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Editorial
Reflections on the Clean Air Journal Mentorship Programme

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"Anyone who stops learning is old, whether at twenty or eighty. Anyone who keeps learning stays young."
Henry Ford, the father of the modern automobile

I served as an Associate Editor of the Clean Air Journal (CAJ) from the beginning of 2023 until the end of December 2024. From working on the NACA conference floor passing around the roving microphone to becoming Associate Editor of the CAJ, the journey has been worth it. Upon seeing the CAJ mentorship programme advertisement, I knew I had to take the leap of faith and apply for it in 2022. What a journey it has been. Henry Ford's quote about continuous learning is the theme for my mentorship programme; it is through wanting to continually learn that I joined the CAJ editors' team.

My tasks as an Associate Editor ranged from identifying suitable experts to review manuscripts, to assessing the fairness of the reviews, proofreading manuscripts, ensuring that a manuscript goes to production with no scientific errors, promoting policies and working on the CAJ portal. Indeed, I have learnt a lot.

I am so grateful to the Editors-in-Chief of the Clean Air Journal who welcomed me with warm hands to the team and were always willing to help when needed. During the mentorship programme I learnt the following:

- Time management is of the essence. Deadlines need to be met as only two volumes can be released per year, mid-year and at the end of the year.
- Working in a team, managing stakeholders and constant communication are essential. For example, I had to communicate to authors if there were delays with the reviews and providing guidance to novice authors.
- I developed my leadership skills through developing the CAJ's Language Policy which I presented at the 2023 NACA conference. I also presented the CAJ Annual Report at the 2024 NACA conference.

I am forever grateful to have been under the guidance of esteemed experts like Professors Kristy Langerman, Rebecca Garland and Dr Gregor Feig. Although my term as Associate Editor comes to an end, they forever remain my mentors. I would like to thank them very much for the opportunity.

Figure 1: *Presenting the International Day of Clean Air for Blue Skies and the CAJ Language Policy at the NACA conference in 2023*

Dr Mbalenhle Mpanza
Associate Editor 2023-2024

Message

Message from the Incoming NACA President

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The recent World Air Quality Report that is published through IQ Global's Air Quality monitoring platform, paints a very bleak picture on the state of clean air quality across the globe with no signs of immediate abatement. According to the World Health Organization (WHO), air pollution still accounts for one in every nine deaths globally with many people suffering from the effects of fine particulate matter which results in several acute and chronic respiratory diseases such as lung cancer, strokes, and heart diseases. The WHO reports that poor air quality is responsible for over seven million premature deaths worldwide. The hardest hit by these impacts are low to middle income countries. There is much still to be done to improve ambient air quality for ordinary citizens throughout the world.

Between 4-6 September 2024, NACA hosted its 55th Annual Conference with the theme primed as "*Air Quality Evolution: Reflecting on 20 Years of Progress and Charting Future Paths*". The theme was informed by the progress that has been made in South Africa since the birth of the National Environmental Management: Air Quality Act 39 of 2004 (NEMAQA), which repealed or replaced the Atmospheric Pollution Prevention Act 45 of 1965 (APPA). The 55th Conference was unique and educational with standout presentations from all the speakers, including five keynote addresses, and illuminating three-minute research presentations from several university students and professionals who are advocating for clean air quality through their respective roles in society.

Since its inception in 2004, NEMAQA has seen the promulgation of twenty sub-ordinate pieces of legislation which have been aimed at regulating and improving the standards of air quality across South Africa, and this is compared to just six notices and regulations that were published during the twenty-nine-year operation of APPA. As Winston Churchill wisely observed, "the further you look back at your history the further you can see the future", the evolution of air quality legislation and standards in the past twenty years combined with the robust collaboration between academia, industry and government leaders provides hope that future generations can still breathe clear air for generations to come.

