. These data products were sourced from http://giovanni.gsfc.nasa.gov/giovanni/.

2. Materials and Methods

2.1. Instruments

2.1.1. Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS satellite was launched in December 1999. The second was launched on May 4, 2002, on board the aqua platform [19] [20]. It has 36 channels spanning the spectral range from 0.44 to 15μm. These measurements are used to derive spectral aerosol optical thickness and aerosol size parameters over both land and ocean [21]. The sensor has a swath of ~2330km, with a temporal resolution of 1 - 2 days and acquires data at three spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). Seven of these bands operating in near-ultra-violet (UV), visible and near infrared spectroscopy (IR) wavelength regions (0.415 - 2.155 μm), can effectively retrieve AOD over land and ocean [20] [22] using two different algorithms: dark target (DT) and "deep blue (DB)" [22].

2.1.2. Ozone Monitoring Instrument (OMI)

The Ozone Monitoring Instrument provides high-resolution data sets with daily global coverage. The instrument measures a reflectance in wavelength range 264 – 504 nm. It was launched in July 2004 by Nasa's Earth Observing Systems (NEOS) onboard the aura satellite by Netherlands agency for aerospace programme in collaboration with the Finnish Meteorological Institute [23] [24]. Although designed to retrieve datasets of trace gases, OMI's wavelength of a range of ~400 nm allows detection of elevated layers of absorbing aerosols hence providing vital information on aerosol types of particular regions at four processing level; - level 1, level 2 and level 3. The level -3 AOD at 1˚ × 1˚ grid resolution used in this study was sourced from https://disc.sci.gsfc.nasa.gov).

2.1.3. Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)

MERRA-2 model is a long-term global reanalysis that assimilate the space-based observations of aerosols and represent their interactions with other physical processes in the climate system. It provides datasets for combined dark blue AOD at λ = 500 nm, AE at λ = 440 nm and SSA. The spatial distribution of each pollutant was obtained and specified for our area of interest. The selected aerosol optical properties (AOD, AE and SSA) satellite data was collected from 2019 to 2021 over Kenya. The data accessed from the GIOVANNI (Goddard Earth Sciences Data and Information Services Centre, or GES DISC), indicates various Geoscience data from NASA satellites directly on the web portal (https://earthdata.nasa.gov/), without any disturbances of traditional data acquisition and analysis methods.

2.2. Methodology

AOD (τ) which is defined as the integrated extinction coefficient over a vertical column of unit cross-section was determined using Beer-lambert-Bouguer law in Equation (1) [25]. It describes the degree to which aerosols prevent the transmission of light from the sun by either absorption or scattering [19] [25] [26]. The Voltage (V) measured by a sun photometer is proportional to spectral irradiance (I) reaching the instrument at surface. The estimated top of the atmosphere spectral irradiance (I_o) in terms of voltage (V_o) is obtained by sun photometer measurements from sensors on board satellites. The Beer-lambert-Bouguer law has been used by a number of researchers [24] [26] [28];

$$V(\lambda) = V_o(\lambda) d^2 \exp\left[-\tau(\lambda)_{tot} * m\right] \quad (1)$$

where V is the digital voltage measured at wavelength λ, V_o is the extraterrestrial voltage, d is the ratio of the average to the actual Earth-Sun distance, (τ_{tot}) is the total optical depth and m is the optical air mass [23] [25].

The size of aerosols can be estimated from spectral aerosol optical depth from 440 nm to 870 nm. The negative slope (first derivative) of AOD with wavelength in logarithmic scale is known as the angstrom exponent (α).

$$\alpha = -\frac{d \ln \tau_a}{d \ln \lambda} = \frac{\log\left(\frac{\tau\lambda_1}{\tau\lambda_2}\right)}{\log\left(\frac{\lambda_1}{\lambda_2}\right)} \tag{2}$$

where α is the Angstrom exponent, τ_a is the aerosol optical depth, and λ is the wavelength.

