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An assessment of aerosol optical depth over three AERONET sites in South Africa during the year 2020

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\textbf{A B S T R A C T}

It is important to notice that the world health organization (WHO) on the 11th of March 2020, declared COVID-19 a global pandemic and in response governments around the world introduced lockdowns that restricted human and traffic movements including South Africa. This pandemic resulted in a total lockdown from 26 March until 16 April 2020 in South Africa with expected decrease in atmospheric aerosols. In this present study, the aerosol optical depth (AOD) over Southern Africa based on ground-based remotely sensed data derived from three AERONET sites (Durban, Skukuza and Upington) during 2020 were used to determine the restriction response on atmospheric aerosol pollution. The study used data from 2019, 2018 and 2017 as base years. The AERONET derived data was complemented with the HYSPLIT Model and NCEP/NCAR Reanalysis data. The study findings show that peak increase of AOD corresponds to Angstrom exponent (AE) enhancement for two sites Durban and Skukuza during winter (JJA) while the Upington site showed a different trend where peak AOD were observed in spring (SON). The study also observed the influence of long transport airmasses particularly those originating from the Atlantic and Indian ocean more so for the Durban and Skukuza sites (summer and autumn) thus these sites received fresh marine aerosols however this was not the case for Upington which fell under the influence of short-range inland airmasses and was likely to receive anthropogenic and dust aerosols. The major results suggest that the lockdowns did not translate into a significant decrease in AOD levels compared to previous immediate years. The results have presented restriction response of AOD over South Africa but additional analysis is required using more locations to compare results.

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\textbf{Introduction}

It is well known that WHO on the 11th of March 2020, declared COVID-19 a global pandemic. To curtail the spread of the disease, most governments around the world introduced national or regional lockdowns that restricted human movement, restricted economic activities and restricted traffic movements including South Africa [4,10,17,55]. The reduced economic

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activities resulted in the improvement of ambient air quality status [48,49]. This was confirmed in studies by [9,11,32,53,65] including cities across China and India [44,68,72]. The restrictions gave the scientific and policy makers a rare opportunity to have a near ideal real world state of ambient air status from which to make comparisons from. Poor air quality contributes to negative health outcomes as well as increasing the burden of disease [3,24,47]. There are six criteria pollutants namely SO₂, NO₂, Particulate Matter (PM₂.₅,PM₁₀), O₃, CO₂ and NO₂. Our study sought to investigate particulate matter falling under atmospheric aerosols.

The atmospheric aerosols affect atmosphere processes and human health (Zang et al., 2015; Bates et al., 2019; [73]). PM is formed as a result of the total summation of all suspended particles within the atmosphere [59] and is stratified into classes of PM₂.₅ (fine) and PM₁₀ (coarse). PM₂.₅ are particulates with an aerodynamic size ≤2.5 while PM₁₀ are those with an aerodynamic size of ≤10 [2,47]. Fine particulate matter is damaging to human health due to its ability to penetrate the human respiratory system and the bloodstream causing such conditions as stroke, respiratory as well as cardiovascular diseases [30,48]. At the atmospheric level aerosols play a key role in the earth’s energy balance because when they react with solar radiation they modify clouds microphysics [35] while also providing a cooling effect from their reflective nature [34]. Estimates suggest that aerosols can offset 25–30% over greenhouse gases [34]. It is well known that these suspended particles have both natural (volcanic eruption, sea salt, wind advection) and anthropogenic (fossil fuel combustion, industrial action) cadence to enter the atmosphere. Aerosols that are a challenge are those emitted from biomass combustion or carbonic fuels and contain dark matter or soot [34] thus trapping incoming solar radiation hence inducing global warming and climate change [22]. Nonetheless, both concentration and size distribution depend on production or emission source (Qi et al., 2016). However, the size distribution allows accurate prediction of what extent wind transports particulate matter and aerosols. It is well known that reduction in size particle prompts its surface increase making easy absorption of elements on PM (Zhang et al., 2018). Therefore, elements could easily be transported through PM.

