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Contents

CALL FOR PAPERS (Submission deadlines extended)

Dear NACA Members and Colleagues,

The Annual Conference of the National Association for Clean Air will be held from 7 to 8 October 2021. The NACA Council are hoping to host a hybrid event. Should this however not be possible we will revert to an online conference. The two-day NACA Conference will follow on the Department of Forestry, Fisheries and the Environment's (DFFE), Air Quality Governance Lekgotla.

The Lekgotla will be held from Monday to Tuesday, followed by a Multi-Stakeholder Workshop on Wednesday, 6 October 2021.NACA intends hosting a technical session on Wednesday afternoon with the official conference opening on Thursday morning, and the programme ending on Friday afternoon.

The NACA conference's technical programme elements remain intact. Each day will be opened with a local or international plenary speaker, followed by paper and poster presentations. Proceedings will be published.

Despite the novelty and the various logistical complexities involved in hosting a virtual conference we have no doubt that this will again be a wonderful event and we hope that you will be able to take this opportunity to join us.

The conference fees will soon be announced and the sponsorship prospectus and a draft programme will be circulated shortly.

Whether the conference is hosted on-site or online, we will as always, endeavour to keep our rates as low as we possibly can.

Yours sincerely,
Ms Gabi Mkhatshwa
NACA President

CALL FOR PAPERS

The Organising Committee of the 2021 NACA Conference invites submissions of papers for the annual conference. Presenters are requested to register and submit their abstracts on the electronic submission and evaluation system. Guidelines for papers and posters will be made available on the conference page of the NACA website.

Updated: 14 June 2021

Abstract submission
1 July 2021

Notification of acceptance of abstracts
15 July 2021

Full papers due
15 August 2021

Notification of acceptance and comments on papers
29 August 2021

Authors resubmit papers if required indicating how reviewers' comments were addressed
12 September 2021

Reviewers indicate whether comments were sufficiently addressed
19 September 2021

Submission of final papers for inclusion in the electronic conference proceedings
26 September 2021

VISIT THE CONFERENCE WEBSITE AT WWW.NACA.ORG.ZA - CLICK ON CONFERENCE

REGISTRATION OPENS 1 JULY 2021

Message
Message from the NACA President

Gabi Mkhatshwa
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Since its establishment in 1969, the National Association for Clean Air (NACA) has actively promoted the cause for clean air in South Africa. In all its years of advocacy, NACA had never envisaged a year like 2020; where the corona virus (COVID-19) pandemic triggered the South African government to temporarily shut the country down by closing workplaces, emptying roads and public spaces. This reduction in economic activity also resulted in reduced pollution in the country during that period. A number of studies have shown a reduction in SO_x, NO_x and particulate matter at ground level concentrations during the lockdown in early to mid-2020.

A difficult and challenging year for many and NACA was no exception. All plans envisaged for the year, including hosting of seminars, courses and the popular annual conference had to be reviewed; a new normal was upon us. The world of work as we knew it had changed. NACA successfully migrated to the new normal, hosted, and co-hosted a series of Seminars in 2020. A virtual seminar was co-hosted with the Department of Forestry, Fisheries and the Environment (DFFE) in July of 2020 and was titled: *COVID-19 and Air Quality in South Africa*. The event was a success, attended by over 110 people, and highlighted a diverse set of tools available to evaluate air quality in South Africa including ambient monitoring, satellite retrievals and modelling.

The NACA regional branches also adapted to this new normal and Western Cape branch organised a seminar in August, which explored the implementation of policy at an industrial facility level as well as the application of portable and low costs sensors in managing air quality.

KwaZulu-Natal branch organised an outreach event at Sobantu Secondary School and Russell JP Primary School in Pietermaritzburg in October 2020.

From the 16th to the 20th of November, NACA hosted its first virtual conference with over 130 attendees, 21 manuscripts were accepted for presentation and publication in the 2020 proceedings. Special thanks goes out to the organising committee; who tirelessly put in the hours to make this event the success it was under new and challenging circumstances. Our sponsors; who bought into NACA's vision of adhering to COVID-19 restrictions and protocols and financially supported the conference. The scientific review panel; who started the review process early in the year with over 30 submissions, the exhibitors; who adapted to the new way of virtual exhibition and most of all the attendees who in their numbers attended all the conference sessions and afternoon workshops.

As incoming president of NACA my biggest highlight for the year 2020 was the relaunch of our outreach programmes. Many thanks go out to the outgoing president, Professor Stuart Piketh and council members who successfully launched this schools outreach platform on the NACA website, aimed at bringing air quality science and education to both the teacher and the learner at primary and secondary school level.

The Clean Air Journal (CAJ) is NACA's premier platform for electronic dissemination of information on air quality science and management and will continually be supported as such. I look forward to the *special issue on Air Quality on the South African Highveld* planned for this year.

The year 2021 promises to be yet another successful year for NACA, with COVID restrictions being adjusted to more lenient levels, we will be hosting a joint hybrid conference with DFFE. Our outreach programme will grow bigger and go further and, COVID restrictions allowing, more engagements with schools and communities will be held. NACA's social media footprint has a dedicated council member who, through media platforms like Twitter, Facebook and the NACA webpage will seek to increase our visibility, connect with our members and the scientific community at large and give a platform for scientific debate and discussion.

From the NACA council and I, we wish you and your families a safe and healthy 2021.

Gabi Mkhatshwa
NACA President 2021

Clean Air Journal: Advertising Rates 2021

Why advertise in the Clean Air Journal?

The Clean Air Journal publishes articles of importance to Africa in different disciplines in air quality, air pollution, its impacts on the environment and the management thereof.

The Journal is included in the Scopus and SciELO-SA journal lists for 2021, and articles published are eligible for DHET funding. The Journal is furthermore indexed in Google Scholar, SHERPA/RoMEO, and Ulrich's ProQuest.

Publication frequency

The Journal is published twice per year in May/June and November/ December (one volume containing two issues per volume). Peer-reviewed articles are published as Online Early Articles as soon as they are accepted.

Special issue

In early 2022, a special issue of the Clean Air Journal will be published on 'Air Quality on the South African Highveld.' The special issue is envisioned to be a synthesis of atmospheric research conducted on the Highveld since 2004, and to provide an update of Tyson, Kruger and Louw (1988). It will include both new research and review articles. It is intended to be a resource for policy-makers, students, and scientists. Sponsorship is sought in order to print out hard copies of the issue. Sponsors logos will appear on the issue.

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November/December Issue: **19 November 2021**
Special Issue '22: **15 January 2022**

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Obituary
Reflections on the contributions of Bob Scholes† to atmospheric science

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The untimely passing of Bob Scholes (28th April 2021) is a loss to the global science community. His understanding of the interconnectedness of Earth systems is in the tradition and on the scale of Alexander von Humboldt, one of the first scientists to comprehend and articulate the complexities and interactions of earth, water, air and the biosphere. Specifically, von Humboldt, already in 1836 during an epic journey through South America, had observed how deforestation for tillage had changed the local climate (Wulf 2016). After a few years, the cleared land had become barren, and the previously copious rainfall had ceased. In this, Von Humboldt had presaged the contemporary understanding of Global Change wrought by anthropogenic activities. Similarly, Bob Scholes had encompassed an understanding of many diverse disciplines into an integrated understanding of the dynamic interactions that sustain, and could disrupt, the natural order.

Bob started his academic career as a savannah rangeland ecologist. I recall a visit we paid to Bob and Mary during Bob's internship on the Oppenheimer's Klaserie private reserve. Bob had dug a -3-m cubic pit and meticulously recorded the number of roots and rootlets through the soil profile – investigating the secret underground life of plants. To reach the site, we travelled in a beat-up skedonk open Landover (with no operating brakes), pausing and dodging wandering herds of elephants along the way.

These early investigations into the interchanges between the geo- and biospheres on the micro-scale later expanded to include large-scale interchanges between bio-, geo-, hydro- and atmospheres. Realising that plot-scale observations provided fragmented insights, Bob's investigations now focussed on the dynamics of the Miombo woodlands of southern Africa and the African savannah grasslands. In this context, one of the many international collaborations that Bob established was with systems ecologist Hank Shugart of the Environmental Sciences Department, University of Virginia (UVA), Charlottesville. Through this link with UVA, a chance encounter led to one of the most extensive environmental field campaigns to have taken place in Southern Africa – the SAFARI 2000 Regional Science Initiative.

In February 1998, I had attended an atmospheric sciences conference in Arizona. My return routing was to take me through Washington D.C. on route to Johannesburg. Bob Swap, a young

Distinguished Professor Bob Scholes. Photo credit: University of the Witwatersrand

post-doc who had recently returned to UVA from a yearlong fellowship at Wits University, invited me to drop by UVA, seeing as I was passing so close by (actually 200 km). On the day I arrived, I was pressed into attending a meeting in progress between researchers from UVA and NASA. The purpose of the gathering was to plan a proposed field campaign in Southern Africa in support of a soon-to-be-launched Earth-observing satellite – Terra. To my surprise, when I arrived at the meeting, I found my long-time friends and Wits colleagues Bob and Mary Scholes (and their young son Stirling) also in attendance. (They were also visiting UVA at that time to work with Han Shugart.)

We (the South Africans) listened with rapt attention to the plans for a sophisticated field campaign involving surface measurements of land cover, fires, and airborne sampling utilising an instrumented aircraft from the University of Washington. As the morning progressed, we became anxious – *Was this to become another scientific exploitation mission in which international teams arrived in our African territories, collected their data and returned home with their scientific loot, to publish or perish, with African scientists and students participating as fetchers and carriers?* Walking with Bob alone during the lunch

break, I broached how and whether we should manage this situation to avoid scientific colonialism. In his trademark wise counsel, Bob advocated that we welcome the international visitors and facilitate their endeavours. Nevertheless, we agreed to emphasise that opportunities should be created to ensure meaningful participation by South African and other African scholars (despite the disparity of resources invested by the respective parties). On this same stroll, we coined the name of the campaign – SAFARI 2000. We returned to the planning meeting in a buoyant mood and persuaded the UVA and NASA teams that we would not only welcome their efforts but would be happy to host them and expand the scope of their proposed mission. This auspicious day led to the *Southern African Regional Science Initiative* (SAFARI 2000). Bob assumed the leading role in coordinating an interdisciplinary, multi-institutional team in South Africa and successfully raised funding through a Department of Science grant. Bob generously ensured that funding was proportionally distributed among the several participating institutions.

Notable scientific contributions by Bob and colleagues to SAFARI was the Kalahari Transect experiment – examining the effect of climate along a ~2 000-km long N-S transect of a uniform geological substrate (the Kalahari sands) on the vegetation and land cover. Bob's intellectual insights guided researchers to explore novel linkages between the biosphere and the atmosphere from this macro-scale to the micro-scale of measuring gas exchanges of CO_2 and organic gases from individual leaves.

Although we did not intend SAFARI 2000 to focus on wildfires, the dominant effect of wildfires during the southern African spring meant that atmospheric trace chemistry was dominated by wildfire smoke, much of it imported from Angola and Zambia. Several of the terrestrial experiments involved studying fire ecology and emissions. While I was responsible for the management and coordination of the airborne sampling (involving five aircraft – the NASA ER2 high altitude surveillance plane, the University of Washington Convair CV-58, the U.K. Met Office C-13 and two Weather Service Aerocommander 690As), Bob managed all the ground-based operations. For the fire studies, this involved deliberately setting fires, often in protected areas. This task required precise timing for ground-based teams to set and control fully developed fires to coincide with the satellite overpass at 10:20 SAST. To this end, Bob assigned one of his students, Tobi Landman, to be the game park pyromaniac. All the fire intensity and smoke monitoring equipment had to be in place. For remote sensing observations and atmospheric sampling, the ER2 and other aircraft had to be on station simultaneously with the satellite overpass.

The SAFARI 2000 campaign evolved into a significant surface, airborne and spaceborne field campaign across five countries, covering a broad range of issues involving biogeochemical functioning of the southern African system. The campaign ultimately involved sixteen countries, over 180 scientists in the field during August and September 2000. The careers of countless African academic and students were advanced in profound ways by the experiences and opportunities from SAFARI 2000 and its aftermath. Bob, as South African Principal Investigator, handled the whole campaign with natural leadership and calm assuredness. Overall, both hosts and guests comprised a happy group. Bob was a significant author of many of the resulting journal publications, and handled the chore of funding reports with dispatch and minimal fuss.

Bob moved on to further innovative systems studies stemming from SAFARI 2000, including the Africarbon campaign, and coordinated a set of long-term observations from the SAFARI 2000 flux towers in Skukuza and Mongu, Zambia. These large-scale global interest campaigns gave expression to Bob's evolved insight into the global ecological systems. Indeed, only in the last few years, aspects of Bob's scientific output have become recognised as central issues in understanding the role of atmospheric chemistry in driving global change, for instance, the importance of black carbon and methane as short-term climate forcers.

Bob had that innate ability, a characteristic of many great scientists, to see on the other side of the horizon. His science progressed not through "Eureka" moments of sudden or accidental insights but by insightful systems analysis across many contributing threads. Bob drew much from atmospheric sciences (I know from his many probing and often difficult questions that he posed to me as an atmospheric physicist) and contributed much to the discipline. We understand much more about the atmosphere as the conveyor belt of moisture, carbon gases, and trace elements across Africa and the planet through his work. Bob also contributed to creating a whole new generation of atmospheric scientists who have revitalised the discipline in South and southern Africa.

We who had the privilege can celebrate the opportunity to work with Bob as part of this eventful era in South African atmospheric science. To our students and other colleagues, we hope that we can pass on the traits of Bob's inquiring intellect and engaging personality. This man dedicated his life to science and the sharing of knowledge. We share our condolences with his wife Mary, who has made her independent contributions to atmospheric and biological sciences, and their son Stirling.

Reference

Wulf A. 2016, *The Invention of Nature: Alexander von Humboldt's New World*, Vintage Books, New York.

Editorial
The powerful potential of low-cost sensors for air quality research in Africa

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*Dr Subramanian is a guest editor for this special feature on low-cost sensors for air quality research.

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Low-cost sensors (LCS) are becoming popular with air quality stakeholders all over the world, including researchers, policy-makers, and citizen scientists. They are increasingly being used in research where air quality data are sparse, such as in Africa. This featured commentary section showcases three thoughtful, considered efforts, where LCS devices are carefully evaluated against reference monitors and corrected to ensure high data quality.

These three commentaries highlight studies where LCS are being used for higher spatial and temporal resolution monitoring for later comparison with satellite data and models (Giordano and Jaramillo, 2021), for public awareness and stakeholder engagement for pollution mitigation (Sewor et al. 2021), and epidemiological studies and investigating household air pollution (Wernecke et al. 2021). The efforts highlighted here are focused on measuring ambient particulate matter mass concentrations (PM); however, it is important to note that other pollutants, especially ozone (O_3) and nitrogen dioxide (NO_2), are also major environmental concerns. More effort is needed to increase the monitoring of those pollutants using both LCS and reference monitors.

In addition to highlighting the potential of LCS for air quality research, these contributions reveal some important challenges. LCS data completion can be affected by power outages and WiFi connectivity. The former can be mitigated by the use of solar powered sensors. Data connectivity can be solved with general packet radio service (GPRS), narrow-band internet of things (NB-IoT), and similar wireless networks, but these options may be expensive and local laws may not be IoT-friendly.

Commercial sensors like PurpleAir and Clarity may be low-cost for many users, but they are still too expensive for scientists in many African countries. Opportunities for local development, such as those by AirQo and Code for Africa, should be supported in order to reduce costs and ensure compatibility with local climates.

Currently, there are no standards or certification for low-cost sensors; standardized testing conducted by American or European bodies (e.g. the South Coast Air Quality Management District's Air Quality Sensor Performance Evaluation Center, AQ-SPEC) may not reflect performance in African environments, pollution levels, and PM composition. Hence, there is a need for instrument inter-comparisons and for local testing centers. Wernecke et al. (2021) describes such an effort at the North-West University in South Africa. The need and potential for similar facilities in other regions and environments (e.g. equatorial, desert) should be explored and linked to form a collaborative network of such facilities.

We strongly encourage data transparency that empowers citizens to consider personal changes and support systemic efforts to reduce their exposure to air pollution; the power of LCS networks is only truly unleashed with open data (Sewor et al. 2021). National air quality monitoring data are publicly available from only a few countries across Africa, such as South Africa and Rwanda. The US Department of State has installed near-reference air quality monitors at twelve embassies across Africa, and the data are available in near real-time. Many LCS datasets are also available through international repositories like OpenAQ or manufacturer websites - but only when the sensor owner chooses to share such data. One concern for LCS data sets is whether appropriate corrections have been applied to such openly-shared data; the data are not useful for research if uncorrected. Nevertheless, data transparency is increasingly the norm, and we strongly encourage researchers using LCS to share their corrected data. Giordano and Jaramillo (2021) describe a nuanced approach taking into account the need to recognize the efforts put into collecting such data while ensuring data transparency.

These three commentaries highlight some of the work ongoing on this issue in Africa. The Clean Air Journal welcomes submissions on all aspects of this topic including sensor development, sensor calibration and performance, monitoring data, air pollution analysis, and exposure studies using carefully-calibrated low-cost sensors.

References

Giordano, M.R. and Jaramillo, P. 2021 AfriqAir's mission towards cleaner air for Africa and a call for action. Clean Air Journal, 31(1) doi: 10.17159/caj/2021/31/1.11173

Sewor, C., Obeng, A.A., Amegah, A.K. 2021. The Ghana Urban Air Quality Project (GHAir): Bridging air pollution data gaps in Ghana. Clean Air Journal, 31(1) doi: 10.17159/caj/2021/31/1.11172

Wernecke, B. et al. 2021. Opportunities for the application of low-cost sensors in epidemiological studies to advance evidence of air pollution impacts on human health. Clean Air Journal, 31(1), doi: 10.17159/caj/2021/31/1.11219.

Commentary
The Ghana Urban Air Quality Project (GHAir): Bridging air pollution data gaps in Ghana

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Air pollution has been recognized as a pressing sustainability concern seeing that it is directly mentioned in two SDG targets: SDG 3.9 (substantial reduction of health impacts from hazardous substances) and SDG 11.6 (reduction of adverse impacts of cities on people) (Rafaj et al., 2018). Air pollution, both ambient and indoor, is known to contribute significantly to the global burden of disease, contributing to a majority of non-communicable disease-related deaths in low to middle-income countries in Africa and Asia (WHO, 2016). In 2018, air pollution was attributed to 28,000 deaths in Ghana (Odonkor and Mahami, 2020).

In most developing countries particularly in Sub-Saharan Africa (SSA), this precarious situation of deteriorating air quality is driven by rapid population growth and industrial expansion (Amegah and Agyei-Mensah, 2017, Satterthwaite, 2017). In fact, some of the highest fine particle levels ($PM_{2.5}$) in the world have been recorded in cities of SSA and other developing regions with $PM_{2.5}$ in some SSA cities being at 70-140 µg/m^3, most exceeding the WHO Interim Target 1 for annual average $PM_{2.5}$ concentrations of 35 µg /m^3 (Anenberg et al., 2019).

Despite the alarming rate of the deterioration of air quality in most SSA countries, addressing the situation has proven increasingly difficult owing to the paucity of data on air pollution levels in countries as a result of weak and non-existent air quality monitoring capacity (Amegah and Agyei-Mensah 2017). In Ghana, air quality monitoring is often limited to only a few locations with most being centered in the country's capital (Arku et. al., 2008). As has often been the case, national Environmental Protection Agencies (EPA) are poorly resourced with their staff lacking the requisite technical know-how for air quality monitoring. Aside from this, data generated by the EPA is often not readily accessible to the public (Usman et. al., 2019), thus making it difficult for relevant air pollution research to be undertaken and hampering the independent evaluation of air pollution control policies.

In addressing this problem, various studies have suggested that low-cost sensors could be an excellent opportunity to bridge the air pollution data gap within the SSA region (Amegah, 2018, Mead et al., 2013). Low-cost sensors hold much promise for monitoring the levels of air pollution particularly in areas where little data is available. Low-cost sensors can enable the creation of a dense network with wide spatial coverage in virtually any geographical setting owing to their relatively small size and lower power requirements (Kumar et al., 2015, Pinder et al., 2019). In fact, in regions where air monitoring is weak, low-cost air quality sensors can be leveraged to complement the limited reference-grade monitors that may be available.

It is against this background that the Ghana Urban Air Quality Project (GHAir) was established in May 2019 with the overall goal of bridging the air pollution data and epidemiologic research gap in Ghana. The objectives of the project are to: (1) develop a dense network of low-cost air quality sensors interspersed with reference monitors in urban areas of Ghana to provide real-time high spatiotemporal air quality data to influence air pollution control policies, (2) raise public awareness about the dangers of air pollution to enable the citizenry to act accordingly to protect their health, (3) advocate for behavioral changes and actions within communities and amongst individuals for improved air quality, and (4) conduct research on the health effects of air pollution exposure among vulnerable groups to provide local evidence for public health action and influencing clinical practice.

The project currently has deployed low-cost sensors, a mixture of PurpleAir sensors, Clarity nodes, RAMPs, and Modulair-PM, in five metropolitan areas of Ghana, namely Accra, Tema, Cape Coast, Takoradi, and Kumasi. Through these deployments, the project has forged strong collaborations with the metropolitan authorities, notably the Accra Metropolitan Assembly (AMA) in the area of air pollution control and awareness creation among vulnerable groups such as street vendors. The project has recently received 10 sets of TEOM 1400ab, a regulatory grade particulate matter monitor, from the UK Environmental Agency (Automatic Urban and Rural Network) for deployment to improve air quality measurements. The TEOMs will be deployed in the metropolitan areas for validation of the data from the low-cost sensors. The project also collaborates with sister projects in other African countries as part of the AfriqAir network to help build a strong air quality network across the continent for fostering the sharing of knowledge and expertise in air quality monitoring and air pollution modelling.

Despite the significant strides made, the project continues to face challenges with Wi-Fi connectivity and power supply, which severely impacts data quality. There can be several days and weeks without data from the sensors owing to these challenges. This is because the project leverages on internet connectivity at the establishments where they are installed and hence at their mercy as it relates to Wi-Fi connectivity for data telemetry. Power supply can also be unstable in some of the deployment sites.

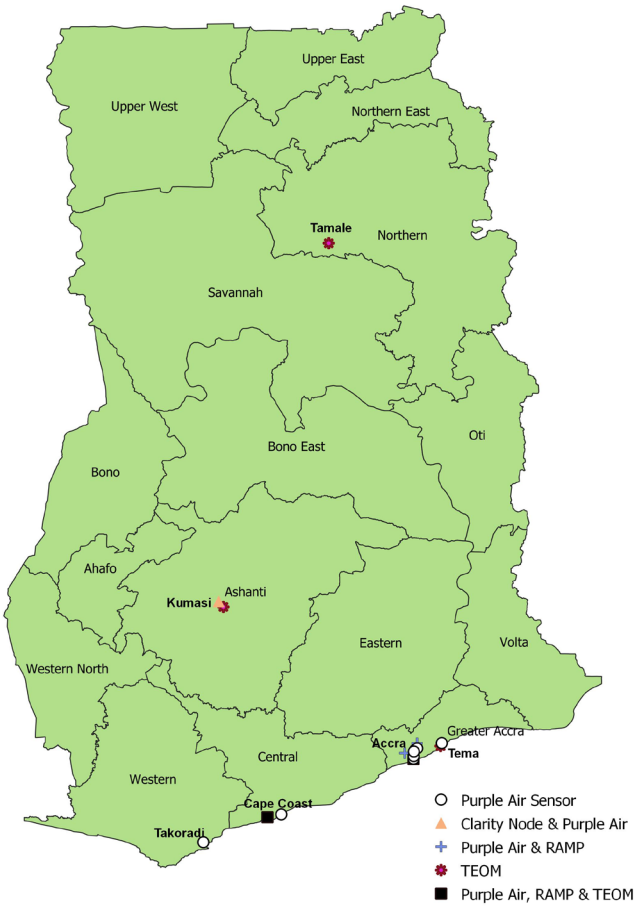

Figure 1: *Map of Ghana showing the location of sensors*

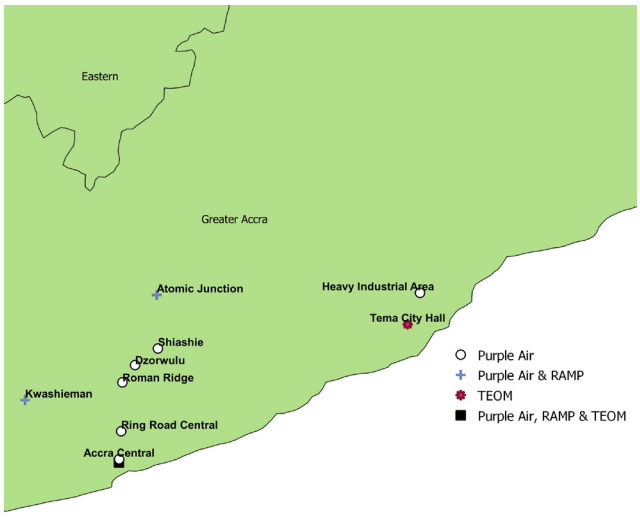

Figure 2: *Map of the Greater Accra region showing the location of sensors*

In conclusion, the GHAir project holds huge prospects in helping bridge the air quality data gap in Ghana but requires support in terms of air quality monitoring equipment and funding for maintenance of the installations. The power and connectivity challenges can be addressed by building sensors locally that use solar power and rely on GPRS for data telemetry.

References

Amegah, A. K. & Agyei-Mensah, S. 2017. Urban air pollution in Sub-Saharan Africa: Time for action. *Environ Pollut*, 220, 738-743.

Amegah, A. K. 2018. Proliferation of low-cost sensors. What prospects for air pollution epidemiologic research in Sub-Saharan Africa? *Environ Pollut*, 241, 1132-1137.

Anenberg, S. C., Achakulwisut, P., Brauer, M., Moran, D., Apte, J. S. & Henze, D. K. 2019. Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide. *Sci Rep*, 9, 11552.

Arku, R. E., Vallarino, J., Dionisio, K. L., Willis, R., Choi, H., Wilson, J. G., Hemphill, C., Agyei-Mensah, S., Spengler, J. D. & Ezzati, M. 2008. Characterizing air pollution in two low-income neighborhoods in Accra, Ghana. *Sci Total Environ*, 402, 217-31.

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L. & Britter, R. 2015. The rise of low-cost sensing for managing air pollution in cities. *Environ Int*, 75, 199-205.

Lewis, A., & Edwards, P. (2016). Validate personal air-pollution sensors. *Nature*, 535(7610), 29-31. doi:10.1038/535029a

Mead, M. I., Popoola, O. A. M., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., Mcleod, M. W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J. R. & Jones, R. L. 2013. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, 70, 186-203.

Odonkor, S. T. & Mahami, T. 2020. Knowledge, Attitudes, and Perceptions of Air Pollution in Accra, Ghana: A Critical Survey. *J Environ Public Health*, 2020, 3657161.

Pinder, R. W., Klopp, J. M., Kleiman, G., Hagler, G. S. W., Awe, Y. & Terry, S. 2019. Opportunities and Challenges for Filling the Air Quality Data Gap in Low- and Middle-Income Countries. *Atmos Environ* (1994), 215, 116794.

