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Using remote sensing to monitor Aerosol Optical Thickness (AOT) and its relationship with land cover in Lagos Metropolis, Nigeria

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ABSTRACT

Aerosol Optical Thickness (AOT) is the most fundamental parameter for determining the optical properties of aerosols, which can be extracted from remotely sensed images using the atmospheric correction equation for atmospheric reflectance and radiative transfer model. This study used multi-temporal and multi-spectral Landsat imageries of Lagos Metropolis at two epochs (2002 and 2020) to evaluate the AOT levels in the metropolis. The 6S model was used to generate a Look-Up Table (LUT) using Py6S, a python based 6S module. This was used to simulate the AOT using land surface reflectance and top of atmosphere reflectance. A comparative assessment of the method against the ground-based measurements of particulate matter (PM) at three different locations shows a strong positive correlation between the imagery-derived AOT values and PM . Generally, the AOT values increased from 2002 to 2020 and this could be explained by the increased urban expansion in the metropolis. This alarming scenario requires urgent intervention and mitigation efforts. Remote sensing-based AOT monitoring is a possible solution.

1. Introduction

Air pollutants such as Ozone (O_3), Nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), Carbon monoxide (CO), Particulate matter (PM, also known as aerosol) have negative impacts on human health and the environment (Nguyen et al., 2019; Althuwaynee et al., 2020). These pollutants have led to more deaths in Nigeria than in South Africa, Kenya, and Angola combined. Atmospheric aerosols from either natural or anthropogenic sources have significant impacts on air quality and climate. These aerosols consist of solid and liquid microscopic particles and gas carriers and are poly-disperse systems suspended in the atmosphere with particle sizes ranging between 10^{-3} μm and 10^{2} μm (Yang, 2017). According to Zhang et al. (2015), AOT is a typical atmospheric monitoring measure of aerosols. Ground-based sun photometers and satellite sensors are the two primary approaches for monitoring aerosols (Wei et al., 2020). The ground-based platforms can provide real-time data that can be used in calibrating satellite-borne AOT instruments to improve the accuracy of the AOT retrieval algorithm in the remote sensor. Also, satellite monitoring systems play vital roles in broad-level or macro-scale derivation of spatial data (Ranjan et al., 2020). Compared to the ground-based technique of aerosol monitoring, Remote Sensing (RS) and Geographic Information Systems (GIS) offer a cost-effective and timely approach to atmospheric aerosols monitoring. From a holistic perspective, this study assesses the spatio-temporal dynamics of aerosol concentration in the Lagos megacity, specifically within the 17 Local Government Areas (LGAs) of the metropolis using multi-spectral and multi-temporal Landsat imageries. The spatial variability of AOT was estimated based on the improved dark target method. The dense dark vegetation (DDV) technique was used to estimate the land surface reflectance. The DDV approach involves detecting dark pixels and estimating their reflectance and this mainly implements two visible bands (blue and red) and one SWIR band.

Furthermore, the retrieved AOT values were used to analyze the concentrations of fine particulate matter (PM), which is a major contributor to air pollution. Validation of the AOT results from the satellite imageries was done using ground-based PM measurements. Information concerning the concentration and variability

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could help decide where to set up air pollution monitoring stations in the state. With the view of making cities and human settlements inclusive, safe, resilient, and sustainable, this study contributes to the United Nations Sustainable Development Goal (SDG) Number 11. Specifically, goal 11.6 aims to reduce the adverse per capita environmental impact of cities, with special attention to municipal and other waste management by 2030. The rapid growth of the Lagos megacity and its projected increase justifies the need to study the dynamics and futuristic outlook of air quality in the state.