Several studies have characterized PM size distribution using the Angstrom Exponent (AE) including [5,8,35,57,71]. On the other hand, [1] investigated aerosols variation over South Africa using ground-based AERONET stations focusing on microphysical properties of aerosols at the Skukuza site while Anoruo [6,7] studied aerosols interactions over Skukuza with the findings indicating a strong summer seasonal interaction of aerosols. Skukuza is located in the Southern Africa sub-tropical zone characterized by biomass burning [37]. Furthermore, [38] studied intercomparison of ground-based and space-based aerosols characterization using Moderate Resolution Imaging Spectroradiometer (MODIS) and AERONET (AERonet Robotic Network). The results of the study indicated mixed aerosols typing over all seasons. Also, [63] presented spatial and seasonal aerosols climatology over Upington. Furthermore, [37] investigated aerosol optical depth over Skukuza using the AERONET network. Although the study was limited to one year (December 2005 to November 2006) the results of the study show strong mineral dust aerosol sources. Also, over the West Africa Sahel region and other stations of Africa, the potential clue for the investigation of aerosols indirect impact on climate change is presented by Anoruo et al., (2022a, 2022b) over aerosols seasonal variations through the application of AERONET derived data.

It is therefore observed that this present study aims to expand on the results of [37] and investigate the AOD over additional sites of Upington and Durban. The purpose of our study was to investigate the impact of COVID-19 related lockdowns on atmospheric aerosols using a seasonal characterization approach over three selected stations located in Southern Africa namely Durban, Skukuza and Upington. The study also further investigated the association between atmospheric aerosols and meteorological parameters during the COVID-19 lockdowns as aerosols have demonstrated a lot of variations on a Spatio-temporal level [54]. It could be seen that [29] postulates that lockdowns alone cannot improve air quality but rather meteorological conditions are a key factor too as they play an important role in the transformation of atmospheric aerosols [74]. The results of this study presents the state of atmospheric aerosols during the pandemic over South Africa in Section 3.

Methods and materials

Description of the study area

Our study focused on three study sites namely Durban (site located at 29.82 S; 30.94 E), Skukuza (site located at 24.99 S; 31.59 E) and Upington (site located at 28.38 S;21.16 E) as illustrated in Fig. 1. In terms of elevation, Durban is the site located at the lowest elevation followed by Skukuza and while Upington is located at the highest elevation. Skukuza lies at an elevation of 365 m above sea level and receives mean annual rainfall between 160 mm to 550 m with 65% sandy soils (Majozi et al.,2017) while Upington is located inland at an estimated elevation of 836 m above sea level [54], with an average daily maximum temperature ranging between 28°C and 40°C [50] annual rainfall ranging between 100 mm (Western region) to 500 mm (eastern region) with a generality climatic conditions being classified as semi-arid and arid conditions [61]. On the other hand, Durban lies at an estimated elevation of 8 m above sea level [54]. Besides, the elevation differences the other factor between the sites is the source of aerosols with the Durban site likely to be affected by marine aerosols while Upington is likely to influenced by desert aerosols and Skukuza being affected by marine aerosols originating from the Mozambiquan corridor.
Aerosol optical depth (AOD)

In this study, we assessed aerosol optical depth (AOD) using extinction and backscatter coefficient from three AERONET stations (Durban, Skukuza and Upinton). Statistical data management to filter missing gaps were adopted from [7] to iterate month-wise AOD and Ångstrom Exponent (AE) data from each bin. Additionally, we performed size weighting distribution to confirm aerosols asphericity over the study stations using extinction coefficient. The seasonal selection of data allowed knowledgeable evaluations of aerosol size distribution. However, AOD (440 nm) and AE (440–675 nm) in the visible wavelength band gave detailed information on aerosol typing. Data from the AERONET network has been used extensively in research due to its high level of accuracy and low level of uncertainty [35] with estimates putting the uncertainty for AOD at 0.01 [40]. The aerosol advection densities over the stations were inspected using HYSPLIT-4 Model back trajectories at heights of 500 m, 1000 m and 1500 m AGL. The study chose these three heights of trajectories to cater for differentials in airmass movements [49]. The HYSPLIT model has been applied extensively in tracing sources of aerosols including in studies by Matandirotya and Burger [49], Matandirotya et al. [48], Anoruo [8].