Rafaj, P., Kiesewetter, G., Gül, T., Schöpp, W., Cofala, J., Klimont, Z., Purohit, P., Heyes, C., Amann, M., Borken-Kleefeld, J. & Cozzi, L. 2018. Outlook for clean air in the context of sustainable development goals. *Global Environmental Change*, 53, 1-11.

Satterthwaite, D. 2017. The impact of urban development on risk in sub-Saharan Africa's cities with a focus on small and intermediate urban centres. *International Journal of Disaster Risk Reduction*, 26, 16-23.

Usman, M., Ma, Z., Wasif Zafar, M., Haseeb, A. & Ashraf, R. U. 2019. Are Air Pollution, Economic and Non-Economic Factors Associated with Per Capita Health Expenditures? Evidence from Emerging Economies. *Int J Environ Res Public Health*, 16.

WHO 2016. *Ambient air pollution: a global assessment of exposure and burden of disease*, Geneva, World Health Organization.

Commentary

Opportunities for the application of low-cost sensors in epidemiological studies to advance evidence of air pollution impacts on human health

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Introduction

Every year, air pollution is associated with more than 7 million deaths globally (Forouzanfar et al., 2016). It is one of the top environmental health risks in low- and middle-income countries (LMICs) (Joubert et al., 2020). Ambient and household air pollution (HAP) threaten human health and well-being, particularly for vulnerable groups such as infants and children, women, people with pre-existing diseases and the elderly (Forouzanfar et al., 2016).

Annually, 3.8 million premature deaths caused by non-communicable diseases, including stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer, are attributed to HAP exposure (World Health Organisation 2021). While there is good international evidence of the health impacts and patterns of air pollution exposure, there is less evidence in African countries (Zhang and Smith 2007; Khilnani and Tiwari 2018). Constrained by various factors, such as cost, prioritisation and capacity, air pollution data in ambient and household settings are lacking in the African context (Wetsman 2018).

For policy- and decision-makers, and people advocating for clean air, including communities themselves, evidence is required to understand the severity of Africa's air pollution problem and the associated health burden. Data and evidence in a local context are called upon by government and civil society alike, for example, when air pollution is suddenly visible in the atmosphere or smelt in the air. A case of the latter occurred recently when the putrid smell of hydrogen sulphide permeated the air in parts of Gauteng and Mpumalanga, South Africa (eNCA 2021). These occurrences highlight the importance of hard evidence and data to understand, explain and call for action, and interventions to prevent air pollution and its harmful health impacts.

Until recently, air pollution data were primarily available from two sources: ground-based monitoring stations and satellites. Both have their strengths and limitations. Ground-based stations (183 officially listed stations in South Africa) are generally sparse and situated in ambient/ outdoor settings and do not capture HAP exposure. They typically monitor a variety of criteria / regulated pollutants (i.e., PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO) in air pollution hot spots. Satellite air quality data cover a broader geographic area but do not necessarily measure the air people breathe on the ground. The integration of satellite data with atmospheric and/or statistical models along with surface monitored data is necessary to gain a more holistic understanding of air pollution exposure (van Donkelaar et al., 2016).

An exciting and relatively novel solution to air pollution monitoring in both ambient and household settings is

the concept of low-cost air quality sensors. Drawing on technology, connectivity and big data, low-cost sensors have several benefits over ground-based stations and satellite-based instruments. They are (usually) relatively inexpensive so that one can create a high-density network in an area of interest, say, outdoor and indoor locations in an air pollution hotspot. Data can be collected frequently (as often as every few seconds) and sometimes in real-time, generating evidence at appropriate resolutions in space and time. The higher resolution temporal and spatial data 'fill in the gaps' between ground-based monitoring stations and can provide data for epidemiological studies such as indoor air quality data. Researchers can better understand the relationships between air pollution concentrations experienced by individuals rather than for an entire area/community, and human health impacts in micro-environments. In this commentary, we consider the current use of low-cost sensors in air quality assessment and management, including African examples. We discuss how data from low-cost sensors are useful for epidemiological studies to inform interventions and ultimately to prevent adverse health impacts. In addition, we describe a new project, the South African 'Low-Cost Sensor Inter-Comparison Campaign (LCS-SA)' to understand the advantages and limitations of using low-cost sensors in South African epidemiology.

Low-cost sensors in air quality management

The need to better assess and understand air pollution exposure where large air quality data gaps exist in developing countries has led to large-scale air quality measurement programmes. UNEP's "Global Environment Monitoring System for Air (GEMS Air)", for example, integrates data from satellites, air quality reference monitors and complements these measurements with data from low-cost sensors for maximum spatial and temporal coverage across the globe (UNEP 2021a, UNEP 2021b). The programme promotes global stakeholder engagement and collaboration between private and public sectors, academia, civil society, and local governments. It builds capacity for the use of low-cost sensors to develop evidence-based air quality management policies and supports actions for air quality management through the elevation of awareness levels in developed and developing countries alike (UNEP 2021a).

Another example is the World Air Quality Index project, which has been running since 2007, and provides air quality information for more than 130 countries, including South Africa (World Air Quality Index Project 2021).

Studies conducted within Sub-Saharan Africa using low-cost air quality sensors have demonstrated the feasibility and practicality of using in situ low-cost sensors, despite the challenges encountered (power outages, SD memory card issues, connectivity problems, device safety concerns, as well as sensitivity to chemical interference and environmental conditions) (Awokola et al., 2020). These data are being used to enhance coverage of air pollution-related human health and environmental concerns, and for advocacy purposes (Awokola et al., 2020; Amegah 2018). Sensors set up by universities, schools, and local media organizations are also being used to upskill civil society to better understand the quality of the air they breathe and to lobby for cleaner air when necessary (Desouza et al., 2017). Studies using low-cost sensors in Ghana and Nigeria have assessed relationships between air pollution exposure and adverse health outcomes, indicating the potential of such sensors for health research (Quinn et al., 2017; Alexander et al., 2018; Clark et al., 2020).

Though South Africa's ambient air quality monitoring network feeds real-time ground-based air quality data for various primary pollutants into UNEP's Live "Airvisual" tool (the largest real-time air quality databank), South Africa's air quality monitoring network is biased in location towards large industrial sources and their surrounding areas (UNEP 2021c). There is a need for air quality data collection beyond this monitoring network, which could be critical for health studies. Crucial gaps in air quality monitoring efforts exist, especially for HAP, representing a large health risk in low-income communities across the country where air pollution levels are high and where few ground-based monitoring stations are located. Low-cost sensors are a means to fill this gap.

Leveraging air quality data for epidemiological studies

In 2020, an international consortium embarked on a project to consider leveraging air quality data for high-grade epidemiological studies in LMICs. Entitled LEAP-Epi (Leveraging Environmental data for Air Pollution exposure assessment in Epidemiology), the project is a collaboration between the University of Leicester (UK), the South African Medical Research Council and the University of the Witwatersrand. To enrich the project with specific areas of expertise, additional partners have joined LEAP-Epi (e.g., North-West University (NWU) and University of the Free State (UFS)).

The aims of the project are to 1) Perform a comprehensive assessment of available global and local air pollution data across several study sites in South Africa; 2) Develop a sustainable sampling methodology for indoor and outdoor air quality data at different levels of exposure in low and middle-income contexts; and 3) Build local capacity for air quality research, involve local communities in developing sensor deployment and exposure mitigation strategies, and contribute evidence for national policies. Phase 1 of the project is currently underway and entails the LCS-SA Campaign. It is hoped that this study can show the value of low-cost sensors in collecting indoor and ambient air quality exposure data at an unprecedented scale and duration.

Low-cost sensor inter-comparison campaign

Over recent years, the low-cost sensor market has produced many instruments, making it difficult for end-users to evaluate the sensor's reliability for in-field monitoring. The LCS-SA Campaign is coordinated by the SAMRC and NWU in collaboration with several low-cost sensor developers and stakeholders. The collaboration is unique in that it sees researchers, experts and product developers work together to meet one end goal: to

Figure 1: *LCS-SA Campaign set-up at the North-West University Air Quality Monitoring Station at the Vanderbijlpark Campus (NWU-Climatology Research Group)*

evaluate and produce meaningful, user-friendly instruments which can be strategically deployed in areas of concern to generate credible, repeatable, and reproducible results for epidemiological work and effective air quality management. End-users range from researchers to civil society, where local communities can learn to use the sensors for their benefit and to improve local air quality.

Different low-cost sensors measuring a range of pollutants (e.g., PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO) and meteorological data have been co-located and run parallel with reference method instruments. Low-cost sensors have been provided by scientific research groups, instrument suppliers and instrument manufacturers. The instruments have been deployed simultaneously at the North-West University Air Quality Monitoring Station at the Vanderbijlpark Campus, located in the Vaal Triangle Airshed Priority Area (Figures 1 & 2).

Instruments are being operated as per the manufacturer's specifications for six months, starting in May 2021. This period spans typical air pollution conditions ranging from periods of relatively low air pollution to extreme pollution events. The LCS-SA Campaign will provide data and information on each sensor's performance relative to each other and to the reference instruments in a field setting. Data recovery rates and data comparisons will help identify sensor issues such as bias, inaccuracies and imprecision, for which correction factors will be determined. Finally, user-friendliness will be evaluated.

In conclusion, the deployment of these low-cost sensors will supplement ground-based readings and contribute to verification exercises when considering satellite data or improve understanding of indoor personal exposure. Indicative air quality measurements provided by low-cost sensors would go a long way in identifying pollution hotspots in local communities, thereby empowering civil society.

Figure 2: *LCS-SA Campaign set-up – various low- and medium cost air quality sensors co-located at the same height on a custum-constructed sensor-stand.*

Conclusion

Despite the known impacts of air pollution on human health, research and data are essential to understand its impact on mortality and morbidity in South Africa. A narrative review of HAP exposure and respiratory health outcomes illustrated significant challenges in measuring the exposure variables, namely criteria pollutants, both outdoors and indoors (Shezi and Wright 2018). Instruments to measure exposure tend to be expensive, burdensome to wear in the case of personal monitors, and labour-intensive to manage. However, the data needed to assess the associations between personal air pollution exposure and health effects, such as lung function, inflammation, and chronic diseases (e.g., Chronic Obstructive Pulmonary Disorder), need to be at high resolution and take place where people breathe the polluted air (Cattaneo et al., 2010). Moreover, for comparative purposes, instruments applied in different studies need to be comparable in the data that they generate.

Finally, we aim to generate good quality data to understand the prevalence and distribution of air pollution-related health impacts in South Africa to inform the design of effective interventions that would decrease pollution associated morbidity and mortality at local, provincial, and national scales. Low-cost sensors have the potential to generate epidemiological evidence to inform policy decisions and evidence-based practice.

References

Alexander D.A., Northcross A., Karrison T., Morhasson-Bello O., Wilson N., et al., 2018. Pregnancy outcomes and ethanol cook stove intervention: a srandomised controlled trial in Ibadan, Nigeria. Environ. Int. 111:152-163 https://doi.org/10.1016/j.envint.2017.11.021.

Amegah, A.K. 2018. Proliferation of low-cost sensors. What prospects for air pollution epidemiologic research in Sub-Saharan Africa? *Environ Pollut.* https://doi.org/241:1132-1137. 10.1016/j.envpol.2018.06.044.

Awokola, B., Okello, G., Mortimer, K.J., Jewell, C.P., Erhart, A. and Semple, S. 2020. Measuring Air Quality for Advocacy in Africa (MA3): Feasibility and Practicality of Longitudinal Ambient $PM_{2.5}$

Measurement Using Low-Cost Sensors. Int J Environ Res Public Health. 3;17(19):7243. https://doi.org/10.3390/ijerph17197243.

Cattaneo, A., Taronna, M., Garramone, G., Peruzzo, C., Schlitt, C., Consonni, D. and Vavallo, D.M. 2010. Comparisons between Personal and Individual Exposure to Urban Air Pollutants. Aerosol Science and Technology. 44(5): 370-379. https://doi.org/10.1080/02786821003662934.

Clark S.N., Alli A.S., Brauer M., Ezzati M., Baumgartner J., Toledano M.B., Hughes A.F., Nimo J., Bodform Moses J., Terkpertey S., Vallarino J., Agyei-Mensah S., Agyemang E., Nathvani R., Muller E., Bennett J., Wang J., Beddows A., Kelly F., Barratt B., Beevers S. & Arku R.E. 2020. High- resolution spatiotemporal measurement of air and environmental noise pollution in Sub-Saharan African Cities Study protocol for Accra, Ghana. BMJ Open. 10: e035798. https://doi.org/10.1136/bmjopen-2019-035798.

Desouza, P., Nthusi, V., Klopp, J.M., Shaw, B.E., Ho, W.O., Safell, J., Jones, R. and Ratti, C. 2017. A Nairobi experiment in using low-cost air quality monitors. Clean Air Journal. 27(2): 12-42. http://dx.doi.org/10.17159/2410-972X/2017/v27n2a6.

eNCA. 2021. Badsmall concerns Gauteng Residents. 17 February. [WWW Document]. URL https://www.enca.com/life/bad-smell-concerns-gauteng-residents (accessed 29/03/21).

Forouzanfar, M.H. et al., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental, and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015.Lancet. 2016; 388: 1659-1724. https://doi.org/10.1016/S0140-6736(16)31679-8.

Joubert B.R., Mantooth S.N., & McAllister K.A. 2020. Environmental Health Research in Africa: Important Progress and Promising Opportunities. Front. Genet. 10:1166. https://doi.org/10.3389/fgene.2019.01166.

Khilnani G.C. and Tiwari P. 2018. Air pollution in India and related adverse respiratory health effects: past, present, and future directions. Curr Opin Pulm Med. 24(2):108-116. https://doi.org/10.1097/MCP.0000000000000463.

Quinn A.K., Ae-Ngibise K.A., Kinney P.L., Kaali S., Wylie B.J., Boamah E., et al., 2017. Ambulatory monitoring demonstrates an acute association between cookstove related carbon monoxide and blood pressure in a Ghanaian cohort. Environ. Health. 16(1):76. https://doi.org/10.1186/s12940-017-0282-9.

Shezi B and Wright, C.Y. 2018. Household air pollution exposure and respiratory health outcomes: a narrative review update of the South African epidemiological evidence. Clean Air Journal, 28(1): 43-56. https://dx.doi.org/10.17159/2410-972x/2018/v28n1a11.

United Nations Environment Programme (UNEP). 2021a. Why low-cost sensors? Opportunities and challenges. [WWW Document]. URL https://www.unep.org/explore-topics/air/what-we-do/monitoring-air-quality/why-low-cost-sensors-opportunities-and (accessed 29/03/21).

United Nations Environment Programme (UNEP). 2021b. GEMS Air Strategic Pan. [WWW Document]. URL https://www.unep.org/explore-topics/air/what-we-do/monitoring-air-quality/gems-air-strategic-plan (accessed 29/03/21).

United Nations Environment Programme (UNEP). 2021c. Multilateral Environmental Agreements. Air Pollution. [WWW Document]. URL https://wesr.unep.org/airvisual (accessed 29/03/21).

Van Donkelaar A., Martin R. V., Brauer M., Hsu N. C., Kahn R. A., Levy R. C., Lyapustin A., Sayer A. M. & Winker D. M. 2016. Global Estimates of Fine Particulate Matter Using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors. Environ. Sci. Technol. 50 (7): 3762– 3772. https://doi.org/10.1021/acs.est.5b05833.

Wangui, I. 2019. Air quality sensors air coverage of health and environment in Africa. International Center for Journalists, 29 July. [WWW Document]. URL https://www.icfj.org/news/air-quality-sensors-aid-coverage-health-and-environment-africa (accessed 29/03/21).

Wetsman, N. 2018. Air-pollution trackers seek to fill Africa's data gap. Nature News. 11 April. [WWW Document]. URL https://www.nature.com/articles/d41586-018-04330-x (accessed 29/03/21).

World Air Quality Index project. 2021. About the World Air Quality Index project. [WWW Document]. URL https://aqicn.org/sources/ (accesses 29/03/21).

World Health Organisation. 2021. Fact Sheet: Air Pollution. [WWW Document]. URL https://www.afro.who.int/health-topics/air-pollution (accessed 29/03/21).

Zhang, J.J. and Smith, K.R. 2007. Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions. Environmental Health Perspectives. 116(6): 848-855. https://doi.org/10.1289/ehp.9479.

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Commentary
AfriqAir's mission towards cleaner air for Africa and a call to action

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Poor air quality has long been recognized as one of the major threats to human health. Particulate matter (PM) exposure in particular has been linked to cardiovascular and cerebrovascular diseases as well as asthma, respiratory infections, and cancer (WHO 2013). In Africa, this problem is especially acute: recent work has estimated that poor air quality causes nearly 800,000 premature deaths in Africa every year (Bauer et al., 2019). Indeed, this number has been steadily increasing over the past few decades, from an estimated 180,000 premature deaths in 1990 and 246,000 in 2013 (Roy, 2016; though there are methodological differences between these two papers, the qualitative trends should still hold). There is a major caveat to these estimates: these are estimates based on limited air quality measurements over the continent. Instead, these estimates relied on models and satellite retrievals, which are also constrained by the unavailability of measurements that enable accurate ground-truthing (Anenberg et al., 2020). Herein lies the crux of the problem for most of Africa: over the vast majority of the continent, there exists a significant data and knowledge gap with regards to air quality.

The extent of the knowledge gap over Africa spans multiple issues. First and foremost, there is simply a lack of air quality monitoring infrastructure. In Western Africa, there is approximately 1 reference-grade $PM_{2.5}$ (PM with an aerodynamic diameter less than 2.5 micrometers) monitor per 10 million people. In Eastern Africa, the problem is even worse with approximately 1 reference-grade monitor per 100 million people (Malings et al., 2020). Second, this lack of monitoring is compounded by the fact that the sheer diversity of sources of PM and other atmospheric pollutants (e.g., ozone precursors, NO_x, SO_x) is much greater than the sources in most of the OECD or Global North (Kiesewetter, 2016). The emission profiles for the majority of these sources are still unknown. Lastly, the atmospheric chemistry and physics that occurs between these anthropogenic emissions and natural and biogenic emissions from sources endemic to the continent (e.g. the Sahara, Congolian rainforests) are likewise broadly unknown. The good news is that there is currently work being done to shrink these knowledge and data gaps to improve African air quality.

One such group working on this problem is Africa qualité de l'air (AfriqAir). Hosted by the Kigali Collaborative Research Centre, AfriqAir is a consortium of 15 institutions across the globe with members in Western Africa, Eastern Africa, South Africa, the US, and Australia who are dedicated to improving air quality in Africa. The founding members of the organization are Kofi Amegah (Ghana), Timothy X Brown (Rwanda), Rebecca Garland (South Africa), Jimmy Gasore (Rwanda), Paulina Jaramillo (USA), V. Faye McNeill (USA), Albert Presto (USA), R Subramanian (USA, France), Emilia Tjernström (Australia), and Daniel Westervelt (USA). AfriqAir's mission statement is to develop long-term, sustainable air quality monitoring efforts over the continent. To accomplish this, AfriqAir takes a three-pronged approach:

- help build the physical infrastructure required for air quality monitoring,
- help build the capacity to locally manage, analyze, and use this physical infrastructure, and
- ensure that the knowledge generated from these efforts are accessible and actionable.

From AfriqAir's perspective, meeting all three of these goals is the best way to move towards cleaner air in Africa.

To accomplish the first of these goals, the physical infrastructure for air quality monitoring, AfriqAir is helping implement hybrid networks of low-cost air quality monitors centered around reference-grade monitors. The benefits of using low-cost sensors, particularly in Africa, to increase the spatiotemporal resolution of air quality monitoring efforts have been noted elsewhere (Rahal, 2020). The drawback of low-cost sensors, however, is that they require calibration to ensure their output can be trusted. The hybrid network approach helps mitigate this issue by offering a local calibration point. Currently, AfriqAir has hybrid networks deployed in Abidjan, Côte d'Ivoire (with reference-grade $PM_{2.5}$, NO_x, and O_3), Nairobi, Kenya (reference-grade $PM_{2.5}$, and NO_x), and Accra, Ghana (reference-grade O_3 and NO_x). AfriqAir also currently has a number of other low-cost sensors deployed around the continent in Ghana, Côte d'Ivoire, Niger, Democratic Rep. of Congo, Rwanda, Uganda, Kenya, and South Africa, with plans to deploy reference-monitors to create hybrid networks in the near future (Fig 1). Part of this effort includes deploying 25 reference-grade $PM_{2.5}$ monitors (TEOM-FDMS 1400ab, Thermo Fisher Scientific, Waltham, MA, USA) that AfriqAir obtained as a gift from the UK Environment Agency, around the continent over the coming year. Overall, this approach of hybrid networks to increase the physical

Figure 1: *AfriqAir network map (including monitors run by affiliated partners)*

infrastructure for air quality monitoring is the best balance between cost, accuracy, and high spatiotemporal resolution to provide air quality monitoring coverage to the largest areas and number of people.

Increasing the physical infrastructure for air quality monitoring is, however, insufficient without ensuring that local partners are trained and provided with necessary supplies to operate and maintain said infrastructure. Having local partners and stakeholders running these monitoring networks is the only way to ensure there is a long-term, sustainable future for these monitoring solutions. Current partners include the University of Rwanda, University of Cape Coast, Université Félix Houphouët-Boigny, University of Nairobi, Jomo Kenyatta University, Kenyatta University, University of Ghana, North-West University, and the network is expanding. From AfriqAir's perspective, local partners and stakeholders should be able to not only run air quality monitors but also be able to analyze their data and work towards applying the data towards value-added products such as air quality reports, air quality management plans, interventions, and air quality models. To this end, AfriqAir is part of multiple efforts across the continent to build air quality monitoring and management capacity. Some of these efforts are in collaboration with other multi-national projects such as CAMS-Net. Furthermore, AfriqAir provides technical assistance and training to our African partners if requested. Without local

buy-in of monitoring efforts, such efforts will not contribute to long-term, sustainable improvements in African air quality.

Finally, the ultimate goal of improving air quality in Africa cannot be attained if air quality data are not public (as is the usual practice in the Global North). Open and accessible data allow local populations access to important health information, can alert regulators and officials to potential problems, and can help drive international collaborations to address issues. AfriqAir therefore abides by an open-data framework and we aim to make all calibrated data for all of our sensors openly available through our website or upon publication of academic papers. We also encourage everyone who operates air quality monitors on the continent to follow this framework. Of course, there is an important point to recognize that open-data can sometimes lead to a lack of attribution and recognition for those that spent time, money, and effort in collecting the data. For researchers whose professional standing and growth depends on being recognized as a source of data, open-data frameworks can pose some problems. To address this concern, AfriqAir will be using a Creative Commons Attribution-ShareAlike 4.0 International License for all its available data. Under the terms of this license, users can share and adapt our data but are required to provide attribution, describe any changes to the data, and share any derivative materials under the same license. Similarly, any journal paper derived from the AfriqAir efforts will include access to the data through an open-access data repository (e.g. Zenodo, Figshare, Kilthub, or global air quality repositories such as OpenAQ). Developed under the European OpenAIRE program and operated by CERN, Zenodo is a general-purpose open-access repository that allows researchers to deposit data sets, research software, reports, and any other research-related digital artifacts. An advantage of Zenodo is that each submission is linked to a digital object identifier, making the stored items easily citable. We believe that making data available through these mechanisms will increase interest and help generate sustainability in air quality monitoring in Africa.

Ultimately, using these three specific approaches may not fit everyone in the air quality space in Africa, but we reiterate that there is a desperate need for actions to improve air quality to start now. Reducing the number of premature deaths and overall mortality due to poor air quality is of utmost importance all over the African continent. For AfriqAir, the three approaches described here work well but regardless of how the problem is approached, we as a community can make real strides in improving air quality over Africa if we work together and pool our expertise. We invite you to contact us at AfriqAir if you agree with this mission. We are an open community trying to coordinate efforts at tackling one of the great health issues of our time and would be honored to work alongside you. You can contact us through our website (afriqair.org), Twitter (@AfriqAirQuality), or email (mike@afriqair.org, pjaramil@kcrc.rw, airquality@kcrc.rw).

References

Anenberg, S.C., Bindl, M., Brauer, M., Castillo, J.J., Cavalieri, S., Duncan, B.N., Fiore, A.M., Fuller, R., Goldberg, D.L., Henze, D.K. and Hess, J. (2020). "Using satellites to track indicators of global air pollution and climate change impacts: Lessons learned from a NASA-supported science-stakeholder collaborative". GeoHealth, 4(7), e2020GH000270, doi: 10.1029/2020GH000270.

Bauer, S. E., Im, U., Mezuman, K. and Gao, C. Y. (2019). "Desert Dust, Industrialization, and Agricultural Fires: Health Impacts of Outdoor Air Pollution in Africa." J. Geophys. Res. Atmos., 124(7), 4104-4120, doi:10.1029/2018JD029336.

Kiesewetter, G. (2016). "Sources of air pollution in developing countries". [online] Available from: https://iiasa.ac.at/web/scientificUpdate/2015/program/mag/Sources-of-air-pollution.html.

Malings, C., Westervelt, D. M., Hauryliuk, A., Presto, A. A., Grieshop, A., Bittner, A., Beekmann, M. and Subramanian, R. (2020). "Application of low-cost fine particulate mass monitors to convert satellite aerosol optical depth to surface concentrations in North America and Africa". Atmos. Meas. Tech., 13(7), 3873-3892, doi:10.5194/amt-13-3873-2020.

Rahal, F. (2020). "View of Low-cost sensors, an interesting alternative for air quality monitoring in Africa". Clean Air J., 30(2), doi:10.17159/caj/2020/30/2.9223.

Roy, R. (2016). "The cost of air pollution in Africa OECD DEVELOPMENT CENTRE CENTRE DE DÉVELOPPEMENT DOCUMENTS DE TRAVAIL". [online] Available from: www.oecd.org/dev/wp. (Accessed 1 May 2021)

World Health Organization, Regional Office for Europe (2013). "Health effects of particulate matter". [online] Available from: http://www.euro.who.int/pubrequest (Accessed 1 May 2021), 2013.

