Research article

Ambient $PM_{2.5}$, soot, black carbon and organic carbon levels in Kimberley, South Africa

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Abstract

Purpose: Ambient air pollution, particularly fine particulate matter ($PM_{2.5}$), is a major threat to human health and the environment. South Africa faces a burden of $PM_{2.5}$ exposure, leading to non-communicable diseases and premature mortality. International and national organisations have set air quality guidelines to protect public health. Although studies indicate that compliance with these guidelines carries some risk, meeting them can substantially reduce premature mortality rates. Several studies in different South African regions have highlighted the challenges of $PM_{2.5}$ pollution, emphasising the importance of monitoring air quality and implementing mitigation measures. This study aims to provide valuable data on the air quality in Kimberley.

Results: 24-hour $PM_{2.5}$ filter samples were collected manually every sixth day from 25 March 2021 to 25 January 2022 in Kimberley, Northern Cape Province, South Africa. The mean $PM_{2.5}$ concentration recorded in Kimberley was 6.3 µg/m³ (range: 0.7 – 25 µg/m³), slightly exceeding the World Health Organization (WHO) annual air quality guideline of 5 µg/m³. Additionally, the daily WHO guideline of 15 µg/m³ was exceeded on three occasions during the sampling period. The average soot (absorption coefficient), black carbon and organic carbon levels were 0.46 m-1 x 10-5, 0.6 µg/m³ and 0.4 µg/m³, respectively. Six geographic origins of air masses were identified after clustering 4476 generated 72-hour backward trajectories: North West (NW), North (N), East (E), South West (SW), South (S) and Long-range Indian Ocean (LRIO), suggesting diverse long-range transported air pollution from distant source areas.

Conclusions: This study is the first of its kind in Kimberley and provides valuable information on $PM_{2.5}$, soot, black carbon and organic carbon levels and the geographic origin of air masses that passed the sampling site. The findings indicate that the city's $PM_{2.5}$ pollution poses a risk to human health.

Keywords

$PM_{2.5}$, soot, black carbon, organic carbon

Introduction

Ambient air pollution, especially airborne particles with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$), poses a significant threat to human health and the environment (WHO, 2022). Studies reported a range of non-communicable diseases that are associated with $PM_{2.5}$ exposure, such as cardiovascular, respiratory and metabolic diseases (WHO, 2022). The Global Burden of Disease Study estimated that air pollution was the reason for 1.1 million deaths across Africa in 2019 (GBD 2019 Risk Factor Collaborators, 2020). Altieri & Keen (2019) projected that 28 000 premature deaths (6% of all deaths) in South Africa during 2012 were due to chronic exposure to $PM_{2.5}$.

The World Health Organization (WHO) and regulatory bodies of various countries established guidelines and standards for air pollutants, including $PM_{2.5}$. The WHO provides global yearly (5 µg/m³) and daily (15 µg/m³) guidelines for $PM_{2.5}$, to minimise health risks (WHO, 2022). South Africa is one of the few African countries that have an air quality act (UNEP, 2021; Department of Environment, Forestry and Fisheries, 2005). The Act enforces National Ambient Air Quality Standards (NAAQS) for various air pollutants since 2005 and for $PM_{2.5}$ since 2012: yearly NAAQS (20 µg/m³) and daily NAAQS (40 µg/m³) (Department of Environment, Forestry and Fisheries, 2012a). Altieri and Keen (2019) estimated

that 14 000 premature deaths could have been avoided in 2012 if yearly $PM_{2.5}$ levels in South Africa were below or at the yearly NAAQS (20 µg/m^3). Ideally, air pollution levels should be such that they do not pose any risk to human health. However, health effects have been observed for air pollution levels even below the more protective WHO guidelines (WHO, 2022; Brunekreef et al., 2021).

Despite having an air quality act that should enforce the monitoring of air pollution in South Africa, data quality is poor and the air quality monitoring network is not extensive across the country (Department of Environment, Forestry and Fisheries, 2024). Municipal Air Quality Management Plans (AQMP) were introduced by the South African government to decentralise air quality monitoring, shifting responsibility to local rather than national government authorities (Department of Environment, Forestry and Fisheries., 2012b). The municipality of Kimberley (Sol Plaatje municipality) does not have an AQMP. Kimberley is located in the larger Frances Baard District Municipality. The AQMP of the district came into effect in 2010, so prior to the establishment of the $PM_{2.5}$ NAAQS in 2012 (Frances Baard District Municipality, 2010). The current district AQMP is long overdue for a review, as required every five years by the National Environmental Management: Air Quality Act of 2005 (Department of Environment, Forestry and Fisheries, 2005).

Air pollution data are not available for Kimberley, despite the existence of a district AQMP (Department of Environment, Forestry and Fisheries, 2024). No researcher-initiated study ever quantified $PM_{2.5}$ and some of its composition (soot, black carbon (BC) and organic carbon (OC)) in Kimberley. This study addressed these research gaps.