Further, the SSA, which is the ratio of the scattering efficiency to total extinction efficiency can be approximated by power law relation [27].

$$\omega_0 = \frac{\tau_{sp}}{\tau_{ext}} = \frac{\tau_{sp}}{\tau_{sp+\tau_{ap}}} \tag{3}$$

where τ_{sp} is the scattering optical depth, τ_{ap} is the absorption optical depth and τ_{ext} the total extinction optical depth. The single scattering albedo (SSA) represents a key parameter in describing the aerosol optical properties. The SSA describes the portion of solar energy radiation scattered from the main beam passing through the atmosphere. The SSA influences the diffuse radiation, while its effect on direct radiation can be considered negligible.

3. Results and Discussion

3.1. Aerosol Optical Depth Variability

Figure 2 shows the Time series area averaged AOD results during the study period over Kenya. It is noted that MAM and SON have decreased AOD because of increased rainfall washout [17] [20]. These seasons are also characterized by minimum dust loading since the ground is wet. Further, minimum AOD is recorded during April while maximum AOD values are recorded in June. From the start of April, it is noted that AOD increased for all the years 2019, 2020 and 2021. However there is no notable change in AOD variation in 2020 that may be associated with prevailing COVID-19 lockdown over the country. This fact is attributed to negative variation in AOD for all seasons during the year which is a result of the transported pollution inlands since the region experiences dominant South Easterlies and North Easterlies during greater period of the year [12].

Figure 3 depicts the spatial maps for variation in AOD over Kenya during the study period. The first, second and third columns represent April, May and June while the first, second and third rows represent the years 2019, 2020 and 2021 respectively. In the investigation of the spatial variation in AOD for the months of April, May and June in 2019, 2020 and 2021 for the pre-lockdown (2019), lockdown (2020) and post lockdown (2021), it was noted that for April 2020, AOD values over the entire country were lower in MAM as compared to JJA in 2019 to 2021. These results are consistent with the findings of [28]. The lower AOD in MAM is attributed to the prevailing local wet season which enhances the wet scavenging of aerosols while the higher AOD in the local dry month of June is associated with reduced wet scavenging and increased anthropogenic activities such as biomass burning and dust generation [12] [19] [28].

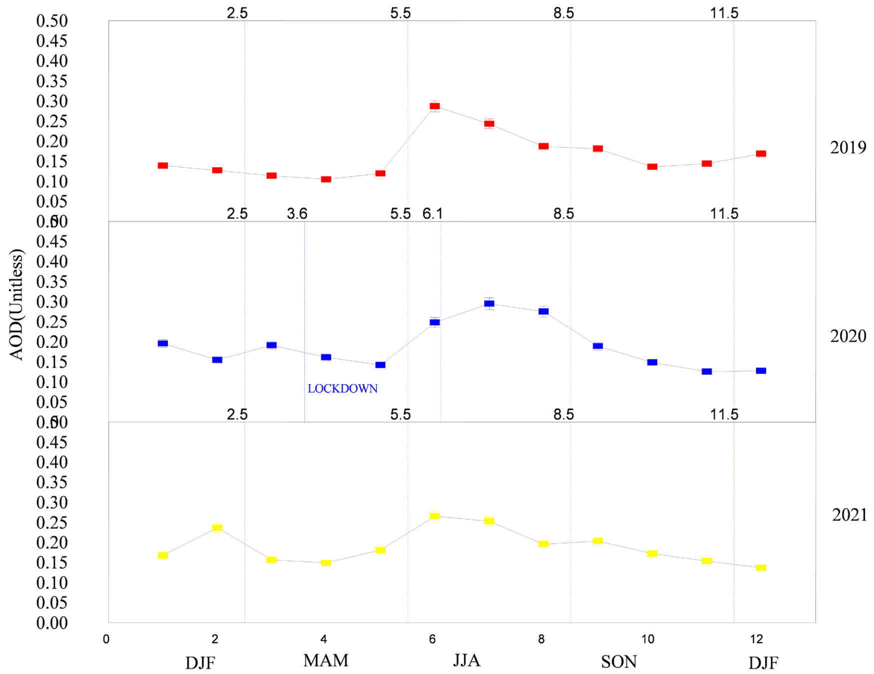

Figure 2. Time series, Area average of AOD over Kenya from January to December for 2019 to 2021.

