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State of ambient air quality in a low-income urban settlement of South Africa

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ABSTRACT

Air pollution remains one of the leading global environmental-health challenges the world is facing today, particularly within urban environments. amidst the COVID-19 pandemic, air pollution has been brought back into the spotlight as both attack the human respiratory systems. The purpose of the study was to investigate the quality of ambient air in a low-income urban settlement of Jabavu located within the City of Johannesburg during the year 2018. Air pollution and meteorological data were gathered from the South African Air Quality System network. The study focused on three pollutants namely PM_{10}, SO_2 and O_3. Findings were that the seasonal ambient mean concentrations for PM_{10} in summer was (28.99 μg/m^3), autumn (33.32 μg/m^3), winter (61.71 μg/m^3) and spring (48.44 μg/m^3). On the other hand, the seasonal ambient mean concentrations for SO_2 was summer (4.45ppb), autumn (3.19ppb), winter (5.65ppb) and spring (3.54ppb). The O_3 seasonal ambient mean concentrations were summer (40.97ppb), autumn (21.01ppb), winter (15.90ppb) and spring (33.59ppb). Furthermore, the study observed that in summer, winter and spring the dominant long-range transport air masses originated from the South Atlantic Ocean, Madagascar Island-India Ocean and the Indian Ocean while in autumn the dominant air masses are short-range inland air masses. For SO_2 and $PM_{10,}$ ambient concentrations were found to be more problematic during winter; while for O_3 substantial levels were unexpectedly recorded in summer. When analysing the diurnal profiles of PM_{10}, SO_2 and $O_{3,}$ each of these pollutants revealed a unique distribution pattern, which, despite having seasonal variance, was consistent throughout the year. For instance, irrespective of the season, PM_{10} mostly peaked in the mornings and evenings; meanwhile SO_2 and O_3 often spiked during the midday and mid-afternoon, respectively. These findings indicate that air quality within this low-income settlement is poor. To improve air quality within low-income settlements there is a need for a shift from reliance on solid fuels to cleaner energy sources such as LP gas, biogas and solar accompanied by an increase in community awareness about air quality issues. This study contributes to knowledge building within the air quality monitoring scientific community while for policymakers it assists in policy formulation to enable air quality management.

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Introduction

Air pollution is a leading environmental-health challenge facing urban areas around the world today [3,21] since 55% of the world's population is urbanised [30] and 60% will be urbanised by 2030 [17]. Furthermore, on a global scale urban environments are estimated to contribute 75% of greenhouse gas emissions [17]. It is further estimated that 90% of the world's population reside in regions that have air quality which exceeds the World Health Organisation thresholds [7]. Sources of air pollution are broadly classified as natural, mobile, major, and indoor sources [23]. Air pollution is particularly a concern for cities in developing countries [2,21] as in most cases there are no legislative frameworks to regulate emissions. Furthermore, in developing countries, it is estimated that 85% of particulate matter is from the combustion of biomass [21]. This is true for South Africa where an estimated 70% of low-income households rely on solid fuels (wood, & coal) to satisfy their domestic energy requirements (cooking and space heating) leading to Household Air Pollution (HAP) [10,26]. Besides, there are also other air pollution sources which include dust storms, coal powered thermal power stations, vehicle emissions, industries, unpaved roads, smokestacks waste and agriculture [6,23].

Meanwhile, the WHO (2016) estimated that 80% of people living in urban cities where air pollution monitoring data is available were found to be exposed to thresholds of contamination beyond the recommended WHO guidelines particularly in developing countries. Globally air pollution was estimated to have caused 4.2 million premature deaths during the year 2019 [4,9,18,21,39]. On the same note during the same year air pollution became the 4th leading cause of premature deaths on a global scale [16]. Besides, being a health issue air pollution has also caused productivity losses leading to an estimated 2% loss in the gross domestic product in low-income to middle-income countries [21]. The COVID-19 pandemic has also brought back the spotlight on air quality issues. There is overwhelming evidence that links air pollution and the proliferation of co-morbidities (for example cardiovascular disease, respiratory illnesses, heart disease, diabetes) and an increase in COVID-19 complicated related deaths [3]. The threat is heightened when an individual is exposed to high levels of air pollution. Air pollutants consist of criteria pollutants namely particulate matter (PM), sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen oxide (NO_2), and ozone (O_3) [6]. Particulate matter refers to small solid and liquid matter whose life expectancy can last for hours, days, weeks, months or even years [6]. Of all the pollutants, $PM_{2.5}$ (aerodynamic diameter of $\leq$ 2.5 um) is of great concern due to its ability to penetrate interior cells that cause respiratory, cardiovascular conditions, stroke and chronic obstructive pulmonary disease, heart failure, heart attacks, hypertension [3,6] leading to cause-specific premature deaths [9,32]. The health impacts of air pollution are classified as short-term or long-term. The former includes temporary effects like coughing and wheezing which may last for a few minutes up to hours and the latter includes chronic and respiratory illnesses like asthma which may develop over months and years [23].

This study sought to expand on the work done by Wernecke et al. [36] and Adesina et al. [1] within low-income urban settlements of South Africa. Air quality monitoring research forms part of tools that can be used in policy formulation and strategy building, therefore, this study was done as part of the knowledge-building process. Also, the study was done to understand to what extent are those residing in urban settlements are affected by the challenge of air pollution. The study focused on three pollutants namely PM_{10}, O_3 and SO_2. Prolonged exposure to all of these mentioned pollutants has human health negative impacts for example respiratory diseases [8]. The study aimed at assessing the ambient air quality within an urban located low-income settlement (Jabavu) to better ascertain the leading pollutants, patterns and trends. To achieve the research aim the study's research questions were:

(i) What is the state of ambient air quality during different seasons in the low-income settlement (focusing on O_3, PM_{10} and SO_2)?
(ii) What are the diurnal-seasonal air quality patterns in the low-income settlement (focusing on O_3, PM_{10} and SO_2)?

