An assessment of NO₂ atmospheric air pollution over three cities in South Africa during 2020 COVID-19 pandemic

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Abstract
To contain the spread of COVID-19 in 2020, several governments around the world imposed national lockdowns including that of South Africa. The purpose of this study was to investigate and give an overview of nitrogen dioxide column levels during the year 2020 over three South African cities (Johannesburg, Durban and Cape Town) using AURA OMI derived measurements, the HYSPLIT model, complemented with NCEP/NCAR reanalysis data. Our findings were that in 2020, all the cities recorded their daily maximum mean NO₂ column levels during the winter season at 1.4 × 10¹⁵ molecules per cm², 3.1 × 10¹⁵ molecules per cm² and 1.7 × 10¹⁵ molecules per cm² for Johannesburg, Durban, and Cape Town respectively. Across all seasons, Cape Town recorded the lowest seasonal mean at 0.6 × 10¹⁵ molecules per cm² (summer 2020) while the highest seasonal mean was recorded over Johannesburg at 9 × 10¹⁵ molecules cm² (winter 2020). Furthermore, an interannual comparison analysis indicated that during summer, there were increases of 6%, 1% and 30% for Johannesburg, Durban and Cape Town respectively. During winter, Johannesburg saw an increase of 19% while a 2% increase was recorded in Durban with Cape town recording a 16% decrease in NO₂ column levels. The study also recorded that Cape Town and Durban were mainly influenced by long-range transport air masses originating from the South Atlantic Ocean, South America, Antarctica and the Indian Ocean particularly during the summer and autumn seasons possibly leading to the formation of marine nitrate aerosols.

Keywords COVID-19 · Column level · Nitrogen oxide · Atmospheric · Air pollution

Introduction
To contain the spread of COVID-19 in 2020, several governments around the world imposed national lockdowns including that of South Africa. Amidst the COVID-19 pandemic, issues of air quality monitoring and management have been brought back into the spotlight. The COVID-19 pandemic was declared a global pandemic by the World Health Organisation (WHO) on the 11th of March 2020 (Chew et al. 2020). To reduce the rate of transmission of the newly discovered SARS-CoV-2 virus, governments around the globe responded through the introduction of national lockdowns that restricted the movement of people in-country and between countries including halting economic activities (Bao and Zhang 2020; Bauwens et al. 2020; Chew et al. 2020; Zhang et al. 2020; Anil and Alagha 2021; Guevara et al. 2021; Querol et al. 2021). South Africa also imposed a total national lockdown from the 26th of March to 16 April 2020 while the subsequent ones were partial. In most countries, the lockdowns entailed restrictions on road traffic, industrial activities and urban movements (Tobias et al. 2020; Guevara et al. 2021; Querol et al. 2021).

Several studies have observed improvements in ambient air quality across several world cities following the COVID-19 induced lockdowns (Awokola et al. 2020; Zhang et al. 2020; Isafian 2020; Kerimray et al. 2020; Mahato et al. 2020; Nakada and Urban, 2020; Otmani et al. 2020; Tobias et al. 2020; Wang and Su 2020; Baral and Thapa 2021; Querol et al. 2021). The national lockdowns presented an opportunity for the air quality monitoring community to make assessments since they present an ideal (Zhang et al. 2020) due to reduced emission sources as industry was shut down...
and no vehicle movement. Furthermore, the most densely populated countries China and India noted a reduction in air pollution during the COVID-19-related lockdowns though in China improvement in ambient air quality have previously been linked to Spring festivals (Wang and Su 2020). On the contrary, (He, Pan and Tanaka, 2020) argues that lock-downs alone cannot improve air quality especially when meteorological conditions are also unfavourable.