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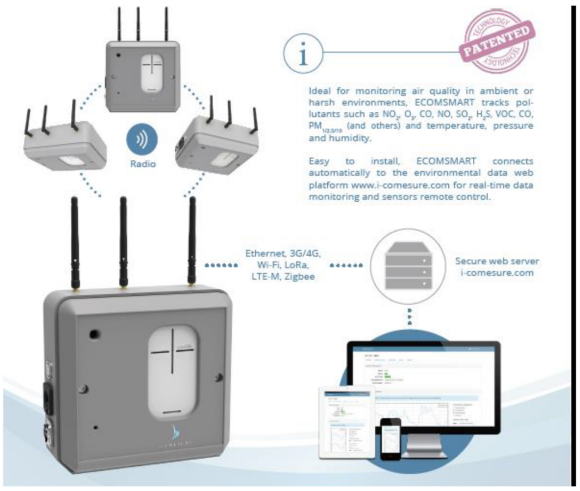

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Research brief
$PM_{2.5}$ chemical composition and geographical origin of air masses in Cape Town, South Africa

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Various indoor and outdoor air pollutants are linked in epidemiology studies to the symptoms, hospital admissions and development of numerous health outcomes — even with the spread and increase of Covid-19's morbidity and mortality and other disease mortality. Most of these epidemiology studies were conducted in the developed world and very few in Africa. An epidemiology study in Cape Town reported that exposure to outdoor PM_{10}, NO_2 and SO_2 levels during 2001–2006 posed a much higher risk to die from cardiovascular and respiratory diseases than reported in developed countries, even though the outdoor levels were on average similar to those in European cities. Another study in Cape Town observed adverse effects on cardiovascular disease hospital admissions during 2011–2016 – with stronger effects on days warmer than 20.3 °C. The South African studies did not investigate $PM_{2.5}$ as this air pollutant is not currently monitored in Cape Town. The daily and yearly $PM_{2.5}$ South African national ambient air quality standard came into effect on 29 June 2012. It is widely accepted that $PM_{2.5}$ is more hazardous to human health than PM_{10}. Very few studies in Africa reported on $PM_{2.5}$ levels. No study ever reported on $PM_{2.5}$ levels in Cape Town.

$PM_{2.5}$ filters samples were collected manually over 24 hours and every third day at an urban background, located on the roof of a house in the suburb of Kraaifontein, Cape Town during April 2017 and April 2018. In addition to the 24-hour filter samples, four composite filter samples were collected over four consecutive weeks during September 2017 and January 2018 to determine the anion and elemental composition of $PM_{2.5}$. After gravimetric analysis, reflectance measurements were performed. Elemental levels and anion levels of the composite samples were determined by Inductively Coupled Plasma-Optical Emission Spectrometry and Ion Chromatography, respectively. The geographical origin of air masses that passed Cape Town was applied as surrogates for long-range transported air pollution from distant sources and its composition, as done in other studies. The Hybrid Single Particle Lagrangian Integrated Trajectory software was used.

In total, 146 24-hour $PM_{2.5}$ filter samples (including 25 duplicate samples) were collected on 121 days during the 1-year study period. The mean $PM_{2.5}$ level of 13.4 $\mu g.m^{-3}$ was lower than the yearly South African National Ambient Air Quality Standard (SA NAAQS) (20 $\mu g.m^{-3}$). The levels exceeded the daily World Health Organization air quality guideline (25 $\mu g.m^{-3}$) on 14 occasions. These exceedances indicate that the population of Cape Town may experience various health outcomes due to outdoor $PM_{2.5}$ exposure, as indicated previously. The mean and maximum were higher than those reported in rural areas of South Africa, but lower than those reported in Pretoria or the South African towns located in the Vaal Triangle and Highveld air pollution priority areas. The mean level in this study was lower than the mean in 499 cities of 24 countries (37.5 $\mu g.m^{-3}$). The maximum level in this study was 39.1 $\mu g.m^{-3}$, which is generally lower than those reported in cities from other African countries.

The mean soot level was 1.38 $m^{-1} \times 10^{-5}$. Very few studies in Africa reported soot levels. The mean soot levels in Pretoria were higher and varied between 2.3 $m^{-1} \times 10^{-5}$ during April 2017 to April 2018 and 0.02 $m^{-1} \times 10^{-5}$ during May 2018 to Apr 2019. The mean soot level in Thohoyandou, a town located in a rural area, was lower: 0.69 $m^{-1} \times 10^{-5}$ during April 2017 to April 2018. A review concluded in 2017 that atmospheric black or elemental carbon is a risk factor for hospital admissions and mortality.

The largest fraction of $PM_{2.5}$ was due to anionic and metallic species ranging from 31 to 54% of mass and 27–51% of mass, respectively. Na and Cl^- were the most abundant constituents. The Atlantic Ocean and Indian Ocean are the most probable sources of Na and Cl^-. The lowest Fe and Zn level was 1.2 $\mu g.m^{-3}$ and 0.03 $\mu g.m^{-3}$, respectively. A large European cohort epidemiology study reported an increase of 3% in natural-cause mortality per 500 $ng.m^{-3}$ increase in Fe or per 20 $ng.m^{-3}$ increase in Zn. The observed Fe and Zn levels, if assumed to be experienced citywide in Cape Town, may thus pose a significant risk to human health.

Zn:Al ratios indicate the relative contribution of local road dust to $PM_{2.5}$ levels. Al is predominantly from natural sources, whilst Zn is mainly from tire wear, but also from solid waste or biomass burning and industrial emissions. The mean Zn:Al ratio in this study was 2.17.

The lowest SO_4^{2-} and NO_3^- level was 0.8 $\mu g.m^{-3}$ and 0.6 $\mu g.m^{-3}$, respectively. A review concluded that natural-cause mortality increased by 15% and 17% per 1 $\mu g.m^{-3}$ increase in SO_4^{2-} and NO_3^-, respectively. The observed SO_4^{2-} and NO_3^- levels, if assumed to be representative of levels in Cape Town, may thus

pose a significant risk to human health. The inorganic carbon fraction ranged from 7.0–14.2% of mass.

Four geographical origins of air masses were identified: Atlantic-Ocean-SW, Atlantic-Ocean-SSW, Atlantic-Ocean-WSW and Indian-Ocean. Air masses emanating from the Atlantic Ocean dominated in winter (87%), summer (73%), spring (77%) and the entire year (71%). In autumn, 51% of the air masses emanated from the Indian Ocean, with 29% in the entire study period. The median 24-hour $PM_{2.5}$ and soot levels did not differ significantly by the geographical origin of air masses.

Recommendations are that all the $PM_{2.5}$ samples are analysed for chemical composition to perform source apportionment and health risk assessment studies.

Reference

Williams, J., Petrik, L. & Wichmann, J. $PM_{2.5}$ chemical composition and geographical origin of air masses in Cape Town, South Africa. *Air Qual Atmos Health* 14, 431–442 (2021)

Research brief

Summary of research paper published in Nature Communications titled: Biomass burning aerosols in most climate models are too absorbing

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In a recent paper published in the high-impact factor journal Nature Communications, data collected at the Welgegund atmospheric monitoring station was one of 12 observational datasets utilised in a study to quantify the uncertainty in the representation of biomass burning (BB) aerosol composition and optical properties in climate models. Biomass burning aerosol make up a majority of primary combustion aerosol emissions (Andreae, 2019), with the main sources of global BB mass being Africa (~52%), South America (~15%), Equatorial Asia (~10%), Boreal forests (~9%), and Australia (~7%) (Van der Werf et al., 2010). The composition, size, and mixing state of BB aerosols determine the optical properties of smoke plumes in the atmosphere, which in turn is a major factor in dictating how they perturb the energy balance in the earth system. Depending on the model, the top-of-the-atmosphere BB aerosol effect can range from cooling to warming.

By relating aerosol absorption relative to extinction and carbonaceous aerosol composition from 12 observational datasets to nine state-of-the-art Earth system models and chemical transport models, varying degrees of overestimation in BB aerosol absorptivity by these models were identified. Modifications to BB aerosol refractive index, size, and mixing state was made in the Community Atmosphere Model version 5 (CAM5), which improved the model in agreement with observational measurements. These improvements led to a global change in BB direct radiative effect of −0.07 W.m^{-2}, while regional changes of −2 W.m^{-2} in Africa, and −0.5 W.m^{-2} in South America and Temperate regions were observed. These findings suggest that current modeled BB contributes less to warming than previously thought, largely due to treatments of aerosol mixing state.

References

Andreae, M. O. Emission of trace gases and aerosols from biomass burning – an updated assessment. Atmos. Chem. Phys. 19, 8523–8546 (2019).

Brown H., Liu X., Pokhrel R., Murphy S., Lu Z., Saleh R., Mielonen T., Kokkola H., Bergman T., Myhre G., Skeie R.B., Watson-Paris D., Stier P., Johnson B., Bellouin N., Schulz M., Vakkari V., Beukes J.P., van Zyl P.G., Liu S. and Chand D. Biomass burning aerosols in most climate models are too absorbing. Nat Commun 12:277 (2021). https://doi.org/10.1038/s41467-020-20482-9.

Van der Werf, G. R. et al. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos. Chem. Phys. 10, 11707–11735 (2010).

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Research article

Intra-urban variability of $PM_{2.5}$ in a dense, low-income settlement on the South African Highveld

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Abstract

High concentrations of the ambient particulate matter remain a concern on the South African Highveld, particularly in densely populated low-income settlements. These areas have several local emission sources that contribute to poor air quality and are often located close to industrial and other urban areas. The local sources vary in magnitude, space, and time. In South Africa, little has been done to assess the impacts of spatiotemporal variability on the credibility of using isolated ambient observations for regulatory purposes. This study aims to evaluate the intra-urban variability of ambient $PM_{2.5}$ concentrations in a dense, low-income community. Ambient fine particulate matter ($PM_{2.5}$) in distinct microenvironments of KwaZamokuhle were simultaneously measured at 4 sites between March and June 2018. These measurements were collected using one permanent ambient monitoring station (AMS) and a temporary network of three E-BAM monitors (Site 2, Site 3, and Site 4). Moreover, the 2011 Census spatial data was used to assess socio-economic conditions impacting $PM_{2.5}$ concentrations in areas surrounding each monitoring station. The daily $PM_{2.5}$ concentrations at AMS, Site 2, Site 3, and Site 4 varied from 10 to 86 $\mu g.m^{-3}$, 10 to 103 $\mu g.m^{-3}$, 11 to 101 $\mu g.m^{-3}$, and 9 to 113 $\mu g.m^{-3}$, respectively. Extreme $PM_{2.5}$ concentrations which exceeded the 24h $PM_{2.5}$ NAAQS of 40 $\mu g.m^{-3}$ were seen during the cold period (May and June); meanwhile, the warm period (March and April) recorded relatively lower $PM_{2.5}$ episodes across different sections of KwaZamokuhle. During May-June, the highest diurnal concentrations of hourly averaged ambient $PM_{2.5}$ were recorded at Site 4, in a downward sequence, followed by Site 3, Site 2, and AMS. It was further found that informal dwellings and solid fuel reliant houses are widely concentrated at Site 4 thus, indicating exposure inequalities across the community. This study, therefore, highlights the complexity of quantifying ambient air quality in an area where several local emission sources vary in space and time. Attempts to use monitoring data from a single station to assess ambient air quality, quantify human exposure, or evaluate the potential impacts of mitigation strategies in dense, low-income settlements should be done with care.

Keywords

fine particulate matter, household air pollution, low-income settlements, South African Highveld, air quality management

Introduction

Exposure to ambient fine particulate matter ($PM_{2.5}$) pollution was the fourth leading global risk factor for premature mortality in 2019, contributing to 6.7 million early deaths (12% of total deaths globally) (Murray et al., 2020). Exposure to household air pollution (HAP) from the use of solid fuels for cooking and heating, contributed to 2.31 million deaths in the same year, with the majority of these deaths occurring in sub-Saharan Africa and Asia (HEI, 2020).

At the national scale, residential solid fuel use in South Africa is low compared to other countries in the region. However, it remains prominent in many low-income urban and peri-urban settlements around the coalfields on the South African Highveld (StatsSA, 2019). It is estimated that household and ambient air pollution exposure contributed to 4 590 and 24 800 premature deaths of South Africans in 2019, respectively (HEI, 2020).

The main drivers of household emissions globally and nationally are poverty and limited access to resources such as good quality housing and clean energy sources (Buthelezi et al., 2019; HEI, 2020). Previous studies have shown that, of all the environments in South Africa, ambient concentrations of particulate matter are highest in solid fuel using areas (Hersey et al., 2015). Residential solid fuel burning, in low-income settlements, has been

estimated to contribute to over 60% of the particulate pollution (Engelbrecht et al., 2002). Coalfields, industrial activities and coal-powered electricity generation are also concentrated in the Highveld region. These activities contribute to poor air quality which often exceeds National Ambient Air Quality Standards (NAAQS) aimed at protecting public health (DOE, 2012). As an economic hub, large parts of the region are densely populated, and air quality management remains a challenge due to the high concentration of industrial and residential sources in the region (Matandirotya et al., 2019). Air quality is expected to decline even more as urban areas on the Highveld become more populated.

In South Africa, 85% of households have access to electricity. However, due to financial constraints, many households are still unable to afford electricity as their only source of energy, using the fuel stacking approach for more energy-intensive practices such as cooking and heating (Langerman and Pauw, 2018; Israel-Akinbo, Snowball and Fraser, 2018). Solid fuels remain a cost-effective alternative energy source, especially during colder winter months. Solid fuels are not only more cost-effective but also more convenient, as the same appliance is used for cooking and space heating simultaneously (Balmer, 2007).

The low socio-economic status of residents in solid fuel burning communities also increases vulnerability to the adverse health impacts of air pollution. Living in areas with high air pollution levels has been linked with increased risk of respiratory, cardio- and cerebrovascular morbidity and mortality, all-cause mortality, as well as acute effects like asthma exacerbation, skin and eye irritation (Pope and Dockery, 2006; Brook et al., 2010; Lelieveld, 2020).

The burden of disease is also not distributed evenly in these communities, women, children, and the elderly are the most affected (HEI, 2020). Several studies conducted in solid fuel burning communities have measured significant differences in indoor and ambient PM concentrations in and around solid fuel burning and non-solid fuel burning households in the same communities (Adesina et al., 2019; Language et al., 2016). Better air quality management on the Highveld is important in order to rectify the disproportionate distribution of the burden of air pollution and address environmental injustice at both the regional and community scales.

Understanding $PM_{2.5}$ sources, ambient concentrations, their trends and spatio-temporal variability inside urban settlements are essential for designing strategies aimed at assessing and managing environmental and health impacts related to poor ambient air quality on the Highveld. An understanding of the socio-economic drivers of solid fuel use is also essential in order to identify at-risk areas and design community-specific interventions. Location-specific variables such as the amount of informal housing, number of households using "dirty" fuels and population density of an area have been shown to have positive correlations to particulate matter concentrations in an area (Lindeque et al., 2018).

Monitoring stations were installed within some of the low-income settlements on the South African Highveld to measure the state of air quality (Gwaze and Mashele 2018). Due to the high costs associated with purchasing and operating these stations, community airsheds are frequently monitored by only one such station (DEAT, 2006). However, studies have shown that residential ambient air concentrations are highly variable in time and space (Petit et al., 2015; Krasnov et al., 2016; Wernecke, 2018; Kumar et al., 2018). This study aims to evaluate how ambient $PM_{2.5}$ varies in space and time inside a solid fuel burning community, in order to better understand the intra-urban variability of air quality in a low-income settlement. It further explores the socio-economic drivers known to influence particulate matter concentrations in low-income settlements, as a means to describe the observed spatio-temporal variability of concentrations. The results could inform the design of future monitoring strategies, mitigation attempts and management approaches in low-income settlements in order to address exposure inequities on the Highveld.

Data and methodology

Study area

KwaZamokuhle is a low-income residential area that is situated in the Mpumalanga Highveld Priority Area (DEAT, 2007) (Figure 1). It is situated in the Nkangala local municipality and has over 20 000 permanent residents (StatsSA, 2012b). The settlement is located near three Eskom coal operated power stations: Hendrina, Arnot, and Komati. Chidhindi et al. (2019) modelled the impacts of these coal-fired power plants and found that they contributed little to ambient $PM_{2.5}$ in comparison to the local sources in KwaZamokuhle. However, their model did not include secondary particulate matter formed due to industrial emissions.

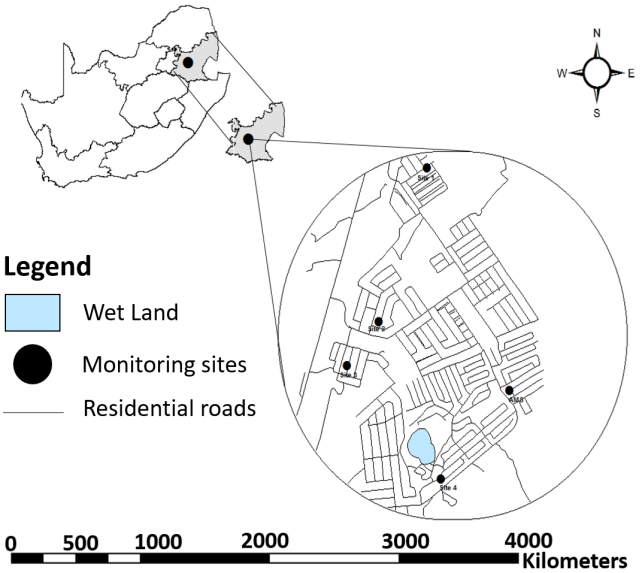

Figure 1: *Map illustrating the geographic location of the ambient $PM_{2.5}$ monitoring sites in KwaZamokuhle, a low-income community within the Nkangala Local Municipality, situated in the Mpumalanga Province of South Africa.*

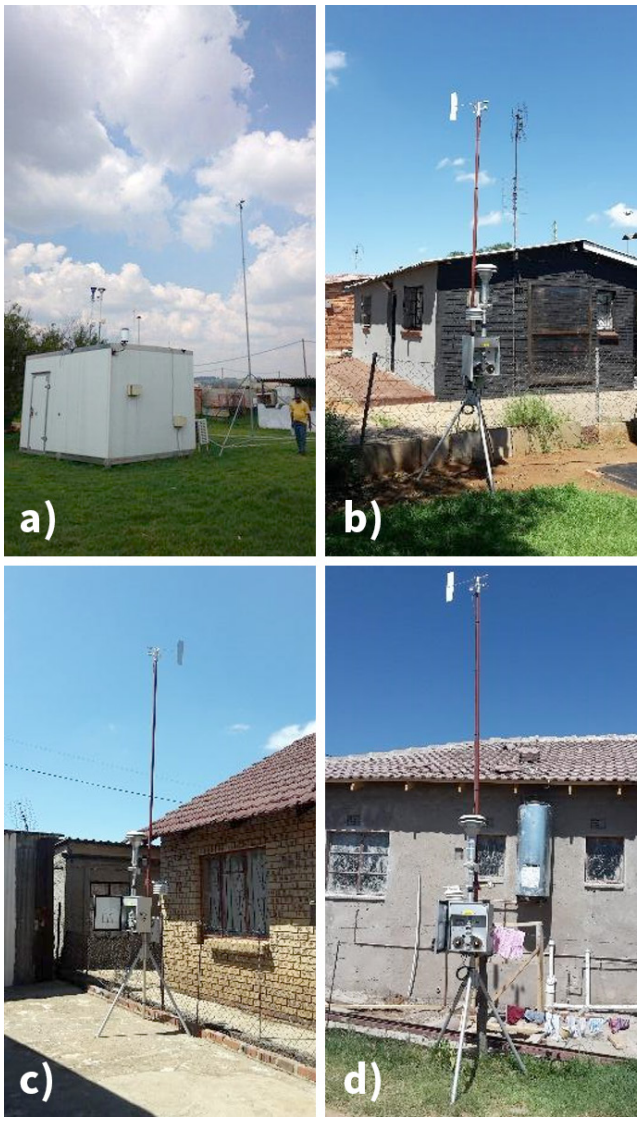

Figure 2: *Photographs of the four ambient sampling sites in KwaZamokuhle: (a) AMS, (b) Site 2, (c) Site 3, and (d) Site 4.*

The average household size in the settlement is 3.5 people per household with a mean annual household income of 1 965 (ZAR), and an unemployment rate of 45% (StatsSA, 2012b). Typically, electricity is used for lighting (89.2% of households) whereas, for cooking and space heating, coal and wood are the more commonly used energy sources (34% and 31.2% of households respectively) (StatsSA, 2012b).

Sampling strategy

The study was conducted during a sampling campaign of four months, from 1 March to 30 June 2018. Ambient $PM_{2.5}$ concentrations measurements were recorded at four sites in KwaZamokuhle.

The first site being a long-term ambient air quality monitoring station (AMS), situated in the eastern part of the community at 26°8'17.64"S and 29°44'20.41"E. The AMS (Figure 2a) is directly surrounded by grass and unvegetated soil. There are buildings 13m to the north, 12m west-south-west, and 10m south-east of the AMS. There is an unpaved road 8m north-east, running parallel to the AMS. The second site (Site 2) was situated ~1.07 km north-west of the AMS at 26°8'0.74"S and 29°43'46.48"E (Figure 2b). Site 2 was surrounded by grass and unvegetated soil, with a paved road 8m to the east of the instrument. There was an open field to the south-east (across the paved road), besides that, households surround the site. The third site (Site 3) (26°8'12.16"S, 29°43'38.67"E) was located ~1.18km west and ~0.41km south-west of the AMS and Site 1 respectively. The site was placed on a concrete surface (driveway) between two houses with a paved road ~14m west-north-west of the site (Figure 2c). The last site (Site 4) was positioned at 26°8'36.39"S, 29°44'3.92"E which was ~0.74km south-west, ~1.0km south-south-east, and ~1.02km south-east of the AMS, Site 2, and Site 3 respectively (Figure 2d).

Sites 2, 3, and 4 were selected based on several factors which included i) the relative distance from each other and the AMS; ii) the availability of electricity, iii) security, and iii) general coverage of different areas of the community. The factor mentioned last was important to determine the differences in the ambient $PM_{2.5}$ concentrations across distinct sections of the community.

Instrumentation

The instruments used for data collection operated by beta-attenuation technology. A Thermo Scientific FH62 C-14 particulate monitor continuously measured ambient $PM_{2.5}$ at the AMS. A temporary network of E-BAM particulate monitors from MetOne Instruments was deployed at Site2, 3, and 4. Detailed information and discussion on the specifications and theory of operation for both the FH62 C-14 (Thermo Scientific, 2010) and E-BAM (MetOne Instruments, 2008; Schweizer et al., 2016) can be found in the literature. Beta-attenuation instruments are often used to measure and explore the spatial and temporal variability of ambient particulate matter (Schweizer et al., 2016; Kumar et al., 2018).

A notable difference was the measurement heights for $PM_{2.5}$ at the static and temporary sampling sites. At the AMS, $PM_{2.5}$ was measured at ~3m while at Sites 2, 3, and 4 was ~1.6m. The data were recorded at a resolution of one minute for the duration of the sampling campaign.

Data quality control and quality assurance

The sites were visited biweekly for general maintenance and data collection activities.

The data gaps displayed in Figure 3 reflect the technical problems encountered during the sampling campaign. These included power cuts, systematic failures due to $PM_{2.5}$ overload, and changing of filter tape. Data were flagged based on the limit of detection, ranges, the sensitivity of the individual instruments and general errors identified during sampling. The flagged data were excluded and not considered for further analysis.

Only days with at least 90% of valid data points for all sites were included in the analysis. The combined data recovery for March,

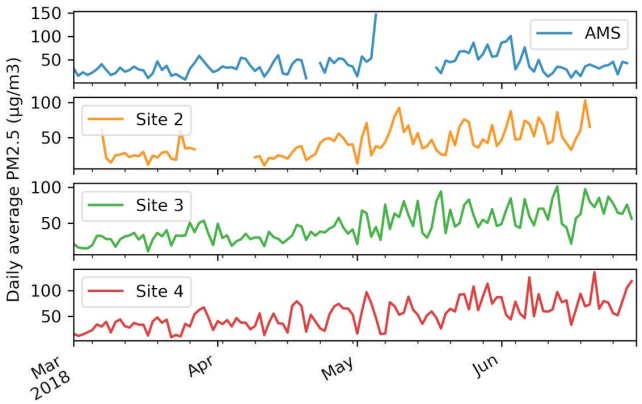

Figure 3: *Time series graph showing the daily average $PM_{2.5}$ concentrations measured at AMS, Site 2, Site 3, and Site 4.*

April, May and June were 48%, 47%, 32% and 27%, respectively. There was a total of 47 valid days (39%) from the 122 days sampled. The valid data were averaged into hourly and daily concentrations.

Data analysis

The distribution of the data was investigated through descriptive statistics as well as box-plots. The spatial and temporal variations were examined by using both the hourly- and daily averaged $PM_{2.5}$ concentration.

Identification of possible socio-economic drivers of the observed variability

Data from the 2011 Census spatial dataset was used for this part of the analysis. Enumeration Areas (EAs) (also called small area levels) were chosen for the scale of analysis as they are the smallest geographical areas, where detailed housing and household-related statistics are recorded during a census. The underlying philosophy of this approach is very similar to that of Wright and Diab (2011), who also used census data to better represent the socio-economic factors that play such an important role not only as drivers of poor air quality but also in exposure and vulnerability to the adverse health impacts of HAP. Relevant data for every EA bordering each of the monitoring sites were extracted and aggregated in order to understand better the socio-economic conditions that are known to drive solid fuel use around each monitoring station. The following variables were included for each EA: 1) the number of households; 2) the percentage of informal dwellings; 3) population density; 4) median annual household income; and 5) the percentage of households using solid fuels for cooking and heating. After aggregation for each monitoring site, data were compared to the observed measurements to explore whether the socio-economic conditions in areas surrounding each monitoring station could have influenced observed spatio-temporal variability.

Results and discussion

The results related to the spatial and temporal variability of ambient $PM_{2.5}$ concentrations in KwaZamokuhle are represented and discussed below.

Variability of ambient $PM_{2.5}$

The spatial distribution of the daily mean ambient $PM_{2.5}$ levels across distinct sections of KwaZamokuhle is shown in Figure 4. The daily $PM_{2.5}$ concentrations at AMS, Site 2, Site 3, and Site 4 ranged from 10 to 86 µg.m^{-3}, 10 to 103 µg.m^{-3}, 11 to 101 µg.m^{-3}, and 9 to 113 µg.m^{-3}, respectively.

Across KwaZamokuhle, the lowest daily mean $PM_{2.5}$ concentration was recorded at Site 2 (36 ±20 µg.m^{-3}), situated farthest north, while the highest mean was measured at Site 4 (53 ± 27 µg.m^{-3}) located farthest south. The AMS site experienced similar $PM_{2.5}$ loadings (37 ± 19 µg.m^{-3}) as Site 2. The $PM_{2.5}$ mass concentrations at Site 3 (44 ± 21 µg.m^{-3}) were midway between that of Site 4 and Site 2. This indicates that the ambient $PM_{2.5}$ loadings tend to increase from north to south over the community. The 99% of the daily averaged measurements for the AMS, Site 2, Site 3, and Site 4 were 86 µg.m^{-3}, 95 µg.m^{-3}, 100 µg.m^{-3}, and 111 µg.m^{-3}, respectively.

Larger variability in the daily averaged $PM_{2.5}$ loadings were observed for Site 4, and to a lesser degree at Site 3. The AMS and Site 2 showed the lowest variability in the daily mean values. The daily averaged mean $PM_{2.5}$ loadings at the AMS, Site 2, Site 3, and Site 4 exceed the 24-h $PM_{2.5}$ NAAQS of 40 µg.m^{-3} for 19 (40%), 16 (34%), 22 (46%), and 28 (60%) of the 47 days (Table 1).