HYSPLIT 4 model and NCEP/NCAR reanalysis data

To trace the sources, paths, and trajectories of long-range transport aerosols the study ran backward trajectories using the HYSPLIT 4 Model. The HYSPLIT Model was complemented by data from the National Centres for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) global reanalysis [33]. Our study chose reanalysis data as they were able to run simulations at the upper boundary-layer level [15] as well as having the ability to offer an understanding of large scale circulation phenomenon [74]. The reanalysis data which we used for our study included geopotential height, temperature and wind direction at a horizontal resolution of 2.5-degree x 2.5° [69]. Both the HYSPLIT and NCEP/NCAR reanalysis are housed at NOAA platforms with the HYSPLIT model residing at the Air Resources Laboratory and while the NCEP/NCAR are at the NOAA Physical Sciences Laboratory. The HYSPLIT model has extensively been used to trace the history of air masses and their origin [74]. The HYSPLIT model run simulations based on the Langrangian models [19] to identify pollutant sources, pathways, and dispersion at different altitudes [66]. During simulations, the model makes use of moving frames for calculating advection and diffusion [60]. Our study used the HYSPLIT 4 Model because of its strength to predict, forecast and identify air masses as well as the existence of validation through its use in several studies [13,16,18,20,26–28, 31,39,43,46,51–53, 62,74]. When running the simulations a backward and clustering approach was used based on National Oceanic and Atmospheric Administration (NOAA) meteorological data [58]. Our study ran a 3 day (72 h) backward trajectory-vertical velocity which wasperformed at three heights of 500 m, 2000 m and 3000 m AGL at 6-hour intervals with each trajectory starting at 0000 UCT. Simulations were performed on the following months and dates that represented seasons
28 February (summer), 31 May (Autumn), 31 August (winter) and 30 November. These dates were chosen as they were best suited to represent different seasons and track the seasonal behaviour of airmasses [37].

Results and discussion

The results presented in this study focus more on the ground-based aerosol measurements and have being suitable to examine aerosols properties and air quality assessment during the COVID-19 pandemic. Recently, the idea to include meteorological parameters is valuable. Moreover, the spatial distributions of aerosols revealed scientific insight over relating aerosols with COVID-19 lockdowns and restrictions. However, there still remains a dearth of imperical studies within the African context that has showcased the state of aerol loads using ground based remotely sensed data. Additionally, the magnitude of health risk has not been sufficiently been given within the African context in recent years therefore our study sort to close this gap. The reason for updated data on air quality monitoring and assessment over the selected stations in this pandemic year is suitable. Fig. 2 shows AOD seasonal variations over the three study sites of Durban, Skukuza and Upington. The winter months (JJA) for Durban (Fig. 2a) shows typical AOD variations. It is important to observe that using AE to characterize spatial distributions of AOD, it is seen that mineral dust aerosol spray dominates over the entire months. However, it could be seen that the peak increase of AOD corresponds to AE enhancement. This could be seen that AE is suitable to characterize AOD [8]. Fig. 2b shows AOD variation. It could be seen that June in the winter month indicated peak AOD variations other than July and August. A different result was obtained in the Upington station over the same months of study (Fig. 2c). However, a clear result of an inverse relationship between AOD and AE is always observed. It could be seen that Spring (SON) season depicts different results. This supports the idea that aerosols have strong seasonal variations [7]. However, Covid-19 transitioning and peak year (2019 to 2020) seasonal AOD variations were studied (Fig. 3). Results show that AOD in Southern Africa recorded lower aerosol variations resulting from the lockdowns. Nonetheless, it is apparent to note that 2019 and 2020 year depicts aerosols downwelling in Durban, Skukuza, with a significant result at the Upington site (Fig. 4).