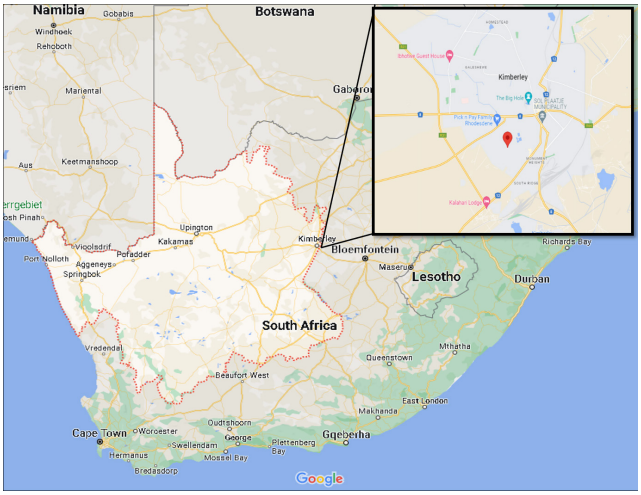

Figure 1: *Location of Kimberley in the Northern Cape province, South Africa. The sampling site is indicated by a red marker in the local map of Kimberley.*

Figure 2: *Sampling setup on the roof of a residential building showing the GilAir5 pump, cyclone and the filter cassette.*

Material and methods

Study area

Kimberley is the capital and most populous city (270 062) in the Northern Cape province, South Africa (Figure 1) (Statistics South Africa., 2023). Compared to larger cities in South Africa (Johannesburg or Cape Town), Kimberley is relatively smaller in terms of population and urban development. Kimberley has a semi-arid climate characterised by dry and arid conditions (Frances Baard District Municipality, 2010).

$PM_{2.5}$ sampling was conducted at a residential building located in Aviva Street, Hadison Park, Kimberley. The sampling site was chosen to represent a background area with low $PM_{2.5}$ levels, away from major air pollution sources. The sampling equipment was positioned on the roof of the building, approximately six meters above the ground, to minimise the deposition of crustal material and potential obstructions from nearby structures. The geographic coordinates of the sampling station were recorded as 28.76 S 24.75 E.

$PM_{2.5}$ sampling and analysis

$PM_{2.5}$ sampling was conducted using a single-channel GilAir5 personal air sampler (Sensidyne, Schauenburg Electronic Technologies Group, Mulheim-Ruhr, Germany), GK 2.05 KTL $PM_{2.5}$ cyclones (Sensidyne, Schauenburg Electronic Technologies Group, Mulheim-Ruhr, Germany) and 37 mm Teflon (PTFE) membrane filters (Zefon International, Florida, USA); as done in other local studies (Figure 2) (Williams et al., 2021; Novela et al., 2021; Adeyemi et al., 2022; Howlett-Downing et al., 2022; van der Westhuizen et al., 2022). A 24-hour filter sample (8 am to 8 am) was collected every sixth day from 25 March 2021 to 25 January 2022.

The choice of sampling equipment was determined by accessibility and cost-effectiveness c ompared t o c ontinuous real-time sampling instruments. A study from Pretoria indicated a good correlation between $PM_{2.5}$ sampling results obtained with the GilAir5 pump and continuous real-time sampling instruments (Spearman rank-ordered correlation coefficient 0.740; $p<0.0001$) (Figure 3 and Supplementary figure 1 (Mwase, 2020).

The flow rate of the GilAir5 pump (4 L/min) was verified using a field rotameter both before and after sampling. Calibration of the field rotameter was carried out using a GilAir calibrator.

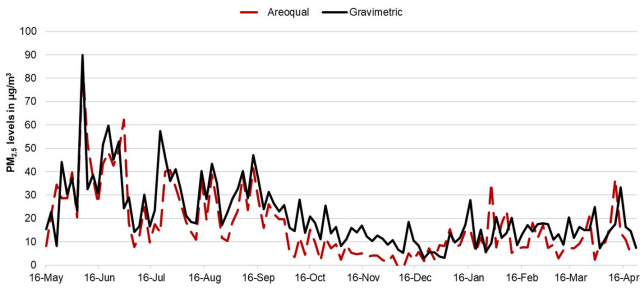

Figure 3: *Comparison between $PM_{2.5}$ levels obtained with gravimetric analysis against the continuous real-time sampling instrument, measured at the University of Pretoria from 19 April 2018 to 23 April 2019 (Mwase, 2020).*

The filters were weighed using a Mettler-Toledo microbalance in a temperature (21 ± 0.5 °C) and humidity (50 ± 5%) controlled weighing room at the School of Health Systems and Public Health (SHSPH), University of Pretoria. Filters were conditioned in the weighing room for at least 24 hours before weighing. The filters were stored in individual filter holders and refrigerated at 4 °C after weighing. Filter samples were couriered between Pretoria and Kimberley in individual filter holders.