This study focuses on one of the trace gas pollutants Nitrogen Dioxide (NO$_2$). NO$_2$ is a short-lived pollutant (Marchenko et al. 2015; Lamsal et al. 2020) that is dominant within urban environments (Georgoulias et al. 2019; Otmani et al. 2020). NO$_2$ has both negative environmental-human health consequences especially in circumstances where there is prolonged exposure (Manisalidis et al. 2020; Otmani et al. 2020). Some of the negative human health impacts include respiratory diseases, coughing, wheezing because NO$_2$ can penetrate and corrode deep into the lungs (Manisalidis et al. 2020; Wang and Su 2020). Furthermore, NO$_2$ also contributes to the formation of nitric acid, nitrate aerosols as well as peroxyacetyl nitrate (HNO$_3$)- (Lamsal et al. 2020; Wang and Su 2020) that can lead to reduced crop yields (Manisalidis et al. 2020) and other environmental damages. NO$_2$ and NO (nitrogen oxide) are key in the photochemistry of Ozone (O$_3$) in both the stratosphere and troposphere (Grajales and Baquero-Bernal 2014; Lamsal et al. 2020; Qin et al. 2020) and this occurs in the presence of solar radiation (Lerma et al. 2021). The main sources of NO$_2$ are anthropogenic activities that include biomass burning, fossil fuel combustion, vehicles, and thermal power stations (Georgoulias et al. 2019; He et al. 2019; Qin et al. 2020; Wang and Su 2020; Lerma et al. 2021). The study aimed at assessing the changes in tropospheric NO$_2$ column levels that culminated as a result of COVID-19-related lock-downs in South Africa while the specific study objectives were to:

i. Assesses the NO$_2$ atmospheric air pollution over three South African cities during the 2020 COVID-19 pandemic year.

Fig. 1  Topographical map of South Africa showing the location of the study cities

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ii. Assess the impact of national lockdowns on air quality over the three cities during the year 2020 COVID-19 pandemic year.

Also, the research question for the study was (i) to what extent did the atmospheric NO$_2$ column levels change across major cities of South Africa during the year 2020 compared to the base year of 2019? The article is divided into five sections: Sect. 2 presents the materials and methods, Sect. 3 presents the results, Sect. 4 presents the study discussion and Sect. 5 presents the study conclusion.

**Materials and methods**

**Description of the study area**

The study was done in three cities of South Africa namely Johannesburg (located at −26.21; 28.04), Durban (located at −29.90; 30.99) and Cape Town (located at −33.98; 18.53). Cape Town and Durban are coastal cities while Johannesburg is located inland. As shown in Fig. 1, both cities of Cape Town and Durban are at lower elevation compared to the city of Johannesburg. The three cities were chosen as case studies that would give an extensive overview of the status of tropospheric nitrogen oxides during the year 2020. Besides, their geographical location differences the three cities sources of emission also vary for example Durban and Cape Town are likely to be influenced by trans-boundary air pollution through air masses landing from other jurisdictions while on the other hand, Johannesburg is likely to be influenced largely by inland sources as well as trans-boundary sources.

Figure 1 highlights the digital elevation model for South Africa indicating that both Cape Town and Durban lie at low elevations than Johannesburg. By being in the coastal regions of the country, the two cities were assumed to have cleaner atmospheric than Johannesburg. One of the tools that have been used extensively in the study of tropospheric NO$_2$ is satellite data (He et al. 2019) due to its wide spatial coverage therefore our study chose satellite-derived data because of this benefit which we complemented with the HYSLIPT Model and NCEP/NCAR reanalysis data as expounded below.

**OMI NO$_2$ column data**

Data for this study were retrieved from the Ozone Monitoring Instrument (OMI) which is aboard the AURA Satellite (Wang and Su 2020) and was launched in 2004 (Schoeberl et al., 2006; Duncan et al. 2013). The OMI instrument makes use of a hyperspectral imaging mechanism with a nadir field of view (FOV) of $13 \times 24$ km (along-track x cross-track) circulating in a 98.2° inclination sun-synchronous polar orbit at a height of 705 km (Levet al. 2006) and can identify urban sources of air pollution (Schoeberl et al. 2006; Lee and Koutrakis 2014; Krotkov et al. 2017). The instrument also has a swath width of 2600 km (Qin et al. 2020).

Besides, the OMI carry sensors that provide daily global coverage (Krotkov et al. 2017; He et al. 2019; Bauwens et al. 2020; Lamsal et al. 2020; Qin et al. 2020; Shah et al. 2020) and makes a total of 14–15 orbits a day (Krotkov et al. 2017; Lamsal et al. 2020). Past and present OMI applications have included, lightning tracking, oil and gas production monitoring, volcano monitoring, air quality monitoring which encompasses tracking NO$_2$ pollution in industrial areas, observation NO$_x$ seasonal patterns, quantification of NO$_x$ emissions from power plants (Levet al. 2018; Lamsal et al. 2020; Wang and Su 2020). This current study focused on the year 2020 which was characterised by total and partial national COVID-19-related lockdowns around the world that saw industrial, economic and human movement activities being restricted in major cities of South Africa.