A survey done in the settlement revealed that most of the residential structures are concrete roofed [29] thus having an impact on the indoor thermal comfort. An estimated 40% of households do not have any income-generating sources while 60% of adults are also estimated to be unemployed [29]. Solid fuel combustion is also proven to be a major source of ambient emissions. 'dirty fuels' are defined as "fuels that have high emission levels and a direct impact on human health like coal, wood, paraffin, and biomass burning" [26].

Materials and methods

Description of the study area

Jabavu (26.2477° S; 27.8751° E) is a low-income settlement located in the South-Western part of Greater Soweto within the City of Johannesburg (CoJ), the province of Gauteng. The township is located at an altitude of 1632 m above sea level with mean annual temperatures of 15.6 and mean annual rainfall of 750 mm [28]. Jabavu is surrounded by several townships with similar socio-economic characteristics namely Zola, Jabulani, Emndeni and Dube. Jabavu is also located within the Vaal Triangle Priority Area (VTAPA). The settlement has an estimated population of 45 128 (Harrison and Harrison [15]) and is densely populated, and, in some instances, two households occupy spaces meant for one [29]). Old spatial plans lead to the location of densely populated settlements near industrial areas which inevitably increases exposure to ambient air pollution [24]. Low-income settlements are also characterised by a lack of waste removal systems and services which also worsens ambient air pollution levels (Department of Environmental Affairs [[12- 2019]. The other spatial characteristic of low-income

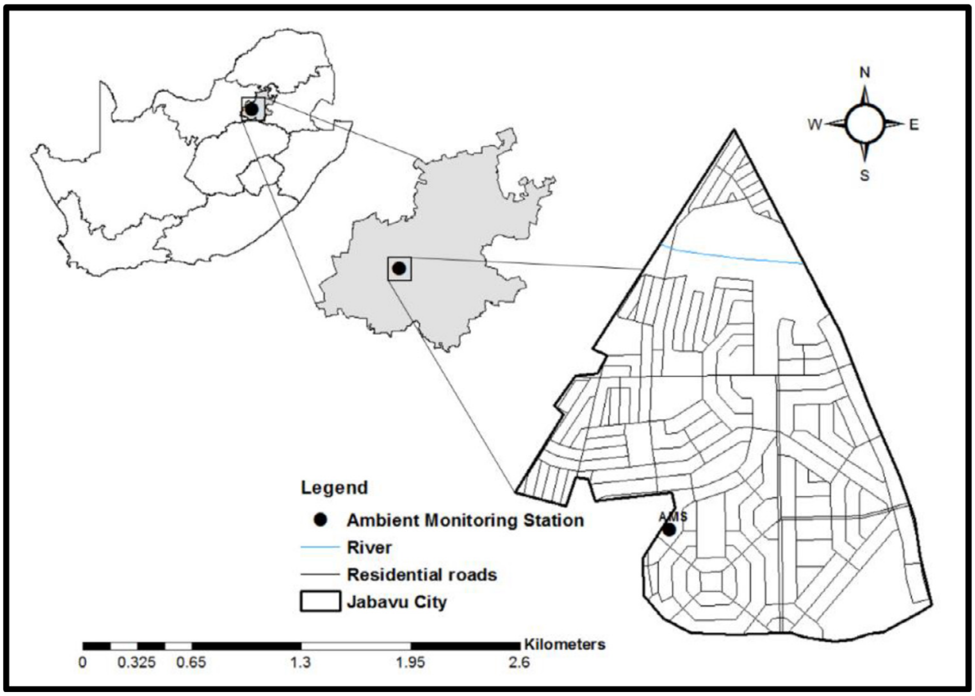

Fig. 1. Study area of Jabavu low-income settlement (−26.2477° S, 27.8751° E)

settlements is the closeness of residential structures that in turn minimises transport and dispersion rates which ultimately increases the accumulation of pollutants within these settlements (DEA, 2019). Continuous use of 'dirty' fuels ultimately impacts and decreases ambient air quality. Fig. 1 shows the study area.

Pollutant and meteorological data

To investigate the quality of air in Jabavu we analysed a single year of ambient monitoring data of PM_{10}, SO_2, O_3 and temperature for the year 2018 [35]. Air pollution data were gathered from a stationary ambient monitoring station (26.2526° S, 27.8721° E) which is owned and operated by the City of Johannesburg (CoJ) and is part of the South African Air Quality Information System (SAAQIS) from which air pollution and meteorological parameters data were downloaded. The air pollution and meteorological data were obtained at an hourly mean temporal resolution in a Comma Separated Values (CSV) file format. In this monitoring station, the instruments are manufactured by Met-One. Before analysis, the data were further cleaned starting by locating missing and negative values. After cleaning the data were arranged into 4 seasonal compartments for example summer (DJF), autumn (MAM), winter (JJA), and spring (SON) according to seasons on the South Africa Highveld. Further analysis and visuals generation were performed using descriptive statistics within the MATLAB software Version 2016a and Microsoft Excel 365 environments. The study used ArcGIS Software Version 10.23 to make maps.

HYSPLIT model-4

To establish the effect of dispersion of pollutants the study used the HYSPLIT 4 model through the backward trajectories. The HYSPLIT makes assessments of air parcel trajectories based on Langrangian models [13] to identify sources, pathways of pollutants and transportation within the atmosphere over time [22,25,33]. It makes use of moving frames for calculating advection and diffusion [31]. The HYSPLIT was used to estimate the air masses landing at the study area during different seasons of the year. During analysis, a backward and clustering technique was used based on National Oceanic and Atmospheric Administration (NOAA) meteorological data [38]. Backward trajectories have been used widely to trace the paths used by pollutants from sources [33]. In the current study, a 3-day backward trajectory-vertical velocity was performed at three heights of 500 m, 1000 m and 1500 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 [19]. Also, the advection process and transportation of pollutants relies on seasons [20].