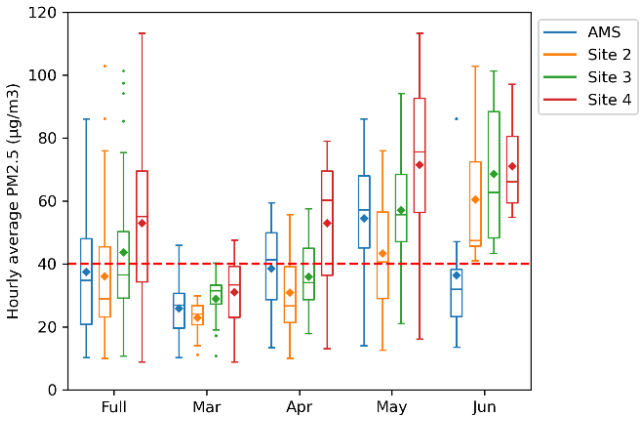

Figure 4: *Spatial variation of the daily averaged ambient $PM_{2.5}$ concentrations at AMS, Site 2, Site 3, and Site 4. The box-and-whisker plots show the minimum and maximum values (horizontal lines perpendicular to the whiskers); 25th, 50th, and 75th quartiles; means (triangles in the boxes); outliers (circles beyond the whiskers); and the 24-h NAAQS (red dotted lines).*

Considerable spatial variability of the monthly daily mean $PM_{2.5}$ concentrations was recorded across KwaZamokuhle (Figure 4). Throughout all the sampled months, the daily average $PM_{2.5}$ concentrations measured at AMS, Site 2, Site 3, and Site 4 ranged from 26 to 36 µg.m^{-3}, 23 to 60 µg.m^{-3}, 29 to 69 µg.m^{-3}, and 31 to 71 µg.m^{-3}, respectively. Extreme $PM_{2.5}$ concentrations were seen during the cold period (May and June); meanwhile, the warm period (March and April) represented relatively lower $PM_{2.5}$ episodes across different sections of KwaZamokuhle. These results agree with previous observations that were made in KwaZamokuhle (Langerman et al., 2018; Yahia and Langerman 2018; Wernecke 2018; Adesina et al., 2019).

The studies mentioned above attributed substantial winter increments of $PM_{2.5}$ concentrations to domestic fuel combustion. As mentioned earlier, there is considerable residential reliance on coal and wood for space heating and cooking in KwaZamokuhle (StatsSA, 2012b). A significant portion of these fuels is burned during the winter period to keep households warm from cold ambient temperatures (Langerman et al., 2015; Yahia and Langerman, 2018). Poor air quality over the Highveld is further exacerbated by prevailing wintertime anticyclonic circulation that leads to the formation of inversion layers causing poor vertical dispersion of pollutants (Langerman et al., 2018).

During March, the highest daily mean $PM_{2.5}$ concentration of 31 $\mu g.m^{-3}$ was observed in Site 4. This was 1.4 and 1.2 times greater than the daily average $PM_{2.5}$ concentration measured at Site 2 and AMS, respectively. However, Site 3 and Site 4 showed less variation. At AMS, Site 2, Site 3, and Site 4, 99% of the daily particulate concentrations were 45 $\mu g.m^{-3}$, 30 $\mu g.m^{-3}$, 40 $\mu g.m^{-3}$, and 48 $\mu g.m^{-3}$, respectively (Figure 4). The maximum daily readings at Site 2 were below the 24-h $PM_{2.5}$ NAAQS of 40 $\mu g.m^{-3}$, while those at AMS, Site 3, and Site 4 were beyond. However, the number of exceedances measured at AMS (1), Site 3 (1), and Site 4 (3) were below the allowed annual exceedances of 4 (Table 1). Therefore, more than 80% of the 15 days, which were sampled across KwaZamokuhle during March had cleaner air quality.

The daily concentrations measured in April ranged from 13 to 59 $\mu g.m^{-3}$, 10 to 56 $\mu g.m^{-3}$, 18 to 58 $\mu g.m^{-3}$, and 13 to 79 $\mu g.m^{-3}$, at AMS, Site 2, Site 3, and Site 4, respectively. Across all sites, Site 4 (53 ± 21 $\mu g.m^{-3}$) recorded the highest daily averaged $PM_{2.5}$ concentration. This was 35%, 70%, and 47% higher than the mean daily concentrations measured at AMS, Site 2, and Site 3, respectively. It is noticeable that 99% of the daily average concentrations measured in different sections of KwaZamokuhle were higher than the 24-h $PM_{2.5}$ NAAQS of 40 $\mu g.m^{-3}$. However, the frequency of these exceedances was different for most of the sites. This is indicative of a heterogeneous spatial distribution of local emission sources within KwaZamokuhle.

The highest monthly daily mean $PM_{2.5}$ concentrations were recorded in June at all sites, except for AMS. At AMS, Site 2, Site 3, and Site 4, 99% of the daily $PM_{2.5}$ concentrations were 36 $\mu g.m^{-3}$, 60 $\mu g.m^{-3}$, 69 $\mu g.m^{-3}$, and 71 $\mu g.m^{-3}$, respectively. These $PM_{2.5}$ concentrations exceeded the 24-h $PM_{2.5}$ NAAQS at all sites except the AMS. The observed exceedances at Site 2, Site 3, and Site 4 are attributable to the direct exposure to emissions from dirty solid fuel combustion. Meanwhile, the compliance at AMS is likely due to less exposure to emissions from domestic fuel combustion. Therefore, these results suggest that the compliance status of a single point monitoring station in a particular microenvironment does not confirm that air quality is similar across the entire township.

Diurnal distribution

Figure 5 depicts the diurnal distribution of the hourly averaged ambient $PM_{2.5}$ mass concentrations for AMS, Site 2, Site 3 and

Table 1: *Descriptive statistics for the daily averaged ambient $PM_{2.5}$ mass concentrations in $\mu g.m^{-3}$ at four monitoring sites in KwaZamokuhle, for the period 1 March to 30 June 2018, sub-categorised by month.*

		N	Mean	±SD	Min	Median	99%	Max	N Exc.
AMS	Full	47	37	19	10	35	86	86	19
	M	15	26	9	10	27	45	46	1
	A	14	39	14	13	41	58	59	8
	M	10	54	24	14	57	86	86	8
	J	8	36	23	13	32	83	86	2
Site 2	Full	47	36	20	10	29	95	103	16
	M	15	23	5	11	24	30	30	0
	A	14	31	13	10	27	55	56	3
	M	10	43	20	13	41	75	76	5
	J	8	60	23	41	47	102	103	8
Site 3	Full	47	44	21	11	37	100	101	22
	M	15	29	8	11	31	40	40	1
	A	14	36	11	18	34	56	58	5
	M	10	57	21	21	56	92	94	8
	J	8	69	24	43	64	101	101	8
Site 4	Full	47	53	27	9	55	111	113	28
	M	15	31	12	9	33	47	48	3
	A	14	53	21	13	60	78	79	9
	M	10	71	33	16	76	113	113	8
	J	8	71	15	55	66	96	97	8

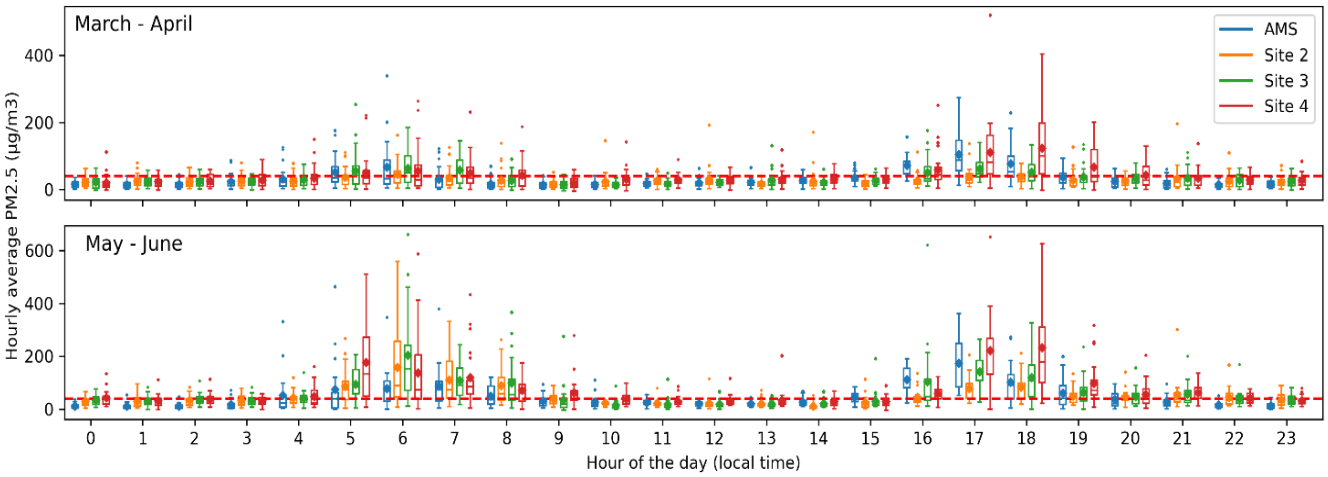

Figure 5: *Diurnal distribution of the hourly averaged ambient $PM_{2.5}$ concentrations at AMS, Site 2, Site 3, and Site 4. The graphs are grouped by months: March-April and May-June. The box-and-whisker plots show the minimum and maximum values (horizontal lines perpendicular to the whiskers); 25th, 50th, and 75th quartiles; means (diamonds in the boxes); outliers (circles beyond the whiskers); and the 24-h NAAQS (red dotted lines).*

Site 4 in KwaZamokuhle. The data were grouped into two periods, namely, March-April and May-June. The first period mentioned is typical of a transitional period between summer and winter conditions, whereas the latter moves toward typical winter conditions.

All four sites showed the typical diurnal pattern, which includes bimodal morning and evening peaks, typical of low-income communities in South Africa. These periods usually occur within the periods of increased community- and household activities. The 24-h $PM_{2.5}$ NAAQS limits are typically exceeded during these peak concentration periods. The higher the extreme concentrations on any given day, the more likely it is that the daily averages will exceed the NAAQS limit value of 40 µg.m^{-3}.

Morning peak $PM_{2.5}$ concentrations are observed from 05h00 to 07h00 lasting 3 hours from March-April while from May-June peak concentrations are observed from 05h00 to 08h00 lasting for 4 hours. During May-June, the highest mean concentrations were observed at Site 4 followed by Site 3, and Site 2. The AMS had the lowest ambient $PM_{2.5}$ levels. A possible explanation could be that the AMS is situated on church/community grounds, whereas the other three sites were all located between residences.

Evening $PM_{2.5}$ concentrations typically peaked between 16h00-20h00 in March-April and 16h00-21h00 for May-June. Upon closer investigation, it is clear that there are specific activities/sources which contribute to increased particulate loadings at individual sites. For example, in March-April, Site 3 experienced the highest peak concentrations during the morning, followed by Site 4, AMS, and Site 2. At all four sites, the morning peak gradually increases and then decreases. However, this is somewhat different during the evening. The $PM_{2.5}$ concentrations at the AMS rapidly increase at 16h00, significantly higher than other sites, and then stabilise again by 19h00. Thus, the AMS morning and evening peaks are similar. Site 4 had the highest particulate loadings starting at 17h00, approximately two times higher than the remaining sites. This indicates that there is a definite/specific source contributing to increased concentrations at Site 4. This is likely due to the duration of domestic fuel burning events and the frequency of emissions produced, which are different for each section in the community, therefore, suggesting that air quality in KwaZamokuhle is not polluted by industrial emissions (Collett et al., 2010). Site 3 had the third-highest concentrations during the evening with Site 2 experiencing the lowest particulate loadings. These trends were also observed for May-June. Note, the mean evening concentrations during May-June were a factor of one to two higher than during March-April.

The microenvironments of this township showed significantly different concentration distributions; thus, indicating that $PM_{2.5}$ sources are local by origin. A further ANOVA analysis of hourly data for the full monitoring period (1 March 2018 – 30 June 2018) rejected the null hypothesis that the means of the four sites are from the same population (p-value 1.2e-14).

Socio-economic drivers of observed $PM_{2.5}$ variability

Data from Census 2011 was extracted at the EA level for each EA bordering every monitoring Site. Data were aggregated, and a summary of the socio-economic conditions that could influence HAP emissions is given in Table 2.

Observed $PM_{2.5}$ concentrations show the daily and seasonal peaks typically in solid-fuel burning communities on the Highveld (Language et al., 2016; Nkosi et al., 2018; Wernecke, 2018).

The highest daily and seasonal mean $PM_{2.5}$ concentrations were measured at Site 4. The areas surrounding Site 4 have the highest percentage of households using solid fuels for cooking and heating (Figure 6a). These areas also have the highest number of informal dwellings (117), where cold indoor temperatures often cause residents to burn solid fuels for space heating (Figure 6b).

These findings concur with the findings of Lindeque et al. (2018), which found the number of informal dwellings in an area to be the most significant socio-economic predictor of high household emissions, followed by the percentage of households using solid fuels as the second predictor, and population density as the third.

One of the three EAs included for the analysis of areas surrounding Site 4 (SAL code 8690100), had the highest number of informal dwellings (60% of all households) and the lowest median annual household income (ZAR 7200) of all EAs in KwaZamokuhle (Figure 6c). Ninety-three percent of households in this EA use solid fuels for cooking and heating, and this could be a contributing factor to the high concentrations (min, max and mean) measured at Site 4 for all seasons. This finding also reiterates the importance of using spatially refined data when assessing the drivers of HAP in low-income communities, as averaging at even this small scale could conceal areas of concern for air quality management. It furthermore supports the evidence that poverty and poor quality housing contribute significantly to poor air quality over the South African Highveld.

Table 2: *Summary of socio-economic conditions in areas surrounding each of the ambient monitoring Sites in KwaZamokuhle.*

Socio-economic variable	AMS	Site 2	Site 3	Site 4
Number of EAs bordering monitor Site	4	2	2	3
Population density (persons/km^2)	11070	4518	2400	5052
Total no. of households	699	276	276	414
Number of informal dwellings	69	10	31	117
Percentage of households using solid fuels	45	32	39	55
Median annual household income (ZAR)	12 750	21 750	21 750	16 900

Population density does not seem to have a significant influence on concentrations in areas around the monitoring sites, as the lowest concentrations were observed at AMS, the section of the township with the highest surrounding population density. Site 3, where high concentrations were observed, has the lowest surrounding population density of all Sites (Figure 6d).

It is important to note that this part of the analysis is purely descriptive, and does not imply a direct correlation between the discussed socio-economic factors and ambient particulate matter concentrations. The last complete census was conducted in 2011, and significant demographic changes could have occurred between then and the time of sampling in 2018.

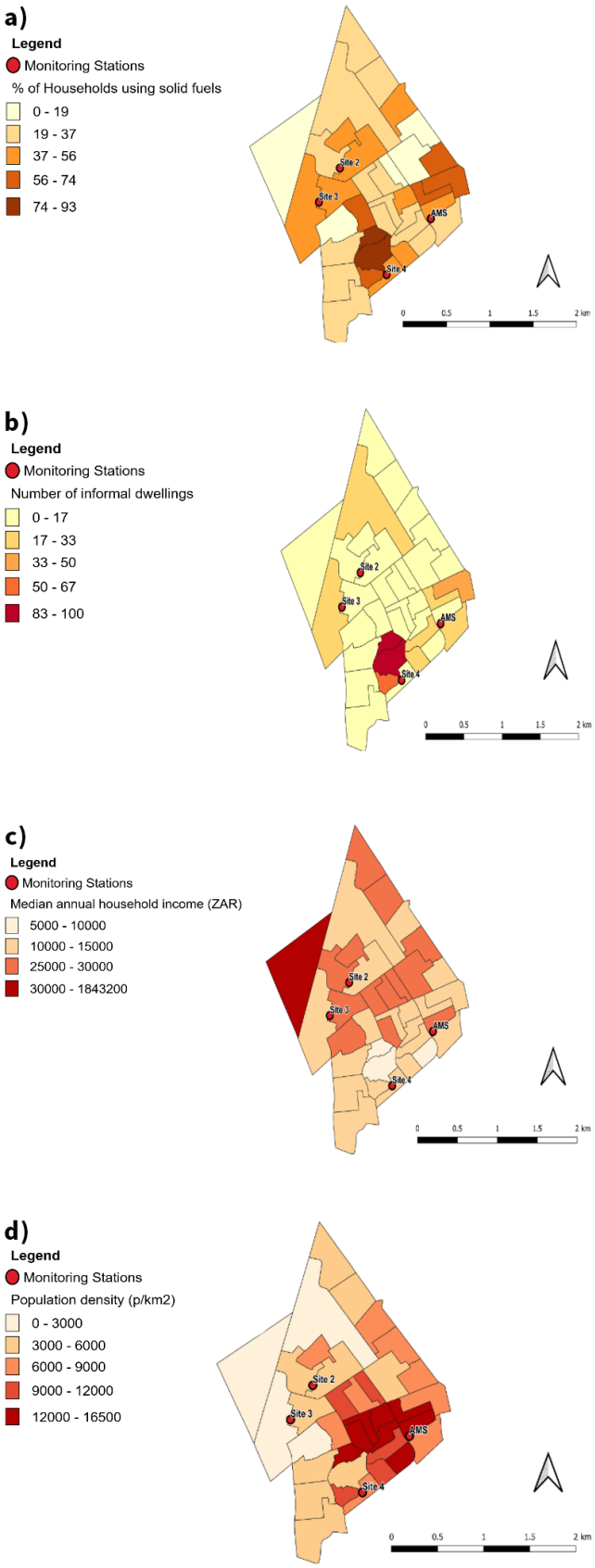

Figure 6: *Maps showing the socio-economic aspect of enumerator areas surrounding each of the ambient monitoring Sites in KwaZamokuhle: a) percentage of households using solid fuels, b) the number of informal dwellings in each enumerator area, c) median annual household income, and d) population density.*

Conclusions

Ambient $PM_{2.5}$ concentrations were monitored in four different sections of KwaZamokuhle to evaluate how they vary in space and time. This was done using a permanent ambient monitoring station and a network of three temporary monitoring stations in various sections of the township. Moreover, a characterisation of ambient $PM_{2.5}$ was done and showed poor quality with varying frequencies across the entire settlement.

The diurnal variability suggested that the duration of domestic combustion of solid fuel events is different across KwaZamokuhle and has a significant effect on ambient $PM_{2.5}$. The daily ambient $PM_{2.5}$ concentrations at AMS, Site 2, Site 3, and Site 4 were found to be significantly different.

A descriptive analysis of the socio-economic conditions in the areas surrounding each monitoring site was conducted. This part of the study highlighted the importance of using spatially refined data when assessing the drivers of HAP in low-income communities and supported the evidence that poverty is a driver of poor air quality in low-income settlements on the Highveld.

The results of this study highlight the complexity of quantifying ambient air quality in an area where there are several local pollution sources. Therefore, care should be taken when data from one site is used to assess air quality, human exposure, or the potential impacts of mitigation strategies in dense, low-income settlements.

Acknowledgements

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References

Adesina J.A., Piketh S.J., Qhekwana M., Burger R., Language B. and Mkhatshwa G. 2019, 'Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa Highveld.' Science of the Total Environment.134403. https://doi.org/10.1016/j.scitotenv.2019.134403

Balmer, M. 2007. Household coal use in an urban township in South Africa. Journal of Energy in Southern Africa, 18(3):27–32. https://doi.org/10.17159/2413-3051/2007/v18i3a3382

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L., Kaufman, J.D. 2010. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation, 121(21):2331–2378. Research and Public Health, 16(4):550. https://doi.org/10.1161/CIR.0b013e3181dbece1

Buthelezi S.A., Kapwata T., Wernecke B., Webster C., Mathee A. and Wright C.Y. 2019, 'Household fuel use for heating and cooking and respiratory health in a low-income, South African coastal community.' International Journal of Environmental Research and Public Health, 16(4):550. https://doi.org/10.3390/ijerph16040550

Chidhindi P., Belelie M.D., Burger R.P., Piketh S.J. and Mkhatshwa G. 2019, 'Assessing the impact of Eskom power plant emissions on ambient air quality over KwaZamokuhle.' Clean Air Journal, 29(1):29-37. https://doi.org/10.17159/2410-972X/2019/v29n1a2

Collett K.S., Piketh S.J. and Ross K.E. 2010, 'An assessment of the atmospheric nitrogen budget on the South African Highveld.' South African Journal of Science, 106(5-6):35-43. https://doi.org/10.4102/sajs.v106i5/6.220

DOE. 2012. 'A survey of energy-related behaviour and perceptions in South Africa'. Pretoria: Department of Energy.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modelling, in South Africa. Environmental Science & Policy, 5(2002):157–167. https://doi.org/10.1016/S1462-9011(02)00029-1

Gwaze P. and Mashele S.H. 2018, 'South African Air Quality Information System (SAAQS) mobile application tool: bringing real time state of air quality to South Africa.' Clean Air Journal, 28(1):1-4. https://doi.org/10.17159/2410-972X/2018/v28n1a1

Health Effects Institute. 2020. State of Global Air 2020. Special Report. Boston: MA: Health Effects Institute.

Hersey S., Garland R.M., Crosbie E., Shingler T., Piketh S. and Burger R. 2015, 'An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data.' Atmospheric Chemistry and Physics, 15:4259. https://doi.org/10.5194/acp-15-4259-2015

Israel-Akinbo, S. O., Snowball, J. and Fraser, G. 2018. 'The energy transition patterns of low-income households in South Africa: An evaluation of energy programme and policy', Journal of Energy in Southern Africa, 29(3):75–85. https://doi.org/10.17159/2413-3051/2018/v29i3a3310

Krasnov H., Kloog I., Friger M. and Katra I. 2016, 'The spatio-temporal distribution of particulate matter during natural dust episodes at an urban scale.' PlOS ONE, 11(8). https://doi.org/10.1371/journal.pone.0160800

Kumar M.K., Sreekanth V., Salmon M., Tonne C. and Marshall J.D. 2018, 'Use of spatiotemporal characteristics of ambient $PM_{2.5}$ in rural South India to infer local versus regional contributions.' Environmental Pollution, 239:803-811. https://doi.org/10.1016/j.envpol.2018.04.057

Langerman K., Wernecke B., Mkhatshwa G., Herbst D., Piketh S., Burger R., Pauw C., Snyman H., Murray H., Fischer T. and Weston M. 2015, 'Domestic fuel burning emission reduction: Eskom's KwaZamokuhle pilot study.' In: NACA Conference. Bloemfontein, South Africa, October 2015.

Langerman K.E. and Pauw C.J. 2018, 'A critical review of health risk assessments of exposure to emissions from coal-fired power stations in South Africa.' Clean Air Journal, 28(2):68-79. https://doi.org/10.17159/2410-972x/2018/v28n2a19

Langerman K.E., Pauw C.J., Smith H.J. and Piketh S.J. 2018, 'Moving households to cleaner energy through air quality offsets.' In: 2018 International Conference on the Domestic Use of Energy (DUE). https://doi.org/10.23919/DUE.2018.8384405

Language B., Piketh S.J., Wernecke B. and Burger R. 2016, 'Household air pollution in South African low-income settlements: a case study.' WIT Transactions on Ecology and the Environment, 207:227-236. https://doi.org/10.2495/AIR160211

Lindeque, L.F., Van Schalkwyk, E.V., Burger, R.P., and Piketh, S.J. 2018. Land Use Regression as a Tool to Quantify $PM_{2.5}$ Concentrations and Identify Suitable Offset Sites on the Highveld. Paper in: National Association for Clean Air. Vanderbijlpark, South Africa, 30 October – 1 November 2018. ISBN: 978-0-620-81025-8

Matandirotya N.R., Cilliers D.P., Burger R.P., Pauw C. and Piketh S.J. 2019, 'The potential for domestic thermal insulation retrofits on the South African Highveld.' Clean Air Journal, 29(1):21-28. https://doi.org/10.17159/2410-972X/2019/v29n1a1

Met One Instruments, Inc. 2008, 'E-bam particulate matter monitor operation manual E-bam 9800 Rev L.'

Murray, C. J. et al. 2020. 'Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019', The Lancet, 396(10258):1223–1247.

Nkosi N.C., Piketh S.J. and Burger R.P. 2018. 'Fine PM emission factors from residential burning of the solid fuels using traditional cast-iron coal stoves.' Clean Air Journal, 28(1):35-41. https://doi.org/10.17159/2410-972X/2018/v28n1a10

Petit J.E., Amodeo T., Meleux F., Bessagnet, Menut L., Grenier D., Pellan Y., Ockler A., Rocq B., Gros V., Sciare J. and Favez O. 2015, 'Characterising an intense PM pollution episode in March 2015 in France from multi-Site approach and near realtime data.' Climatology, variabilities, geographical origins and model evaluation, 155:68-84. https://doi.org/10.1016/j.atmosenv.2017.02.012

Pope, C.A. and Dockery, D.W. 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air and Waste Management Association, 56(2006):709–742. https://doi.org/10.1080/10473289.2006.10464485

Schweizer D., Cineros R., and Shwan G. 2015, 'A comparative analysis of temporary and permanent beta attenuation monitors: The importance of understanding data and equipment limitations.' Atmospheric Pollution Research, 7:865-875. https://doi.org/10.1016/j.apr.2016.02.003

South Africa. Department of Environmental Affairs and Tourism. 2007, 'Declaration of the Highveld as priority area in terms of section 18(1) of the national environmental management: Air quality Act, 2004 (ACT NO. 39 OF 2004).' Government Gazette, No.30518:3-4.

South Africa. Department of Environmental Affairs and Tourism. 2006, 'Environmental quality and protection.' Pretoria.

Statistics South Africa (StatsSA). 2012b, 'Census 2011. Statistical Release.' Pretoria: Statistics South Africa.

Thermo Scientific. 2010. Instruction Manual: Continuous Ambient Particulate Monitor Part Number 100230-00.

Wernecke B. 2018, 'Ambient and indoor particulate matter concentrations on the Mpumalanga Highveld.' Potchefstroom: North-West University. (Dissertation- MSc).

Wright, C. Y. and Diab, R. 2011. 'Air pollution and vulnerability: solving the puzzle of prioritisation.', Journal of Environmental Health, 73(6):56–64.

Yahia Z. and Langerman K. 2018, 'Assessing the implication of South Africa's integrated national electricity supply connections.' In: 2018 Proceedings of the International Conference on the Industrial Engineering and Operations Management.

Research article

Ambient air quality data reported at Sasol Secunda monitoring stations during COVID-19 lockdown – Mpumalanga, South Africa

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Abstract

Various local and international research has been published on the effects of COVID-19 lockdown on ambient air quality. In most cases, a reduction in ambient NO_x and PM concentrations have been observed with varying changes in ambient SO_2 levels. The Mpumalanga province of South Africa is known for its large industrial facilities utilising coal as primary feedstock and is located in the Highveld Priority Area. The ambient air quality in the Secunda region of Mpumalanga province was assessed. This region contains, amongst others, the towns of Secunda, Trichardt and eMbalenhle from which the majority of the Sasol Secunda workforce originates. This specific region was assessed due to the authors' familiarity with the Sasol facility and the strategic locations of ambient air quality stations, as well as the known changes in human behaviour during the lockdown period.

Results show decreases in ambient CO, NO_x and PM concentrations, especially during the first two weeks of lockdown. Only smaller changes were observed for ambient H_2S and SO_2 concentrations at the ambient monitoring stations. An increasing trend in all ambient species was observed towards the end of- and post lockdown in addition to declining ambient temperatures with the onset of winter. This is in spite of the reduction in emissions from the factory that conducted annual maintenance in the month following lockdown (phase shutdown).

