Research article

Evaluating the potential of remote sensing imagery in mapping ground-level fine particulate matter ($PM_{2.5}$) for the Vaal Triangle Priority Area

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Abstract

The quality of air breathed in South Africa is of great concern, especially in industrialised regions where $PM_{2.5}$ concentrations are high. Long term exposure to $PM_{2.5}$ is associated with serious adverse health impacts. Traditionally, $PM_{2.5}$ is monitored by a network of ground-based instruments. However, the coverage of monitoring networks in South Africa is not dense enough to fully capture the spatial variability of $PM_{2.5}$ concentrations. This study explored whether satellite remote sensing could offer a viable alternative to ground-based monitoring. Using an eight-year record (2009 to 2016) of satellite retrievals (MODIS, MISR and SeaWIFS) for $PM_{2.5}$ concentrations, spatial variations and temporal trends for $PM_{2.5}$ were evaluated for the Vaal Triangle Airshed Priority Area (VTAPA). Results were compared to corresponding measurements from the VTAPA surface monitoring stations. High $PM_{2.5}$ concentrations were clustered around the centre and towards the south-west of the VTAPA over the highly industrialised cities of Vanderbijlpark and Sasolburg. Satellite retrievals tended to overestimate $PM_{2.5}$ concentrations. Overall, there was a poor agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. Root mean square error values ranged from 6 to 11 µg/m³ and from -0.89 to 0.32 for the correlation coefficient. For satellite remote sensing to be effectively exploited for air quality assessments in the VTAPA and elsewhere, further research to improve the precision and accuracy of satellite-retrieved $PM_{2.5}$ is required.

Keywords

Satellite retrievals, ground-based data, $PM_{2.5}$ concentration, spatial variations

Introduction

At a global scale, air pollution is ranked fourth amongst the leading risk factors to human health, with recent estimates linking it to over 5 million premature deaths (Mannucci and Franchini, 2017; Bhanarkar et al., 2018; Health Effects Institute, 2019). In sub-Saharan Africa (SSA), particularly in the urban areas, the deterioration in air quality as a result of rapid urbanisation, population growth and industrial expansion is evident (Amegah and Agyei-Mensah, 2017; Fayiga, Ipinmoroti and Chirenje, 2018). Of great concern to public health, are the levels of fine particulate matter ($PM_{2.5}$) in the cities of SSA, which are amongst the highest in the world (Fayiga, Ipinmoroti and Chirenje, 2018; Katoto et al., 2019). Long-term exposure to high levels of $PM_{2.5}$ is harmful to humans as it can lead to increased severity in the symptoms of asthma and chronic obstructive pulmonary disease (Dieme et al., 2012; Feng et al., 2016).

In South Africa, air pollution has become an important issue, especially in industrialised regions like the Vaal Triangle Airshed Priority Area (VTAPA) where strong economic growth has taken place (Naiker et al., 2012; Zhu et al., 2012). The VTAPA routinely experiences poor air quality as a result of strong emissions from industries, residential burning, vehicles and fugitive dust sources coupled with unfavourable meteorological conditions that have led to the accumulation of $PM_{2.5}$ in high concentrations (Annegarn and Scorgie, 1997; Scorgie et al., 2003).

To improve air quality and public health in the VTAPA, the Department of Environmental Affairs (DEA) developed an air quality management plan that outlined strategies to reduce emissions from key sources (Department of Environmental Affairs and Tourism, 2009; Tshehla and Wright, 2019). Furthermore, air quality monitoring stations were placed at identified hotspots in the VTAPA, so as to assess pollution trends and to ascertain whether concentrations of $PM_{2.5}$ and other pollutants are being kept within the regulatory limits (Ngcukana, 2016; Altieri and Keen, 2019). However, similar to other urban areas across the world (Gupta et al., 2006; Tian and Chen, 2010; Hu et al., 2014), the spatial coverage of stationary ambient monitors in the VTAPA is low. Intra-urban variability of $PM_{2.5}$ concentrations is therefore not accounted for. In order to capture the full-scale variability of $PM_{2.5}$ concentrations in the VTAPA, there is need for a vast network of monitoring stations. However, this requires large financial resources (Munir et al., 2016).