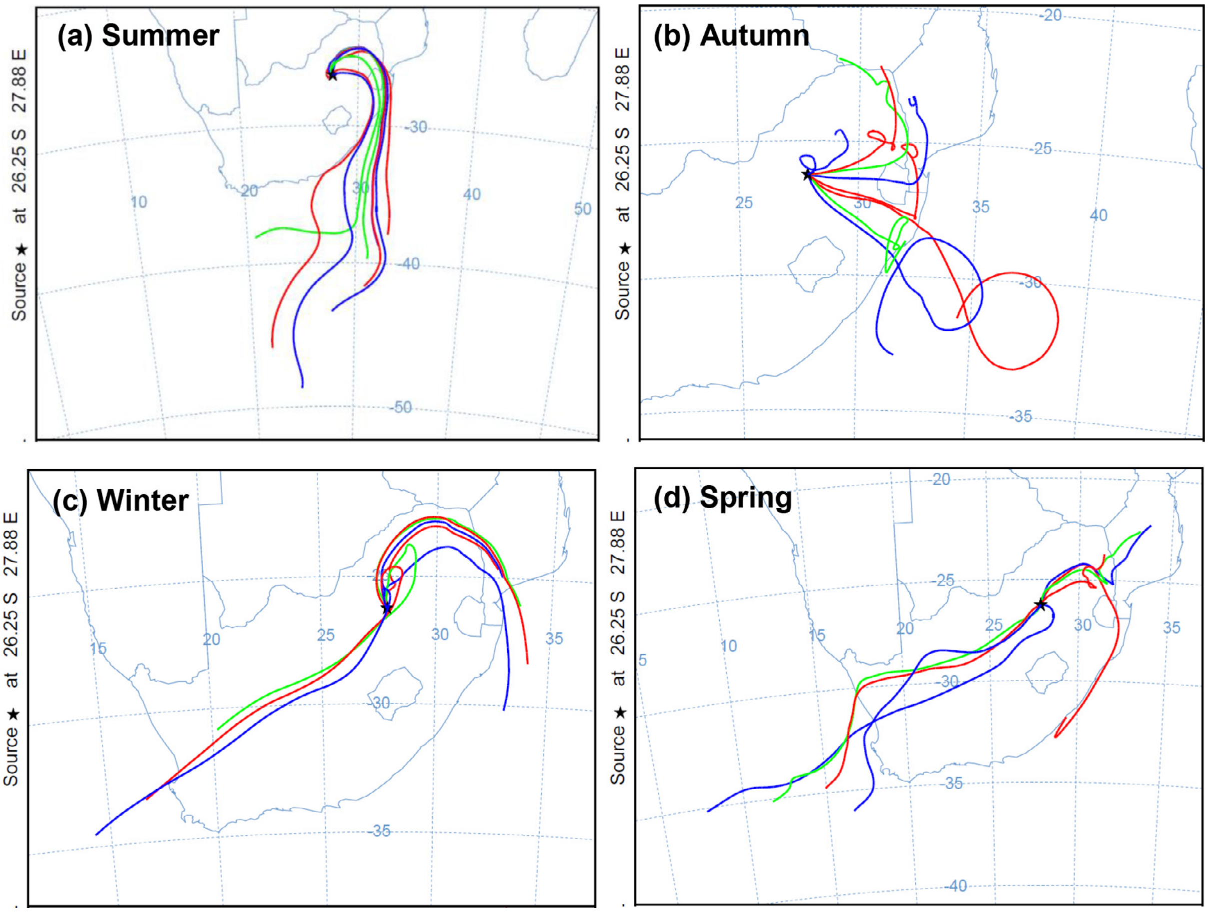

Fig. 2. (a) Summer 3-day backward trajectory (DJF); (2b) Autumn 3-day backward trajectory (MAM) (c) Winter 3-day trajectory (JJA) (d) Spring 3-day trajectory (SON).

Results and discussion

Fig. 2 illustrates the seasonal airmasses that influence the study area. Using a 3-day backward trajectory for different seasons the study established that various airmasses landed in Jabavu originating from various sources. In summer the dominant air masses landing in Jabavu were of long-range nature emanating mostly from the Madagascar Island-India Ocean. On the other hand, in autumn the dominant air masses were of short-range nature mostly even considering various altitudes. This can suggest localised sources of air pollution for example biomass burning [19]. While in winter Jabavu was under the influence of both the Madagascar Island-India Ocean as well as South Atlantic air masses which are of long-range in nature hence enabling the transportation of pollutants from faraway sources which ended up landing in Jabavu. As illustrated in Fig. 2 the air masses travelling at higher altitudes (>1500 m AGL) travel from far away than those at low altitudes (< 500 m AGL). The HYPSLIT analysis indicated the influence of long-range air masses on air pollution [6] in the Jabavu settlement particularly in summer, winter, and spring.

As shown in Fig. 3a at low wind speed the ambient concentration of PM_{10} is low for example during the autumn season. On the other hand at high south-westerly winds during the spring season the ambient PM_{10} concentrations are at their peak levels. For O_3 and SO_2 the seasonal concentrations were recorded at the highest during the autumn season where winds were blowing in a northwesterly direction.

Fig. 4 shows the diurnal profiles of SO_2, O_3, and PM_{10} concentrations recorded during summer (January & February), autumn (March-May), winter (June-August), and spring (September-November). For each season, the plots for each respective pollutant were generated using the hourly concentrations that consisted of at least 50% of data points. During the hours of the day, SO_2, O_3, and PM_{10} revealed three different diurnal patterns, with each pollutant having its unique trend, which was somewhat consistent throughout the year, regardless of the season.