Data were downloaded for the years 2019 and 2020 and 2019 was used as the base year. The study downloaded Version 4 Aura OMI Nitrogen Oxide Standard Product (OMNO$_2$) quality-controlled data which was cloud screened and contains an effective cloud fraction of <30% (Qin et al. 2020) that is devoid of any anomalies (Duncan et al. 2013). Furthermore, data are calculated from 1-degree×1 degree around each city centre (Johannesburg, Cape Town and Durban)- (Duncan et al. 2013). The study assumed that the COVID-19-related lockdowns improved the atmospheric quality of air over the three cities. In recent years, South Africa vehicular population has rapidly increased while coal-based electricity production has been maintained especially on the South African Highveld where the city of Johannesburg is located.

**HYSPLIT model and NCEP/NCAR reanalysis data**

To determine the airmasses paths and trajectories that ended up landing in Johannesburg, Cape Town and Durban with a possibility of influencing the NO$_2$ column levels during 2020, the study used the HYSLIPT 4 Model and augmented with NCEP/NCAR reanalysis data as applied in (Jiao et al. 2021). Reanalysis data can provide boundary-layer meteorological conditions and characteristics (Bu et al. 2020) that can give indications on large-scale circulation phenomena (Zheng et al. 2021). The HYSPLIT and NCEP/NCAR are housed at NOAA platforms with the HYSPLIT model residing at the Air Resources Laboratory and the latter being at the Physical Sciences Laboratory. The HYSPLIT model has extensively been used to show paths of air masses, origin including the atmospheric transportation of pollutants...
Fig. 2  Summer seasonal NO$_2$ column temporal variations during 2019 and 2020 (a) Johannesburg, (b) Durban, (c) Cape Town. Autumn season (d) Johannesburg, (e) Durban, (f) Cape Town
Fig. 3  Winter seasonal mean NO$_2$ column levels during 2019–2020 (a) Johannesburg, (b) Durban, (c) Cape Town. Spring seasonal mean NO$_2$ column levels during 2019–2020 (d) Johannesburg, (e) Durban, (f) Cape Town
The HYSPLIT makes simulations based on the Langrangian models (Draxler and Hess 1998) for identifying pollutant sources, pathways, and dispersion in the atmosphere over space and time (Toledano et al. 2009). The models utilise moving frames for calculating advection and diffusion at the atmospheric level (Stein et al. 2015).

The HYSPLIT model was ideal for the study because of its capability to predict, forecast and identify air masses that land in the study area. In addition, the model was used to estimate the air masses landing at the study area during different seasons of the year. During analysis, a backward and clustering was used based on National Oceanic and Atmospheric Administration (NOAA) meteorological data (Sangeetha et al. 2018). Backward trajectories have been used widely to trace the paths used by pollutants from sources (Toledano et al. 2009). In the current study, a 3-day (72 h) backward trajectory-vertical velocity was performed at three heights of 500 m, 2000 m and 3000 m AGL. The trajectories were performed at a 6-h interval. The analysis was performed on the following dates 28 February (summer), 31 May (Autumn), 31 August (winter) and 30 November. These dates were chosen to show the seasonal behaviour of airmass origins and pathways (Kumar et al. 2013). In the next section (Sect. 3), the study presents the results followed by a discussion in Sect. 4.

**Results**

**Seasonal NO₂ column temporal variations**

Figure 2a–f highlights and showcases the seasonal temporal variations of NO₂ over the three cities for the years 2019 and 2020 during the summer and autumn season including the total lockdown of 21 days from 30 March 2020 to 16 April 2020. Comparing the 3 cities in 2020, Johannesburg recorded the highest NO₂ column levels at 10.1 × 10¹⁵ molecules per cm² in the autumn season (May 2020) while the lowest column levels were recorded in the city of Cape Town at 0.8 × 10¹⁵ molecules per cm² also in May 2020.

Figure 3a–f illustrates the seasonal time series for the winter and spring season over the years 2019–2020. Similar to other seasons, Johannesburg remained higher than the other two cities. The high NO₂ column levels in Johannesburg can be attributed to the large number of manufacturing industries that are located within the city as well as its close proximity to coal-based electricity power generating stations. All these are local emission sources while the city also receives transboundary long-range emissions from neighbouring provinces and countries especially during the winter season.