Satellite remote sensing can provide repeated observations of atmospheric pollution at large spatial scales. The monitoring of air pollutants using satellite observations is gradually gaining more attention in atmospheric pollution studies (Engel-Cox, Hoff and Haymet, 2004; Duncan et al., 2014). Advancements in regional algorithms have allowed for the large scale retrieval of $PM_{2.5}$ concentrations at fine spatial resolutions that have a reasonable agreement with ground measurements (van Donkelaar et al., 2015; van Donkelaar et al., 2016). These retrievals have been successfully used to assess long term spatial-temporal patterns of $PM_{2.5}$ in regions experiencing poor air quality such as China and Saudi Arabia (Lu et al., 2017; Munir et al., 2016; Shi et al., 2012).

In the case of South Africa, knowledge on the applicability of remote sensing to monitor air pollution levels is insufficient. A regional case study by Kneen et al. (2016) revealed that satellite technology has the potential to offer a practical and credible option to ground-based monitoring in South Africa. However, further investigation is still required in order to have more concrete evidence to advocate the use of remote sensing for air quality monitoring in South Africa. This study evaluated the potential use of remote sensing imagery for air quality assessment in the VTAPA using a publicly available high resolution remotely sensed $PM_{2.5}$ concentration global dataset developed by van Donkelaar et al. (2015). This dataset begins in 1998 and ends in 2016. Spatial variations in satellite-retrieved $PM_{2.5}$ concentrations were examined, and temporal trends were explored.

Methods

Study region

The VTAPA is an industrialised region lying on the South African Highveld, a high central plateau of South Africa that forms part of the grassland biome. It stretches from southern Gauteng down to the northern section of the Free State province with an area of over 4 900 km^2 (Figure 1). The region is host to industries including iron and steel manufacturers (ArcelorMittal steel and Davesteel), ferroalloy (Samancor Metalloys) and petrochemical companies (Sasol Chemical Industries, Natref and Omnia fertilisers). Eskom's Lethabo power station is also located in this region.

The VTAPA has a population of over 3 million people with most of its inhabitants residing in south-western Johannesburg, Soweto, Sebokeng, Sharpeville, Vereeniging, Vanderbijlpark, Sasolburg and Zamdela.

Satellite-derived data

Global satellite-derived $PM_{2.5}$ concentration data with a high spatial resolution (1 km x 1 km) covering a 10-year period from 2007 to 2016 was obtained from the Atmospheric Composition Analysis Group of Dalhousie University (http://fizz.phys.dal.ca/~atmos/martin/). This global dataset was generated by merging satellite