To generate the plot, the daily mean concentrations of each pollutant recorded during each season (as defined earlier), which had at least over 50% of data points were used. For PM_{10} the highest concentrations were recorded during the winter

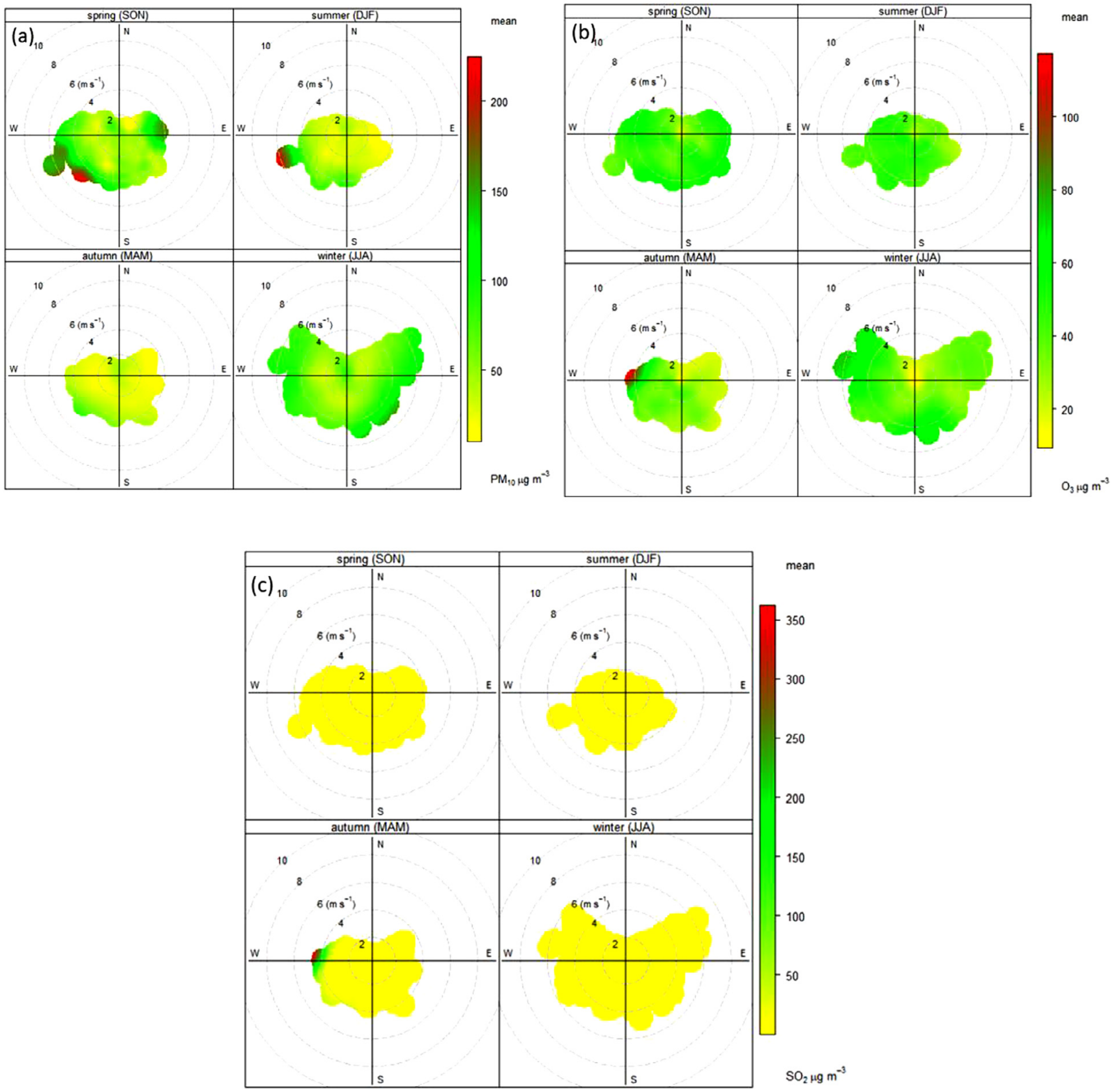

Fig. 3. (a) Seasonal bivariate polar plots for PM$_{10}$ (b) Seasonal bivariate polar plots for O$_3$ (c) Seasonal bivariate polar plots for SO$_2$.

season reaching a maximum pick of 428 µg m^3 in June as this makes the main heating season [22] while there were occasional plumes during the spring season and summer season.

The highest seasonal average PM$_{10}$ pollution was recorded during winter (for example from June-August) and the least episodes were measured in Summer (for example January & February). The observed substantial PM$_{10}$ during the winter period can be attributed to two factors. Firstly, given that at this time of the year ambient temperatures sharply drop, this results in an increment in the domestic burning of solid fuels as residents resort to such energy sources as are cheap and easily available within these communities [26,27]. An increment in residential consumption of solid fuel, especially during winter thus makes this season to be characterized by substantially high PM$_{10}$ pollution. The second attribution of extreme PM$_{10}$ in the winter season points to can be explained by the formation and dominance of the inversion layer over the Highveld region, especially during this period of the year. As such, the particulate concentration emitted from domestic burning is blocked from dispersing and mixing up in the atmosphere thus, remaining trapped at the ground level and resulting in the worst particulate scenarios being measured in winter.

Fig. 6a–6c depicts the seasonal mean-variance of SO$_2$, O$_{3,}$ and PM$_{10}$ concentrations measured within the low-income settlement in 2018. Furthermore, Table 2 provides the statistical summary of the seasonal comparison of each of the cri-