This article concludes that community behaviour has a material local ambient impact on CO, NO_x and PM pollutant species, while H_2S concentration profiles are more directly related to the local industrial complex's levels of activity. Ambient SO_2 trends did not show a similar correlation with the facility's activities, but a stronger correlation was observed with diverse local and regional sources on the Highveld. The influence of effective stack emission heights for better dispersion, especially for SO_2 and on a local scale, is considered material. Meteorological factors has been shown to be a substantial contributor to observed ambient air quality levels in the study domain.

Keywords

Ambient air quality, COVID-19, highveld priority area, nitrogen oxides, particulate matter, sulphur dioxide, hydrogen sulphide

Introduction

Sasol Secunda, a petrochemical industry, is located within the Highveld Priority Area, Mpumalanga provine. Sasol owns and operates nine ambient air quality measurement stations in close proximity to the facility. The results obtained from these stations are crucial in delivering accurate information on air quality in the Mpumalanga region and form part of the national data base.

On 15 March 2020 the president of South Africa declared a National State of Disaster due to the COVID-19 pandemic and introduced a total lockdown. The national Level 5 (L5) lockdown, the most severe form of lockdown, commenced on 27 March 2020 and was relaxed to level 4 (L4) on 1 May 2020. 1 June 2020 brought about further relaxations with the onset of Level 3 (L3) lockdown, each level allowing for more freedom of movement and economic activity.

These lockdown periods gave rise to unprecedented opportunities to study the impact of economic activity and social behavior on ambient air quality. This article describes the measurements and observations made during the lockdown

at the towns of Secunda and eMbalenhle. The study period of 1 February 2020 – 30 June 2020 was chosen to ensure a pre- and post-lockdown baseline is included. Moreover, the influence of lower industrial activity at Sasol Secunda due to annual maintenance during the L4 period (May 2020), as well as human behavior recorded during the lockdown period will be elaborated on.

Ambient air quality monitoring stations

Sasol Secunda owns nine ambient air quality monitoring stations that are located within the Mpumalanga province and surround the Secunda facility. Three of the nine are located within the communites immediately adjacent to the facility as indicated in Figure 1. All monitoring stations measure basic metereological parameters i.e. temperatures, wind speed, wind direction, rainfall and humidity while six stations closest to Sasol Secunda measure atmospheric pollutants: O_3, SO_2, CO, $PM_{2.5}$ and PM_{10}, H_2S and NO_x. Three background stations located in Amersfoort, Springs and Grootvlei measure only H_2S. All the stations are accredicated under SANAS ISO/IEC 17025:2017. The measurement stations are visited regulary for maintenance and upkeep, these include bi-monthly zero and span verifications and quarterly indepent dynamic gas calibrations on all stations. The stations report realtime to the South African Air Quality Information System (SAAQIS), however, downloaded data is quality assured before reporting.

The data quality assurance excludes any periods of uncertainty, power failures and recovery, calibrations, checks and maintenance.

In Figure 2 the wind roses for Secunda (from Secunda Club monitoring station) for the period pre-, post- and during levels four and five of lockdown are shown (February to June 2020). The reported meteorological data from Secunda Club is in excellent agreement with measurements from the eMbalenhle station. Figure 2 shows the variation in wind speed by colour grouping and the frequency distribution is indicated by the percentage markers. For Figure 2(a) the wind rose prior to lockdown shows little wind from the South West with highest wind speeds from the Eastern regions. The frequency distribution shows that less than 30% of the time the wind direction would be directly West. Lower wind speeds (yellow and grey) are prevalent during the months of investigation. During April and May in Figure 2(b) a more even wind distribution is seen from the West North West (~30%) and from the East North East (~27%). After lockdown in Figure 2(c), the highest wind speeds (5.7 – 8.8 m/s) were recorded towards the North West (total of ~11% of the time) with wind blowing from the East accounting for ~39% of the total. The dominant wind direction was from the North West to the South East and from the East towards the West with some fluctuations to the North and South. While some West and Easterly winds are noted, directly North or South winds are near absent.

To further investigate the impacts of the factory and possible community behavioural changes during lockdown, the eMbalenhle station was selected since it is located due east of the factory and between the factory and the community, and is therefore expected to yield results from both industry and community. The graphs from Sasol club air quality monitoring station (Secunda) showed very similar trends and are therefore not presented in this paper.

Figure 1: *Five of Sasol's ambient monitoring stations*

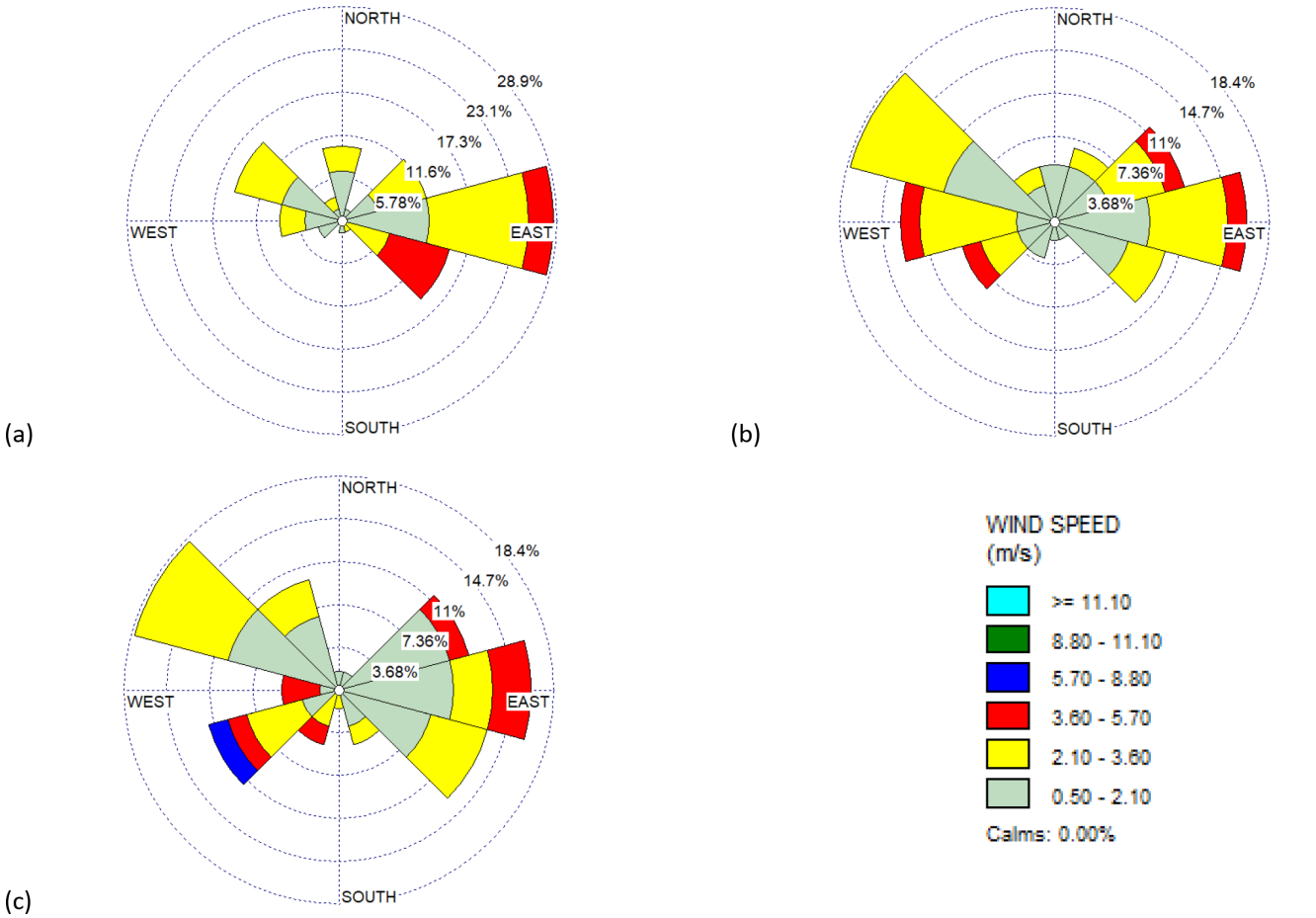

Figure 2: *The hourly average wind direction for (a) February to March 2020, (b) L5 and L4 lockdown, (c) after lockdown*

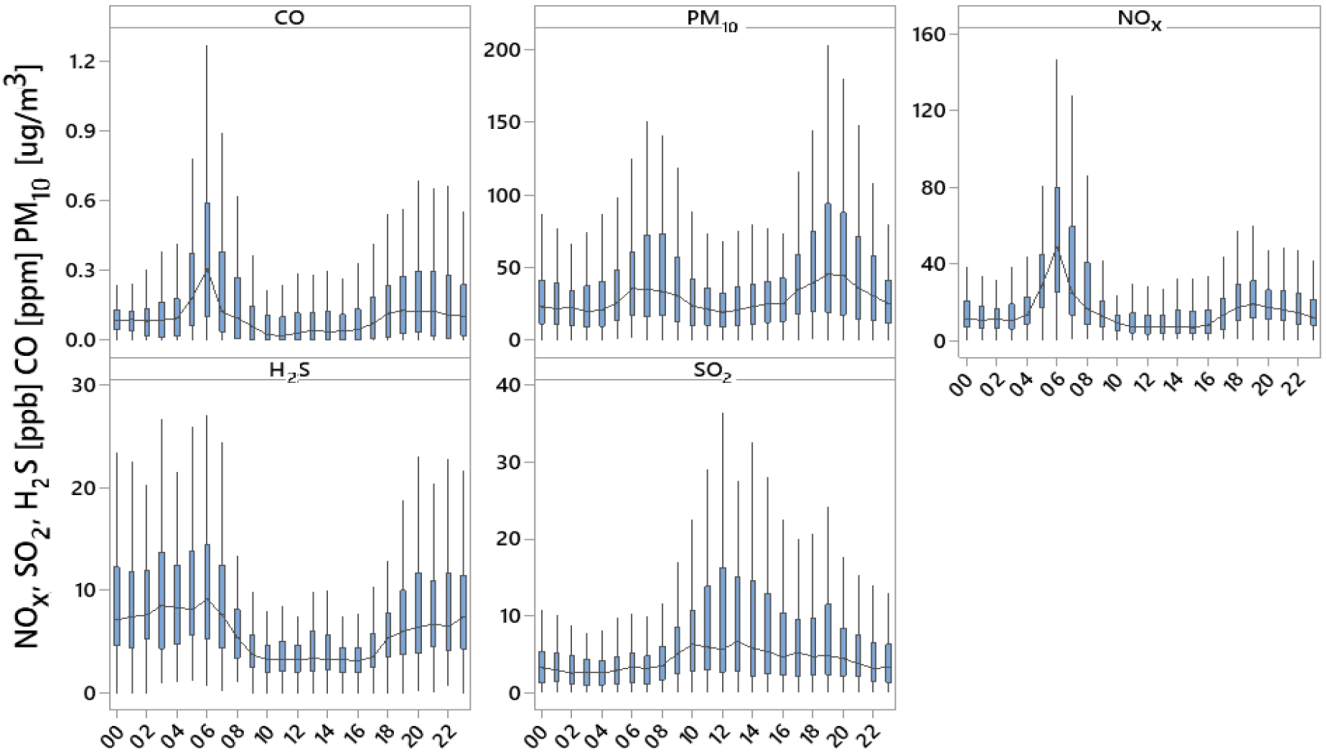

Figure 3: *Diurnal plots showing the hourly average data distribution for the entire reporting period. The medians are connected by the black line. Bimodal diurnal trends are seen for CO, PM_{10} and NO_x.*

Results

In Figure 3, diurnal plots showing the hourly average data distribution for the entire reporting period is presented. The medians are connected by the black line. Bimodal diurnal trends are seen for CO, PM_{10} and NO_x. Bimodal peaks are typically associated with domestic activity since the peak times coincide with traffic, cooking, etc (Malaza 2017, Clerbaux et al. 2008, Venter et al. 2015). The H_2S trend indicates an inverse relation between day and night and is typical the results of prevailing meteorological conditions. During the evenings stable atmospheric conditions are persistent in the region, thereby trapping local ground level emissions and only allowing proper dispersion during the daytime hours when the atmospheric turbulence increases with the heating of the earth's surface. Another trend influenced by the atmospheric turbulence during the day is SO_2 , where peaks during mid-day. The design of the tall stacks is to emit above the surface inversion layer and only when the atmosphere is most unstable, plumes are forced to ground level. The surface inversion layer thereby acts as a buffer to local communities and promotes long range dispersion.

These average trends have been further unpacked in the individual time-series sections below to investigate any changes during lockdown and industry maintenance.

Carbon monoxide (CO)

Carbon monoxide (CO) is a typical marker pollutant of combustion (Clerbaux et al. 2008, Venter et al. 2015). In the natural environment, veld fires will also produce CO amongst other components. Mostly, CO links to human activities and incomplete combustion (Venter et al. 2012). Some activities include industrial combustion (like coal combustion for steam generation) and domestic cooking and space heating. CO (Figure 4) as measured at the ambient air quality station adjacent to the Secunda factory and eMbalenhle community (Sasol Secunda Operations Embalenhle air monitoring station) was investigated. In the months prior to lockdown CO shows some diurnal variation but on average remains stable with no discernible trend. The monthly average ambient CO concentrations from 2015 to 2019 are shown by the grey line while the monthly average temperatures are indicated by the green line. When L5 lockdown commenced, a slight decrease (orange) in ambient CO was observed, while an increase can be seen during L4 lockdown and thereafter (blue). Although Sasol Secunda did reduce production during L5 (in line with a decreased demand) and utilised the L4 lockdown to conduct annual maintenance, the ambient concentrations do not reflect this reduced industrial activity, showing rather an increase in ambient CO concentrations as winter approaches. An inverse relation can be seen between the average daily ambient temperature (yellow) and CO. A five year ambient temperature trend (green) was compiled. 2020 was on average ~2 ˚C cooler than 2016 for the reporting period but compared well with the average ambient temperatures in 2018. It can therefore not be concluded that 2020 was abnormally cold or different than preceding years.

During lockdown domestic travel was forbidden, schools closed and families remained indoors and therefore more time was spent cooking, especially during the Easter long weekend of 10 – 13 April 2020. A few local residents also reported increased local activity during L4. With the onset of winter, domestic heating also increased. Local residents also reported increased waste burning due to poor service delivery and veld fires towards the dry winter season. While industry operated at a constant rate (before and after lockdown), a strong diurnal pattern could be attributed to domestic heating during the colder night temperatures and the formation of stable atmospheric inversion layers towards the winter months.

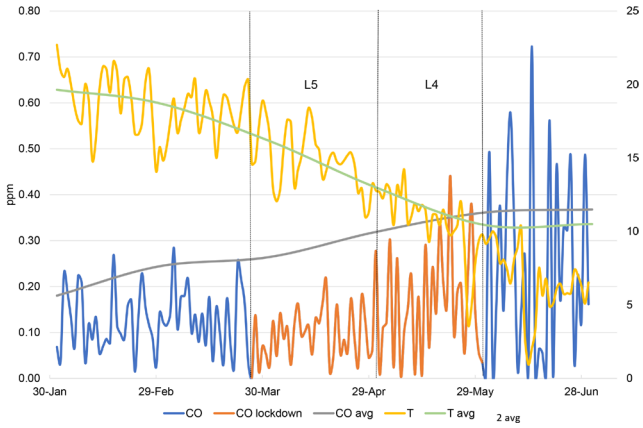

Figure 4: *Ambient CO and T shows an inverse relation, with increasing CO concentrations with the onset of winter.*

Particulate matter ($PM_{2.5}$ and PM_{10})

Ambient particulate matter (PM) concentrations are regulated by the national ambient air quality standards (NAAQS) for particles smaller than 10 micron (PM_{10}) and 2.5 micron ($PM_{2.5}$). PM is specifically regulated because it has been identified as a health concern on the Mpumalanga Highveld and elsewhere in South Africa – the Highveld itself being declared a priority area, viz. Highveld Priority Area (Lourens et al. 2011). Ambient PM originates from various sources including windblown dust (agriculture, roads, tailing dams, etc.) and as a product of combustion. PM is especially problematic during the dry season since rain not only scrubs the atmosphere, but also aids in supression. In addition to industrial sources of PM, during colder months domestic cooking and space heating as well as veld fires produce PM. (Venter et al. 2012). Therefore, an increase in PM is typically seen between May and September every year (Lourens et al. 2011). In Figure 5 the PM measurements before lockdown are low on average (PM_{10} ~33 µg/m^3 and $PM_{2.5}$ ~14 µg/m^3) with some elevated days. During the first days of L5 lockdown, PM ambient concentrations are on average lower with less variability with PM_{10} values of 16 µg/m^3 and $PM_{2.5}$ of 6 µg/m^3. This may be due to both lower domestic and industrial activity. However, the PM concentration increases with more variability in May, even though Sasol industrial activity is still limited due to the annual maintenance. Higher PM concentrations are observed after L4 lockdown, with industrial activity remaining stable. This trend follows the discussion on CO and the change in environmental

conditions, i.e. the lower ambient temperatures with the onset of winter. A decrease in ambient PM is noted towards the end of June. Further investigation showed that the nights preceding the 26 June 2020 had prolonged hourly average temperatures below freezing with minima as low as -5.8 ˚C. Some rain events were also detected during this week. The first day with low ambient PM measurements, the 26 June 2020, only had two hours below freezing with a minimum of -1.8 ˚C. The increase in daily average temperatures likely resulted in less space heating that affected ambient PM concentrations. The daily average wind direction was mostly from the East and North East towards the factory. The grey line represents the average PM_{10} from 2015 to 2019. It can be noted that an increase in PM during the onset of winter is a reoccurring trend. Also the PM during lockdown was lower than the reported average but higher outside of the lockdown periods.

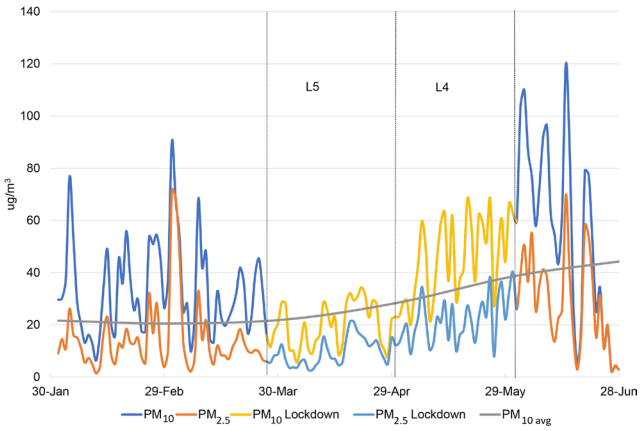

Figure 5: *Ambient PM (PM_{10} and $PM_{2.5}$) shows diurnal variability with a drop during lockdown L5 and steady increase thereafter.*

Nitrogen oxides (NO and NO_2)

Ambient NO_x is naturally produced by lightning and during veld fires. Anthropogenically NO_x is produced during combustion such as industrial activities, cooking and space heating as well as vehicular emissions (Ross et al. 2007, Venter et al. 2012). High levels of NO_2 have been observed over the highveld of South Africa using satellite-based proxies (Lourens et al. 2012) and these elevated levels are generally attributed to industrial activity (Josipovic et al, 2009, Laakso et al, 2012). This cannot be directly linked to ground based measurements considering industrial sources emit well above ground level at elevated heights as is supported by the design intent of tall stacks, to emit pollutants even above the surface inversion layer for adequate dispersion and to least impact ground based receptors such as communities. A limitation of satellite measurements is their overpass frequency and time, i.e. once a day and not capturing morning/evening peaks (Lourens et al. 2012). Investigating ambient NO_x concentrations, utilising ground level measurement data, during the pandemic period gives a unique insight to the contributing sources. While Figure 6 indicates a similar trend to PM and CO, due to lockdown restrictions a data gap exists because essential instrument maintenance could not be performed. NO_x concentrations differ before and after lockdown and increase during the onset of winter and fewer restrictions on mobility. The average NO_x concentrations from 2015 to 2019 are indicated by the grey line. It can be noted that NO is always present and not completely converted to NO_2 as it would be for an aged air mass or a background site (Malaza 2017), thereby indicating sources of NO in close proximity to the ambient measurement station. It is also noted that peak NO and NO_2 events are not always related, thereby indicating long range transport of NO_2 from distant sources. The NO concentration seldom exceeds the NO_2 concentration, also indicating that large primary emission sources seldom contribute to the ambient measurements described here.

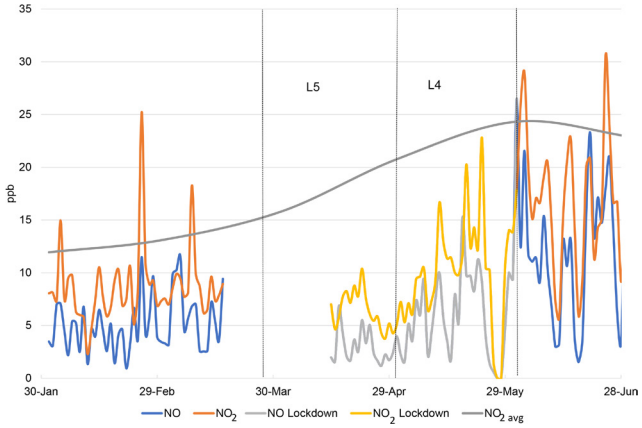

Figure 6: *NO and NO_2 indicate increasing trends after lockdown with on average lower concentrations during lockdown.*

Hydrogen sulphide (H_2S)

Ambient H_2S is typically associated with sewerage plants, abattoirs and industrial emissions relating to sulphur (Rubright et al. 2017, Chou et al. 2016). Some H_2S will also be emitted during domestic cooking and space heating when coal is used. From Figure 7, pre and post lockdown ambient averages of H_2S are similar. Further more, the average (2015 - 2019), as indicated by the grey line, shows almost no variability irrespective of the season or known economic activity such as lockdown. This is expected from an industrial emissions point of view and is in contrast to PM, NO_x and CO as discussed. Some high peaks were recorded after lockdown which could be an indication of the onset of winter with stronger inversion layers that trap low level pollution or result in peaks with the breakup of inversion layers. This is supported by the diurnal plots in Figure 3. The higher peaks during winter observed in this paper correlate with prominent peaks observed during winter months at Elandsfontein (Mpumalanga province) and attributed to inversion layers and possibly long range transport (Cogho 2019). A slightly lower average is observed during lockdown which can be ascribed to lower emissions emitted from an industrial point source. However, the nearby Elandsfontein ambient station reported an H_2S source apportionment of 14,3% from the Secunda region, urban emissions contributed 41,3% in excess of the baseline H_2S concentrations, the Johannesburg-Pretoria conurbation 15,3% and finally, pyrometallurgical smelters, coal-fired power stations and cattle feedlots contributed 11.2%,

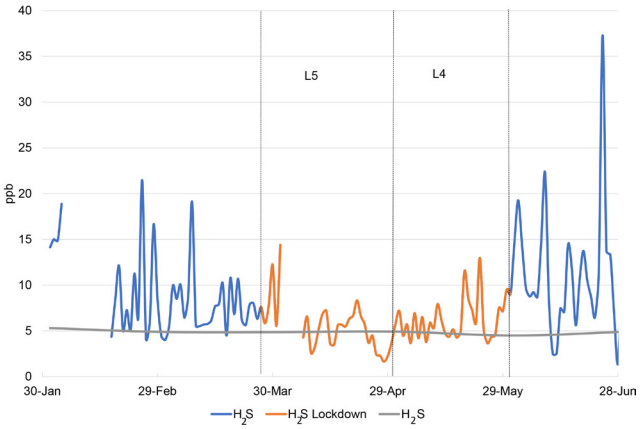

Figure 7: *H_2S indicates an increasing trend after lockdown with on average lower concentrations during lockdown.*

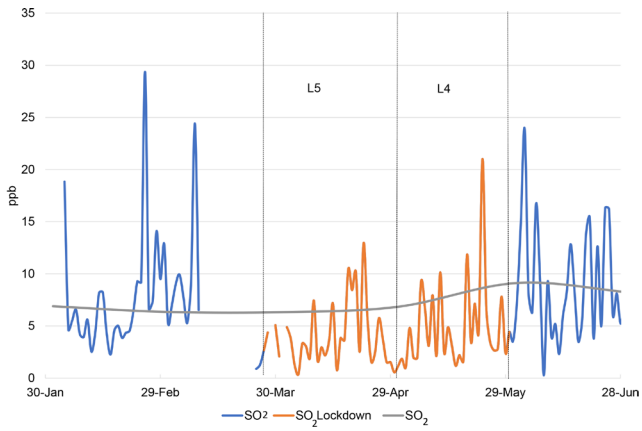

Figure 8: *SO_2 indicates an increasing trend after lockdown with on average lower concentrations during lockdown*

5.9% and 1.0% respectively to the ambient H_2S in excess of the baseline (Cogho 2019). These urban sources are expected to be heavily influenced by lockdown restrictions.

Sulphur dioxide (SO_2)

Similarly to H_2S, SO_2 concentrations at ambient level differ only slightly before and after lockdown with averages mostly similar (Figure 8). A slight decrease in ambient SO_2 is seen during lockdown. This may be attributed to lower anthropogenic emissions in general. The clear inverse trend with daily average ambient temperatures as was seen with CO, is not evident although variability increases. Further, the average (grey line) does show more variability than in Figure 7 but less than Figures 4 - 6. Ambient SO_2, being a prominent industrial pollutant (Josipovic et al, 2009, Laakso et al 2012, Lourens et al, 2011, Venter et al. 2012), is expected to follow the trend of nearby point source emissions. The reduction in factory SO_2 emissions is not clearly reflected in the ambient measurements. The weak correlation may suggest the co-contribution of other sources in the Highveld region other than the local Sasol Secunda influence. In addition, the influence of better dispersion especially on a local scale brought about by more effective emission heights of the industrial sources is considered material. SO_2 is therefore considered a regional pollutant.

Contextualization

Comparison of Sasol Secunda measurements with other literature observations is presented in Table 1.

The results from this study are in agreement and show the impact of lockdown on ambient PM and NO_x concentrations, especially during the first two weeks of L5 lockdown. The increase in ambient concentrations after L4 lockdown can be ascribed to both seasonal changes and the increase in socio-economic activity.