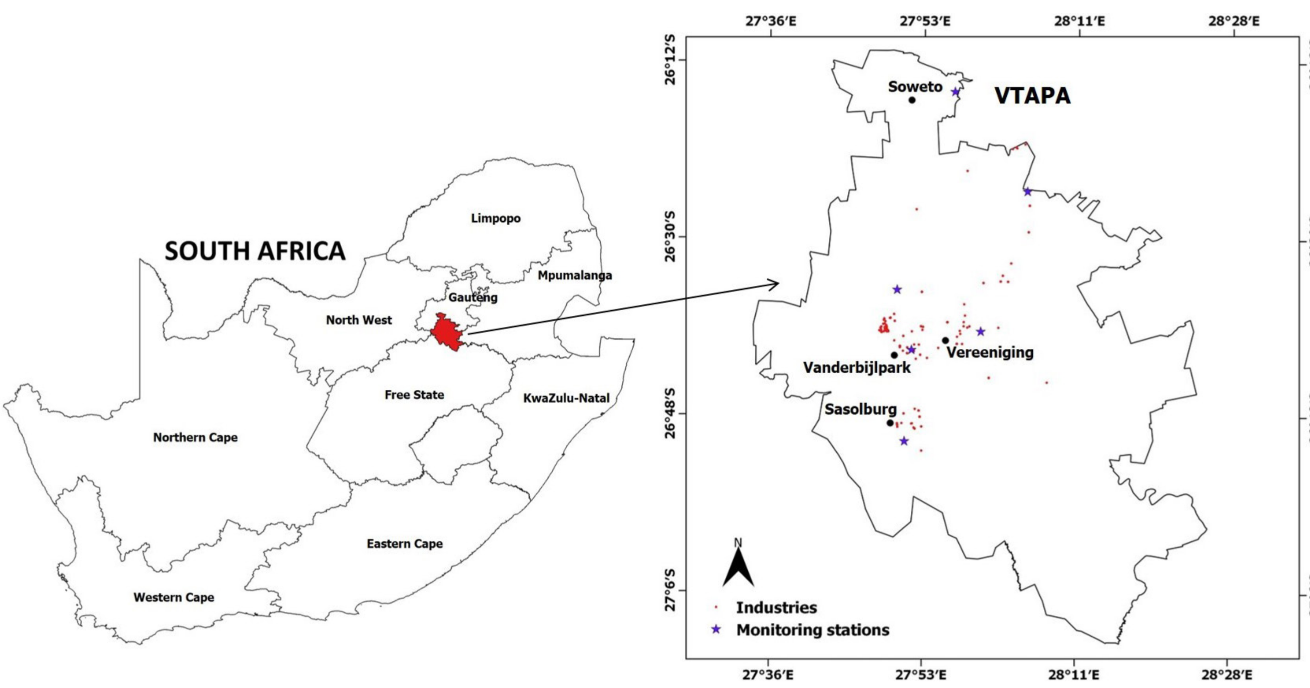

Figure 1: *Study area map showing the location of the VTAPA in South Africa*

retrievals of AOD (Aerosol Optical Depth) from the NASA MODIS (MODerate resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging SpectroRadiometer) and SeaWIFS (Sea-viewing Wide Field-of-view Sensor) instruments with AOD simulated using the GEOS-Chem chemical transport model in order to produce $PM_{2.5}$ estimates (van Donkelaar et al., 2016). The $PM_{2.5}$ estimates were then calibrated by means of a Geographically Weighted Regression (GWR) based on ground observations (van Donkelaar et al., 2015). These estimations have a good agreement with ground-based $PM_{2.5}$ measurements (R^2 = 0.81, slope of 0.82).

Based on previous research, uncertainty may exist in the global $PM_{2.5}$ data as a result of the satellite retrieval method (van Donkelaar et al., 2015). Existing studies have resolved this by applying a three-year average as an annual average (Han, Zhou and Li, 2015; Peng et al., 2016; Shisong et al., 2018). For this research, three-year moving averages were applied to the satellite retrievals from the period 2009 to 2016. A subset of the global $PM_{2.5}$ dataset for each year was extracted to cover the VTAPA study area using the Integrated Land and Water Information System (ILWIS) program (ITC, 2011).

Ground measured data

The VTAPA air quality monitoring network consists of six stations (Figure 1), which are located in Diepkloof (26.2507S, 27.9564E), Kliprivier (26.4203S, 28.0849E), Sebokeng (26.5878S, 27.8402E), Sharpeville (26.6898S, 27.8678E), Three Rivers (26.6583S, 27.9982E) and Zamdela (26.8449S, 27.8551E), and have been operational since 2007. Based on the simulated spatial distribution of air pollutants from dispersion modelling these monitoring stations, except for Kliprivier, are considered to be located in high PM_{10} concentration zones (Thomas, 2008; Department of Environmental Affairs and Tourism, 2009; Ngcukana, 2016). $PM_{2.5}$ concentration data (2007–2016) for the VTAPA network was acquired from the South African Air Quality Information System (SAAQIS). This data was quality checked by removing negative values. For consistency with the satellite retrievals, three-year moving averages were also applied to the ground $PM_{2.5}$ concentration data from the period 2009 to 2016.

Results and discussion

Comparison of temporal variations between satellite-retrieved and ground measured $PM_{2.5}$ concentrations

A comparison between satellite-retrieved and ground measured $PM_{2.5}$ concentrations for the six monitoring stations in the VTAPA for the period 2009–2016 is shown in Figure 2. It can be observed that in most cases, there was an overestimation of observed $PM_{2.5}$ concentrations by the satellite retrievals, with the exception for the Kliprivier and Sebokeng stations, where ground measurements were much higher than the satellite-retrieved estimates. Both satellite retrievals and ground measurements showed that $PM_{2.5}$ concentrations for all sites, except Diepkloof, were above the annual National Ambient Air Quality Standards (NAAQS).