One of the highlights of the 55th Conference was the topics which were covered by each of the five keynote speakers in reflection of the theme of the Conference. Dr Peter Lukey from the Department of Forestry, Fisheries and Environment presented about the birth of NEMAQA and the transition to objectives-based air quality governance in South Africa. Dr Patience Gwaze, who is the National Air Quality Officer, presented about the future direction of air quality management in South Africa. Dr Hanlie Liebenberg-Enslin from Airshed Planning Professionals spoke of the constant journey in air quality evolution in South Africa for the past twenty years. Prof Jesse van Griensven from Lakes Environmental Software, gave a virtual presentation from the United States on artificial intelligence in atmospheric science and how it is transforming environmental modelling and forecasting. As one of the keynote speakers, I had to stay true to my legal profession by delivering a presentation on the intersection between the Climate Change Act and the existing suite of air quality legislation in South Africa.

As we look into the future, it is becoming more and more evident that the rapid impacts of anthropogenic activities which result in the significant release of pollutants and greenhouse gas emissions to the Earth's atmosphere continue to pose a serial threat to the universal aspirations of clean air quality and climate change resilience for all countries including South Africa. NACA will continue with its quest and objectives for clean air quality in South Africa by ensuring that it promotes clean air initiatives and provides a collaborative platform for industry, government, and academia to develop unique solutions to combat air pollution and the resultant effects.

The Clean Air Journal (CAJ) provides a professional platform for the publication of world class researched and peer reviewed papers on clean air quality. The journal continues to expand its reader footprint beyond South Africa, and its research papers and publications are making a significant contribution to the global effort to reduce atmospheric pollutants and to educate the public about the adverse impacts of air pollution. On behalf of NACA and our council members, we thank you for your faithful support of the CAJ and we look forward to our joint efforts to achieve clean air quality for all.

Siya Mkhize
Incoming NACA President

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Commentary

Air quality evolution in South Africa over the past 20 years: A journey from a consultant's viewpoint

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Introduction

Over the past 20 years, South Africa has made significant progress in implementing frameworks and strategies for the purpose of enhancing air quality through evolving regulations; however, challenges persist. As consultants, we have been at the forefront of navigating and implementing these new regulations, often with some practical difficulties which were not necessarily foreseen. We have been working closely with regulatory bodies to ensure compliance and help industries understand and meet the new regulations. The introduction of stricter regulations demanded innovative solutions, and our role has been crucial in assisting both government and private sectors in fulfilling their obligations. This period has been both challenging and rewarding for air quality consulting.

This narrative, chronicles a journey marked by scientific dedication, regulatory hurdles, and a relentless pursuit of cleaner air for South Africa's communities. It explores the comprehensive process of air quality impact assessments and the development of air quality management plans, covering approaches and methodologies, tools and techniques, the effectiveness of evaluation tools, data requirements and availability, progress and developments, as well as the legal and regulatory framework guiding these processes.

The start of air quality awareness in South Africa

Air pollution in South Africa has been a concern since the 1960's with no formal control of air emissions from industrial and mining operations. Following the Great Smog of 1952, a series of laws were introduced in England (Clean Air Act of 1956 and 1968) to ban black smoke emissions. In South Africa the Air Pollution Research Group at the CSIR (Council of Scientific and Industrial Research) promoted the legal control of air pollution, and as such the Air Pollution Prevention Act, No. 45 of 1965 came into effect, mainly based on the United Kingdom Clean Air Act. The focus was on four main areas: (i) *Industrial sources*, where scheduled processes were controlled by national government through Registration Certificates, mostly dictated through negotiations and based on best practical means; (ii) *Smoke* controlled by local authorities, not allowing open burning and declaring smoke control areas; (iii) *Dust control* applicable only to declared dust control areas but where mine dumps ended up being controlled by Government Mining Engineer, and (iv) *Vehicle emissions*, also controlled by local authorities through smoke opacity readings but never well executed. The Act provided ambient air quality guidelines, but since these were not regulations, it was not legally enforceable.

Changes under the new constitution

The Constitution of the Republic of South Africa (No. 108 of 1996) states "*Everyone has the right to an environment that is not harmful to their health and well-being, and to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures…*"

The early 1990's marked a new era in environmental management and awareness, and the first formal Environmental Management courses commenced in 1992 at the University of Cape Town and in 1993 at the Rand Afrikaans University (now the University of Johannesburg). During this period, air quality was not a primary focus in environmental management. Most air quality specialists worked in industry, academia, and at the CSIR, and there was no clear guidance as to what air quality assessments should entail.