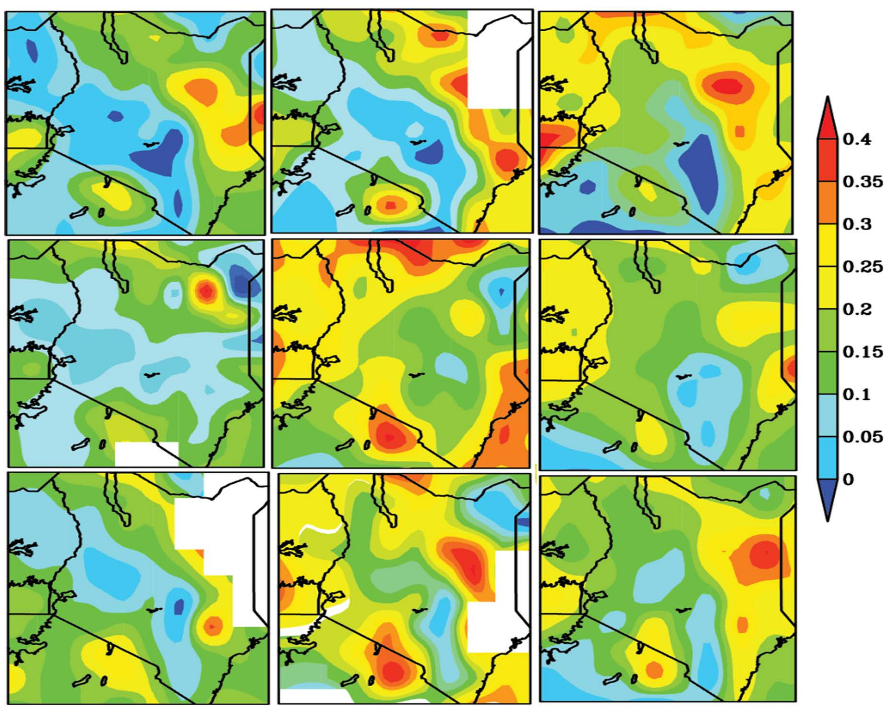

Figure 3. Spatial maps for variation of AOD over Kenya between April to June from 2019 to 2021.

The government instituted lockdown protocols in April 2020 to curtail normal operations had insignificant variations on AOD spatial distributions as indicated by **Figure 3**. It is noted that COVID-19 lockdowns instituted by the government in April had no significant influence on AOD spatial-temporal variation over Kenya. The AOD variability is influenced by long-distance transport as justified by the results from the HYSPLIT model as reported by [28]. The central and southeastern Kenya had slightly lower mean AOD as compared to the north and northeastern regions of the country during the study period. This is as a result of the higher dust levels in the northeastern and northern parts of the country as compared to the wet central and southwestern parts of the country. These facts agree with the findings of [12] which postulated that aerosol optical properties over East Africa region are controlled by monsoon precipitation that enhance long distance transport [28]. The relatively higher AOD over the coast region is as a result of sea salt aerosols that are domicile there because of the marine environment. Cumulatively during the entire lockdown period in Kenya, (22nd March 2020 to 30th June 2020), no observable change in spatial variability of AOD was noted as compared to the mean AOD in 2019 and 2021 for the same time period.

3.2. Angstrom Exponent

The average annual seasonal pattern of AE is shown in **Figure 4**. It is clear that AE values over Kenya peaked in May and November during the study period. This is associated with high concentration of aerosols of the fine mode species from burning of biofuels and biomass burning which are least washed down by rainfall as a result of reduced precipitation.