Soot measurements

Soot measurements were performed at the SHSPH with an M43D EEL smoke stain reflectometer (Williams et al., 2021; Novela et al., 2021; Adeyemi et al., 2022; Howlett-Downing et al., 2022; van der Westhuizen et al., 2022). An absorption coefficient (m^{-1} x 10^{-5}) is calculated from the measurements (Equation 1).

$$a = \left(\frac{A}{2*V}\right) * \left(\frac{R_O}{R_f}\right) \quad (1)$$

where a is the absorption coefficient (m^{-1} x 10^{-5}), V is the sampled volume (m^3), R_0 is the reflection of a primary control filter (%), R_f is the reflection of the sampled filter (%) and A is the loaded filter area (m^2).

BC and OC analyses

The analyses of BC and UV-PM (a proxy for organic carbonaceous particulate matter absorbing UV light at 370 nm; hereafter OC) were performed using a Model OT21 Optical Transmissometer (Magee Scientific Corp., Berkeley, CA, USA) at the University of Gothenburg, Sweden (Williams et al., 2021; Novela et al., 2021; Adeyemi et al., 2022; Howlett-Downing et al., 2022; van der Westhuizen et al., 2022). The additional absorption in the UV light, at 370 nm, due to the organics indicate the presence of biomass burning (Sandradewi et al., 2008; Teich et al., 2017).

Geographical origin of air masses

The geographical origin of air masses that passed the sampling site in Kimberley were applied as surrogates for long-range transported air pollution from distant source area (Wichmann et al., 2014; Molnár et al., 2017; Williams et al., 2021; Novela et al., 2021; Adeyemi et al., 2022; Howlett-Downing et al., 2022; van der Westhuizen et al., 2022).

For each day in the 11-month study period, 72-hour backward trajectories were generated using the HYSPLIT software. The software is executed using the National Centers for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Global Reanalysis Meteorological Data at the web server of the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL). An analysis field (resolution 2.5° x 2.5° and 17 vertical levels) was provided every six hours (0:00, 6:00, 12:00, 18:00) for a 72-hour backward trajectory and the wind field was interpolated linearly between each analysis. Since a single backward trajectory has a large uncertainty and is of limited significance, an ensemble of trajectories with 500 m starting height and a fixed offset grid factor of 250 m was used in this study (i.e. 250 m and 750 m also used). In total, 4476 backward trajectories were generated and applied in the cluster analysis with the HYSPLIT software. The optimal number of clusters was determined as six.

In a sensitivity analysis, 24-hour backward trajectories starting every six hours (0:00, 6:00, 12:00, 18:00) were also applied in the cluster analysis. These 24-hour clusters would indicate air pollution source areas that are closer than those indicated by the 72-hour clusters.

Meteorological data

Daily temperature, relative humidity, precipitation and windspeed data and hourly wind direction data were requested from and provided by the South African Weather Service (SAWS).

Statistical analysis

Statistical analyses were performed with SAS version 9.4. The predominant wind direction of each day was estimated from the hourly data, i.e. the mode value. Descriptive statistics were reported for the $PM_{2.5}$, soot, BC, OC and meteorological variables.

Non-parametric tests were applied as the Shapiro-Wilk's test indicated that the $PM_{2.5}$, soot, BC, OC and the meteorological variables did not have normal Gaussian distributions. Spearman rank-ordered correlation analyses were applied to investigate the correlation between the $PM_{2.5}$, soot, BC, OC and meteorological variables. Seasons were defined as autumn (March to May), winter (June to August), spring (September to November) and summer (December to February). Kruskal–Wallis tests were conducted to determine whether the median $PM_{2.5}$, soot, BC, OC and meteorological variables differed significantly between seasons, day of the week, wind direction and geographical origins of air masses. Wilcoxon's rank-sum tests were conducted to determine whether median air pollution levels and meteorological variables differed significantly between weekdays and weekends/public holidays.

Ethics approval

The study obtained approval from the Faculty of Health Sciences Research Ethics Committee, University of Pretoria (References 229/2020 and 231/2023).

Results and discussion

$PM_{2.5}$ levels

Fifty filter samples were collected during the 11-month study period. Four samples were excluded as the $PM_{2.5}$ level was below the detection limit. Descriptive statistics are reported in Table 1. The seasonal variation of $PM_{2.5}$ levels is illustrated in Figure 4.

The average $PM_{2.5}$ level was 6.3 µg/m³. This average, although based on 11 months, was below the yearly South African NAAQS (20 µg/m³) (Department of Environment, Forestry and Fisheries, 2012a), but exceeded the yearly WHO air quality guideline (5 µg/m³) (WHO, 2022). The daily WHO guideline (15 µg/m³) was exceeded on three occasions, once during winter, spring and summer. The daily South African NAAQS (40 µg/m³) was never exceeded.