The National Environmental Management Act of 1998 paved the way for the new Air Quality Act (Act 39 of 2004), which changed the way in which air quality was to be managed in South Africa. The Air Quality Act: (i) shifted the approach to the receiving environment through air quality objectives, (ii) decentralised air quality management with responsibilities at provincial and local government levels, (iii) included baseline air quality characterisation by identifying priority areas, key pollutants, and main contributing sources, (iv) addressed all sources, (v) incorporated a range of emission reduction measures such as command and control, market incentives and disincentives, voluntary reductions, etc., (vi) standardised monitoring (QA/QC, information management, and reporting), and (vii) included public participation and access to information as a requirement.

Not all sections of the Air Quality Act were developed and implemented by the time it was promulgated, and several projects followed resulting in some 40 gazetted publications over the following 20 years. Air quality consultants played an integral part in the development of certain components of the Air Quality Act, such as the Listed Activities and Minimum Emission Standards, the National Ambient Air Quality Standards (NAAQS), Atmospheric Emissions Licence (AEL) application form and format, the National Dust Control Regulations (NDCR) and Air Quality Modelling Guideline, to name a few.

Air Quality Impact Assessments became an integral part of Environmental Impact Assessments, with a growing demand for qualified air quality consultants to conduct these specialist studies and assist industry with their new legal responsibilities such as AEL applications and National Atmospheric Emissions Inventory System (NAEIS) reporting.

National Priority Areas

As part of the drive to cleaner air, three priority areas were declared with the Vaal Triangle Airshed Priority Area (VTAPA) the first in 2005, followed by the Highveld Priority Area (HPA) in 2007 and the Waterberg Bojanala Priority Area in 2012. For each of these, an Air Quality Management Plan (AQMP) had to be developed with the first, *Regulations for Implementing and Enforcing the VTAPA AQMP*, published on 29 May 2009. With the VTAPA AQMP being the first to be developed, this is used as an example of the progress in air quality management.

The drive for clean air in the Vaal Triangle started in the early 1990’s due to concerns expressed by the public about levels of air pollution and the respiratory health status of children in the Vaal Triangle. An Air Quality Management Strategy for the Vaal Triangle, aimed at developing intervention strategies to improve poor air quality over the Vaal Triangle region, was conducted in 1997, and the Vaal Triangle Air Pollution Health Study or VAPS, developed by the South African Medical Research Council in 1998, was a comprehensive epidemiological study which investigated the upper and lower respiratory health status in school children. Another study conducted in the early 2000’s quantified the source contributions and identified cost-effective solutions for certain pollutants, areas and sources of concern in the Vaal, including a dose-response for PM_{10}. These initiatives to determine and address the poor air quality in the Vaal Triangle gave rise to the slogan: “*Blue skies over the Vaal by the year 2000*”.

The VTAPA AQMP process and results

The VTAPA AQMP was developed between 2007 and 2009, with the main objective to establish an AQMP that, once implemented, would ensure that the air quality of the area would effectively and efficiently be brought into sustainable compliance with ambient air quality standards within agreed timeframes.

The outcome of the VTAPA AQMP was limited by available ambient monitoring and source data at the time. The Department of Environmental Affairs (now called Department of Fisheries, Forestry and the Environment) commissioned six ambient air quality stations in 2007, with available data indicating elevated PM_{10}, SO_2 and ozone levels. An emissions inventory was developed based on available industry and other source data and used in a dispersion model to determine the main areas of concern. Six “hot spot” areas were identified within the Vaal Triangle indicating the contribution from various source groups to the main pollutants, over the short- and long-term. The Logical Framework Approach (LFA) was then used to determine intervention strategies based on cause-and-effect relationships, resulting in eleven identified problem complexes.

A medium-term review conducted in 2013 found that 46% of the set interventions were successfully implemented, with 18% in progress, 22% could not be achieved, and 14% could not be ascertained. It was found that the industrial stakeholders mostly met their obligations compared to other sectors, with performance of government and municipalities generally low. The Multi Stakeholder Reference Group (MSRG) members overall view was that inadequacy in capacity and the failure to achieve many of the planned interventions and objectives were the main reasons for failing at implementing the 2009 VTAPA AQMP.