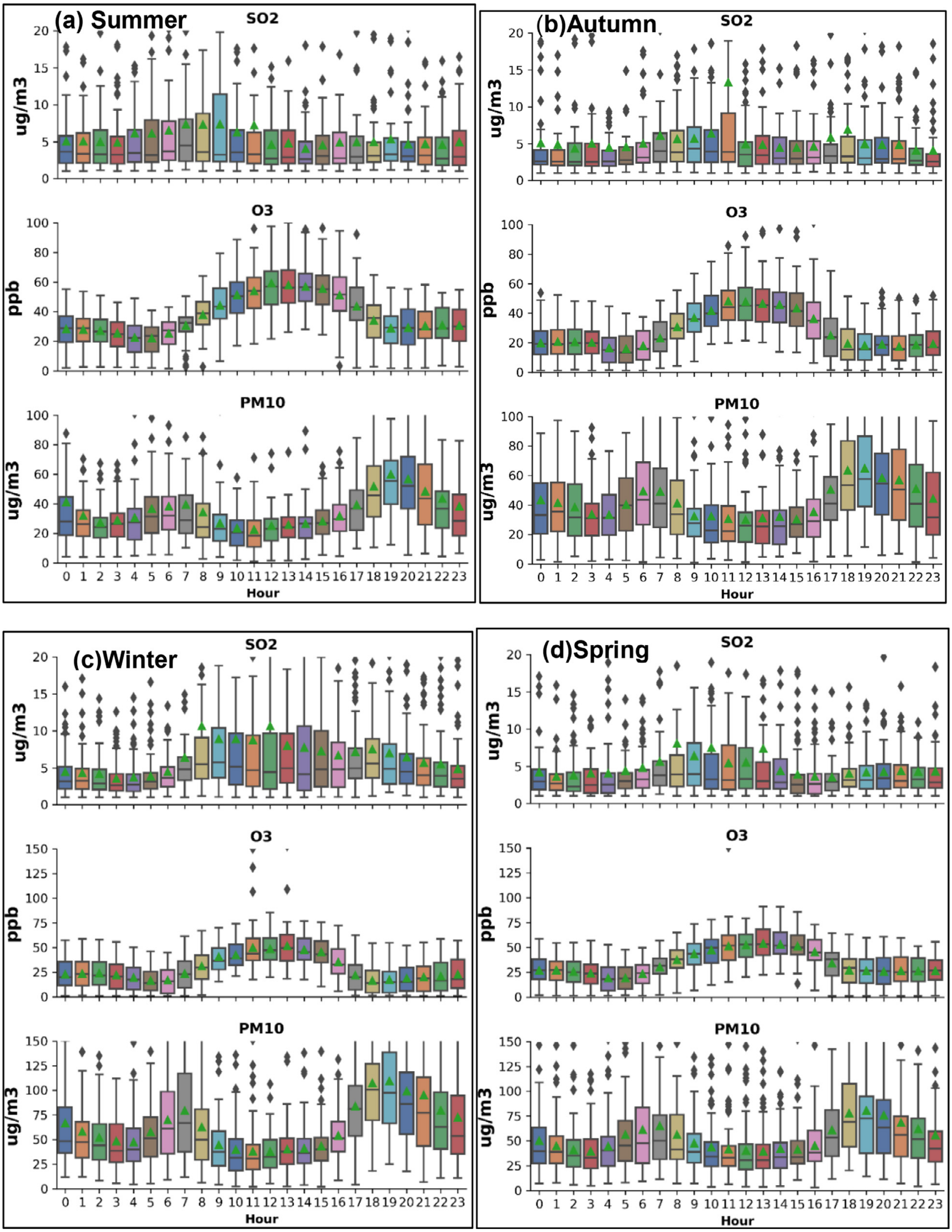

Fig. 4. Diurnal distribution of SO_2, O_3 and PM_{10} recorded during (a) summer (b) Autumn (c) Winter (d) Spring.