2. Methods

2.1. Study area

The study area (Lagos Metropolis, shown in Figure 1) lies between latitudes 6˚20'00''N - 6˚42'10''N and longitudes 3˚02'30''E - 3˚42'40''E. It comprises of 17 Local Government Areas (LGAs). Lagos Metropolis is known in Lagos State as one of the world's megacities experiencing rapid urbanization and urban sprawl (Obiefuna et al., 2018). The climate is controlled by two air masses: tropical continental and tropical maritime air masses. The latter is wet and originates from the Atlantic Ocean, while the former originates from the Sahara Desert and is warm, dry and dusty (Obiefuna et al., 2013). The region experiences typically two seasons: the rainy season (April-October) and the dry season (November-March). Lagos City is strongly affected by sea-based disturbances with an average wind speed of 4.3 km/h and monthly average temperatures ranging from 28.6 ˚C in July/August to 33.7 ˚C in February/March, whilst the air is very hot throughout the year (Ojeh et al., 2016).

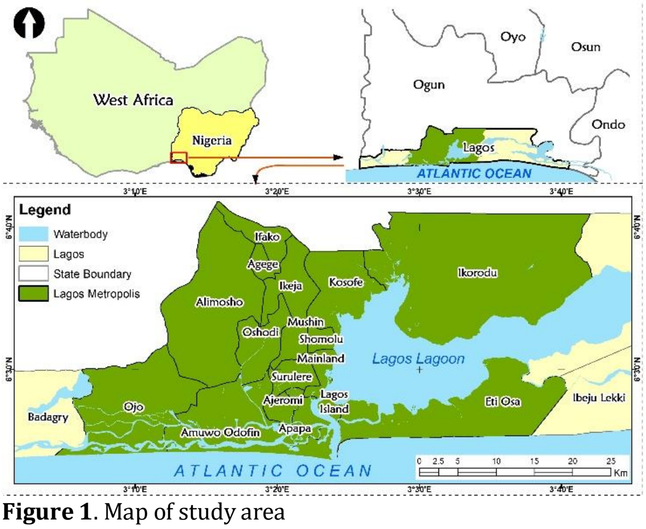

Figure 1. Map of study area

2.2. Datasets

Landsat Imagery: Landsat 7 Enhanced Thematic Mapper (ETM) (2002-12-28) and Landsat 8 Operational Land Imager (OLI) (2020-01-20) satellite imageries were downloaded from the online archive of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/).

Particulate Matter: Particulate matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}) data were obtained with the ground-based air quality egg instrument. The device was used to acquire the PM data at the selected critical sites (Ojota, Iwaya, and Mushin). The data were measured on a weekly basis between 9:00 am and 5:00 pm from February 2019 – July 2019.

2.3. Land surface reflectance determination

The DDV technique was adopted in this study to estimate the land surface reflectance. This was done using the improved dark-pixel method developed by Levy et al. (2010), which is dependent on Normalized Difference Vegetation Index (NDVI) and scattering angle. The equations for determining the surface reflectance are given in Luo et al. (2015) and Ou et al. (2017).

2.4. Constructing the Look-up Table (LUT)

Radiative Transfer Models (RTMs) are commonly used in atmospheric science to simulate the passage of solar radiation through the atmosphere. They have a variety of applications, including atmospheric analysis and the design of solar energy systems, and are commonly used in remote sensing and earth observation, but with regard to the various parameters of input and outputs, they are also seen as challenging to use (Wilson, 2013). The 6S mode of radiation transfer is a model of atmospheric radiation transfer that has been used in the Earth-atmosphere system to simulate the transmission of solar radiation, and it is a commonly accepted and applied model (Vermote et al., 1997; Zhao et al., 2016). 6S is used operationally as part of the atmospheric correction procedure for Landsat Thematic Mapper (TM) and MODIS. In addition, 6S is often widely used by end-users for atmospheric correction of images from various sensors. Py6S is a Python interface to the 6S model. In this study, the 6S model was run on the Python interface to simulate the atmospheric properties of the Landsat 8 OLI and Landsat 7 ETM sensor for blue and red bands.