In 2017, eight years after the implementation of the 2009 AQMP, the development of the second generation AQMP was initiated with the objective to characterise the air quality and determine the improvement in air quality, if any. This second generation AQMP aimed to establish new strategies and intervention plans, based on a better understanding of the cause-and-effect relationships, that would ensure further improvement and eventual compliance within the area.

Over the 10 years between the publication of the first and finalisation of the second VTAPA AQMPs, there was very little to no improvement in ambient air quality. Large and smaller industry emissions reduced per 2009 intervention commitments

(35% reduction in NO_2, and 25% reduction in PM_{10}) although this was not evident in the ambient air quality. Compared to 2009, domestic fuel burning emissions and vehicle emissions reduced and these are reflected in the $PM_{2.5}$ ambient air quality data. Mining, biomass burning, waste burning and transportation emissions, however, showed little if any improvements. A contributing factor not accounted for in the evaluation is the population in the region, which increased by 22% according to the 2016 Community Survey statistics.

Shortfalls of AQMP implementation

Several factors contributed to the limited improvement in air quality in the VTAPA, with the lack of implementation of the AQMP being the primary one. No political buy-in from decision-making powers resulted in budgetary constraints and a lack of planning. Also, there were too many interventions with some not clearly defined, and limited human resource capacity. Additionally, a shortage of technical skills didn't help. Many of the ambient monitoring stations went out of operation due to the high cost required for maintenance.

Possible reasons for the lack of implementation of the AQMP may be that there are no consequences for failing to implement the set interventions, with no synergy between government departments, and between government and industry, and the public. Over time, stakeholders lost interest in the plan and the methods to create public awareness were inadequate.

Other hurdles included the ironing out of legal requirements, and some factors outside the realm of air quality management. For example, some of the Listed Activities sub-categories were not well-defined resulting in misinterpretation by industry, consultants, and government officials. The aging infrastructure of the government monitoring stations resulted in poor data availability and quality, with load shedding affecting most of the stations. Frequent changes in local municipalities management, with some placed under administration, further hampered air quality management.

The way forward

Since 2009, there have been several publications to assist with AQMP development and implementation, more comprehensive emissions inventories have been developed, and there is a better understanding of the contributing air pollution sources as well as improved technical skills and capacity in the various spheres of government. Furthermore, stakeholder engagements have improved through formal available forums and reporting, and there is overall better public awareness about air quality.

Valuable lessons have been learnt over the past 20 years since the Air Quality Act came into effect, and these have prepared us to make the necessary changes in the next 20 years. So, let's aim for "*Blue skies over SA by the year 2040.*"

This commentary is based on a keynote address given by Dr Hanlie Liebenberg-Enslin at the National Association of Clean Air (NACA) Conference in September 2024, in keeping with the conference theme of "Air quality evolution: Reflecting on 20 years of progress and charting future paths."


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Commentary

A Critical Reflection on Air Quality Monitoring in Ethiopia: Challenges, Progress, and the Way Forward

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Introduction

The strategic measures that improve environmental air quality contribute to better public health. The role of air pollution in environmental effects continues to be a major factor affecting health among populations living within urban settings. This is because air pollution has been identified as one of the highest contributors to health problems in cities worldwide (Oleszkiewicz et al., 2023).

Rapid economic growth in Ethiopia has resulted in the many technological, industrial and agricultural improvements. However, such rapid economic and population growth with expanding technology has also resulted in increased emissions of various air pollutants. The general climatic condition is seasonal, with rainfall levels varying in relation to topography. During the rainy season (from June to September), there is high precipitation, while during the semi-rainy season (from February to May) the amount of rain is moderate, and during the dry season (from October to January) it is generally dry. Therefore, these seasonal variations might be influencing the measured ambient air pollution level and air quality index.