Table 1: *Comparing Sasol Secunda measurements to literature reported observations*

Unpacking source contributions to air quality during COVID-19 lockdown (Piketh et al., 2020)	**Impacts of COVID-19 lock-down measures on air quality over the Highveld: Initial assessment (Garland et al., 2020)**	**Sasol Secunda air quality investigation (This study)**
RSA Highveld shows decreases in the air pollution (NO_2 and PM_{10}) during lockdown	Decrease in NO_2 during lockdown observed	The first two weeks of lockdown show low ambient levels of pollutants
NO_2 has the highest overall drop with some places recording as much as 50% drop	Satellite NO_2 hotspot does not reflect at ground-based measurements. Weekend effect of NO_2 indicates traffic	Lower NO_2 concentrations observed with a clear decrease in variability
Changes in SO_2 concentrations are mixed with no distinctive pattern at the sites	Mixed trends	SO_2 levels are relatively constant
PM shows a significant drop in concentration during Lockdown	N.A.	Lower PM is recorded especially the first weeks of lockdown
Concentration drops in NO_x and SO_2 from Eskom alone don't account for observed changes in ambient	Ambient mixtures are complex. Potential added stress from communities: service delivery – waste burning	Some trends do differ across sites, especially SO_2. A correlation to industry alone is not evident
First two weeks of Lockdown seem to have a larger drop in Township and Industrial sites	First two weeks (beginning April) reflect largest decrease	The first two weeks of lockdown show low ambient levels of pollutants. Communities also report poor service delivery and a relaxation of movement in latter periods of lockdown
After the hard lockdown concentrations of most pollutants rise dramatically	NO_2 and SO_2 increase from satellite-based measurements.	After the hard lockdown concentrations of most pollutants rise dramatically - Communities also report poor service delivery and a relaxation of movement in latter periods of lockdown. A strong decrease in ambient temperatures are observed (Winter)

Conclusion

During the period of assessment, ambient air quality changes could be seen relating to reduction of factory emissions, local community behaviour, Highveld sources in general as well as seasonal changes. The impact of lockdown 2020, was noticeable in the ambient air quality data, with a strong reduction (in all pollutants) during the first two weeks of lockdown and a strong increase after lockdown. Ambient PM and CO did not show a clear relationship to local factory shutdowns. A better correlation with seasonal changes was found. A decrease in ambient NO_2 measurements agreed well with the lockdown periods, likely relating to lower vehicular emissions. Increased ambient NO_x in the late stages of lockdown and thereafter agree with the colder months, increased community based activities, waste burning and veld fires (dry season). H_2S trends correlated well with local factory activities, however, some peaks remain unexplained and may be the result of long range transport. SO_2 had some relation to local factory emissions while some anomalies could not be explained. The data suggest a significant contribution of sources outside the study domain.

References

Chou S., Ogden J.M., Phol H.R., Scinicariello F., Ingerman L., Barber, L. & Citra M. 2016, 'Toxicalogical profile for hydrogen sulphide and carbonyl sulphide', *Agency for Toxic Substances and Disease Registry*: Atlanta, GA

Clerbaux C., Edwards D.P., Deeter M., Emmons L., Lamarque J-F., Tie X.X., Massie S.T. & Gille J. 2008, 'Carbon monoxide pollution from cities and urban areas observed by the Terra/ MOPITT mission' *Geopysical research letters*, 35(L03817) doi:10.1029/2007GL032300.

Cogho E. 2019, 'Source apportionment of hydrogen sulphide at Elandsfontein in Mpumalanga Highveld' Dissertation Masters. North- West University.

Josipovic M., Annegarn H.J., Pienaar J.J., Piketh S.J. 2009, 'Concentrations, distributions and critital level exceedance assessment of SO_2, NO_2 and O_3', South Africa, Environmental monitoring assessment, DOI 10.1007/s10661-009-1270-5

Garland R., Naidoo M. John J., Kwatala N., Naidoo S., Marais E. 2020, 'Impacts of COVID-19 lock-down measures on air quality over the Highveld: Initial assessment. Joint Online Seminar Department of Environment', Forestry and Fisheries and the National Association for Clean Air, COVID-19 and Air Quality in South Africa.

Laakso L., Vakkari V., Virkkula A., Laakso H., Backman J., Kulmala M., Beukes J. P., van Zyl P. G., Tiitta P., Josipovic M., Pienaar J. J., Chiloane K., Gilardoni S., Vignati E., Wiedensohler A., Tuch, T., Birmili W., Piketh S., Collett K., Fourie G. D., Komppula M., Lihavainen H., de Leeuw G. & Kerminen V.-M. 2012, 'South African EUCAARI measurements: seasonal variation of trace gases and aerosol optical properties', *Atmosospheric Chemistry Physics*, 12 -p1847–1864, https://doi.org/10.5194/acp-12-1847-2012

Lourens A.S.M., Beukes J.P., Van Zyl P.G., Fourie G.D., Burger J.W., Pienaar J.J., Read C.E. & Jordaan J.H. 2011, 'Spatial and Temporal assessment of Gaseous Pollutants in the Mpumalanga Highveld of South Africa', *South African Journal of Science*, 107(1/2). p1-8.

Lourens A.S.M., Butler T.M., Beukes J.P., Van Zyl P.G., Beirle S. & Wagner T. 2012, 'Re-evaluating the NO_2 hotspot over the South African Highveld', *South African Journal of Science*, 108(11/12). p1-6.

Malaza L.S. 2017, 'An assessment of spatial and temporal variations of nitrogen dioxide over Mpumalanga highveld'. *MSc*, Johannesburg, 2017

Piketh S.J., Burger R.P., Havenga H., Mbatha N. 2020, 'Unpacking source contributions to air quality during COVID-19 lockdown', Joint Online Seminar Department of Environment, Forestry and Fisheries and the National Association for Clean Air, COVID-19 and Air Quality in South Africa.

Ross K., Broccardo S., Heue K-P., Ferguson K. & Piketh S. 2007, 'Nitrogen oxides on the South African Highveld', *Clean Air Journal*, 2 (16).

Venter A. D., Vakkari V., Beukes J.P., Van Zyl P.G., Laakso H., Mabaso D., Tiita P., Josipovic M., Kulmala M., Pienaar J.J., Laakso L. 2012, 'An air quality assessment in the industrialised western Bushveld Igneous Complex', South Africa, *South African Journal of Science*, 108(9-10). p1-10

Venter A.D., Jaars K., Booyens W., Beukes J.P., Van Zyl P.G., Josipovic M., Hendriks J., Vakkari V., Hellén H., Hakola H., Aaltonen H., Ruiz-Jimenez J., Riekkola M.L. & Laakso L. 2015, 'Plume characterization of a typical South African braai', *South African Journal of Chemistry*, 68. p181-194

Rubright, S.L.M., Pearce, L.L. & Peterson, J. 2017, 'Environmental toxicology of hydrogen sulfide', *Nitric Oxide*, 71, 1-13, doi:10.1016/j.niox.2017.09.011

Research article

Assessing SO_2, NO_2 and O_3 in rural areas of the North West Province

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Abstract

Air quality monitoring has been lacking in the rural and western North West Province. Here ambient sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3) concentrations, monitored with passive samplers at 10 sites, are presented. Widespread SO_2 and NO_2 problems weren't observed. However, regular O_3 standard limit exceedances are likely across the province. Increased SO_2 and NO_2 concentrations in the colder and drier months were evident. Inversion layer trapping of low-level emissions during the colder months and open biomass burning in the drier months increased ground level pollutant concentrations. Wet deposition of SO_2 and NO_2, and enhanced SO_2 conversion to particulate sulphate, result in lower wet season concentrations. O_3 concentrations were lower from May to July and higher from August to March. Three phenomena contributed to this. Firstly, shorter daylight hours (less photochemistry) and secondly, lower biogenic volatile organic compound (O_3 precursors) concentrations during the colder months. Thirdly, the late winter/early spring open biomass burning peak lead to elevated carbon monoxide (CO) concentration (also an O_3 precursor). Spatial patterns indicated higher SO_2 concentrations in the west, due mainly to industrial emissions. The NO_2 spatial map indicated two areas of higher concentration, i.e. Bapong in the east due mainly to industrial emissions, and Taung with its higher population density. The O_3 spatial map was almost the inverse of NO_2. The lower O_3 and higher NO_2 around Taung indicated that O_3 is likely titrated there. Additionally, the results indicate that non-point source emissions of NO_2 are high enough to results in exceedances of the O_3 standard limit. Overlay back trajectory maps showed that sites in the east are more frequently impacted by pollution transported from the Mpumalanga Highveld, Vaal Triangle and the Johannesburg-Pretoria megacity if compared to the west. Conversely, cleaner air masses impact the west more than sites in the east.

Keywords

Air quality, North West Province, spatial patterns, seasonal patterns, passive samplers

Introduction

Anthropogenic activities are increasing the ambient tropospheric concentrations of inorganic gaseous pollutants, which include nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3). These species are globally considered as important pollutants and are criteria pollutants according to the South African National Environment Management: Air Quality Act of 2004 (Government Gazette 2005).

Human health issues associated with NO_2 and nitrogen oxide (NO) (combined referred to as NO_x), as well as SO_2 include irritation of the respiratory system, which can cause breathing difficulties. People who suffer from asthma are particularly sensitive to chronic inhalation of elevated NO_x and SO_2 concentrations, which may result in long-term effects such as pulmonary asthma and chronic bronchitis (Pandey et al. 2005). Exceedances of the South African NO_2 and SO_2 ambient air quality standard limits have been reported for numerous locations/areas (e.g. DEA 2010).

Oxidation of SO_2 and NO_2 lead to the formation of sulphate (SO_4^{2-}) and nitrate (NO_3^-), respectively. In South Africa it has been indicated that these species contribute significantly to the acidity of atmospheric particulate matter (Venter et al. 2018),

acid rain (Conradie et al. 2016), eutrophication of the terrestrial and aquatic environment (Dunnink et al. 2016), and secondary aerosol formation (Vakkari et al. 2015). SO_4^{2-} and NO_{3-} also scatter radiation (IPCC 2013) and are important species within the context of aerosol climate forcing in South Africa (Venter et al. 2020).

Tropospheric O_3 is a secondary pollutant formed from the photochemical reaction of NO_2 (Seinfeld and Pandis 2016). O_3 can have detrimental impacts on crops and vegetation (Laakso et al. 2013). Additionally, O_3 is a short-lived greenhouse gas, which has a net warming effect (IPCC, 2013). Exceedances of the South African O_3 air quality standard limit has been reported for large areas of the South African interior (Laban et al. 2018).

Major sources of atmospheric pollutants in South Africa include fossil fuel combustions, traffic, open biomass burning (veld fires), mining and metallurgical activities, and household combustion. The Mpumalanga Highveld, Johannesburg-Pretoria (JHB-Pta) megacity and the Vaal Triangle are all regions that are relatively polluted and where ambient air quality standard limits are regularly exceeded (Government Gazette 2012, 2020). In addition, numerous large point and area sources are located in the western Bushveld Complexes (wBC) (Rustenburg, Brits and Sun City areas) within the North West Province. This area was included in the Waterberg Priority Area (Government Gazette, 2010), due to current and possible future exceedances of ambient air quality standard limits there. Typical sources of pollutants in the wBC include pyro-metallurgical smelters, mining activities, household combustion, open biomass burning and vehicular emissions (Piketh et al. 2005).

Due to the above-mentioned air quality issues associated with the Mpumalanga Highveld, JHB-Pta megacity, Vaal Triangle and wBC, numerous regulatory and research studies are/have been conducted there. However, to the knowledge of the authors, no systematic air quality studies have been conducted in the rural areas of the western North West Province. Therefore, the general aim of this study was to assess SO_2, NO_2 and O_3 concentrations in rural areas of the North West Province. The specific objectives were to: i) measure SO_2, NO_2 and O_3 with a cost effective manner at 10 sites for at least two full seasonal cycles; ii) contextualise SO_2, NO_2 and O_3 concentrations, in terms of air quality standard limits, as well as with measurements conducted elsewhere; iii) establish seasonal and spatial patterns of the pollutant species; iv) indicate possible sources and/or contributing factors and v) give guidance to possible future ambient measurements of SO_2, NO_2 and O_3 in the area.

Experimental

Passive sampling and associated analytical methods

Since the rural North West Province covers a large surface area, it was impractical (too expensive and logistically difficult) to conduct this study with active sampling. Therefore, passive diffusive samplers developed by the North-West University (NWU) (Pienaar et al. 2015) were used to measure monthly average concentrations. Although passive samplers do not give instantaneous concentration values (as with active samplers), they are ideal to map a large region and identify potential areas where higher resolution measurements should be conducted.

Passive sampler preparations were conducted as specified by Dhammapala (1996) with sodium hydroxide (NaOH) dissolved in methanol, NaOH and sodium iodide (NaI) dissolved in methanol, and sodium nitrite ($NaNO_2$), potassium carbonate (K_2CO_3) and glycerol dissolved in a water-methanol mixture used as adsorbent solutions for SO_2, NO_2 and O_3, respectively. After preparation, each sampler was labelled according to the preparation date, designated site and pollutant species. Thereafter, each sampler was placed in an airtight plastic vial and sealed in an airtight bag. For each pollutant species a laboratory blank sampler was prepared for every monthly sample batch that was deployed. These blanks were sealed and stored in the laboratory freezer until analysis.

The passive samplers were deployed and exposed in pairs for each pollutant species. Exposure of pairs reduced data loss should a specific sampler suffer any sort of interference. A log sheet was kept for every sampler, in order to record important variables needed for calculations and/or observations that would assist in explanations (e.g. exposure and collection times and date, and unusual events such as nearby fires). The passive samplers were exposed by placing them in a stainless-steel rail, mounted under an aluminium sampler hood. Hoods were either attached to an aluminium shaft and stand base, or a bracket that was screwed onto a suitable structure (e.g. wooden power/telephone pole, or road sign) approximately 1.5m above ground level. The sampler hood act as a shield, which protect the exposed samplers against direct sunlight and rain.

After the exposure period was complete, the passive samplers were removed, sealed in plastic vials and bags. Directly thereafter, fresh unexposed samplers were deployed for the following month. Exposed samplers were sent back to the lab for analysis. Upon receipt, the samplers were logged as received and stored in a freezer until analysis.

In preparation for chemical analysis, the pollutant specific impregnated filters of the passive samplers were leached as previous specified (Dhammapala 1996, Pienaar et al. 2015). Analyses of the leached solutions were conducted with an Ion Chromatography Dionex ICS 3000 system, fitted with an Ionpac AS16 (4 mm) analytical column, an AS16 guard column (4 mm) and a conductivity detector. Background conductivity was lowered by a self-regenerating electrochemical suppressor (4 mm AERS-500), fitted with a carbonate removal device. The flow rate was maintained at 1.2 cm^3min^{-1}. The system was also equipped with an eluent (hydroxide, OH-) generator. Calibration of the IC was conducted using stock solutions with concentrations of 0.02, 0.2, 0.8, 1.5 and 2.5 $\mu mol.dm^{-3}$ of the relevant chemical species.

The combination of passive samplers and analytical procedure have been used in numerous published studies (e.g. Swartz et al. 2020, the most recent). In addition, the accuracy (how close to calibrated active samplers) and precision (repeatability) of the passive samplers have been demonstrated in national (Dhammapala 1996) and international (Pienaar et al. 2015) inter-comparisons. Quality assurance of the analytical procedure was further verified by participating in the bi-annual Laboratory Inter-Comparison Study (LIS) organised by the World Meteorological Organisation (WMO) (e.g. as presented in Conradie et al. 2016, Swartz et al. 2020).

Ancillary data

Air mass movements were determined by calculating 96-hour back trajectories for air masses arriving at a height of 100m above ground level, for every hour during the sampling campaigns. This was done by using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT, version 4.8) (Draxler and Hess 2004). The model was run with meteorological data of the Global Data Assimilation System (GDAS) archive of the National Centre for Environmental Prediction (NCEP) of the United States National Weather Service and the Air Resources Laboratory (ARL) archive, accessed 01/09/2020.

Overlay back trajectory maps (introduced in Vakkari et al. 2011) were compiled in order to get an overview of air mass movement for a specifics site during specific measurement months, or for the entire measurement period. In such maps a colour code was used to indicate the percentage of the hourly arriving trajectories passing over 0.2° x 0.2° grid cells that were superimposed on the South African map, with the colours red and blue indicating the highest and lowest percentage overpasses, respectively.

The National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectrometer (MODIS) collection 5 burned area product (Roy et al. 2008) was used to determine open biomass burning fire locations. Such data is expressed as gridded 500 m fire burn scar pixels (Boschetti et al. 2009, 2013).

Measurement campaigns

Monthly SO_2, NO_2 and O_3 measurements were conducted at 10 sites during two sampling campaigns, i.e. April 2014 to March 2015 and February 2018 to October 2019. In addition, a more intensive campaign was conducted in June, July and August (JJA) 2019. During this intensive campaign, 15 additional sites were monitored. The additional sites were located mostly in-between (via tar road access) the 10 sites that were monitored over the entire time, during both campaigns. The intensive campaign was done for two reasons. Firstly, to distinguish whether the trace gas concentrations at the 10 sites, which were located in small urban areas, differed from concentrations in-between the urban areas. Secondly, the larger number of sites made it possible to obtain a better spatial representation of pollutant concentrations across the province.

Measurement sites

The Directorate Environmental Quality Management; Rural, Environment and Agricultural Development (READ), of the North West Provincial Government indicated numerous municipal areas for which no air quality data existed. Based on this information 10 measurement sites were selected, to balance the limited financial resources available, logistical access and likely scientific information that could be obtained. The locations of these measurement sites at Tosca, Morokweng, Ganyesa, Vryburg, Sannieshof, Taung, Christiana, Schweizer-Reneke, Bapong and Ottoshoop are indicated within a regional perspective in Figure 1.

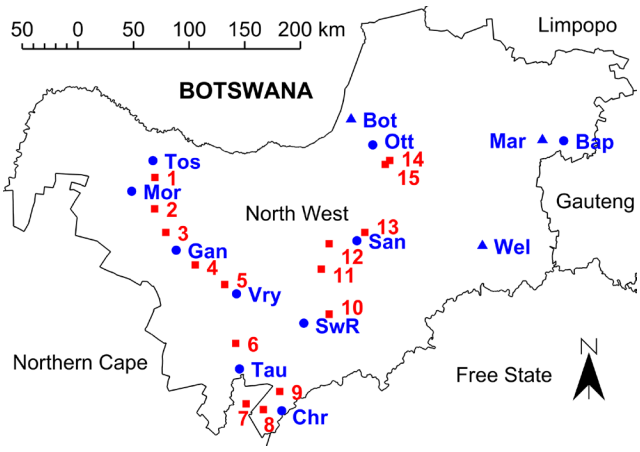

Figure 1: *The locations of the 10 sites where measurement were conducted over the entire measurement period, i.e. Tosca (Tos), Morokweng (Mor), Ganyesa (Gan), Vryburg (Vry), Sannieshof (San), Taung (Tau), Christiana (Chr), Schweizer-Reneke (SwR), Bapong (Bap) and Ottoshoop (Ott), are indicated with blue dots. Blue triangles indicate the references sites Welgegund (Wel), Marikana (Mar) and Botsalano (Bot), while red squares indicate the 15 additional sites monitored during the intensive campaign.*

The locations of the 15 additional sites considered during the JJA intensive campaign are also indicated in Figure 1 (as sites numbered 1-15). Furthermore, the locations of Welgegund (Jaars et al. 2016 and 2018), Marikana (Van Zyl et al. 2014) and Botsalano (Laakso et al. 2008; Vakkari et al. 2013), all located in the North West Province, are also shown. Continuous measurements of the pollutant species considered in this paper are/have been conducted there. Therefore, these stations were used as reference sites.

Results and discussion

SO_2, NO_2 and O_3 sampling efficiency and contextualisation of concentrations

Overall, a 95.83% sampling efficiency was achieved during the combined 33-month sampling period, which can be considered as very good.

In order to contextualise the results, the statistical spread of SO_2, NO_2 and O_3 concentrations measured at each site, over both sampling campaigns are presented in Figures 2a, b and c, respectively (associated data is presented in Table A1, Appendix). The variation in median/mean concentrations for the sites reflect the spatial distribution of pollutant concentrations.

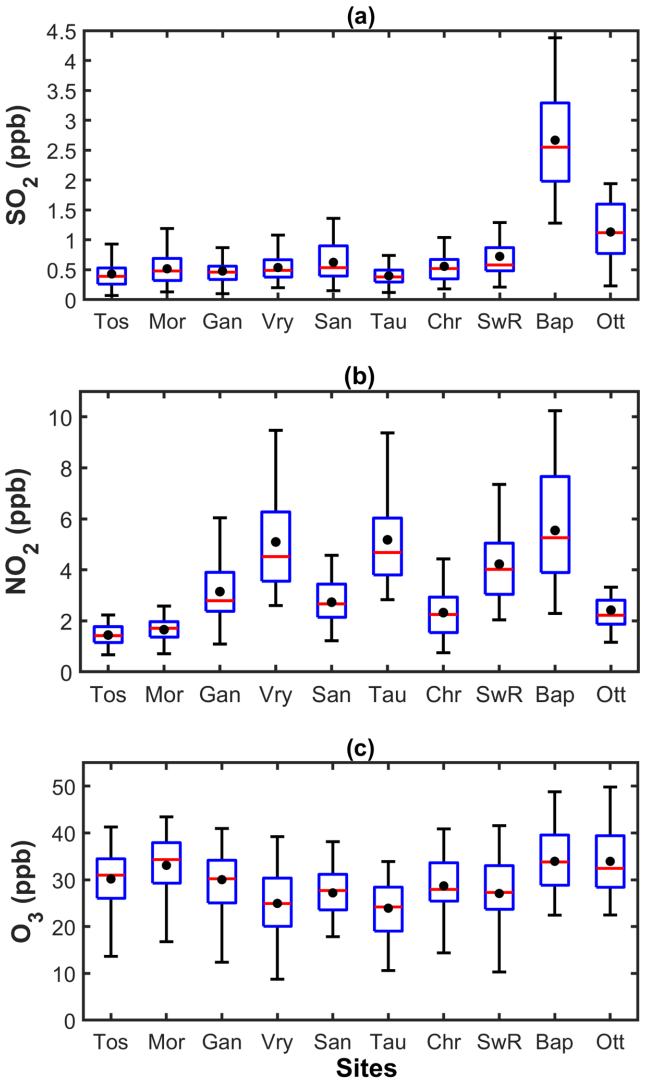

Figure 2: *Statistical distribution of monthly SO_2 (a), NO_2 (b) and O_3 (c) concentrations for each site, over both sampling campaigns. The red line indicates the median, the black dot the mean, the top and bottom edges of the blue box the 25 and 75% percentiles and the black whiskers 1.5 times the interquartile range from the bottom or top of the box.*

However, it (the spatial distribution) is discussed in spatial distribution and is therefore not considered further here.

Taung and Tosca had the lowest median and mean SO_2 concentrations, of 0.38 and 0.40, and 0.39 and 0.43 ppb, respectively (Figure 2a and Table A1, Appendix). These median/mean concentrations compare well with the mean SO_2 concentrations reported by for Okaukuejo in Namibia (0.43 ppb), a relatively unpolluted southern African continental background site (Martins et al. 2007). Bapong had the highest median and mean SO_2 concentrations of 2.55 and 2.67 ppb, respectively, which were significantly higher than the other sites considered in this study. The Bapong median/mean concentrations were lower than the 3.80 ppb reported for Marikana (Venter et al. 2012) located close to several smelters in the North West Province, and within the concentration range reported for the Mpumalanga Highveld (2.80 to 13.30 ppb according to Martins et al. 2007, Lourens et al. 2011, Laakso et al. 2012).

Tosca and Morokweng had the lowest median and mean NO_2 concentrations of 1.42 and 1.44, and 1.65 and 1.71 ppb, respectively (Figure 2b and Table A1, Appendix). These median/mean concentrations were significantly higher than the mean NO_2 concentrations reported for Okaukuejo in Namibia (0.34 ppb) and Louis Trichardt in the Limpopo Province (0.74 ppb) (Martins et al. 2007). Bapong, Taung and Vryburg had the highest median and mean NO_2 concentrations of 5.26 and 5.55, 4.68 and 5.18, and 4.52 and 5.16 ppb, respectively, which were significantly higher than the other sites considered in this study. The Bapong, Taung and Vryburg median/mean concentrations falls in the concentrations range reported for the Mpumalanga Highveld (2.50 to 9.20 ppb, according to Martins et al. 2007, Lourens et al. 2011, Laakso et al. 2012) and is lower than the 8.50 ppb reported for Marikana (Venter et al. 2012).

Taung and Vryburg had the lowest mean and median O_3 concentrations of 23.29 and 24.19, and 25.02 and 25.47 ppb, respectively (Figure 2c and Table A1, Appendix). These median/mean concentrations are similar to mean O_3 concentrations reported for Okaukuejo in Namibia, i.e. 23.00 ppb (Martins et al., 2007). Ottoshoop, Bapong and Morokweng had the highest median and mean O_3 concentrations of 33.51 and 34.74, 33.96, and 34.76 and 34.94 and 33.61 ppb, respectively. These median/mean concentrations were higher than the 29.10 ppb mean concentration reported for Marikana located close to several smelters in the North West Province (Venter et al. 2012), and within the concentration range reported for the Mpumalanga Highveld (16.30 to 37.10 ppb, according to Martins et al. 2007, Lourens et al. 2011, Laakso et al. 2012).

In order to contextualise the results further, the measured concentrations were compared to the South African ambient air quality standards limits (Government Gazette, 2009). However, as no monthly standard limit values exist for any of the three species considered, such comparisons are not straight forward. As previously mentioned, the relatively long averaging periods required for passive sampling is one of the disadvantages of this method.