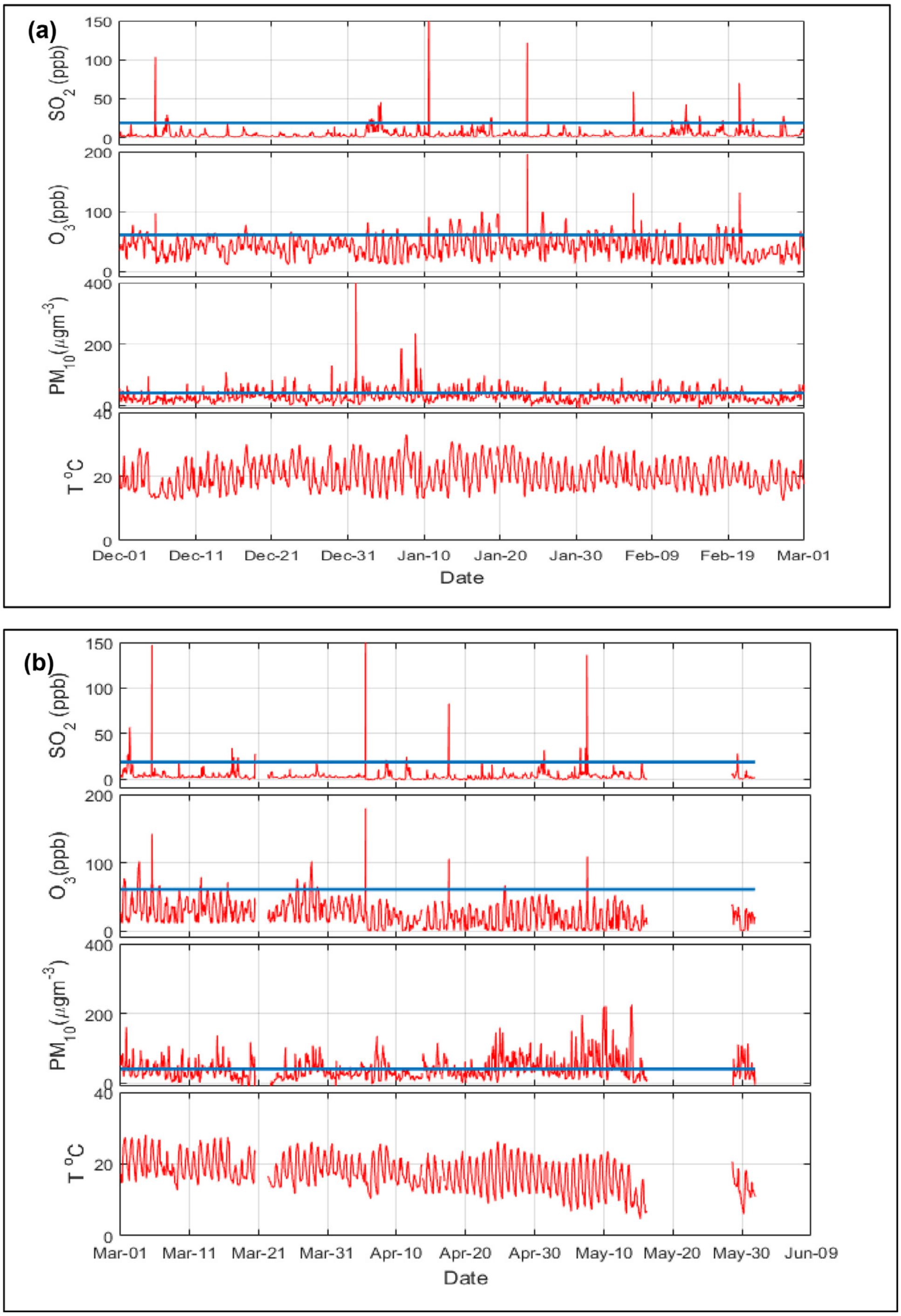

Fig. 5. Seasonal pollutant variations: (a) Summer (DJF) (b) Autumn (MAM) (c) Winter (JJA) (d) Spring (SON). *the blue line indicates the annual South African National Ambient Air Quality Standard threshold (60ppb for O_3, 19 ppb for SO_2 and 10 ug/m^3).

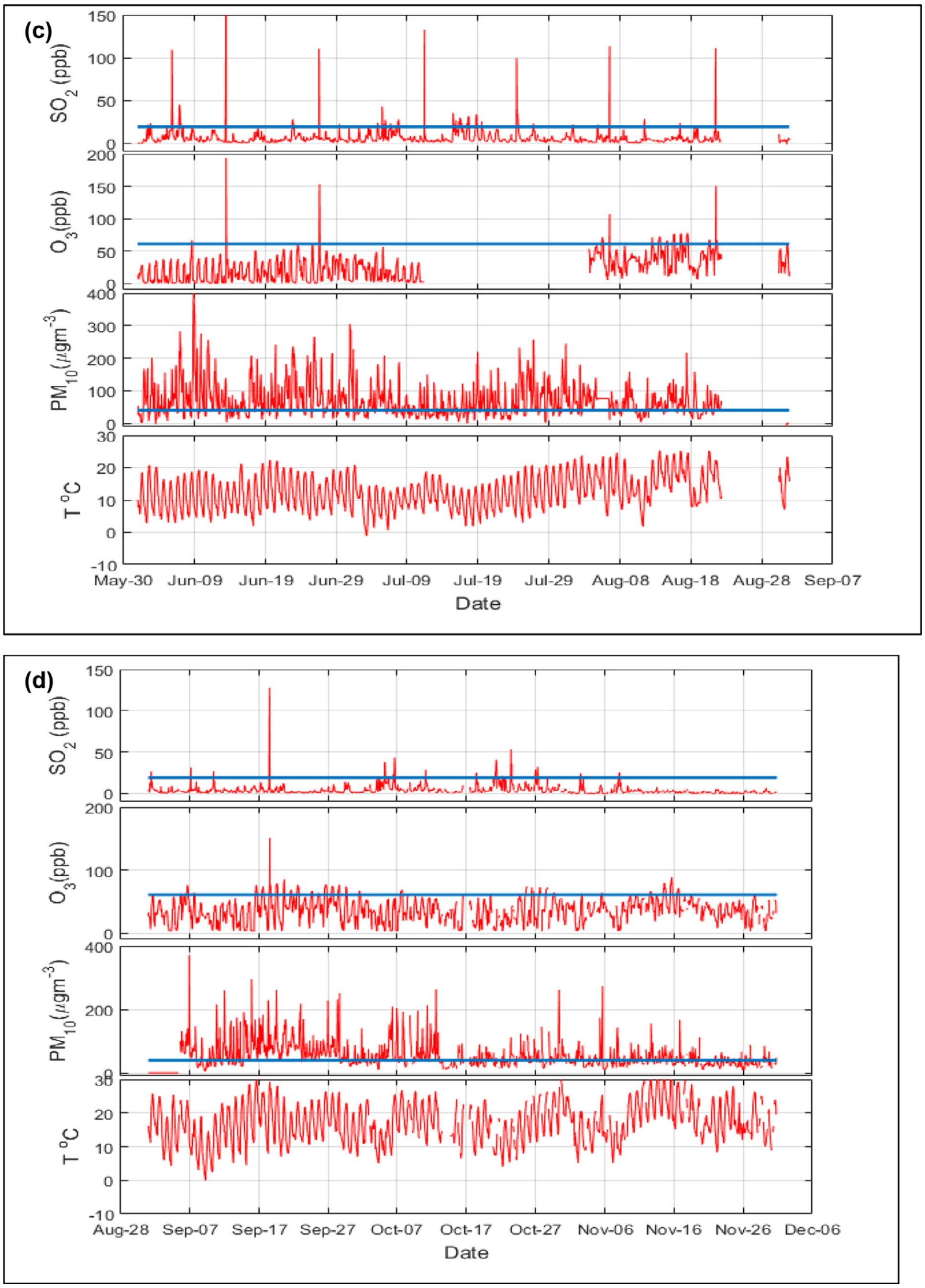

Fig. 5. Continued

teria pollutants. For SO$_2$, the highest seasonal mean concentration of 5.65.ppb was measured during winter (June to July) meanwhile, the least air pollution episode of 3.19.ppb was recorded in summer Fig. 6a.

Discussion

Our study characterised the state of ambient air quality within a low-income settlement of Jabavu, South Africa during the year 2018. Notably, the study observed high ambient PM$_{10}$ concentrations during the winter season. This can be attributed to the extensive dependence on solid fuels (coal and wood) by households in low-income settlements across South Africa to satisfy domestic energy requirements. Besides, PM$_{10}$ is a coarser version of particulate matter and has also been