The most serious threat to human health comes from urban air pollution. People residing in urban areas are highly threatened, and exposure to pollution can thus prevail over their health status. The poor and children are among the most disproportionately affected segments as to environmental, economic, and health challenges (WHO, 2021). Simultaneously, exposure to polluted air can cause of various diseases. For example, in Addis Ababa, cases of Chronic Obstructive Pulmonary Disease (COPD) annually increased by 53.44% from eight cases in 2013 to 1,871 cases in 2017, while pneumonia cases increase from 575 to 29,844 within the same period of time (Tarekegn and Gulilat, 2018). Respiratory and cardiovascular diseases, such as acute upper respiratory infections, bronchitis, asthma, COPD, and pneumonia, are likely to increase in Addis Ababa due to long-term exposure to air pollution.

Besides these developing problems, air quality monitoring (AQM) and evaluation still remain one of the major challenges in air quality management in Ethiopia. Such a challenge might be important to be addressed, with rapid urbanization and economic growth that increase air pollution. It might be because of the lack of AQM devices, shortage of qualified experts, inadequate knowledge regarding how to maintain the existing monitoring systems, and the absence of a revised national level air quality guideline (NAQG) and unavailability of national air quality index (NAQI). While air pollution is still deteriorating, the prevalence of respiratory cases has become one of the leading health burdens of many people (US EPA, 2021a). Although there is some improvement, AQM in the country remains underdeveloped. These inhibit the potential of Ethiopia to address health risks, environmental degradation, and economic impacts effectively. Hence, it is vital to point to challenges, opportunities, and possible means of enhancement in order to underline an integrated, robust approach toward AQM.

Challenges and current gaps

The current infrastructure setup of Ethiopia's AQM has some drawbacks, which ultimately lead to many issues with data availability, public access, and policy implementation efficiency. Major issues regarding this question are linked to the fact that most of Ethiopia's monitoring stations are located within only urban city centers like Addis Ababa. Moreover, this only provides limited coverage and fails to capture a comprehensive picture of air quality, especially over rural areas affected by agricultural and biomass burning emissions that often involve the burning of wood, agricultural residues, and other organic material for cooking and heating. Besides, existing devices are outdated and lack consistent maintenance, affecting data accuracy and continuity. The current form of the AQM device, for example, includes the Ethiopian Meteorology Institute (EMI) have federal equivalent method AQM device, NASA MAIA PurpleAir device, Ethiopian Environmental Protection Authority and , Athletic Federation have Kunak cloud device, and GeoHealth and UNDP have BAM device. These all suffer from huge challenges due to power disruptions, malfunctioning sensors, and a lack of qualified personnel for regular equipment maintenance. As a result, real time data is barely available to the public, which makes it difficult to create awareness and thereby involve citizens in the reduction of pollution. Transparency of data shall facilitate the dissemination of information and support proactive actions at the level of public health.

Regulatory and policy gaps

Even though there have been some recent air quality plan updates In Ethiopia (US EPA, 2021b); nevertheless, the air quality management system of Ethiopia is rudimentary at present, with some serious gaps regarding enforcement and the development of new standards and an air quality index. While there are, in fact, laws to protect air quality, these regulations typically do not have explicit, enforceable provisions, so implementation and monitoring across the country are not consistently carried out. Operating laws are either so old or so vague that regulatory bodies find it tough to bring polluters to justice. Such ambiguity and laxity in the laws have kept efforts at bay in an attempt to rid the skies of pollution, as industries and other sources can be seen with minimal accountability. Lacking an integrated central data repository that would bring together and oversee multiple sources of data for management, effective policy operations and mechanisms for response by sectors remain unreachable. Consequently, health risks from deteriorated air quality continue to increase. For this reason, the fight against air pollution requires an update of air quality standards, a development of better mechanisms for enforcement, and consistent use of regulations throughout the nation.

Strengths and opportunities

The partnerships developed with entities like the United Nation Environmental Programme (UNEP) and the World Bank provides immense technical as well as financial support. These partnerships are helpful in capacity building as well as knowledge and infrastructural development agreements. Also, the Ethiopian governmental and public awareness of the health implications of air pollution is growing, as evidenced through advocacy, public health workshops on pollution-related diseases, and urban air quality studies; thus, this sets a good prospect to start community-led and government-supported initiatives.