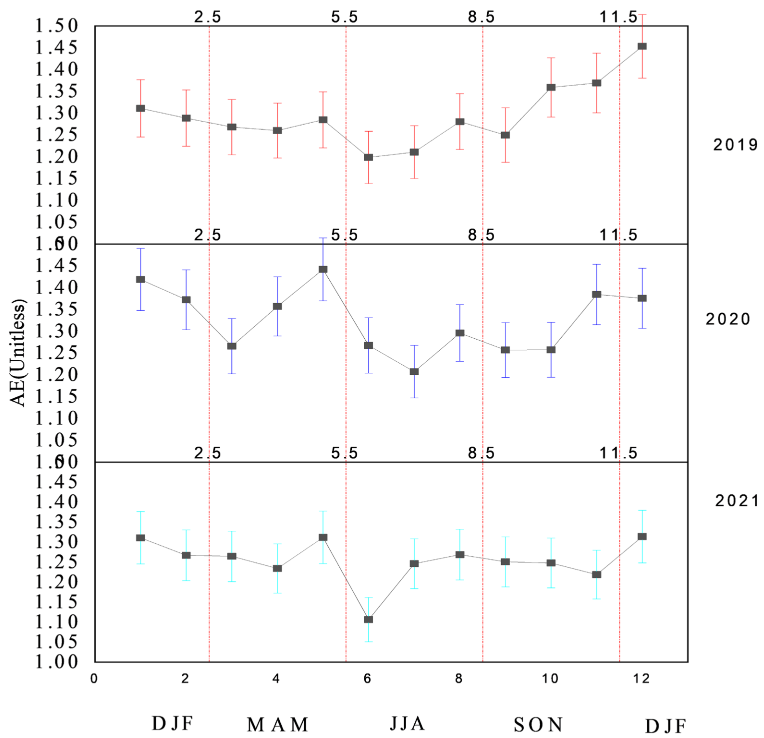

Figure 4. Time series, Area average of AE over Kenya from January to December from 2019 to 2021.

Lower values closer to 1 *i.e.* 1.1, 1.2 and 1.2 for 2019, 2020 and 2021 are observed during the months of June respectively. These values depicted more contribution of course-mode dust particles relative to fine-mode particles since June is considered a dry month [28]. The average spatial patterns of $AE_{470\text{ -}870}$ over Kenya observed during the study period is illustrated in **Figure 5**. The first, second and third columns represent April, May and June while the first, second and third rows represent the years 2019,2020 and 2021 respectively. The values of AE_{470} are observed to vary between 0.6 to 1.15 with lower values $AE_{470} < 1$ dominating most parts of the study domain. This is attributed to dominance of course mode aerosols resulting from desert dust produced locally [29] as well as transported from the Saharan and Arabian Peninsula [30]. The coastal region had moderately low AE_{470} associated with course mode aerosols such as sea salt [25] [26] [28]. The arid areas of northwest Kenya around Lake Turkana posted low values of AE_{470}, resulting from local production of dust aerosols from the Chalbi desert along with carbonaceous aerosols from the alkaline Lake Turkana [31].

From **Figure 5**, it was also noted that there is no significant relation between AE trends to the national wide COVID-19 lockdown. The COVID-19 lockdowns instituted by the Kenya and regional governments did not result in any change in total AE over Kenya during the period of study. This points to the fact that there was marginal change if any in the size of aerosols in the atmosphere over Kenya during this period. The inter-seasonal disparity in the meteorological conditions at the coastal strip and dust generation in the north-eastern drought prone area is the strongest contributing factor to the lower values of AE along the coastal line and in the north and northeastern part of the country.

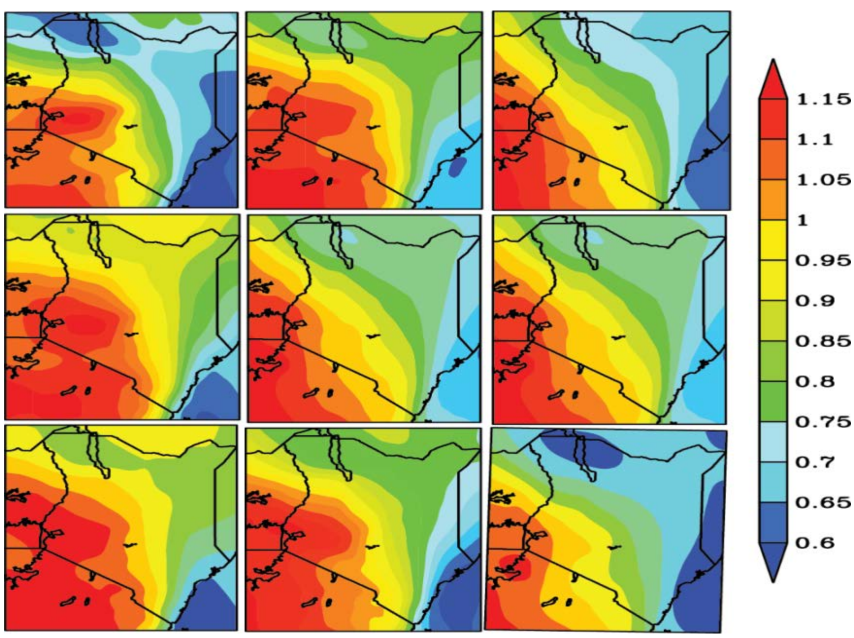

Figure 5. Spatial maps of Area-Average of Deep Blue Angstrom Exponent over Kenya between April to June from 2019 to in 2021.