Figure 3 shows the 8-year averages for satellite-retrieved and ground observed $PM_{2.5}$ concentrations at all stations. The Sharpeville station had the smallest offsets with a difference of 0.7 µg/m³ between observed measurements and estimates retrieved from satellite imagery. Fairly high offsets were observed for the Sebokeng (-4 µg/m³), Zamdela (5 µg/m³) and Klipriver stations (-6 µg/m³). The performance of the satellite retrieved model was less encouraging for the Diepkloof and Three Rivers stations that both had considerably large offsets of 10 µg/m³.

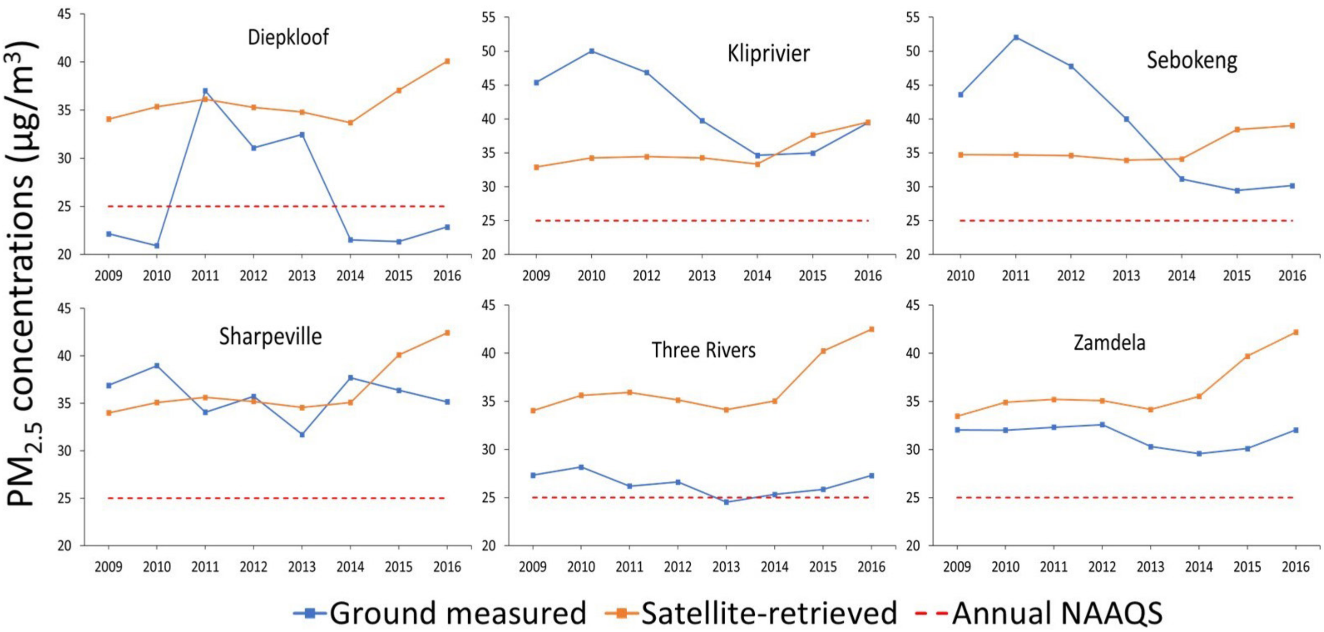

Figure 2: *Comparisons between satellite-retrieved and ground measured $PM_{2.5}$ concentrations at Diepkloof, Kliprivier, Sebokeng, Sharpeville, Three Rivers and Zamdela stations from 2009 to 2016*

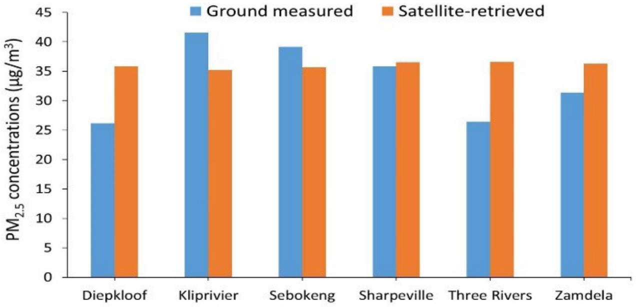

Figure 3: *Comparison of the ground measured and satellite-retrieved 8-year averaged $PM_{2.5}$ concentrations at Diepkloof, Kliprivier, Sebokeng, Sharpeville, Three Rivers and Zamdela stations.*

Table 1: *Comparisons between $PM_{2.5}$ satellite retrieval and ground measurements for the period 2009 – 2016 using RMSE and R statistics.*