Recommendations

Adequate AQM and control needs accurate and complete data to underpin its evidence based policies and actions. The gaps in the AQM system and management in Ethiopia require expanding coverage, reliability, and accessibility of data. This would also involve increasing the number of monitoring stations both in urban and rural areas, with sophisticated monitoring technologies, quality assurance on regular calibration, and a centralized repository for efficient sharing and analysis. These would potentially facilitate improved decision-making, enhancing public health outcomes and enforcement of sustainable environment-based practices. Of more importance, investments should be done on advanced air quality monitors with rigorous maintenance protocols. This would involve budgeting for technical training and the adoption of real-time data integration technologies. Publishing air quality data through accessible platforms would increase the awareness of the public about air quality issues and aid community action against pollution. A centralized data platform would facilitate effective policy development and compliance monitoring and offer timely responses to air quality challenges. Additionally, public awareness through campaigns about the health consequences of air pollution may be launched in order to gain community support for the measures on air quality improvement and result in behavioral changes.

Conclusion

The Ethiopian effort towards the achievement of air quality monitoring and management for sustainability reflects both significant strides and substantial challenges. Strengthening the air quality monitoring system can help protect public health and contribute to the broader sustainability goals of Ethiopia. These will ensure more infrastructure expansion, regulations, and public engagement in ways that will significantly set one on the path toward cleaner, safer air for all.

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I am indeed grateful to those persons who gave me useful information about air quality monitoring and management, particularly the experts from the Federal Environmental Authority and GeoHealth Hub through personal contact and in forums.

Conflict of interest

The author declares no competing interests.

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Sustainable Development Goals

News

55th Annual Conference of the National Association for Clean Air (NACA), 2024 - Air quality evolution: Reflecting on 20 years of progress and charting future paths

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The 2024 Annual NACA Conference, in collaboration with the Department of Forestry, Fisheries, and the Environment's (DFFE) Air Quality Governance Lekgotla, was a significant event. This year, the conference centred on the theme "Air quality evolution: Reflecting on 20 years of progress and charting future paths."

This theme highlighted South Africa's transformative journey in air quality management since the enactment of the National Environmental Management: Air Quality Act (Act 39 of 2004). The conference served as a unique platform to reflect on the achievements of the past two decades, analyse ongoing challenges, and gather key insights to shape the future.

Held from 4-6 September 2024 at the Mintek Conference Centre in Randburg, the conference brought together leading experts, policymakers, and researchers to discuss critical issues in air quality management and climate change in South Africa. The multi-day event featured a rich and diverse programme, including keynote presentations, technical workshops, oral sessions, and hybrid panels. Topics ranged from emissions inventories and innovative monitoring technologies to the relationship between air quality and climate change policies, ensuring a high level of engagement and interest among the attendees.

The conference showcased a lineup of distinguished keynote speakers who addressed critical topics in air quality management. Peter Lukey from the Department of Forestry, Fisheries and Environment (DFFE) offered an engaging historical perspective on South Africa's shift towards objectives-based air quality governance, highlighting lessons learned from the National Environmental Management: Air Quality Act (NEM: AQA) and the challenges associated with fossil fuel dependency. Dr Patience Gwaze, also from DFFE, discussed the future direction of air quality management in South Africa. Dr Hanlie Liebenberg-Enslin of Airshed Planning Professionals shared insights from her two decades of consulting on evolving air quality regulations and their practical impacts. Siyabonga Mkhize of Shepstone & Wylie Attorneys explored the relationship between the new Climate Change Act and existing air quality legislation, emphasizing the importance of resilience and mitigation strategies. Prof. Jesse Van Griensven from Lakes Environmental Software highlighted the transformative role of Artificial Intelligence in atmospheric science, focusing on pollutant modelling and forecasting. Finally, Deidre Herbst from Eskom reflected on the complex relationship between air quality and electricity management, stressing the need to integrate environmental considerations into energy planning. These keynote presentations provided a rich blend of historical insights, technical innovations, and forward-looking strategies for addressing air quality challenges.

The scientific review process was both thorough and inclusive, reflecting the collaborative spirit within the air quality community. Out of more than 40 submissions, over 20 full scientific papers, more than 15 posters, and around 10 engaging three-minute research presentations were accepted. A panel comprising over 30 experts from more than 10 organizations — including top academic institutions, industry representatives, and non-governmental organizations — oversaw the review process. This diverse group ensured a comprehensive evaluation of the submissions, upholding high standards while welcoming a variety of perspectives and disciplines.