3.3. Single Scattering Albedo

A lower SSA indicates an enviromental episode dominated by either desert dust or biomass burning while a Single Scattering Albedo at 440 nm between 0.9 - 0.98 indicate urban/industrial aerosols, 0.92 - 0.93 indicate desert dust and 0.89 - 0.95 indicates biomass burning [32].

The SSA over Kenya ranges between 0.156 to 0.160 from January to mid-June during the study period indication that the urban/industrial aerosols dominated the atmosphere during this period (as depicted in **Figure 6**). Coincidently this period corresponds to the lockdown period declared by the government of Kenya. However past this period, the SSA is erratic hitting as low as slightly over 0.166 in July and as high as 0.168 during the month of September.

In **Figure 7**, the first, second and third columns represent April, May and June while the first, second and third rows represent the years 2019, 2020 and 2021 respectively. The values of SSA over northeastern Kenya as indicated by **Figure 7** are associated with desert dust.

It is apparent from the time series of the SSA over Kenya that the COVID-19 lockdown is seen to create no disruption of the normal distribution and concentration of main pollutants and aerosols over the Kenyan territory however, there is no significant impact of the lockdown on SSA values over Kenya.

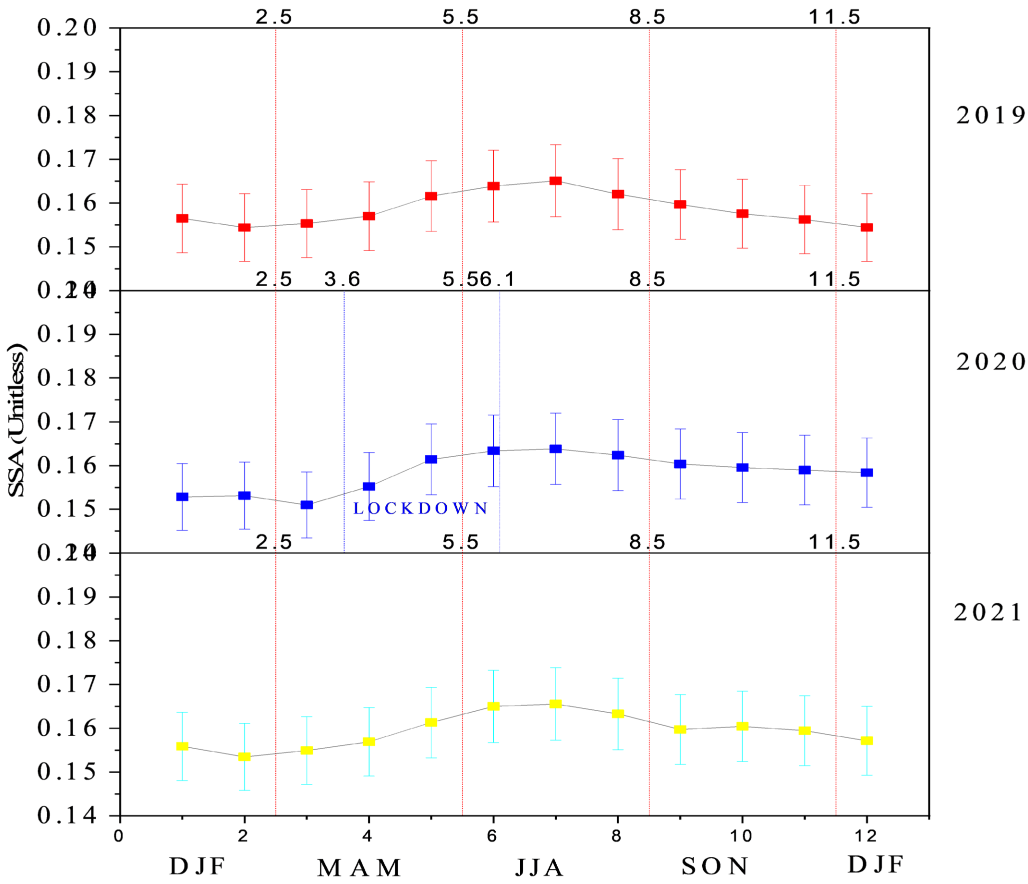

Figure 6. Time series, area average of SSA over Kenya from 2019 to 2020.