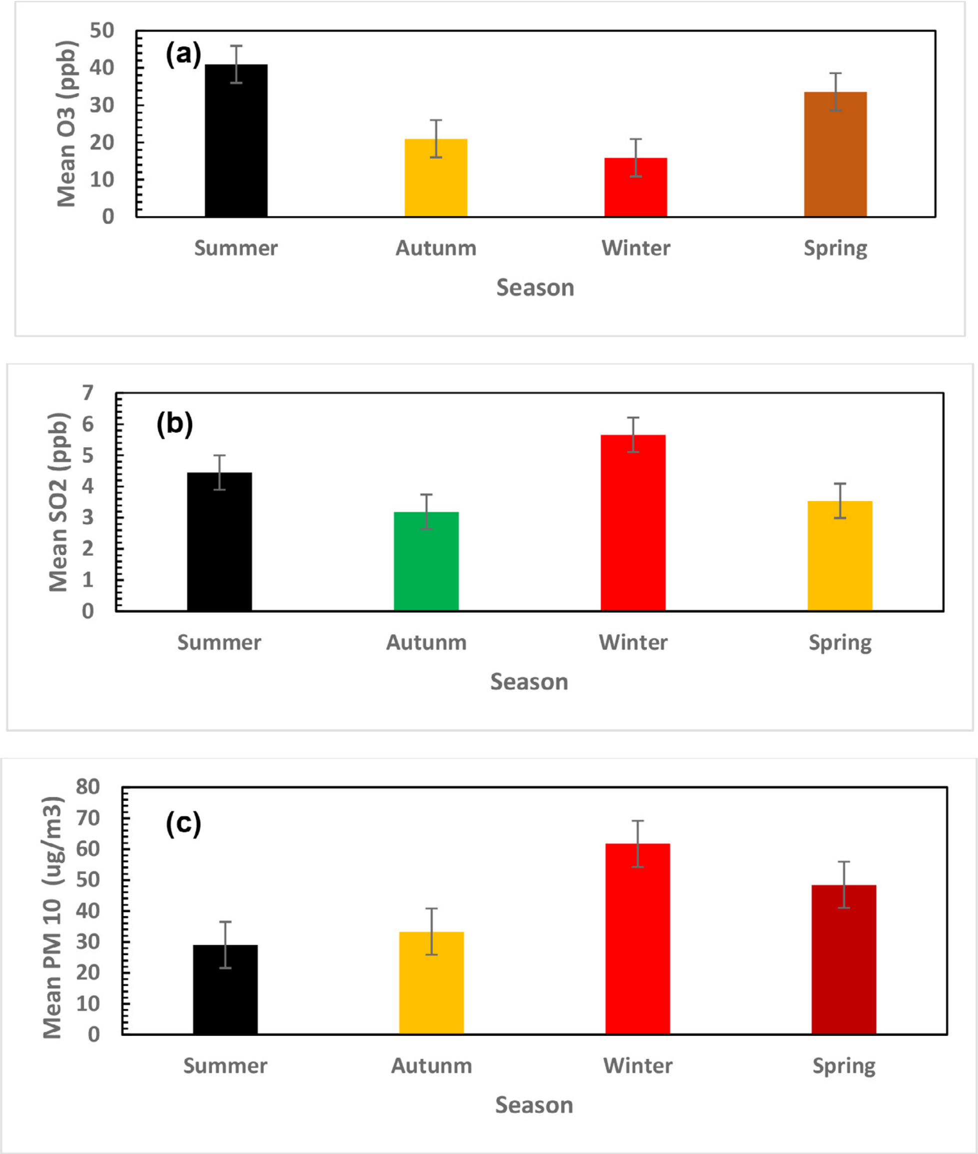

Fig. 6. Mean seasonal pollutant variations: (a) O_3 (b) SO_2, and (c) PM_{10}.

linked to unpaved roads within these settlements. During the winter season the highest PM_{10} concentrations recorded were at 76 µg.m^3 for the morning peak (i.e. from 3. 00 h to 10.00 h) and the evening peak at 105 µg.m^{-3} between 15.00 h and 23.00 h similar to findings by Ma et al. [22]. Therefore, the overall PM_{10} increment during winter season for both early and late hours of the day lasted for approximately 13 h. The morning and evening spikes recorded during winter were higher by an order magnitude of almost 2; 2; and 2 in comparison to those recorded during summer; autumn; and spring, respectively. This can be attributed to the elevated use of solid fuels by a vast majority of households in the settlement to keep warm from cold ambient temperatures experienced during winter. These results, therefore, suggest that the winter season increases the exposure for vulnerable population groups (elderly, individuals suffering from respiratory diseases) to PM_{10} related health risks in the settlement.

Furthermore, winter months are characterised by high gusty winds which makes dispersion of particulates easier. The high PM_{10} can also be linked to particulate loads coming from far away locations as shown in Fig. 2c wherein airmasses landing in Jabavu were originating from the Indian Ocean, Madagascar as well as the South Atlantic Oceanic. Across all the seasons the least concentrations were observed in the autumn months. This can be linked to the less usage of solid fuels to cater for space heating while the winds are also calmer as compared to winter. Also, Fig. 2b illustrates that air masses are mostly localised circulations indicating that pollutants are mostly local sources.

Regarding the gaseous pollutants of SO_2 and O_3, the study established that the peak concentrations were recorded during winter and summer respectively. O_3 peaked at 196 ppb while SO_2 highest was in winter at 244.23 ppb. The high SO_2 concentrations during winter can also be linked to heavy solid fuel use during the winter season. Some of the human health impacts of prolonged O_3 exposure include respiratory diseases and premature mortality [37] as well as increasing chances of pre-term births in pregnant mothers [14]. The substantial winter SO_2 high ambient concentration can be attributed to the formation of the inversion layer, which becomes dominant over the Highveld region, particularly during this season of the year. This, therefore, reduces the dispersion rate of emissions and results in SO_2 emissions being trapped from escaping into the atmosphere. The diurnal cycles of SO_2 displayed a midday peak approximately between 7.00 h and 16.00 h and this was seen in autumn, in a downward order, followed by winter, spring, and summer (Fig. 4). The absence of the morning and evening spikes suggests that the observed SO_2 peak in the mid-afternoon is not reflective of the domestic burning of solid fuels in Jabavu City. If this was never the case, then the diurnal pattern of SO_2 concentrations would have spiked during the morning approximately between 3.00 h and 10.00 h, and the evening between 16.00 h and 23. 00 h [11]. The midday peak of SO_2 captured in the Jabavu City low-income settlement can arguably be attributed to the regional point sources surrounding this community. The reason being, the mid-afternoon peak recorded in our study coincides with the time of the day when tall stack emissions are released down into the ground surface as a result of the breaking down of the inversion layer. These findings agree with other SO_2 observations which were made in other low-income settlements by Collett et al. [11] and Venter et al. [34], however, disagrees with the recent findings of Adesina et al. [1] in KwaZamokuhle a low-income settlement with similar socio-economic characteristics.