The median $PM_{2.5}$ levels differed significantly by season ($p<0.05$) (Table 1), with the highest median level in summer (8.0 µg/m³), followed by winter (5.8 µg/m³), spring (5.4 µg/m³) and autumn (2.5 µg/m³) (Table 1). Possible reasons for the seasonal variation may be due to various air pollution sources that were identified in the 2010 AQMP of the Frances Baard District, such as transportation and traffic (motor vehicles and railways), domestic and commercial fuel burning, waste-related processes (incineration, landfills and sewage), mining operations, biomass burning (veld fires), agricultural activities, asphalt production (for road building), cement manufacturing, petrol stations (associated with fuel storage) and various industrial activities (Frances Baard District Municipality, 2010). The maximum $PM_{2.5}$ level (25 µg/m³) was observed in winter.

The median $PM_{2.5}$ level on weekends were lower (2.9 µg/m³) than on weekdays (5.9 µg/m³) ($p>0.05$) (Supplementary table 1). The highest median $PM_{2.5}$ level was recorded on a Wednesday (9.0 µg/m³) and the lowest on a Saturday (2.7 µg/m³), although the median levels did not differ significantly by day of the week ($p > 0.05$) (Supplementary table 2).

The mean $PM_{2.5}$ level in Kimberley was lower than those reported in other South African cities: Thohoyandou (11 µg/m³), Pretoria (24 µg/m³), Cape Town (13 µg/m³), Bloemfontein (11 µg/m³), the industrial Greater Tubatse Municipality in the Limpopo Province (12 µg/m³), the industrial areas of the Vaal Triangle Air Pollution Priority Area (30 µg/m³) and the Highveld Airshed Priority Area (32 µg/m³) (van der Westhuizen et al 2022; Howlett-Downing et al., 2022; Olutola & Wichmann, 2021; Novela et al., 2020; Tshehla & Djolov, 2018; Williams et al., 2021; Mwase et al 2022). In 16 countries the yearly mean level was 36 µg/m³; the highest in China (52 µg/m³) and the lowest in Australia (7 µg/m³) (Liu et al., 2019). The study noted a mean of 31 µg/m³ for South Africa.

Due to the lack of $PM_{2.5}$ ground-based observations in Africa, researchers often rely on models to estimate the pollutant's levels. Bachwenkizi et al. (2021) estimated $PM_{2.5}$ levels from 1998 to 2018 using a combination of satellite data, chemical transport model simulations, and ground-based observations. In South

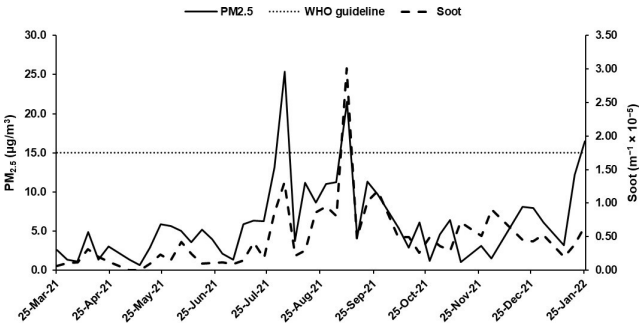

Figure 4: *Time-series graph of $PM_{2.5}$ and soot levels during 25 March 2021 and 25 January 2022 in Kimberley, South Africa.*

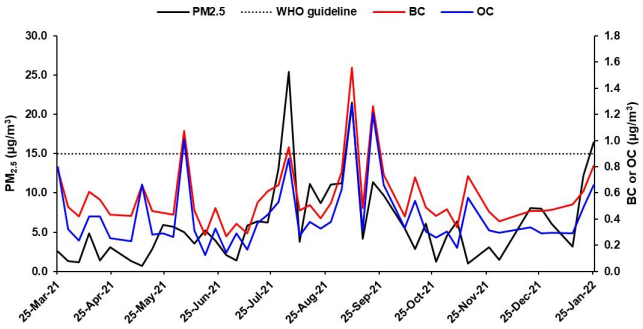

Figure 5: *Time-series graph of $PM_{2.5}$, BC and OC levels during 25 March 2021 and 25 January 2022 in Kimberley, South Africa.*

Africa, the estimated annual mean $PM_{2.5}$ level was 13 µg/m³, with estimates ranging from 14 µg/m³ in Angola to as high as 69 µg/m³ in Nigeria. A study from Nairobi, Kenya, reported a mean of 21 µg/m³ for $PM_{2.5}$ at an urban background site and 13 µg/m³ at a suburban site (Gaita et al., 2014). In Jinja and Kampala, Uganda outdoor $PM_{2.5}$ daily levels ranged from 0 to 535 µg/m³ (Kirenga et al., 2015). Daily mean $PM_{2.5}$ levels in industrial locations ranged from 8 to 384 µg/m³ in Kampala (Kirenga et al., 2015). Agbo et al (2021) observed that the daily WHO guideline (15 µg/m³) was exceeded in the majority of 22 cities across Africa.