2.5. Image classification

Using the maximum likelihood classification algorithm, the satellite imageries were classified into five information classes – bare land, built-up area, vegetation, water body and wetland. This image processing operation was carried out with the ENVI Classic v 5.0.

2.6. Quantitative analysis and validation

The quantitative analysis enabled an understanding of the values associated with spatial and temporal changes. Descriptive statistics were used to summarize the data for interpretation. For validation, Pearson's correlation coefficient was used to infer the level of interdependence between imagery-based AOT for year 2020 and the ground-based PM data.

3. Results

This section presents the imagery-derived AOT maps and land cover maps for 2002 and 2020 and the spatial and temporal analysis, as well as the validation with ground-based PM data. Figures 2 and 3 present the variation in aerosol optical thickness and the spatial variation in land cover respectively over Lagos Metropolis. Tables 1 and 2 present the AOT distribution per land cover class and the coefficients of correlation between PM and AOT.

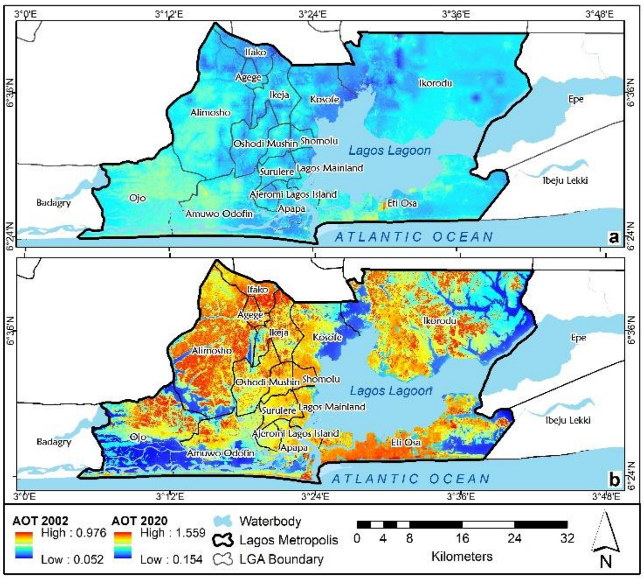

Figure 2. Variation in aerosol optical thickness over Lagos Metropolis – (a) 2002 (b) 2020

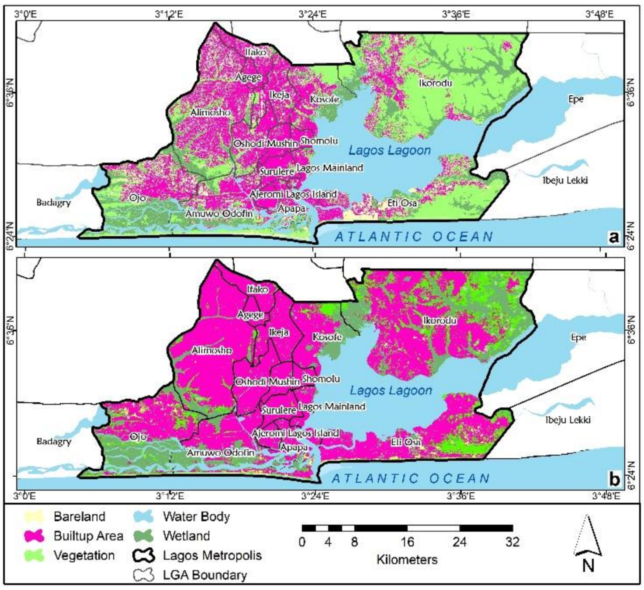

Figure 3. Spatial variation of land cover over Lagos Metropolis – (a) 2002 (b) 2020

Table 1. AOT distribution per land cover class

Class	Year	Count	Min	Max	Mean
Bare land	2002	131625	0.11	0.98	0.40
	2020	27294	0.37	1.70	1.25
Built-up area	2002	483444	0.05	0.60	0.35
	2020	896934	0.37	1.75	1.32
Vegetation	2002	554683	0.07	0.80	0.33
	2020	207787	0.37	1.68	1.03
Wetland	2002	231202	0.08	0.48	0.32
	2020	280720	0.36	1.66	0.73