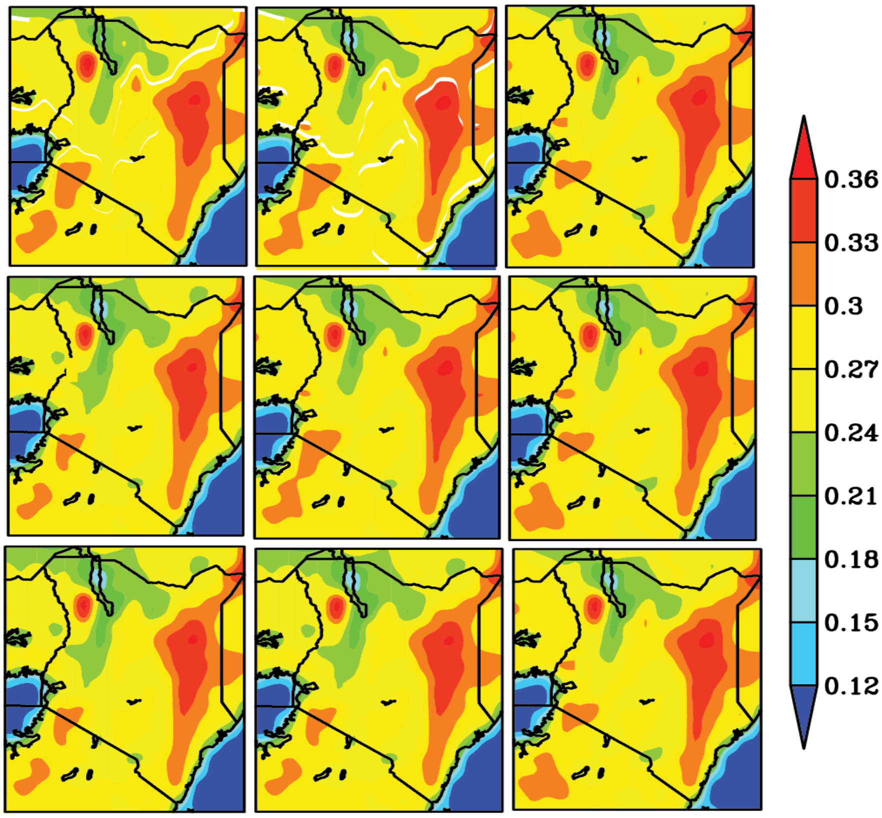

Figure 7. Spatial maps of area-average of single scattering Albedo over Kenya between April to June from 2019 to in 2021.

4. Conclusion and Recommendation

Meteorological and anthropogenic factors modulate the seasonality and diurnal variation of the selected aerosol optical properties over Kenya. The high AOD in some places is related to proximity of aerosol sources in such places. However the significant pollutant concentration registered during lockdown months is primarily due to natural sources such as geothermal emissions, dust generation and sea salt aerosols. However, time series for all the aerosol optical properties (AOD, AE and SSA) recorded an annual variation, registered as a result of meteorological factors such as rainfall which cause downwash of aerosols and temperatures which affect atmospheric chemistry.

The short-term impact of COVID-19 lockdown gives an important memorandum to all the world leaders, administrators and policymakers to recover the damaged environmental quality along with global human health. The short-term lockdown system is the best remedy for all industrial and non-industrial nations to manage high pollution of the total environment. The partial lockdowns may not be a permanent solution to recover the health of the total environment, so more research and development is required in this specific research gap, however, the findings of this research are highly essential to combat the terrific situation and scientists should take proper responsibility to minimize the pollution standard for sustainable urban and rural environmental management.

Conflicts of Interest

The authors declare no conflicts of interest.

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