The behaviour of O_3 during the hours of the day showed a different distribution than that of SO_2 but also revealed a considerable seasonal variance, more especially between the summer and the winter period (Fig. 4a and 4c). It displayed no peak during the morning and the evening hours, instead, it only peaked during mid-afternoon, approximately between 6.00 h and 18.00 h, and this was seen throughout the year which can be attributed to up and down convection activities thus pollutant levels can be lower during daytime [22]. These observations agree with those which were made by Adesina et al. [1] and Collett et al. [11], within other low-income settlements that are located on the Highveld region. The aforementioned studies attributed the midday peak of O_3 in a township setting to atmospheric photochemical reaction. The maximum peak of 60.ppb was recorded during summer and was found to be almost 2; 1.5; and 2 times higher than the O_3 concentrations measured during autumn, winter, and spring, respectively. This, therefore, is indicative that residents in the settlement are more prone to substantial O_3 concentrations during afternoon hours, particularly over summer because surface ozone is a product of solar radiation catalysed chemicals reactions in the presence of nitrogen oxides and volatile compounds and concentrations are usually high when wind speeds are low [37].

Unexpected observations were also shown for O_3. The maximum O_3 seasonal mean of 40.97.ppb was recorded during the summer-autumn period (February and March) in a descending sequence, followed by spring (33.59.ppb), autumn (21.01.ppb), and ultimately, the winter period (15.90.ppb) Fig. 5b. This was a surprise, more especially because in South Africa O_3 typically peaks either during the late winter season (i.e. between July and August) or in spring (i.e. September to November) (Collett et al., 2011). The highest summer O_3 ambient concentration observed during the study could be as a result of the impacts of El Nino- Southern Oscillation (ENSO) over the Highveld region [5]. The same authors found that the influence of El Nino on the Highveld region is likely to amplify the formation of O_3, during the summer period (December, January and February). When investigating the seasonal mean of PM_{10} concentrations, a considerable seasonality was observed in the settlement. However, this was not the case, particularly between the summer (28.99 $\mu g.m^3$) and autumn (33.32 $\mu g.m^3$) periods since both these seasons measured somewhat similar PM_{10} concentrations (Table 1). All pollutants were however within the South African Ambient Air Quality Standards thresholds.

The study had limitations which included that it only focused on three pollutants due to the unavailability of data on other pollutants including $PM_{2.5}$, BC, CO, NO_x and NO_2. This limited the level of in-depth understanding regarding the ex-

Table 1
Descriptive statistics PM_{10}, SO_2 and O_3.

PM_{10}	Summer	Autumn	Winter	Spring
Mean	28.99	33.32	61.71	48.44
Median	24.69	26.18	50.46	39.46
Standard deviation	21.68	31.77	51.32	39.95
Maximum	401.29	224.49	428.21	371
SO_2	Summer	Autumn	Winter	Spring
Mean	4.45	3.19	5.65	3.54
Median	2.51	2.10	3.52	1.97
Standard deviation	7.02	7.56	9.70	5.57
Maximum	163.99	209.26	244.23	127.81
O_3	Summer	Autumn	Winter	Spring
Mean	40.97	21.01	15.90	33.59
Median	40.13	18.54	4.92	34.62
Standard deviation	17.05	19.05	19.82	19.68
Maximum	196.02	179.56	193.68	151.12

tends of air pollution within the settlement. Also, the other limitation is concerning the period as the study was only able to focus on a year cycle. For future studies, the authors intend to focus on long term analysis of other pollutants that include (PM_{10}, SO_2, O_3, $PM_{2.5}$, NO_2, BC, CO, heavy metals) within the settlement. The understanding of long-term patterns of all criteria pollutants can enable the crafting of future appropriate mitigation intervention strategies in the community to enable the improvement of clean air. Furthermore, future studies will also focus on the involvement of communities to understand the level of knowledge regarding air quality issues.

Conclusion

The current study characterised ambient air quality in a low-income urban settlement of Jabavu, South Africa. The study observed marked seasonal air quality variations and draws the following conclusions:

- During winter the most dominant pollutant was PM_{10} and throughout the study period, it exhibited bimodal distributions characterised by morning and evening peaks. The winter mean was 61.71 μg/m^3 which was lower than the South African Ambient Air Quality threshold of 75 μg/m^3. The study attributed these PM_{10} patterns to the extensive use of solid fuels in low-income settlements as well as an extensive network of unpaved roads.
- O_3 was more dominant during the summer season with a mean of 40.97 ppb. The peak periods were between 12. 00 h and 16. 00 h as the creation of O_3 is catalysed by the presence of solar radiation in the presence of NO_2 and NO_x.
- SO_2 is also picked during winter and the study linked this to the extensive use of household domestic solid fuels which are also good emitters of SO_2 especially coal. The mean ambient concentrations during winter were however below the South African Ambient Air Quality Standard threshold of 50 μg/m^3.
- During both summer and winter, dominant air masses the Madagascar-India Ocean and South Atlantic air masses particularly at high altitudes and this suggest that some of the pollutants land at Jabavu were from far away sources and not localised inland sources.
- During autumn and spring, the dominant air masses were mostly of local origins suggesting local sources being dominant in these seasons.

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Declaration of Competing Interest

We declare that we have no Conflict of Interest.

CRediT authorship contribution statement

Newton R. Matandirotya: Conceptualization, Writing – original draft, Methodology, Formal analysis. **Simon D. Moletsane:** Data curation, Formal analysis, Writing – original draft. **Electdom Matandirotya:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Roelof P. Burger:** Conceptualization, Methodology, Writing – review & editing.

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