4. Discussion

Generally, the AOT distribution over the Lagos metropolis is observed to have increased over the years. This could be due to the increasing urbanization as observed by Offor et al. (2016). It can be observed that the correlation between the imagery-derived AOT for year 2020 and the different sizes of PM in Ojota are negative, possibly, due to the time the data was acquired (evening) as opposed to the high positive correlation value in Okobaba, which was acquired during the daytime. The correlation values between AOT and PM in Iwaya are positive but less in magnitude in comparison to that of Okobaba.

Table 2. Correlation coefficients of the relationship between in-situ PM data and imagery derived AOT for year 2020

Location		PM_1	$PM_{2.5}$	PM_{10}	AOT
Ojota	PM_1	1.00	0.99	0.99	-0.62
	$PM_{2.5}$	0.99	1.00	0.99	-0.62
	PM_{10}	0.99	0.99	1.00	-0.67
	AOT	-0.62	-0.61	-0.67	1.00
Iwaya	PM_1	1.00	0.99	0.99	0.26
	$PM_{2.5}$	0.99	1.00	0.99	0.28
	PM_{10}	0.99	0.99	1.00	0.29
	AOT	0.26	0.28	0.29	1.00
Okobaba	PM_1	1.00	0.98	0.98	0.70
	$PM_{2.5}$	0.99	1.00	0.99	0.73
	PM_{10}	0.98	0.99	1.00	0.73
	AOT	0.70	0.72	0.73	1.00

The land cover classification results clearly showed that the study area had undergone tremendous spatial changes in its land cover. The observed changes in the land cover results are corroborated by the results of Obiefuna (2021), where an increase in the built-up area, decrease in bare land, and decrease in vegetation cover were observed between 2001 and 2019. In addition, a slight decrease in water bodies was also reported within the same period. Recently, Faisal et al (2021) reported a similar result in their study on the analysis of urban growth and land cover change scenario in Lagos.

The results of the relationship between AOT and Land cover reveal how AOT varied spatially with different land cover types. The high AOT observed in the built-up areas and bare lands agrees with the studies of Sun et al. (2016), and Liu et al. (2020). However, Liu et al. stated specifically that AOT values are highest in the spring season due to the presence of dust particles in the atmosphere. This corroborated the generally high AOT observed in this study. Although the AOT values over vegetation cover and wetland are relatively low compared to other land cover types, the values are still higher than usual. This could be due to some vegetation and wetlands being sandwiched in between the built-up areas and bare lands.

5. Conclusion

This paper has monitored and examined the AOT concentration in the Lagos Metropolis and its relationship with land cover at two epochs (2002 and 2020). This study only examined the air pollution distribution during the dry season (between December and January). Studies have shown that air pollution is higher in the dry season than in the wet season, during which dust-laden north-easterly trade winds blow in from the Sahara Desert (Offor et al. 2016). Akinyoola et al. (2018) reported that the aerosol loading/concentration is of high increase in the south-south and southwestern (coastal) regions of Nigeria. This corroborates the generally high aerosol concentration observed in the study area in our findings.

The study showed how increased urbanization has increased the AOT concentration in the metropolis drastically over the years. The increased AOT observed in the area indicates the ever-present urbanization activities, including industrial and traffic activities. To curb the ever-increasing urban air pollution in the Lagos metropolis, more research should be carried out to examine the dynamics of AOT and Particulate matter concentration. This is because of the dynamic nature of air pollution in the coastal area has not been fully explored. Also, a full-scale monitoring of air pollution over the whole of Lagos State should be encouraged to inform the government and air quality control agencies of the present state of this perilous atmospheric phenomenon. Researchers should adopt satellite-based methods for air quality monitoring in Lagos State based on cost and timely benefits.

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