For SO_2, annual average concentrations (calculated from April'14 to March'15 and February'18 to January'19) for all 10 sites varied between 0.35 to 2.63 ppb, which is substantially lower than the specified 1-year average limit of 19 ppb (Government Gazette, 2009). To contextualise the monthly results within the context of ambient air quality standard limits, a curve fit was applied to the 10 min., 1-hr., 8-hrs., 24-hrs and 1-year standard limits specified for SO_2 (Government Gazette, 2009), as indicated in Figure A1 (Appendix). By using the equation of the fitted curve, it was possible to estimate a potential monthly average "limit" value, which was found to be 29.53 ppb. Comparing the monthly SO_2 concentration values with the afore-mentioned calculated value indicated that if a monthly limit did exist for SO_2 it would likely not have been exceeded during the measurement period. However, the impacts of SO_2 is not a continuum across a wide concentration range (Katsouyanni et al. 1996), therefore, the method applied here is a simplification of reality, but it does give

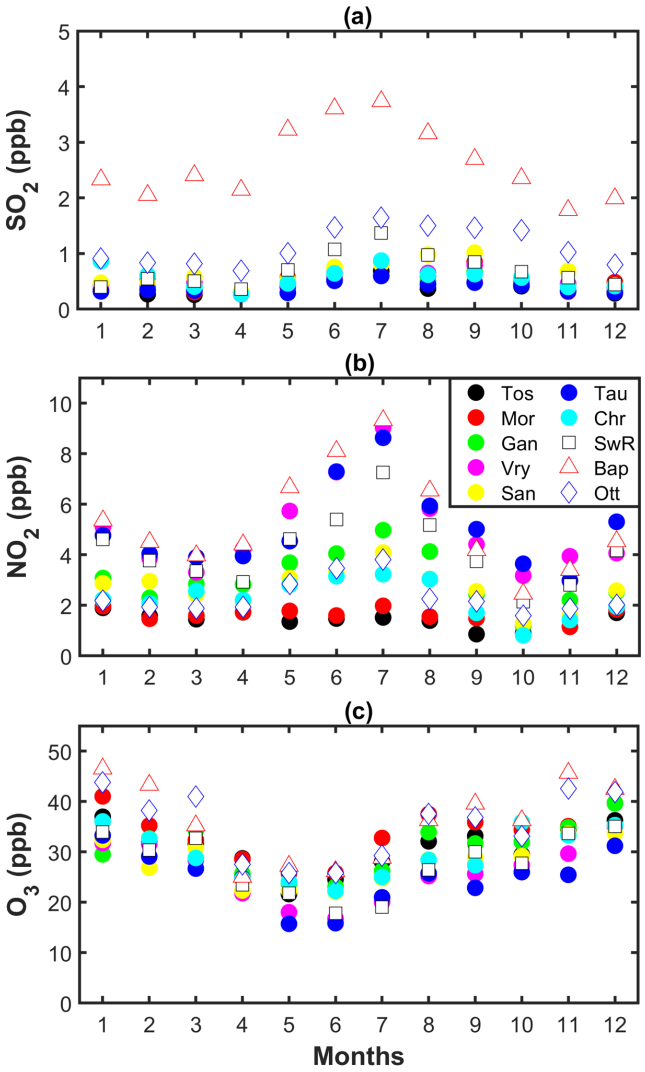

Figure 3: *Combined average monthly (i.e. all January results combined, all February results, etc.) SO_2 (a), NO_2 (b) and O_3 (c) concentrations (ppb) for each of the 10 sampling sites over both sampling campaigns.*

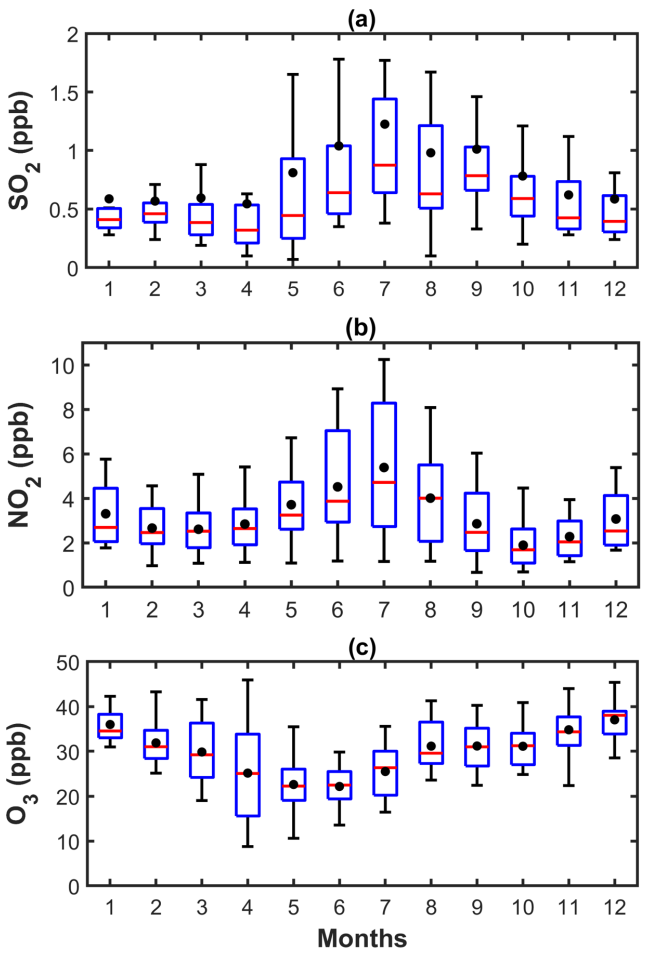

Figure 4: *Statistical distribution of combined monthly (i.e. all January results combined, all February results, etc.) SO_2 (a), NO_2 (b) and O_3 (c) concentrations (ppb) for all 10 sampling sites combined over both sampling campaigns. The red line indicates the median, the black dot the mean, the top and bottom edges of the blue box the 25 and 75% percentiles and the black whiskers 1.5 times the interquartile range from the bottom or top of the box.*

some quantitative indication of monthly average SO_2 air quality. Venter et al. (2012) indicated that on average 4, 0.4 and 0 exceedances of the 10-min (191 ppb), 1-hr (124 ppb) and 24-hrs (48 ppb) SO_2 standard limit values occurred at Marikana, which is approximately 17.5 km (measured in a straight line) from the Bapong site. The average SO_2 concentration measured at Bapong was 2.67 ppb, while that of Marikana was reported as 3.80 ppb (Venter et al. 2012). Therefore, it might be possible that some exceedances of the 10-min and 1-hr standard limit values occurred at Bapong. However, the number of such exceedances are unlikely to be close to the 526 and 88 allowed frequency of exceedances specified for the 10-min and 1-hr standards, respectively (Government Gazette, 2009). It is also unlikely that such exceedances will occur at any of the other sites, since the SO_2 concentrations were significantly lower there (Figure 2a).

For NO_2, annual average concentrations (April'14–March'15 and February'18–January'19) for all 10 sites varied between 1.28 to 5.90 ppb, which is substantially lower than the specified 1-year average standard limit of 21 ppb (Government Gazette, 2009). As previously stated, it is impossible to directly compare monthly average values with shorter standard limit period, such as the 1-hr. standard limits specified for NO_2. It is also impossible to estimate a monthly standard "limit" for NO_2 (as illustrated for SO_2 in Figure A1, Appendix), as there are only two standard limit values specified in the current legislation (Government Gazette, 2009). Similar to the SO_2 results, Bapong again had the highest NO_2 concentrations. The average NO_2 concentration measured throughout the sampling periods at Bapong was 5.55 ppb, while that of Marikana was reported as 8.50 ppb (Venter et al. 2012). Since Venter et al. (2012) did not report any exceedance of the 1-hr standard limit at Marikana, it is unlikely that NO_2 concentrations at Bapong, or any of the other measurement sites, exceeded the 1-hr standard limit of 106 ppb.

O_3 only has an 8-hrs. moving standard limit of 61 ppb (Government Gazette, 2009), therefore, it was impossible to directly indicate exceedances of the afore-mentioned standard limit. However, as indicated in Section 2.3 an intensive campaign was undertaken, during which concentrations of the

three pollutants of interest were measured at 15 additional sites during JJA 2019. During this JJA period the O_3 concentrations were highest at Bapong, Ottoshoop and Morokweng, i.e. 34.33, 32.50 and 31.75 ppb, which are similar to the Welgegund and Botsalano JJA calculated O_3 values of 36.62 and 32.69 ppb, respectively. The lowest O_3 concentrations during the JJA period were measured at Taung, Schweizer-Reneke and Vryburg, i.e. 24.33, 22.71 and 22.70 ppb, respectively, which were similar to the JJA value of 23.21 ppb calculated for Marikana. Relatively recently Laban et al. (2018) presented the average number of days per month on which the O_3 8-hrs moving average standard limit were exceeded at the afore-mentioned reference sites, i.e. Welgegund (up to approximately 9.9 days per month), Botsalano (up to approximately 5.4 days per month) and Marikana (up to approximately 12.1 days per month). Considering the similarly in JJA O_3 average concentrations measured during this study with the afore mentioned published data (Laban et al. 2018), it is highly likely that significant number of O_3 exceedances also occurred at all the sites where measurements were conducted in this study.

Seasonal patterns

The monthly average concentrations (average for all January concentrations, average for all February concentrations, etc.) for SO_2 (a), NO_2 (b) and O_3 (c) are presented for each site separately, combined for both measurement campaigns, in Figure 3. In Figure 4 statistical distribution of combined monthly concentrations (all January concentrations, all February concentrations, etc.) for SO_2 (a), NO_2 (b) and O_3 (c) for all sites combined over both sampling campaigns, are presented as boxplots. The latter gives a regional (Figure 4), rather than a site specific (Figure 3) perspective on seasonal patterns.

From both Figures 3(a and b) and 4(a and b), a relatively well-defined and similar seasonal pattern is evident for SO_2 and NO_2, i.e. higher concentrations in the colder months of June to August, as well as late autumn (May) and early spring (September), while the rest of the year has lower concentration values. Similar seasonal patterns have previously been reported for other areas in South Africa (Josipovic et al. 2010). This seasonal pattern indicates possible additional contribution from sources such as household combustion for space heating that occurs more frequently in the colder months (Adesina et al. 2020), as well as open biomass burning that occurs more frequently in the drier months (Chiloane et al. 2017). Additionally, enhanced trapping of low-level emissions during the colder months by a low-level inversion layer(s) lead to increased concentrations of pollutants at ground level (Garstang et al. 1996). Gierens et al. (2019) reported the formation of such a low-level thermal inversion layer to occur approximately 81% of the time during JJA at Welgegund in the North West Province, while it only occurred approximately 33% during December, January and February (DJF). Also, the daily persistence of the low-level thermal inversion layer is longer during JJA, if compared to DJF (Gierens et al. 2019). Furthermore, increased wet deposition of both SO_2 (as SO42-) and NO_2 (as NO3-) (Conradie et al. 2016), as well as enhanced conversion of SO_2 to particulate SO42-

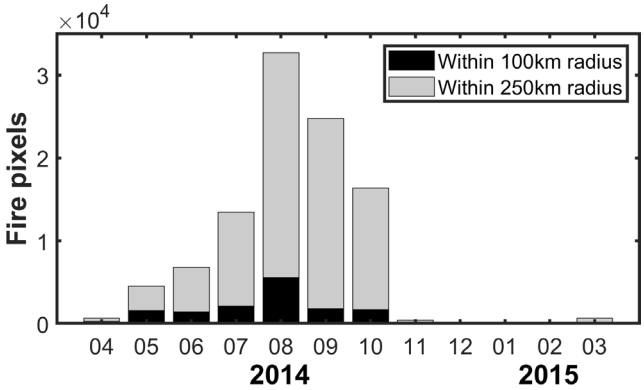

Figure 5: *Number of MODIS fire burn scar pixels (Roy et al. 2008, Boschetti et al. 2009, 2013), representing open biomass burning frequencies, within 100 and 250 km radii around Bapong during the first measurement campaign.*

that occur during the wet season when the relative humidity (RH) is higher (Seinfeld and Pandis 2016), result in lower gaseous concentrations during the warmer/wetter months. Unfortunately, rain volumes and RH were not measured at any of the 10 sites considered in this study, but it was measured at Welgegund. Figures A2a and b (Appendix) present the rain events and RH measured at Welgegund during the first measurement campaign (April 2014 to March 2015), respectively. As is evident, rain events are frequent during the rainy season (approximately middle October to end of March), with very few events during the rest of the year. RH is lower from approximately May to October.

In contrast to the SO_2 and NO_2 seasonal patterns, O_3 concentrations (Figures 3a and 4a) were on average lowest during the colder months of May to July and higher in the period August to December, as well as January to March. Similar seasonal O_3 patterns have previously been presented for Welgegund, Botsalano and Marikana (Laban et al. 2018), which are all situated in the North West Province. Similar to Laban et al. (2018), three phenomena can be considered to partially explain the observed O_3 season pattern. Firstly, the colder months have shorter daylight hours, hence less time for photochemical formation of O_3. Secondly, biogenic volatile organic compound (BVOC) emissions in the North West Provice are lower during the colder months (Jaars et al. 2016). VOCs are important within the context of O_3 formation, since the alkylperoxy radical (ROO•) that form during the oxidation of VOCs convert NO to NO_2, from which O_3 is formed (Seinfeld and Pandis 2016). Thirdly, the peak in open biomass burning in the interior of southern Africa during late winter and early spring (typically August to mid-October) (Chiloane et al. 2017) also lead to a peak in carbon monoxide (CO) concentrations in the North West Province (Laakso et al. 2008). The oxidation of CO results in the formation of the hydroperoxy radical (HOO•), which similar to the ROO• radical enhance conversion of NO to NO_2 (Seinfeld and Pandis 2016). As an example, the frequencies of open biomass burning within 100 and 250 km radii around the Bapong site are presented in Figure 5, for the first measurement campaign. This data clearly indicates a peak in such events during late winter and early spring, which correspond with higher ambient O_3 concentrations. All sites

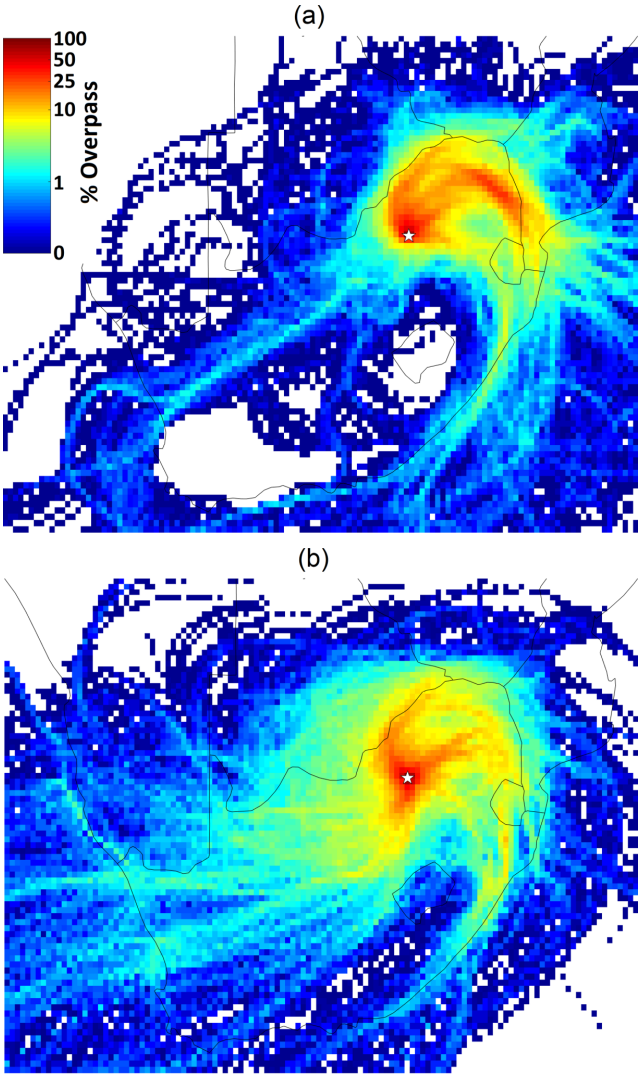

Figure 6: *96-hour overlay back trajectory maps of Bapong (location indicated with stars) for the DJF (a) and JJA (b) periods during both sampling campaigns. The colour code indicates the percentage of the trajectories passing over 0.2° x 0.2° grid cells superimposed on the southern African map, with the colours red and blue indicating the highest and lowest percentage overpasses, respectively.*

exhibited similar seasonal open biomass burning frequency, with the only difference that sites further west had lower overall MODIS fire burn scar pixel counts, due lower productive (less vegetation biomass produced per year) biomes occurring in the western South Africa interior (Figure A3, Appendix).

Thus far, air mass histories were not considered in explaining the observed seasonal patterns (Figures 3 and 4), although it is well-know that it can play an important role (Garstang et al. 1996, Tyson and Preston-Whyte 2000). To illustrate the importance thereof, hourly arriving 96-hour back trajectories for the DJF and JJA periods during both sampling campaigns for Bapong (again used as an example site) are presented in Figure 6. From this example, it is evident that the principal flow of air masses towards Bapong (indicated by red) during DJF (Figure 6a) follows an anti-cyclonic pattern, with dominance from the sector between north northwest to northeast. There is limited airflow from the south (indicated by yellow). During the JJA period (Figure 6b) the anti-cyclonic pattern is still evident, but much more air masses pass over the area directly south of Bapong (indicated by red), where the relatively polluted Johannesburg-Pretoria (JHB-Pta) megacity lie (Lourens et al. 2011 and 2016). Also, more air masses pass over the fairly polluted Mpumalanga Highveld during the JJA period. This example indicates that in additional to local sources and local meteorological contributing factors, regional transport of pollutants could contribute to the observed concentrations. Specifically, SO_2 and NO2 transport from the JHB-Pta megacity, the Mpumalanga Highveld, the Vaal Triangle and the wBC could have impacts on a regional scale.

Spatial distribution

Site specific SO_2, NO_2 and O_3 concentrations were statistically presented in Figure 2. The highest SO_2 concentrations were measured at Bapong (2.55 median and 2.67 ppb mean) throughout the entire sampling period, while the second highest SO_2 levels were measured at Ottoshoop (1.12 median and 1.13 ppb mean) (Figure 2a and Table A1, Appendix). Bapong is situated within the wBC that is part of the Bojanala Platinum district, where a large number of platinum group metal (PGM) and base metal (Xiao and Laplante 2004), ferrovanadium (Moskalyk and Alfantazi 2003), as well as ferrochromium smelters (Venter et al. 2016) occur. Situated relatively close (i.e. 13 to 45 km) to Ottoshoop are three cement factories with kilns, while Mahikeng, the capital of the North West Province, is situated 33 km to the west southwest.

NO_2 concentrations were the highest at Vryburg (5.52 median and 5.16 ppb mean), Bapong (5.26 median and 5.55 ppb mean), Taung (4.68 mean and 5.18 ppb) and Schweizer-Reneke (4.02 median and 4.22 ppb mean) (Figure 2b and Table A1, Appendix). As indicated in the previous paragraph, Bapong is situated in an industrial area, where higher pollutant concentrations can be expected. Both Vryburg and Taung are areas with larger population densities than most of the rural sites considered in this study, hence vehicle and/or household combustion emissions of NO_2 will be more significant. Similarly, vehicle emissions are thought to be the main source of the higher NO_2 concentrations reported for Schweizer-Reneke, since the measurement site was located at a municipal building on a relatively busy intersection. The lowest NO_2 levels were consistently measured at Tosca and Morokweng, which are both rural areas with very low population density and no significant industrial activities.

In contrast to NO_2, the highest O_3 levels were measured at Morokweng (33.61 median and 34.97 ppb mean), Ottoshoop (33.51 median and 34.74 ppb mean) and Tosca (30.99 median and 30.17 ppb mean), while the lowest O_3 concentrations were measured at Taung (24.19 median and 23.92 ppb mean), Vryburg (25.02 median and 25.47 ppb mean), and Schweizer-Reneke (27.44 median and 27.63 ppb mean) (Figure 2b and Table A1, Appendix). Bapong was the exception, since it had higher O_3 and NO_2 levels, while NO_2 and O_3 were inverse of one another at most other sites. SO_2 is a primary pollutant, while NO_2 can be a primary pollutant, but it is mostly a secondary pollutant that

form relatively quickly from NO. During daytime the average ratio of $[NO]/[NO_2] \approx 0.1$ (Seinfeld and Pandis 2016). During nigh time NO reacts rapidly with O_3 to form NO_2 (Seinfeld and Pandis 2016). Hence, NO_2 acts similar to a primary pollutant, such as SO_2. In contrast, O_3 is a secondary pollutant, formed from the photochemical reaction of NO_2 and with precursor species such as VOCs and CO being important (see discussions in Section 3.2). Therefore, air mass history in relation to NO_2 (as well as VOCs and CO) emissions are vital in understanding O_3.

In order to better understand transport of SO_2 and NO_2, as well as regional O_3 formation, 96-hr overlay back trajectory maps were compiled for each of the 10 measurement sites for both sampling campaigns combined. Examples of such overlay back trajectory maps for Bapong and Morokweng are presented in Figure 7. These sites were located on the eastern and western borders of the investigated area in the North West province, respectively. Also, Bapong had the highest and Morokweng the 2nd lowest SO_2 and NO_2 median/mean concentrations during both measurement periods.

As previously indicated, there were numerous large point sources close to Bapong. In addition, it is evident from Figure 7a that Bapong is also frequently impacted by air masses that had passed over other polluted areas, such as the JHB-Pta megacity, the Mpumalanga Highveld and the Vaal Triangle. In contrast to Bapong, the air mass history of Morokweng (Figure 7b) is dominated by anti-cyclonic circulation, but this circulation mostly takes place north of the South African-Botswana border, where much fewer large point sources occur. In addition, air masses from the southwest of Morokweng, where the relatively clear regional background (i.e. Karoo and Kalahari) is situated, affect it fractional more than Bapong.

As indicated earlier, air mass history is also very important to understand O_3. However, since it is a secondary pollutant, and additional phenomena such as titration can occur (Balashov et al. 2014) a more detailed discussion on it (regional O_3 perspective) is presented later.

As stated earlier, an intensive campaign was conducted during JJA 2019. The JJA period was specifically selected, since SO_2 and NO_2 concentrations typically peaked then (Figures 3a and b, Figures 4a and b). In order to visualise the combined results of the 10 original sites, as well as the 15 additional sites, spatially interpolated average concentrations maps for SO_2, NO_2 and O_3 during JJA 2019 are presented in Figure 8. Historic JJA data for Welgegund, Marikana and Botsalano were also included in these figures. These spatially interpolated average concentrations maps are not perfect, since i) only a limited number of sites could be included in this study and ii) the sites could not be equally spaced over the study area. However, notwithstanding these limitations, valuable information can be gained from the maps.

The SO_2 spatial map (Figure 8a) indicate higher SO_2 concentrations on the eastern side of the study area in the North

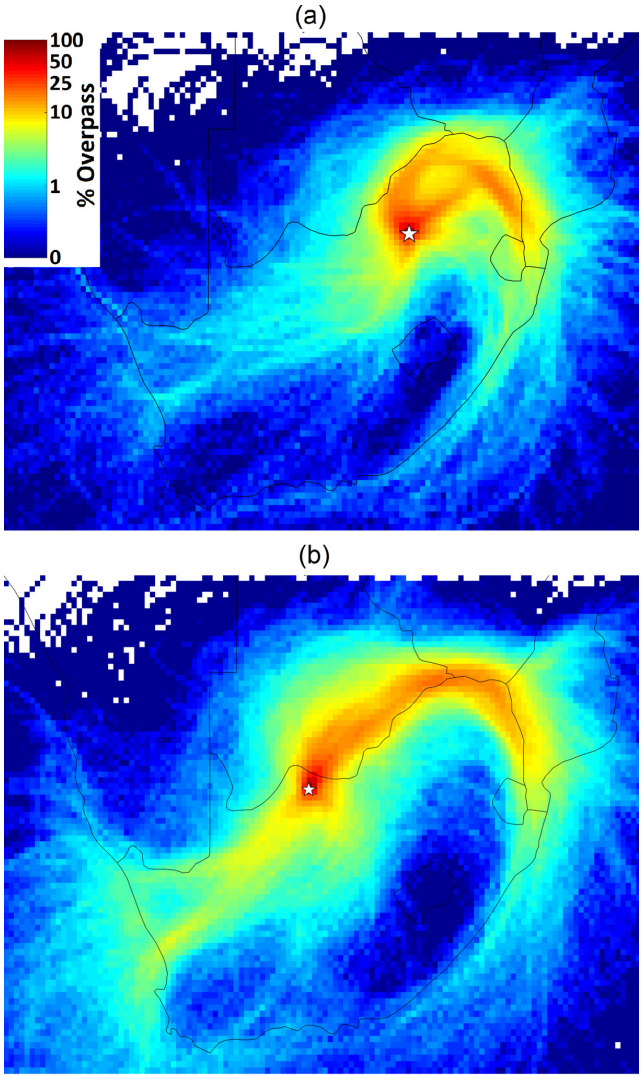

Figure 7: *96-hour overlay back trajectory maps of Bapong (a) and Morokweng (b) (locations indicated with stars) for both sampling campaigns. The colour code indicates the percentage of the trajectories passing over 0.2° x 0.2° grid cells superimposed on the southern African map, with the colours red and blue indicating the highest and lowest percentage overpasses, respectively.*

West Province, than in the west. As indicted earlier, various large point sources occur in the east, that could potentially emit SO_2, whereas in comparison the western region of the study area has no significant industries, thus having lower SO_2 concentrations. Open biomass burning also occur more frequently in the east, if compared to the west of the study area (Figure A3, Appendix). Although open biomass burning is expected to contribute fractionally less than industrial emissions of SO_2 in the context of the study area, savannah and grassland biomes are known to emit 0.47 ± 0.44 g SO_2/kg dry material burnt (Andreae 2019). Recently, Vakkari et al. (2020) reported even higher SO_2 emissions of 1.1 g SO_2/kg for open biomass burning plumes measured specifically at Welgegund in the North-West Province. Hence open biomass burning will also contribute to the higher SO_2 concentrations in the eastern than in the west of the study area.

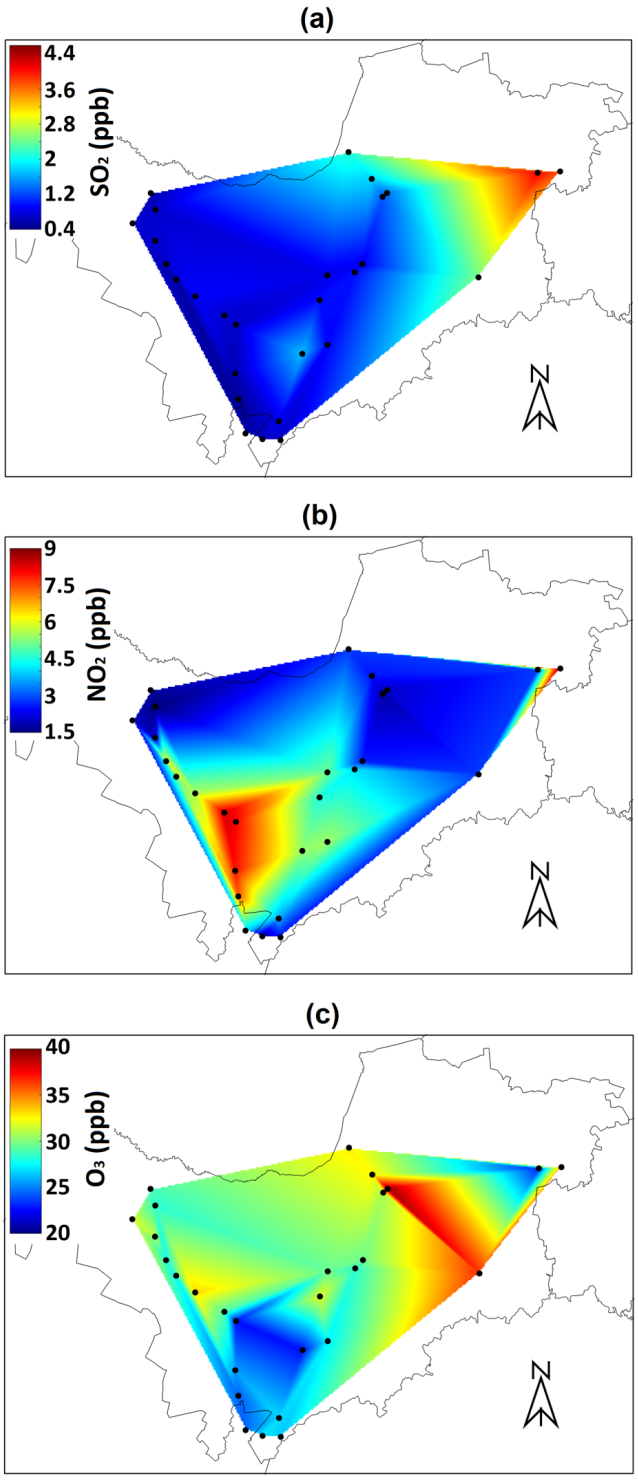

Figure 8: *Spatially interpolated average SO_2 (a), NO_2 (b) and O_3 (c) concentration maps across the area of interest. Spatial interpolations were achieved by using the "grid data" function in Matlab, with triangulation-based linear interpolation.*

In contrast to the spatial map for SO_2, the NO_2 spatial concentrations map (Figure 8b) indicated two areas of higher concentration, i.e. the extreme east near Bapong and the area around Taung. As previously stated, the high number of large point sources and higher population density near Bapong will results in higher NO_2 concentrations. Similarly, the higher population density around Taung (Figure A4, Appendix) and associated higher vehicle emissions result in higher NO_2 concentrations there. The fact that the additional measurement sites, monitored during the intensive campaign, were situated next to the relatively busy R378 road, likely also contributed to the higher NO_2 measured. The lowest NO_2 concentrations were recorded at the Ottoshoop and Welgegund sites.