Year	RMSE (µg/m³)	R
2009	8	-0.79
2010	10	-0.86
2011	9	-0.70
2012	8	-0.89
2013	6	-0.19
2014	7	0.10
2015	10	0.32
2016	11	-0.04

Satellite retrieval performance evaluation

Satellite retrievals for $PM_{2.5}$ were compared with the ground measurements from all monitoring stations for the period 2009 to 2014 using the following performance evaluation metrics: root mean square error (RMSE) and correlation coefficient (R). These statistics were computed in R statistical software using the modstat function in the Open Air package. RMSE values ranged from 6 to 11 µg/m³, with an average of 9 µg/m³, indicating a significant difference between ground measured and satellite-retrieved $PM_{2.5}$ values (Table 1). R values for the years 2009–2012 ranged from -0.70 to -0.89, demonstrating strong negative correlations between satellite retrievals and ground-based measurements. These inverse relationships, however, do not imply a good agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. R values from the period 2013 to 2016, displayed weak correlations between ground measured and satellite-retrieved $PM_{2.5}$ concentrations.

Spatial variations of satellite-derived $PM_{2.5}$ concentrations

Variations in annual $PM_{2.5}$ concentrations over the VTAPA from 2009 to 2016 are presented in Figure 4. The average $PM_{2.5}$ concentrations in this region increased significantly by 25% from 33 µg/m³ in 2009 to 41 µg/m³ in 2016. This large increase took place mainly from 2015 to 2016, during which the highest concentrations (41 µg/m³–44 µg/m³) were observed in the VTAPA. The high $PM_{2.5}$ concentrations from 2015 to 2016 could possibly be due to increased AOD resulting from changes in aerosol mass transport during the *El Niño* episodes experienced in South Africa. *El Niño* events can increase regional aerosol concentrations by