As pointed out earlier, health effects have been observed for air pollution levels even below the updated WHO guidelines (WHO, 2022; Brunekreef et al., 2021). The exceedances of the daily and yearly WHO air quality guidelines at this urban background location suggest that the population of Kimberley may be at risk for various health issues over the short- and long-term (WHO, 2022, Brunekreef et al., 2021). A meta-analysis conducted by Achilleos et al. (2017) included 41 epidemiological time-series studies across 142 cities and found that short-term exposure to $PM_{2.5}$ led to increases in all-cause mortality, respiratory disease mortality, and cardiovascular disease mortality by 0.9%, 1.1%, and 0.8% per 10 µg/m³ increase, respectively. Mwase et al (2022) reported a 1.0% (95% CI -0.3%; 2.4%) increase in respiratory disease hospitalisations per 10 µg/m³ increase in $PM_{2.5}$ over 24 hours in the industrial Vaal Triangle Air Pollution Priority Area, South Africa. A large European study pooled 11 cohort epidemiological data, and reported a 13% increased risk of coronary events associated with a 5 µg/m³ increase in the estimated yearly mean $PM_{2.5}$ (i.e. long-term exposure) (Cesaroni et al., 2014). More recently, the ELAPSE study (Effects of Low-

Table 1: *Descriptive statistics of 24-hour levels of $PM_{2.5}$, soot, black carbon, organic carbon and meteorological conditions in Kimberley, South Africa during 25 March 2021 and 25 January 2022.*

	Variable	Mean	Std Dev	Median	Min	Max
All year (46 samples)	**$PM_{2.5}$**	6.3	5.3	5.1	0.7	25.4
	Soot	0.46	0.50	0.33	0.00	3.01
	Black carbon	0.57	0.25	0.49	0.27	1.56
	Organic carbon	0.43	026	0.33	0.12	1.28
	Temperature	16.5	5.9	17.0	1.5	26.2
	Relative humidity	44.4	16.3	45.2	12.7	81.7
	Windspeed	14.1	7.8	12.7	2.5	39.5
	Rainfall	1.5	4.7	0.0	0.0	23.8
Autumn (11 samples)	**$PM_{2.5}$**	2.8	1.9	2.5	0.7	5.9
	Soot	0.13	0.09	0.11	0.00	0.31
	Black carbon	0.52	0.12	0.46	0.42	0.78
	Organic carbon	0.38	0.19	0.29	0.23	0.80
	Temperature	16.9	4.2	17.0	7.9	22.7
	Relative humidity	51.8	12.1	50.3	35.0	81.7
	Windspeed	11.9	9.7	9.7	4.4	39.5
	Rainfall	0.1	0.2	0.0	0.0	0.6
Winter (15 samples)	**$PM_{2.5}$**	7.5	6.0	5.8	1.4	25.4
	Soot	0.42	0.38	0.24	0.09	1.30
	Black carbon	0.53	0.23	0.49	0.27	1.07
	Organic carbon	0.40	0.25	0.33	0.12	1.01
	Temperature	10.8	4.7	10.7	1.5	17.1
	Relative humidity	40.6	11.3	42.7	12.7	61.7
	Windspeed	12.0	6.6	11.2	2.5	20.9
	Rainfall	0.0	0.0	0.0	0.0	0.0
Spring (13 samples)	**$PM_{2.5}$**	6.8	5.6	5.4	1.0	21.5
	Soot	0.78	0.72	0.50	0.26	3.01
	Black carbon	0.68	0.36	0.49	0.34	1.56
	Organic carbon	0.53	0.35	0.33	0.18	1.28
	Temperature	19.0	3.6	18.2	13.5	24.9
	Relative humidity	37.1	21.8	29.0	14.3	79.7
	Windspeed	17.8	6.9	17.6	10.6	31.7
	Rainfall	2.0	4.8	0.0	0.0	13.8
Summer (7 samples)	**$PM_{2.5}$**	7.9	5.1	8.0	1.5	16.4
	Soot	0.50	0.22	0.45	0.19	0.90
	Black carbon	0.53	0.14	0.47	0.38	0.81
	Organic carbon	0.38	0.14	0.30	0.29	0.66
	Temperature	23.5	1.8	23.8	21.5	26.2
	Relative humidity	54.6	11.4	55.3	37.3	67.7
	Windspeed	15.1	7.0	14.2	5.0	25.8
	Rainfall	6.1	9.2	1.6	0.0	23.8

Units: $PM_{2.5}$, BC and OC (µg/m3), soot ($m^{-1} \times 10^{-5}$), temperature (°C), relative humidity (%), wind speed (km/h), rainfall (mm).
$p<0.05$ for median levels of $PM_{2.5}$, soot, temperature, relative humidity and rain by seasons, but not for BC, OC and windspeed