**Table 1** Descriptive seasonal statistics

| City          | Season | Max 2019 | Max 2020 | Min 2019 | Min 2020 | Mean 2019 | Mean 2020 | Std. d 2019 | Std. d 2020 |
|---------------|--------|----------|----------|----------|----------|-----------|-----------|-------------|-------------|
| Johannesburg | Summer | 5.6      | 7.6      | 2.3      | 2.0      | 3.8       | 4         | 0.9         | 1.4         |
| Cape Town     | Summer | 1.1      | 1.1      | 0.7      | 0.7      | 0.9       | 0.9       | 0.1         | 0.1         |
| Durban        | Summer | 1.4      | 2.2      | 0.6      | 0.8      | 1.1       | 1.4       | 0.2         | 0.3         |
| Johannesburg | Autumn | 14       | 12       | 3        | 2.3      | 7         | 6         | 3.4         | 3           |
| Cape Town     | Autumn | 1.8      | 1.4      | 1        | 1        | 1.3       | 1.1       | 0.2         | 0.2         |
| Durban        | Autumn | 2.6      | 2.5      | 1.0      | 1.0      | 1.6       | 1.6       | 0.5         | 0.4         |
| Johannesburg | Winter | 12.5     | 14.1     | 4.1      | 3.7      | 7.6       | 9.0       | 2           | 3.4         |
| Cape Town     | Winter | 1.8      | 1.7      | 1.1      | 0.8      | 1.4       | 1.2       | 0.2         | 0.2         |
| Durban        | Winter | 3.9      | 3.1      | 1.7      | 2        | 2.7       | 2.6       | 0.6         | 0.3         |
| Johannesburg | Spring | 7.7      | 8.0      | 3.0      | 2.5      | 5.3       | 4.6       | 1.6         | 1.3         |
| Cape Town     | Spring | 1.4      | 1.4      | 0.6      | 0.6      | 1.0       | 1.0       | 0.2         | 0.2         |
| Durban        | Spring | 2.9      | 2.1      | 0.9      | 1.4      | 1.8       | 1.8       | 0.4         | 0.2         |
Fig. 5 Three-day backward trajectory for summer (DJF) and autumn (MAM) 2020: (a) Johannesburg Summer, (b) Durban summer, (c) Cape Town summer; (d) Johannesburg autumn, (e) City Durban autumn, (f) Cape Town autumn
Fig. 6 Three-day back trajectory for winter and spring (a) Johannesburg winter 2020, (b) Durban winter 2020, (c) Cape Town winter 2020, (d) Johannesburg spring 2020, (f) Durban spring 2020, (e) Cape Town Spring 2020
Figure 4 represents the annual NO$_2$ column means for the 3 cities. Johannesburg recorded the highest annual mean at $5.8 \times 10^{15}$ molecules per cm$^2$ (2020) compared to $5.7 \times 10^{15}$ molecules per cm$^2$ (2019) while the lowest annual column mean levels were recorded in Cape Town at $0.7 \times 10^{15}$ molecules per cm$^2$. This suggests that Cape Town had the cleanest atmosphere in the year 2020.
As illustrated in Table 1, Johannesburg had the daily highest maximum mean NO$_2$ column levels at $14.1 \times 10^{15}$ molecules per cm$^2$ which were recorded in winter 2020 compared to $12.5 \times 10^{15}$ molecules per cm$^2$ in 2019. The lowest daily mean was recorded in Cape Town during the spring season at $0.6 \times 10^{15}$ molecules per cm$^2$. Turning to seasonal means the highest mean was recorded in Johannesburg at $9.0 \times 10^{15}$ molecules per cm$^2$ during winter (2020) compared to $7.6 \times 10^{15}$ molecules per cm$^2$ (2019).

Figure 5a–f represents the various air masses landing in the 3 cities throughout the different seasons of the year. During the months of summer (February), the long-range airmasses at heights of above 2500 AGL that landed in the city of Johannesburg mainly originated from the South Atlantic Ocean while those at below 1000 m AGL mainly had local inland sources. The influence of long-range air masses seems to be limited during summer months in the city of Johannesburg even considering all heights from those at 500 m AGL to above 2000 m AGL thus permitting transportation locally especially considering that at all heights the airmasses seem to pass through the Highveld region.