During summer, Durban was influenced by long-range transport air masses originating from the South Atlantic Ocean especially those below the height of 1000 m AGL however the study noted some evidence of short-range winds which originated near sea waters. Furthermore, the Durban site was also influenced by South Westerly winds. During the same season at Skukuza the airmasses that landed at the site were mostly from the Indian Ocean with occasional long-transport airmasses originating from the South Atlantic Ocean particularly those below 500 m AGL. At the same time at the Upington site fell under the influence of inland airmasses thus bringing the chance of local sources of aerosols. In Autumn, the same trend was observed for the Durban site which continued under the influence of long-range transport air masses mostly.

![Fig. 2. AOD seasonal variations 2019–2020 (a) Durban (b) Skukuza (c) Upington.](image-url)
from the South Atlantic Ocean while Skukuza was also influenced by air masses from the South Atlantic Ocean while the Upington site was influenced by long-range airmasses from different origins however 90% of these were from inland sources.

During winter the Durban site continued being influenced by long-range air masses originating from the South Atlantic Ocean while Skukuza came under the influence of airmasses with origins from the Indian Ocean while some airmasses originated from the Mozambiquan channel which is linked to the Indian Ocean. The Upington site was influenced by air masses originating from the South Atlantic Ocean and hence this time there was a chance of receiving marine aerosols,
Fig. 5. 3-day backward trajectory over representative seasonal days (a) Summer-Durban (b) Summer-Skukuza (c) Summer-Upington (d) Autumn-Durban (e) Autumn-Skukuza (f) Autumn-Upington.

unlike the other seasons. During the spring season, the Durban and Sukuza sites continued to be under the influence of South Atlantic airmasses while 70% of airmasses that landed at Upington also originated from the South Atlantic Ocean.

Figs. 5 and 6.

Fig. 7 illustrates the wind field at different heights of 500 mb and 1000 mb over different seasons over South Africa. During the summer months of (DJF) at 500 mb Durban’s mean wind speed was 10 m/s while at Skukuza the seasonal mean wind speed was ≤4 m/s. On the other hand, at Upington ≥8 m/s. The wind direction was mostly originating from a South Westerly. At 1000 mb all three sites had a wind speed of ≤3 m/s while the wind direction was mostly South Easterly direction. During the autumn season (MAM) all sites were under the influence of South Westerly winds with the seasonal mean being ≤8 m/s. The highest wind speeds at 500 mb were recorded during winter (JJA) with the seasonal mean at Upington being ≤10 m/s while at Skukuza the wind speed was ≤8 m/s and the seasonal mean at the Durban site was ≤14 m/s. During other seasons the South Easterly winds continued to dominate at 500 mb while there was a mixed influence of South Easterly and South Westerly during the spring season (SON) at the 1000 mb height.

Fig. 8 illustrates the composite geopotential height over South Africa over different seasons. During summer the Southern Africa region is under a low-pressure regime being influenced by the continental trough as well as the ITCZ therefore (DJF) at 1000 hPa the study recorded that there were low geopotential values of ≤110 for the Upington site while the Durban site was characterized by geo-potential values of ≤130 while the Skukuza site was characterized by geo-potential values of ≥120. As the autumn season commences geo-potential values over Upington started to increase and the seasonal mean was ≤150 hPa while at the Durban site the values were slightly higher at ≤170. On the other hand at Skukuza the geopotential values were ≤160. During the Spring season at 1000 hPa the geopotential values start to fall particularly at Upington. Highest geopotential values were recorded during the winter season (JJA). At the geopotential height of 500 hPa during summer the Skukuza site recorded the highest geopotential values while the lowest was observed at the Durban site. At 500 hPa all sites had a similar cycle with high geopotential values being observed during the winter season too.