Table 2: *Spearman rank correlation coefficients for all the study variables during 25 March 2021 and 25 January 2022 in Kimberley, South Africa (46 sampling days).*

	$PM_{2.5}$	Soot	BC	OC	Temp	RH	Windspeed
Soot	**0.595**	1.000	**0.272**	0.290	0.226	**-0.400**	0.256
BC	**0.363**	**0.403**	1.000	**0.905**	0.132	-0.236	-0.149
OC	**0.394**	**0.505**	**0.905**	1.000	0.098	-0.265	-0.127
Temp	-0.092	0.226	0.180	0.229	1.000	0.208	**0.381**
RH	-0.252	**-0.400**	-0.349	-0.324	0.208	1.000	-0.035
Windspeed	0.030	0.256	-0.162	-0.142	0.381	-0.035	1.000
Rainfall	-0.068	-0.047	-0.092	-0.136	**0.489**	**0.617**	0.249

Bold indicates p<0.05

Table 3: *$PM_{2.5}$, BC, OC and soot levels on 46 sampling days during 25 March 2021 and 25 January 2022 in Kimberley, South Africa: By geographical origin of air masses.*

Variable	Mean	Std dev	Median	Min	Max
North West (NW) (4 samples)					
$PM_{2.5}$	5.4	4.8	4.0	1.3	12.2
Soot	0.23	0.13	0.22	0.11	0.38
BC	0.54	0.09	0.55	0.44	0.62
OC	0.37	0.10	0.37	0.26	0.49
North (N) (11 samples)					
$PM_{2.5}$	8.1	6.9	5.8	1.3	25.4
Soot	0.48	0.47	0.24	0.00	1.30
BC	0.53	0.22	0.46	0.27	0.95
OC	0.39	0.24	0.31	0.12	0.86
East (E) (13 samples)					
$PM_{2.5}$	6.7	6.3	5.9	0.7	21.5
Soot	0.52	0.77	0.30	0.00	3.01
BC	0.63	0.31	0.51	0.43	1.56
OC	0.49	0.29	0.37	0.26	1.28
South West (SW) (12 samples)					
$PM_{2.5}$	4.6	3.1	4.0	1.0	11.3
Soot	0.52	0.31	0.49	0.10	1.03
BC	0.55	0.26	0.47	0.34	1.26
OC	0.40	0.28	0.30	0.18	1.21
South (S) (1 sample)					
$PM_{2.5}$	5.0	.	5.0	5.0	5.0
Soot	0.42	.	0.42	0.42	0.42
BC	1.07	.	1.07	1.07	1.07
OC	1.01	.	1.01	1.01	1.01
Long-range Atlantic Ocean (LRAO) (5 samples)					
$PM_{2.5}$	5.8	3.5	5.7	1.4	11.1
Soot	0.34	0.35	0.18	0.09	0.95
BC	0.48	0.09	0.47	0.36	0.61
OC	0.33	0.07	0.31	0.27	0.44

Units: $PM_{2.5}$, BC and OC ($\mu g/m^3$) and soot ($m^{-1} \times 10^{-5}$)
p>0.05, no significant difference between median levels by geographic origin of air masses

Level Air Pollution: A Study in Europe) pooled cohort study data and reported a significant increase of 30% (95% CI 14%; 47%) in natural-cause mortality per 5 µg/m³ increase in long-term exposure to $PM_{2.5}$ for $PM_{2.5}$ levels below 12 µg/m³ (Brunekreef et al., 2021).

Soot, BC and OC levels

Studies on the ambient levels of soot, BC and OC and their health effects in Africa are scarce. There is currently no South African NAAQS or WHO air quality guidelines for soot, BC or OC. The median soot level was 0.33 m^{-1} x 10^{-5} during the study period (Table 1). The seasonal variation of soot levels is illustrated in Figure 4. The median soot level in spring (0.50 m^{-1} x 10^{-5}) was significantly higher ($p<0.05$) compared to those in summer (0.45 m^{-1} x 10^{-5}), winter (0.24 m^{-1} x 10^{-5}) and autumn (0.11 m^{-1} x 10^{-5}) (Table 1). Median soot levels on weekends (0.28 m^{-1} x 10^{-5}) were not significantly different than on weekdays (0.56 m^{-1} x 10^{-5}) ($p \geq 0.05$) (Supplementary table 1). The highest median soot level was recorded on a Thursday (1.01 m^{-1} x 10^{-5}) and the lowest on a Friday (0.25 m^{-1} x 10^{-5}), although the median levels did not differ significantly by days of the week ($p \geq 0.05$) (Supplementary table 2).