A similar 3-day back trajectory was performed for the months of winter (August) and spring (November) for all the towns (Fig. 6). For Johannesburg, the trajectories indicated that the long-range air masses originated in the South Atlantic Ocean however pacing through the South African Highveld before landing in Johannesburg. Also, short-range air masses originated inland that’s indicating local emission sources. This gave a possibility that pollutants from power generating plants were picked. On the other hand, for Durban and Cape Town, long-range air masses mostly originated in the South Atlantic Ocean. During the Spring (SON) season, long-range air masses indicated origination in the Indian Ocean while the same source was evidenced for Durban while for Cape Town the influence of South Atlantic air masses was maintained throughout all seasons. For Cape Town, the South Westerly winds influence was also evident in the spring season. On the other hand, in Durban during the spring season, the air masses from the Indian Ocean (South Easterly winds) had more influence.

Figure 7a–c shows the tropospheric NO$_2$ column levels during various seasons for 2019–2020 across all three cities. For the representative days, Johannesburg had the highest NO$_2$ column levels at $11 \times 10^{15}$ molecules per cm$^2$ and this was recorded on the 31st of May 2020 as compared to $13.2 \times 10^{15}$ molecules per cm$^2$ recorded in 2019 on the same day. The lowest was recorded in Cape Town which recorded $0.8 \times 10^{15}$ molecules per cm$^2$ as compared to $0.9 \times 10^{15}$ molecules per cm$^2$ on the same day in 2019.

Figure 8 shows the seasonal circulation patterns over the South Africa region at geopotential heights of 1000 hPa and 500 hPa during the 2020 season. During the summer season, the region was characterised by low geopotential values and this can be attributed to the existence of a continental trough (Garstang et al., 1996). As the autumn season approaches, the continental trough shifts in a northern direction due to the influence of the South Atlantic and Indian Ocean.
anticyclone. Still at the same 1000 hPa levels, winter (JJA) recorded the highest geopotential height values and this was also confirmed in a study by (Freiman and Tyson, 2000).

On the other hand, as spring approaches, the continental trough starts shifting southwards thus replacing the South Atlantic and Indian Ocean anticyclone system; hence, the geopotential height values start decreasing. At geopotential levels off 500 hPa, the continental trough influence is not that pronounced across the southern hemisphere region however the values are highest during autumn (MAM) followed by summer (DJF) and winter (JJA) respectively with the lowest being experienced during the spring season (SON). The link to air pollution is that geopotential levels influences the direction of long range air masses thus impacting on the dispersion and transportation of pollutants.

Discussion

This study assessed and investigated the NO₂ column levels over three cities in South Africa namely Johannesburg, Durban and Cape Town during the COVID-19 pandemic year of 2020. The study established that the NO₂ column levels were elevated across all cities during winter (JJA) months as compared to other seasons. This can be attributed to the increase in power generation activities during winter months mostly for indoor space heating as compared to other seasons. The elevated NO₂ column levels during winter can also be linked to the meteorological conditions which are characterised by low ambient temperatures and cloudy conditions. These weather conditions slow down the photochemical reactions; hence, the NO₂ lingers more within the atmosphere as compared to summer, spring or autumn seasons. Even though during 2020 there were intermittent days where partial lockdowns were imposed, the power generation continued through and through.

The most impacted city was Johannesburg due to its close proximity to the thermal power plants which are dotted around the Highveld region especially in Mpumalanga as well as Limpopo. Besides, thermal power generation the study attributes the winter elevated NO₂ column levels to domestic solid fuel (coal, wood) combustion. This was confirmed by a marginal increase from a winter seasonal mean of 7.6 × 10¹⁵ molecules per cm² (2019) to 9.0 × 10¹⁵ molecules per cm² (2020) while in Cape Town, the winter seasonal fell from 1.4 × 10¹⁵ molecules per cm² (2019) to 1.2 × 10¹⁵ molecules per cm² and another marginal decrease in Durban from a winter seasonal mean of 2.7 × 10¹⁵ molecules per cm² to 2.6 × 10¹⁵ molecules per cm². These power plants generate electricity from coal and this can closely be linked to the continued elevated levels of NO₂ in winter.

Our study observed that interannual comparison analysis indicated that during summer, there were increases of 6%, 1% and 30% for Johannesburg, Durban and Cape Town respectively. During winter, Johannesburg saw an increase of 19% a 2% increase was recorded in Durban with Cape town recording a 16% decrease in NO₂ column levels. In autumn the study noted a 3%, 2% increase for Johannesburg and Cape Town respectively while a 13% reduction was observed in Durban. Meanwhile, in spring, Johannesburg recorded a reduction of 9% while Durban and Cape Town recorded an 11% and 2% increase respectively.