At the altitude of 1000 mb during summer (DJF) the lowest relative humidity was observed at the Upington site while the highest was recorded at the Durban site and this was similar during autumn (MAM) with Upington recording the lowest seasonal mean at ≤45% while the Durban site recorded a seasonal mean of ≥85%. On the other hand, the Upington site continued to record low humidity levels with a mean of ≥45% while the Skukuza site had a seasonal mean of 60%. As spring approached the highest level of humidity was recorded at the Durban site which was estimated at ≥85%. The same trend continued at the height of 500 mb across all seasons as at the height of 1000 mb. The highest level of humidity was recorded at the Durban site during summer (DJF) while the lowest was recorded at Upington. This was an expected observation as Durban is a coastal site while Upington is located in a near-desert environment [61]. With regards to the
Fig. 6. 3-day backward trajectory representative of winter and spring (a) Durban-winter (b) Skukukuza-winter (c) Upington-winter (d) Durban-spring (e) Skukuza-spring (c) Upington-spring.

Fig. 7. Wind field (m/s) at 500mb and 1000 mb during different seasons (a) Summer (DJF) 2020 at 500 mb (b) Summer (DJF) 2020 at 1000 mb (c) Autumn (MAM) 2020 at 500 mb (d) Autumn (MAM) 2020 at 1000 mb (e) Winter (JJA) at 500 mb (f) Winter (JJA) at 1000 mb (g) Spring (SON) 2020 at 500 mb (h) Spring (SON) 2020 at 1000 mb.
nature of aerosols across the three sites, Upington was closely associated with coarse aerosols while the Durban site would be associated with mostly fresh marine aerosols.

Discussion

The present study assessed and investigated variations of aerosols using AE over Southern Africa during the COVID-19 pandemic year of 2020 with 2017–2019 as base years. Our study established that aerosol levels peak during the winter season (JJA) showing signs of downwelling as the spring season approached for Durban and Skukuza while Upington had a peak in spring (SON). The winter increase in aerosol accumulation can be attributed to the extensive biomass and solid fuels combustion [36,52] that intensifies during the winter season in the Southern Hemisphere for purposes of space heating hence increasing aerosol formation activity. Besides hyped activity related to solid fuel use and biomass burning, the influence of meteorological parameters can also be linked to the increase in levels of aerosols during winter as the cold weather-low wind speed provide idle conditions for accumulation and formation of aerosols due to reduced chemical activities and less dispersion and transportation [29].

The influence of various meteorological factors on air pollution is also well established in [14,41,45,56,70]. The seasonal circulation influence was also evident in our study with the summer season being characterized by low-pressure zone from the Intertropical Continental Zone (ITCZ) and the continental trough that is active over the Southern region. On the other hand, winter was characterized by an anticyclone high-pressure system over the study sites as evidenced by high geopotential values at both 500 hPa and 1000 hPa (8e-g) which increased as the seasons transition. The circulation patterns over the Southern Africa region are mostly influenced by the Hadley cells and ENSO [21]. In our study, this is further buttressed by Fig. 7e-g which illustrates the probable transport pathways of pollutants from the South Americas continent finding their way into the Southern Africa region.

This current study also expands our understanding between climatic oscillations and local-regional dispersion and transport of pollutants as stable layers lead to accumulation of high local air pollution concentrations [23]. Besides, [23] established that at coastal regions of South Africa’s elevated layers occur at pressure levels of 850 hPa. In the context of our study, it, therefore, implies that meteorological conditions which prevailed in Durban over the study period facilitated more dispersion and transportation during the winter season (JJA). Stable layer occurrences are frequent at geopotential levels of 850 hPa more so in summer than in winter unlike at geopotential levels of 500 hPa [23] however this might not be the case for inland sites of Skukuza and Upington which had a positive geopotential height at 500 hPa [45] and therefore brought in stable weather conditions.
Our study also noted the influence of long-range transport on different sites for example the Durban and the Skukuza site were mostly influenced by long-range air masses originating from the South Atlantic Ocean and the Indian Ocean including the South American continent moreso the Amazon region [21]. This, therefore, meant that at these two sites there was more of fresh marine aerosols while the Upington site was a beneficiary of both marine and old urban (anthropogenic) aerosols [42] that are coarse in nature mostly originating from the desert and inland sources, particularly the South African Highveld as illustrated in Fig. 6c where air masses originate from South Atlantic Ocean pass through inland and land in Upington. The influence of long-range transport on aerosol load was also evident in the study as 90% originated from South Atlantic (South Westerly winds) and Indian Ocean (South Easterly winds). This was also established in [21] who noted that in the Southern Africa region distinct plumes can be identified across the Indian Ocean during October as it is biomass burning season. The influence of long-range on the Southern Africa region was also observed in [12]. Besides, [25] also records the influence of biomass combustion which is done in the Amazon on the air quality of the Southern Africa region. The impact of long-range transport on atmospheric air pollution is also well established by [64] who established that long-range air masses movement were responsible for growing air pollution within the Southern Africa region.