The median soot levels in Thohoyandou, Pretoria and Cape Town were higher: 0.60 m^{-1} x 10^{-5}, 1.00 m^{-1} x 10^{-5} and 0.94 m^{-1} x 10^{-5}, respectively (Novela et al., 2020; Williams et al., 2021; Howlett-Downing et al., 2022). The mean soot level was higher in Bloemfontein (1.2 m^{-1} x 10^{-5}) (van der Westhuizen et al., 2022). Soot levels ranged from 0.6 to 3.2 m^{-1} x 10^{-5} in 11 European countries and an increase of 10% in coronary heart disease hospital admissions were reported per unit m^{-1} x 10^{-5} increase in soot levels (Cesaroni et al., 2014). Chronic exposure to soot in 17 European countries were also reported to increase the risk for lung cancer development by 12% per unit m^{-1} x 10^{-5} increase in soot levels (Raaschou-Nielsen et al., 2013).

The median BC level was 0.49 µg/m³ during the study period (Table 1). Figure 5 indicates the seasonal variation of BC levels. The median BC levels did not differ significantly by season, weekday/weekend nor by days of the week ($p \geq 0.05$) (Table 1, Supplementary tables 1 and 2).

The median BC levels in Thohoyandou (8 µg/m³), Pretoria (2 µg/m³), Cape Town (2 µg/m³) and the industrial areas of the Vaal Triangle Air Pollution Priority Area (3 µg/m³) were higher (Novela et al., 2020; Williams et al., 2021; Howlett-Downing et al., 2022; Mwase et al 2022). The mean BC level was lower in Bloemfontein (0.3 µg/m³) (van der Westhuizen et al 2022). A higher mean (3 µg/m³) was reported in Nairobi, Kenya (Gaita et al. 2014). Mean BC levels were the highest level in Benin (16 µg/m³) and the lowest level in South Africa (2 µg/m³) (Bachwenkizi et al. 2021). Higher mean levels were reported in London, UK (2 µg/m³) and in the Uzice region, Serbia (33.9 µg/m³) (Samoli et al., 2016; Tomic-Spiric et al., 2019).

In terms of health effects due to ambient BC exposure, a study observed that the risk of infant mortality in 15 African countries

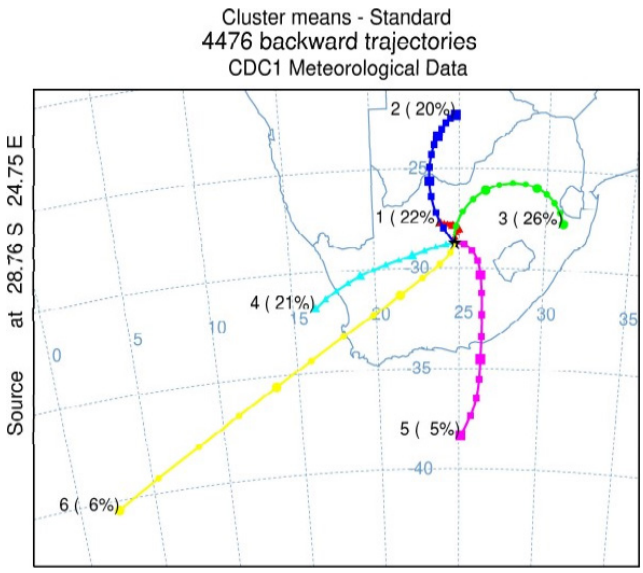

Figure 6: *Six geographical origins of air masses identified in the 72-hour backward trajectory model runs on all days during the study period March 2021 to January 2022 in Kimberley, South Africa. North West (NW) is indicated by the red line, North (N) indicated by the dark blue line, East (E) indicated by the green line, South West (SW) indicated by the light blue line, South (S) indicated by the purple line and Long-range Atlantic Ocean (LRAO) indicated by the yellow line.*

increased significantly by 4% for every 6.6 µg/m³ rise in BC levels (Bachwenkizi et al., 2021). A review reported the following short-term effects per 10 µg/m³ increase in BC: increases of 0.7% in total mortality, 0.6% in cardiovascular disease mortality and 0.8% in respiratory disease mortality (Zhu et al., 2023). Long-term exposure to BC (per 10 µg/m³ increase) were associated with an increases of 29.8% in total mortality (Zhu et al., 2023). Song et al. (2022) found a 1.2% increase in respiratory disease hospital admissions per 1 µg/m³ increase in BC across 10 studies, which aligns with findings from the highly polluted Vaal Triangle Priority Area in South Africa (Mwase et al., 2022).

The median OC level was 0.33 µg/m³ during the study period (Table 1). Figure 5 shows the seasonal variation of OC levels. The median OC levels did not differ by season (Table 1), weekdays/weekends nor by day of the week (Supplementary tables 1 and 2).

The median OC levels in Thohoyandou (1 µg/m³), Pretoria (2 µg/m³) and Cape Town (2 µg/m³) were higher (Novela et al., 2020; Williams et al., 2021; Howlett-Downing et al., 2022). The mean OC level was higher in Bloemfontein (0.5 µg/m³) (van der Westhuizen et al 2022). Bachwenkizi et al. (2021) reported the lowest mean organic matter PM (equivalent to our OC measure) in South Africa (2 µg/m³) and the highest level in Nigeria (13 µg/m³).