Besides the winter conditions which are characterised by cold air temperature and low levels of solar radiation reduce the rate of photochemical processes thus in the end the dispersion rates and transportation were slowed down (Duncan et al. 2013) this is because the chemical life expectancy of NO₂ is very short in summer than other seasons (Duncan et al. 2013). On the other hand, Cape Town and Durban are not that exposed to the source emissions from power plants as compared to Johannesburg. Besides, Johannesburg is also the economic hub of the country and is a resident of several other nitrogen oxides emitters for example iron smelters and other related industries. During winter (JJA), the study also found evidence of air masses originating and migrating inland from the North Eastern suggesting that biomass burning activities for space heating purposes in countries north of South Africa also have an influence on the state of NO₂ column status particularly on the city of Johannesburg more than Durban and Cape Town.

The high frequency of persistent elevated stable layers that are a common phenomenon over South Africa trap aerosols thus preventing turbulent mixing in the vertical (Freiman and Tyson 2000). This put into perspective issues of transboundary air pollution on the SADC block. Furthermore, for Durban and Cape Town, the study established that the seasonal NO₂ column levels did not vary much while for Johannesburg a seasonal decrease was observed in the spring season from 5.3 × 10¹⁵ molecules per cm² (2019) to 4.6 × 10¹⁵ molecules per cm² (2020) and for autumn from 7.0 × 10¹⁵ molecules per cm² (2019) to 6.0 × 10¹⁵ molecules per cm² (2020). Cape Town and Durban did not witness any drastic changes in the NO₂ column levels between 2019 and 2020 because most air masses originate from the high seas more than inland.

The seasonal circulation influence of long-range transport influence was evident in our study particularly on the city of Durban and Cape Town whose location is prone to the influence of the South Atlantic (South Westerly winds) and Indian Ocean (South Easterly winds). This was also established in (Edwards et al. 2006) who noted the influence of biomass burning season long-range transport originating from the Amazon and finding its way to South Africa. The same position was also established in (Bieser et al. 2020) who confirm that 90% of long transport air masses originate...
from the Atlantic, South America and the Antarctic. A similar finding was also further established by (Gloudemans et al. 2006) who also ascertained that biomass burning in the Amazon affects air quality on the whole of Southern Hemisphere region including South Africa.

Besides this current study highlights the influence of climatic oscillations on regional and local dispersion and transportation of local pollutants, this is because stable layers can lead to high local air pollution concentrations (Freiman and Tyson 2000). The same authors also assert that for coastal regions in the South, the elevated layers occur at pressure levels of 850 hPa. In relation to our current study, it, therefore, implies that two coastal regions of Durban and Cape Town conditions facilitated more dispersion and transport during the winter season (JJA). In a study by (Freiman and Tyson 2000), findings were that the stable layer occurrences were frequent at geopotential levels of 850 hPa (4 out of 5 d) more so in summer than in winter unlike at geopotential levels of 500 hPa. Furthermore, the impact of long-range transport on atmospheric air pollution is also well established by (Thompson et al. 2014) who observed that long-range air masses movement was responsible for growing air pollution within the Southern Africa region. Our study findings are in tandem with findings by (He et al. 2020) which emphasised the influence of meteorological factors in air quality pollution.

The study had some limitations that included relying on satellite measurements without being complemented by surface-based measurements; however, the benefit derived from using satellite measurements was that of large spatial coverage compared to ground-based measurements. Secondly, the other limitation was that the study only considered two years; hence, a long-term NO2 column level trend analysis can give a better position regarding the quality of atmospheric pollution over the three cities.

Conclusion

The current study investigated and gave an overview of NO2 atmospheric column levels in three cities of South Africa (Johannesburg, Durban and Cape Town) during 2020, a year in which the world was grappling with the COVID-19 pandemic. An interannual-seasonal comparison between 2019 and 2020 did not show a significant reduction in NO2 column levels over the three cities that were investigated. Furthermore, our study concludes that:

- Johannesburg had the highest NO2 during 2020 with evidence of both local source emissions and transboundary sources, especially during the winter season.
- Long-range air masses that originated from the South Atlantic and Indian Oceans dominated the three cities showing the influence of marine nitrate aerosols besides the NO2 which degrades quickly particularly during the summer season.
- No significant decrease in NO2 was recorded over the three cities during the year 2020 compared to the base year of 2019.

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Author contribution Newton R. Matandirotya- Conceptualisation, Writing original draft, methodology and formal analysis, final draft.
Roelof P. Burger-Conceptualisation, data analysis, methodology development, proofreading manuscript and final manuscript.

Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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