Furthermore, the winter months are also characterised by low atmospheric relative humidity. The study observed that at both 500 mb and 1000 mb the humidity showed the expected patterns at all sites serve for Durban. Skukuza and Upington had low humidity levels (9e-f) and this meant that the rate of aerosol accumulation also increase while the inverse was observed at the Durban site which was characterised by high humidity for over 60% of the study period thus increasing the hygroscopic activities. This is similar to findings by [56] who established that there was a very strong relationship between relative humidity and particulate matter concentration and also affirmed in [42] who found an inverse relationship between atmospheric hygroscopic growth and particle concentrations while on the other hand [67,73] asserts that as relative humidity increases so is the increase in the hygroscopic effect that will end up altering the particle size distribution also affecting the scattering and absorption of solar radiation. Concerning the three study sites, the size of the aerosols at the Durban site was likely to be affected more by the high humidity than Skukuza and Upington where high humidity was observed more during summer (DJF) months.

Our study had some limitations in that there were no other in-situ measurements which were done during the study however this weakness was mitigated in that AERONET derived data has been validated in several studies including [1,7,38, 2021; 71]). Future studies will focus on expanding on investigating aerosol trends and variability on a long term scale.

**Conclusion**

In this present study, we examine AOD over three AERONET sites of Durban, Skukuza and Upington over 2020 which was characterized by COVID-19 related national lockdowns that restricted economic activities, movement of people and transport activities. The expectation was that there was going to be some marked decline in the aerosols load as a result
of the national lockdowns however our study did not observe a drastic decline as compared to 2017, 2018 and 2019. It is important that further analysis using different region be carried out to examine major outcome of this results. Therefore, the major contributions of this study follow these conclusions:

• We observe peak increase of AOD that corresponds to AE enhancement for the Durban and Skukuza site. However for Upington the peak is noted in SON thus showing a different trend from the other two sites.
• The aerosols typing of mineral dust and aerosol spray dominated the study period across all sites and was particularly observed at the Upington site.
• There is no significant decrease in AOD during the national lockdowns over the three sites as compared to previous immediate years of 2019, 2018 and 2017.
• It is seen that high geo-potential values at both 500 hPa and 1000 hPa were observed during winter as characterized by the anticyclone system over the Southern Africa region thus that reducing oscillations, circulations and consequently aerosol transport and dispersion while summer was characterized by low geopotential height values which facilitates transportation and dispersion of aerosols.
• The sites of Durban and the Skukuza fell under the influence of long-range air masses originating from the South Atlantic Ocean and the Indian Ocean including the South American continent while the Upington site was under more influence of localised air masses thus receiving dust and anthropogenic aerosols sources while Skukuza and Durban were likely to receive fresh marine aerosols.

Authors contribution statement

Newton.R. Matandirotya- Conceptualisation, Writing original draft, methodology and formal analysis, final draft. Anoruo C.M-Conceptualisation, data analysis, methodology development, proofreading manuscript and final manuscript

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Data availability

Data will be made available upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing interest or personal association or relationships that could have influenced the direction of the study.

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