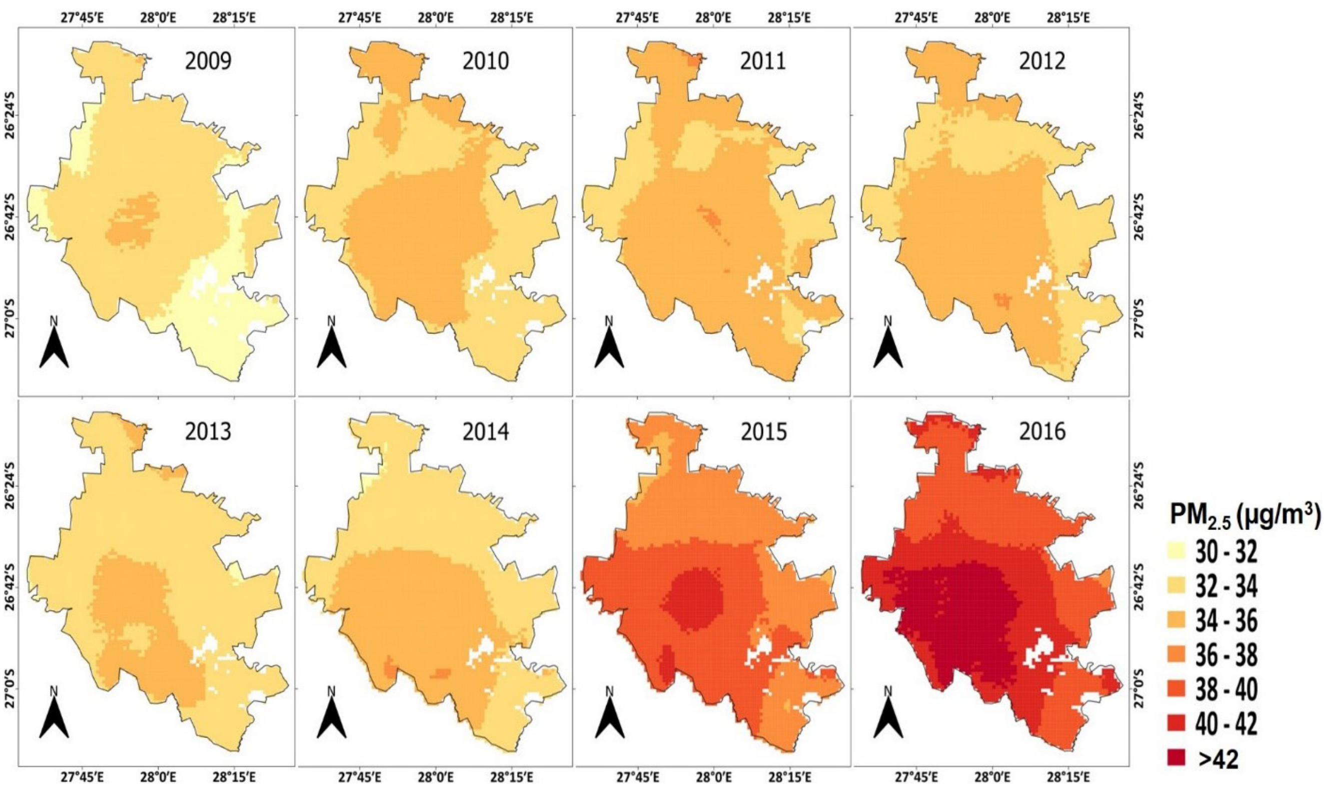

Figure 4: *Spatial distributions of annual $PM_{2.5}$ concentrations in the VTAPA from 2009 to 2016.*

altering atmospheric circulation systems which leads to changes in the transport and removal of aerosols (Yu et al., 2019). Wang et al., (2019) found a positive link between the *El Niño* Southern Oscillation (ENSO) index and $PM_{2.5}$ concentrations in North China during the 2015/2016 *El Niño* event. Mean $PM_{2.5}$ concentrations in North China were significantly higher in 2015 (51 µg/m^3–95 µg/m^3) as compared to 2017 (41 µg/m^3–74 µg/m^3).

Similar spatial patterns for $PM_{2.5}$ concentrations in the VTAPA were observed throughout the period (2009–2016) in which the majority of PM pollution is concentrated around the centre and towards the south-western region of the VTAPA. These spatial patterns are comparable to those observed by Thomas (2008), who modelled PM_{10} concentrations in the VTAPA using a dispersion model. Due to the low dispersion potential of pollutants in the VTAPA, high $PM_{2.5}$ concentrations were clustered in the central to the south-west region over the cities of Vanderbijlpark and Sasolburg, where heavy industrial (iron and steel, ferroalloy and petrochemical) activities, domestic burning and mine operations take place. Spatial distributions for the VTAPA show that high $PM_{2.5}$ concentrations were also concentrated in the northern part of the area. The main source for $PM_{2.5}$ in this area is residential combustion from the Soweto township and windblown dust from gold mine dumps.

Conclusion

This study evaluated the potential value of satellite remote sensing as a viable alternative to $PM_{2.5}$ ground-based monitoring in the VTAPA. There was a poor agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. Satellite retrievals tended to overestimate $PM_{2.5}$ concentrations resulting in inflated values throughout most of the VTAPA. According to Kneen et al. (2016), due to financial constraints in South Africa, monitoring stations are placed in regions with the predicted worst air quality that is mainly urban and industrial centres. This will lead to mainly high values being used in the calibration of $PM_{2.5}$ estimates in the GWR model which in turn can result in the overestimation of satellite-retrieved $PM_{2.5}$ concentrations. Therefore, in order to improve the accuracy of the GWR model for satellite retrievals, the positioning of ground-based stations in South Africa needs to be optimised so as to have monitoring data that is more spatially representative.

The relationship between AOD and $PM_{2.5}$ is an important source of uncertainty in satellite retrieval accuracy as the AOD-$PM_{2.5}$ relationship can vary across space and countries. This could have contributed to some of the inconsistencies between ground measured and satellite-derived $PM_{2.5}$ concentrations for the VTAPA. There is a need for an independent assessment of the AOD-$PM_{2.5}$ relationship through an integrated monitoring strategy like SPARTAN (Surface PARTiculate mAtter Network) in which $PM_{2.5}$ monitoring instruments are collocated with ground-based sun photometers for AOD measurements. This will help in evaluating AOD-$PM_{2.5}$ model accuracy and enhance $PM_{2.5}$ estimates from satellite AOD retrievals.

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Author contributions

The majority of the work was conducted by Luckson Muyemeki, who was responsible for data processing, analysis, interpretation, and writing the manuscript. Stuart. J. Piketh and Roelof Burger conceptualised the study and assisted in interpretation of data and editing the manuscript.

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