Exposure to ambient OC has been linked to a 4% increase in infant mortality in 15 African countries per 5.7 µg/m³ increase in organic matter PM (Bachwenkizi et al, 2021). Achilleos et al., (2017) reported an increase in all-cause mortality by 1.3% per 6.1 µg/m³ increase in OC levels.

Meteorological conditions

The mean temperature during the study was 16.5 °C, with a range of 1.5 to 26.2 °C. The wind speed ranged from 2.5 to 39.5 km/hr, with the rainfall ranging from 0 to 23.8 mm (with rain on eight of the 46 sampling dates), and the relative humidity ranging from 12.7% to 81.7% (Table 1). Temperature, humidity and rainfall varied significantly by season, but not windspeed (Table 1). The predominant wind direction was from the north (19 sampling days) (Supplementary figure 2).

Correlation between $PM_{2.5}$, soot, BC, OC and meteorological conditions

Table 2 reveals a significant correlation ($p < 0.05$) between $PM_{2.5}$ and soot, BC and OC. The correlation between BC and OC was the strongest, which may indicate that they share common sources. A study involving 15 African countries reported a stronger correlation between estimated $PM_{2.5}$ and BC levels (0.67) (Bachwenkizi et al. 2021). Soot had a slightly stronger correlation with OC than BC.

Meteorological conditions can diffuse, dilute, and accumulate air pollution. However, none of the meteorological variables had significant correlations with $PM_{2.5}$, soot, BC and OC in the study, except between relative humidity and soot. Relative humidity and rainfall had negative corrections with the pollutants. Temperature in general had positive correlations with the pollutants, except with $PM_{2.5}$. Windspeed had both positive and negative correlations with the pollutants.

$PM_{2.5}$, soot, BC and OC levels by geographical origin of air masses and wind direction

Six geographical origin of air masses were identified in the 72-hour backward trajectory model runs: North West (NW), North (N), East (E), South West (SW), South (S) and Long-range Indian Ocean (LRIO) (Figure 6). During the 46 sampling days air masses emanated from the E (13 sampling days), SW (12 sampling days), N (11 sampling days), NW (4 sampling days), LRIO (5 sampling days) and S (1 sampling day) (Table 3). The percentages indicated in Figure 6 are based on all days during the study period, whereas Table 1 only reports on the 46 sampling days.

Although the median $PM_{2.5}$, soot, BC and OC levels did not differ significantly by the six identified geographical origins of air masses ($p \geq 0.05$) (Table 2), valuable insights can still be made of possible distant air pollution source areas that may have an influenced their levels. Distant air pollution source areas included Botswana (N air mass; highest median $PM_{2.5}$ level 6.9 µg/m^3) and Gauteng, Mpumalanga, and KwaZulu-Natal provinces in South Africa (E air mass; second highest median $PM_{2.5}$ level 6.3 µg/m^3). The highest and second highest median soot levels were observed when air masses originated from the East and North, respectively. BC and OC levels were in general low. Botswana has numerous mines, whilst Gauteng, Mpumalanga, and KwaZulu-Natal provinces in South Africa have industrialised areas and mines. Mines and industrialised areas are just a few among various activities contributing to $PM_{2.5}$ concentrations.

The 24-hour backward trajectory model runs revealed five geographical origins of air masses (Supplementary figure 3). These 24-hour clusters would indicate air pollution source areas that are closer than those indicated by the 72-hour clusters. Similar directions were observed as in the 72-hour model runs. As with the 72-hour clusters, no significant difference in the median $PM_{2.5}$, soot, BC and OC levels were identified ($p \geq 0.05$) (Supplementary table 3). This was also the case with wind direction ($p \geq 0.05$) (Supplementary table 4).

Conclusions

The mean $PM_{2.5}$ level recorded at the study site was 6.3 µg/m^3, surpassing the yearly WHO guideline of 5 µg/m^3. Additionally, on three out of the 46 sampling days, the daily WHO guideline of 15 µg/m^3 was exceeded. Given that the $PM_{2.5}$, soot, BC and OC levels were observed at an urban background study site, it is essential to recognise that if these concentrations are representative of the broader citywide conditions in Kimberley, they could pose a significant risk to human health. The exceeded WHO guidelines emphasise the need for an updated AQMP for the Frances Baard District Municipality that will include $PM_{2.5}$, which was excluded in the current 2010 AQMP.

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Author contributions

DB: conceptualisation; methodology; data collection; data analysis; data curation; writing. AA: methodology; writing. JW: conceptualisation; methodology; data analysis; data curation; writing. PM: writing. JB: writing.

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Supplementary material

Supplementary material can be accessed at https://cleanairjournal.org.za/article/view/20100/23450