The O_3 concentration spatial map (Figure 8c) exhibited almost the inverse spatial trend than the NO_2 map (Figure 8b). Particularly the lower O_3 measured around the Taung area is of interest. This low O_3 concentration area, associated with higher NO_2, suggests that O_3 is being titrated there during night-time. The spatial map also shows that although significant industrial NO_2 emissions do not occur in the western part of the North West Province, non-point source emissions (e.g. vehicle, household combustion and open biomass burning) emit enough NO_2 to results in exceedances of the O_3 standard limit there.

Conclusions and recommendations

With regard to SO_2, the results indicated that it is unlikely that ambient air quality issues are persistent or wide spread in the western, more rural North West Province. Therefore, no monitoring of SO_2 is currently required there. It was evident that SO_2 was generally higher in the eastern North West Province that is located in, or in proximity to larger point sources. This includes the wBC (Rustenburg/Brits/Sun City area), where one monitoring site (Bapong) was situated. It is therefore recommended that compliance monitoring by industry and/or government in such areas be continued and/or expanded if required.

The atmospheric chemistry of NO_2 and O_3 are linked to one another, therefore it makes sense discussing them together. The results indicated that widespread exceedances of the 8-hrs. moving standard limit of 61 ppb for O_3 is likely across the entire province, even in the more rural western part. Therefore, systematic and continued measurement of O_3 would be advisable, in order to quantify the problem and to estimate impacts better. No exceedances of the annual average limit were reported for NO_2, nor were any exceedances of the 1-hr. standard limit predicted. However, tropospheric O_3 can only form from NO_2, hence it would be important to measure NO_2 with O_3. Measurements of NO_2 and O_3 in the Taung area would be particularly meaningful, since the spatial maps indicated that O_3 is titrated there. The higher NO_2 emitted from there is likely a regional source of O_3, in addition to regional transport of NO_2 from more well-known source areas such as the Mpumalanga Highveld, Vaal Triangle, JHB-Pta megacity and the wBC. Vehicle emissions is also an important source of NO_2 across the province, which can only be addressed if the vehicular fleet is updated to higher specification over time and if road worthiness emission regulations are implemented. The release of nitrogen from the fuel consumed during household combustion is also an important source of NO_x.

In future studies, particulate matter with an aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) concentrations should be mapped across the province, since the health effect of ambient PM is likely to be more severe than the gaseous species considered in this study. For such a project, passive measurement of PM could also be considered and/or gravimetric filter-based measurements that do not require costly instrument, to make the project feasible. Lastly, it is recommended that possible future studies be augmented by dispersion modelling to at least partially address the non-gradual interpolation of spatial concentrations with triangulation-based linear interpolation that was used here.

Permission to publish

All co-authors agreed to the submission of this paper. The manuscript has not been published or offered elsewhere. Acknowledgment and references have made where required.

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Author contribution

MN conducted the work as part of her MSc study; JPB, PGvZ, VL, PK and SM conceptualised the project; J-SS and MN prepared and analysed all samplers; VL, PK, SM and MN handled sampler logistics; JPB, MN and PGvZ drafted the paper; MK, VV, LL, JPB and PGvZ conceptualised and contributed to the operations of the Botsalano, Marikana and Welgegund stations. All co-authors edited and commented on drafts.

References

Adesina, J.A., Piketh, S.J., Qhekwana, M., Burger, R., Language, B. and Mkhatshwa, G. 2020, 'Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa Highveld', Science of the Total Environment 699:134403. https://doi.org/10.1016/j.scitotenv.2019.134403

Andreae, M.O. 2019, 'Emission of trace gases and aerosols from biomass burning - an updated assessment', Atmospheric Chemistry and Physics 19:8523-8546. https://doi.org/10.5194/acp-19-8523-2019

Balashov, N. V., Thompson, A. M., Piketh, S. J., and Langerman, K. E. 2014, 'Surface ozone variability and trends over the South African Highveld from 1990 to 2007', Journal of Geophysical Research: Atmospheres 119:4323-4342. https://doi.org/10.1002/2013JD020555

Boschetti, L., Roy, D., Hoffmann, A.A. 2009, *MODIS Collection 5 Burned Area Product - MCD45. User's Guide Version 2.0*.

Boschetti, L., Roy, D., Hoffmann, A.A., Humber, M. 2013, *MODIS Collection 5.1 Burned Area Product - MCD45. User's Guide Version 3.0.1.*

Chiloane, K.E., Beukes, J.P., Van Zyl, P.G., Maritz, P., Vakkari, V., Josipovic, M., Venter, A.D., Jaars, K., Tiitta, P., Kulmala, M., Wiedensohler, A., Liousse, C., Mkhatshwa, G.V., Ramandh, A. and Laakso, L., 2017, 'Spatial, temporal and source contribution assessments of black carbon over the northern interior of South Africa', Atmospheric Chemistry and Physics, 17:6177–6196. https://doi.org/10.5194/acp-17-6177-2017

Conradie, E.H., Van Zyl, P.G., Pienaar, J.J., Beukes, J.P., Galy-Lacaux, C., Venter, A.D. and Mkhatshwa, G.V. 2016, 'The chemical composition and fluxes of atmospheric wet deposition at four sites in South Africa', Atmospheric Environment 146:113-131. https://doi.org/10.1016/j.atmosenv.2016.07.033

DEA (Department of Environmental Affairs) 2010, *The Highveld Priority Area air quality baseline assessment report 2010*, Department Environmental Affairs, South Africa, ISBN: 0621396982, 9780621396980

Dhammapala, R. 1996, *Use of diffuse samplers for the sampling of atmospheric pollutants*, MSc Dissertation, Potchefstroom University for CHE.

Draxler, R.R. and Hess, G.D. 2004, *Description of the HYSPLIT 4 Modelling System*. National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum ERL ARL–224.

Dunnink, J.A., Curtis, C.J., Beukes, J.P., Van Zyl, P.G. and Swartz, J. 2016, 'The sensitivity of Afromontane tarns in the Maloti-Drakensberg region of South Africa and Lesotho to acidic deposition', African Journal of Aquatic Science, 41:413-426. https://doi.org/10.2989/16085914.2016.1244509

Garstang, M., Tyson, M., Swap, R., Edwards, M., K°allberg, P., and Lindesay, J. A. 1996, 'Horizontal and vertical transport of air over southern Africa', Journal of Geophysical Research: Atmospheres 101:23721-23736. https://doi.org/10.1029/95JD00844

Gierens, R.T., Henriksson, S., Josipovic, M., Vakkari, V., Van Zyl, P.G., Beukes, J.P., Wood, C.R., and O'Connor, E.J. 2019, 'Observing continental boundary-layer structure and evolution over the South African savannah using a ceilometer', Theoretical and Applied Climatology 136:333-346. https://doi.org/10.1007/s00704-018-2484-7

Government Gazette (No. 27318) 2005, National Environment Management: Air Quality Act, 2004.

Government Gazette (No. 32816) 2009, National ambient air quality standards.

Government Gazette (No. 33600) 2010, Notice of intention to declare the Waterberg Priority Area.

Government Gazette (No. 35072) 2012, Highveld Priority Area air quality management plan.

Government Gazette (No. 43418) 2020, Draft second generation air quality management plan for Vaal Triangle Airshed Priority Area.

IPCC (Intergovernmental Panel on Climate Change) 2013, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. ISBN: 978-1-107-05799-1, 978-1-107-66182-0

Jaars, K., Van Zyl, P.G., Beukes, J.P., Hellén, H., Vakkari, V., Josipovic, M., Venter, A.D., Räsänen, M., Knoetze, L., Cilliers, D.P., Siebert, S.J., Kulmala, M., Rinne, J., Guenther, A., Laakso, L., and Hakola, H. 2016, 'Measurements of biogenic volatile organic compounds at a grazed savannah grassland agriculture landscape in South Africa', Atmospheric Chemistry and Physics 16:15665-15688. https://doi.org/10.5194/acp-16-15665-2016

Jaars, K., Vestenius, M., Van Zyl, P.G., Beukes, J.P., Hellén, H., Vakkari, V., Venter, M., Josipovic, M. and Hakola, H. 2018, 'Receptor modelling and risk assessment of volatile organic compounds measured at a regional background site in South Africa', Atmospheric Environment 172:133-148. https://doi.org/10.1016/j.atmosenv.2017.10.047

Josipovic, M., Annegarn, H.J., Kneen, M.A., Pienaar, J.J. and Piketh, S.J. 2010, 'Concentrations, distributions and critical level exceedance assessment of SO_2, NO_2 and O_3 in South Africa', Environmental Monitoring and Assessment 171:181-196. https://doi.org/10.1007/s10661-009-1270-5

Katsouyanni, K., Schwartz, J., Spix, C., Touloumi, G., Zmirou, D., Zanobetti, A., Wojtyniak, B., Vonk, J.M., Tobias, A., Ponka, A., Medina, S., Bacharova, L. and Anderson, H.R. 1996, 'Short term effects of air pollution on health: a European approach using epidemiologic time series data: the APHEA protocol', Journal of Epidemiology and Community Health 20 (Suppl 1, S12-S18)

Laakso, L., Laakso, H., Aalto, P.P., Keronen, P., Petäjä, T., Nieminen, T., Pohja, T., Siivola, E., Kulmala1, M., Kgabi, N., Molefe, M., Mabaso, D., Phalatse, D., Pienaar, K. and Kerminen, V.-M. 2008, 'Basic characteristics of atmospheric particles, trace gases and meteorology in a relatively clean southern African savannah environment', Atmospheric Chemistry and Physics 8:4823-4839. https://doi.org/10.5194/acp-8-4823-2008

Laakso, L., Vakkari, V., Virkkula, A., Laakso, H., Backman, J., Kulmala, M., Beukes, J.P., Van Zyl, P.G., Tiitta, P., et al. 2012, 'South African EUCAARI measurements: seasonal variation of trace gases and aerosol optical properties', Atmospheric Chemistry and Physics 12:1847-1864. https://doi.org/10.5194/acp-12-1847-2012

Laakso, L., Beukes, J.P., Van Zyl, P.G., Pienaar, J.J., Josipovic, M., Venter, A.D., Jaars, K., Vakkari, V., Labuschagne, C., Chiloane, K. and Tuovinen, J-P. 2013, *Chapter 20: Ozone Concentrations and Their Potential Impacts on Vegetation in Southern Africa*, In: R. Matyssek, N. Clarke, P. Cudlin, T.N. Mikkelsen, J.-P. Tuovinen, G. Wieser and E. Paoletti (eds.), Developments in Environmental Science, 13:429-450, Elsevier, ISSN: 1474-8177, ISBN: 9780080983493.

Laban, T.L., Van Zyl, P.G., Beukes, J.P., Vakkari, V., Jaars, K., Borduas-Dedekind, N., Josipovic, M., Thompson, A.M., Kulmala, M. and Laakso, L. 2018, 'Seasonal influences on surface ozone variability in continental South Africa and implications for air quality', Atmospheric Chemistry and Physics 18:15491-15514. https://doi.org/10.5194/acp-18-15491-2018

Lourens, A.S, Beukes, J.P., Van Zyl, P.G., Fourie, G.D., Burger, J.W., Pienaar, J.J., Read, C.E. and Jordaan, J.H.L. 2011, 'Spatial and Temporal assessment of Gaseous Pollutants in the Mpumalanga Highveld of South Africa', South African Journal of Science, 107(1/2), Art. #269, 8 pp, https://doi.org/10.4102/sajs.v107i1/2.269

Lourens, A.S.M., Butler, T.M., Beukes, J.P., Van Zyl, P.G., Beirle, S., Wagner, T., Heue, K-P., Pienaar, J.J., Fourie, G.D., Lawrence, M.G. 2012, 'Re-evaluating the NO_2 hotspot over the South African Highveld', South African Journal of Science, 108(11/12), Art. #1146, 6 pp. https://doi.org/10.4102/sajs.v108i11/12.1146

Lourens, A.S.M., Butler, T.M., Beukes, J.P., Van Zyl, P.G., Fourie, G.D. and Lawrence, M.G. 2016, 'Investigating atmospheric photochemistry in the Johannesburg-Pretoria megacity using a box model', South African Journal of Science, 112(1/2), Art. #2015-0169, 11 pp. https://doi.org/10.17159/sajs.2016/2015-0169

Martins, J.J., Dhammapala, R.S., Lachmann, G., Galy-Lacaux, C. and Pienaar, J.J. 2007, 'Long term measurements of sulphur dioxide, nitrogen dioxide, ammonia, nitric acid and ozone in Southern Africa using passive samplers', South African Journal of Science 103:336-342.

Moskalyk, R.R. and Alfantazi, A.M. 2003, 'Processing of vanadium: a review', Minerals Engineering 16:793-805. https://doi.org/10.1016/S0892-6875(03)00213-9

Mucina, L., Rutherford, M.C. 2006, *The Vegetation of South Africa, Lesotho and Swaziland, South African*, Strelitzia 19. South African National Biodiversity Institute, Pretoria, 807 pp. ISBN: 1919976213, 9781919976211

Pandey, J.K., Kumar. R. and Devotta, S. 2005, 'Health risks of NO_2, SPM and SO_2 in Delhi (India)'. Atmospheric Environment 39:6868-6874. https://doi.org/10.1016/j.atmosenv.2005.08.004

Pienaar, J.J., Beukes, J.P., Van Zyl, P.G., Lehman, C.M.B. and Aherne, J., 2015, Chapter 2: *Passive diffusion sampling devices for monitoring ambient air concentrations*, In: Forbes, P. (ed.), Monitoring of air pollutants – Samling, sample, preparation and analytical techniques, 70:13-52, Elsevier. https://doi.org/10.1016/bs.coac.2015.09.002, ISBN: 978-0-444-63553-2.

Piketh, S., Van Nierop, M., Rautenbach, C., Walton, N., Ross, K., Holmes, S., Richards, T. 2005, R*ustenburg Local Municipality Air Quality Management Plan*, Gondwana Environmental Solutions (Pty) Ltd, 161 pp.

Roy, D.P., Boschetti, L., Justice, C.O., and Ju, J. 2008, 'The collection 5 MODIS burned area product – global evolution by comparison with the MODIS active fire product', Remote Sensing of Environment 112:3690-3707. https://doi.org/10.1016/j.rse.2008.05.013

Seinfeld, J.H. and Pandis, S.N. 2016, *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*, John Wiley & Sons, 1152 pp. ISBN: 978-1-118-94740-1

Swartz, J.-S., Van Zyl, P.G., Beukes, J.P., Labuschagne, C., Brunke, E.-G., Portafaix, T., Galy-Lacaux, C. and Pienaar, J.J., 2020, 'Twenty-one years of passive sampling monitoring of SO_2, NO_2 and O_3 at the Cape Point GAW station, South Africa', Atmospheric Environment 222:117128. https://doi.org/10.1016/j.atmosenv.2019.117128

Tyson, P. D. and Preston-Whyte, R. A. 2000, *The Weather and Climate of Southern Africa*, Oxford University Press, 408 pp, ISBN: 0-19-571806-2.

Vakkari, V., Laakso, H., Kulmala, M., Laaksonen, A., Mabaso, D., Molefe, M., Kgabi, N. and Laakso, L. 2011, 'New particle formation events in semi-clean South African savannah', Atmospheric Chemistry and Physics, 11:3333-3346. https://doi.org/10.5194/acp-11-3333-2011

Vakkari, V., Beukes, J.P., Laakso, H., Mabaso, D., Pienaar, J.J., Kulmala, M. and Laakso, L. 2013, 'Long-term observations of aerosol size distributions in semi-clean and polluted savannah in South Africa', Atmospheric Chemistry and Physics 13:1751-1770. https://doi.org/10.5194/acp-13-1751-2013

Vakkari, V., Tiitta, P., Jaars, K., Croteau, P., Beukes, J.P., Josipovic, M., Kerminen, V-M., Kulmala, M., Venter, A.D., Van Zyl, P.G. Worsnop D.R. and Laakso, L. 2015, 'Reevaluating the contribution of sulfuric acid and the origin of organic compounds in atmospheric nanoparticle growth', Geophysical Research Letters, 42:10486-10493. https://doi.org/10.1002/2015GL066459

Vakkari, V., Beukes, J. P., Josipovic, M. and van Zyl, P. G. 2020, 'Observations of ozone formation in southern African savanna and grassland fire plumes' Atmosphercv Environment 223:117256. https://doi.org/10.1016/j.atmosenv.2019.117256

Van Zyl, P.G., Beukes, J.P., Du Toit, G., Mabaso, D., Hendriks, J., Vakkari, V., Tiitta, P., Pienaar, J.J., Kulmala, M. and Laakso, L. 2014, 'Assessment of atmospheric trace metals in the western Bushveld Igneous Complex, South Africa', South African Journal of Science, 110(3/4), Art. #2013-0280, 11 pp. https://doi.org/10.1590/sajs.2014/20130280

Venter, A.D., Vakkari, V., Beukes, J.P., Van Zyl, P.G., Laakso, H., Mabaso, D., Tiitta, P., Josipovic, M., Kulmala, M., Pienaar J.J. and Laakso, L. 2012, 'An air quality assessment in the industrialised western Bushveld Igneous Complex, South Africa', South African Journal of Science, 108(9/10), Art. #1059, 10 pp. https://doi.org/10.4102/sajs.v108i9/10.1059

Venter, A.D., Beukes, J.P., Van Zyl, P.G., Josipovic, M., Jaars, K. and Vakkari, V. 2016, 'Regional atmospheric Cr(VI) pollution from the Bushveld Complex, South Africa', Atmospheric Pollution Research 7:762–767. https://doi.org/10.1016/j.apr.2016.03.009

Venter, A.D., Van Zyl, P.G., Beukes, J.P., Swartz, J-S, Josipovic, M., Vakkari, V., Laakso L. and Kulmala, M. 2018, 'Size resolved characterisation of inorganic ionic species in atmospheric aerosols at a regional background site on the South African Highveld Air Quality', Journal of Atmospheric Chemistry, 72:285-304. https://doi.org/10.1007/s10874-018-9378-z

Venter, M., Beukes, J.P., Van Zyl, P.G., Vakkari, V., Virkkula, A., Josipovic, M., Kulmala, M. and Laakso, L. 2020, 'Six-year observations of aerosol optical properties at a southern African grassland savannah site', Atmospheric Environment 230:117477. https://doi.org/10.1016/j.atmosenv.2020.117477

Xiao, Z., and Laplante, A.R. 2004, 'Characterizing and recovering the platinum group minerals - a review', Minerals Engineering 17:961-979. https://doi.org/10.1016/j.mineng.2004.04.001

Appendix

Table A1: *5, 25, 50 (median), 75 and 95 percentiles, as well as the minimum, mean and maximum monthly SO_2, NO_2 and O_3 concentrations for each measurement site over both sampling campaigns.*

	Tos	Mor	Gan	Vry	San	Tau	Chr	SwR	Bap
SO_2									
min	0.07	0.13	0.10	0.20	0.15	0.12	0.18	0.21	1.28
5%	0.16	0.19	0.19	0.26	0.22	0.17	0.21	0.30	1.56
25%	0.27	0.33	0.34	0.38	0.40	0.30	0.35	0.49	1.99
median	0.39	0.48	0.46	0.49	0.54	0.38	0.52	0.58	2.55
mean	0.43	0.52	0.48	0.54	0.62	0.40	0.56	0.72	2.67
75%	0.52	0.68	0.54	0.65	0.89	0.49	0.66	0.87	3.25
95%	0.90	1.02	0.83	0.88	1.18	0.66	1.15	1.61	4.18
max	0.97	1.19	1.23	1.08	1.36	0.91	1.44	2.05	4.38
NO_2									
min	0.67	0.71	1.09	2.60	1.22	2.83	0.75	2.04	2.29
5%	0.76	0.88	1.67	2.78	1.45	2.99	1.10	2.21	2.62
25%	1.16	1.37	2.40	3.58	2.14	3.96	1.54	3.06	3.94
median	1.42	1.71	2.79	4.52	2.67	4.68	2.25	4.02	5.26
mean	1.44	1.65	3.15	5.09	2.73	5.18	2.32	4.22	5.55
75%	1.77	1.97	3.80	6.18	3.42	5.96	2.93	5.05	7.63
95%	2.03	2.36	5.01	8.81	3.99	8.40	3.79	7.15	9.41
max	2.23	2.58	6.04	9.47	4.57	9.37	4.43	8.28	10.24
O_3									
min	13.64	16.77	12.38	8.76	11.60	10.60	14.38	10.30	10.28
5%	20.40	21.02	19.87	14.29	18.51	14.64	20.55	16.70	22.53
25%	26.15	29.55	25.09	20.34	23.64	19.04	25.58	23.70	29.00
median	30.99	34.31	30.21	24.93	27.70	24.19	27.94	27.29	33.80
mean	30.17	33.08	30.02	24.95	27.20	23.93	28.70	27.07	33.95
75%	34.35	37.93	34.05	30.14	31.10	28.31	33.59	32.71	39.47
95%	38.56	41.82	39.36	35.75	37.41	33.27	36.46	36.80	46.95
max	41.27	43.44	40.95	39.21	38.14	33.89	40.87	41.56	48.79

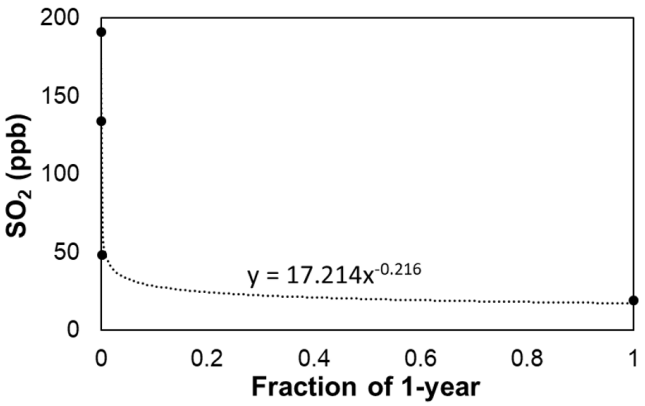

Figure A1: *Power order curve fitted to the current South African air quality standard limits for SO_2.*

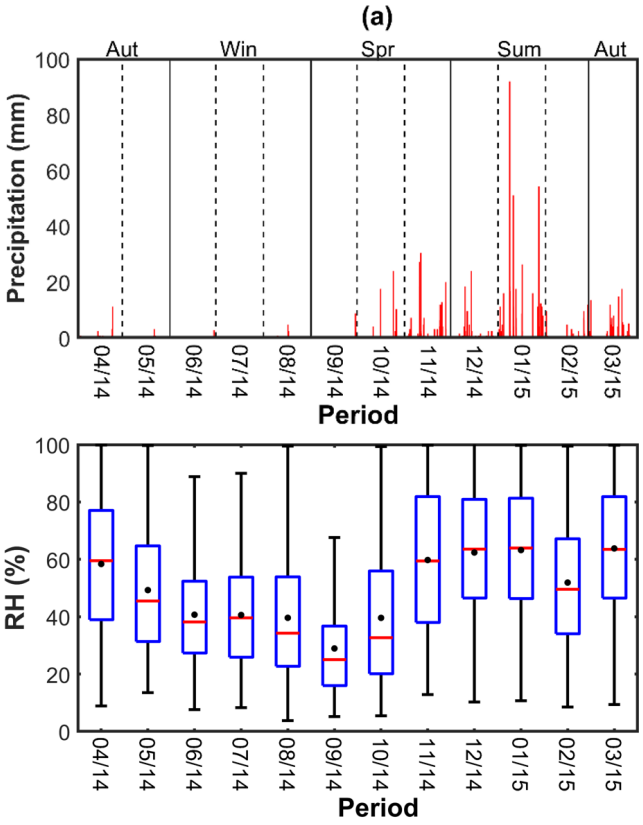

Figure A2: *Rain events (a) and RH (b) measured at Welgegund during the first measurement campaign (April 2014 to March 2015).*

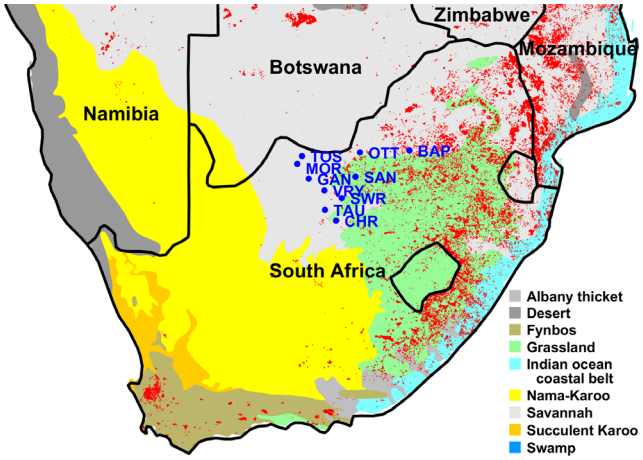

Figure A3: *MODIS fire pixels (Section 3.5) during the first measurement campaign (April 2014 to March 2015) superimposed on biomes in southern Africa (Mucina and Rutherford 2006).*

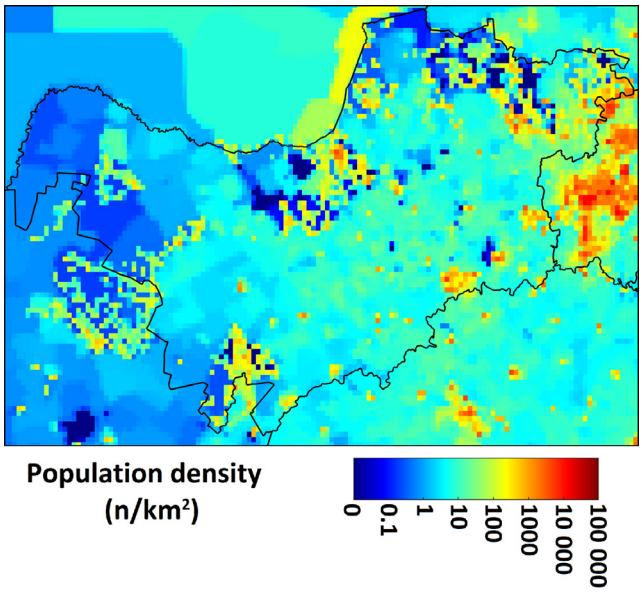

Figure A4: *Population density in the North West Province (Center for international Earth Science Information Network (CIESIN). http://sedac.ciesin.columbia.edu/gpw, accessed 01/08/2010).*