NACA Awards

The following awards were presented at the 2024 NACA Conference:

NACA Golden Award: Sally Benson

NACA Golden Award: Dr Gerrit Kornelius

Company award: Airshed Planning Professionals Pty Ltd

Best scientific paper (student): S. Bridges, H.W.J.P. Neomagus, J.R. Bunt, F.H. Conradie and H.J. Annegarn (North-West University): *Emission performance of a clean cookstove and oven utilising predominant South African wood species*

Best scientific paper (non-student): G. Kornelius, P. Forbes and R.M. Garland (University of Pretoria): *Tier 2 greenhouse gas emission factors for South African solid fuels*

Best 3-minute research talk: B. Koovarjee and J.R.C. von Holdt (University of Cape Town): *Mapping and managing air pollution risks in mining areas*

Best poster presentation: A. Richter, C. Roos, S.J. Piketh, R.P. Burger and B. Language (North-West University): *Estimating $PM_{2.5}$ emissions in Sharpeville: Emission factors for waste burning in air dispersion models*

Sponsors

The conference proudly received support from various sponsors who contributed significantly to its success. Eskom served as a Platinum sponsor. Silver sponsors included Lakes Software, Shepstone & Wylie Attorneys, and SACNASP. Bronze sponsors featured Air Resource Management (ARM), Mine Dust Network, EnviroServ, EnviroServe, SRK Consulting, and C&M Consulting Engineers. Merchandise sponsors included Airshed Planning Professionals and Skyside. At the same time, student sponsors, such as SI Analytics, North-West University (NWU), and the NOVA Institute, helped reinforce the importance of fostering the next generation of environmental professionals.

Exhibitors highlighted cutting-edge solutions and services in air quality management and environmental sciences. Organizations such as Envirocon Instrumentation, AMS Haden, Gondwana Environmental Solutions, and ERO Africa presented innovative technologies. Meanwhile, Umoya Nilu Consulting and C&M Environmental Consultants emphasized their expertise in environmental consultancy. Professional bodies like EAPASA and SACNASP shared valuable insights into industry standards, while scientific institutions such as NMISA and Mintek demonstrated their contributions to research and development. Companies like Testo South Africa, Ansyco SA, and Argos Scientific offered advanced instrumentation, and Levego Environmental Services and SI Analytics focused on environmental monitoring solutions. This diverse group of exhibitors enriched the conference by fostering collaboration and sharing groundbreaking advancements with attendees.

In summary, the 2024 Annual NACA Conference marked a significant milestone by celebrating 20 years of advancements in air quality management while paving the way for future progress. Under the theme "Air quality evolution," the event served as a vibrant platform for collaboration, innovation, and thoughtful reflection. The outstanding contributions from keynote speakers, sponsors, exhibitors, and researchers highlighted the urgent need to tackle air quality and climate challenges in South Africa. The scientific rigour and diverse perspectives shared, coupled with the recognition of outstanding achievements through the NACA Awards, emphasised the conference's vital role in promoting advancements in air quality science, policy, and practice. This united effort establishes a solid foundation for ongoing strides toward cleaner air and a healthier planet.

GAS ANALYSIS

The National Metrology Institute of South Africa is mandated by the Measurement Units and Measurement Standards Act, 2006 (Act No. 18 of 2006) to provide accurate and internationally recognised national measurement results. The NMISA Gas analysis laboratory enables compliance to legislation and reliable reporting of emission measurements through the provision of traceable and reliable primary reference gas mixtures. The laboratory is responsible for the dissemination of primary reference gas mixtures, provision of reference measurements and calibration services, including training, proficiency testing schemes, assessments and consultation.

Our Services

- **Primary reference gas mixtures**
  - Criteria air pollutants
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  - Reactive gases
  - Volatile organic compounds
  - Oxygenated volatile organic compounds
  - Energy gases
  - Stack emission gases
  - Automotive exhaust gases
- **Purity Analysis for high purity gases**
- **Reference measurements**
  - Certification of gas mixtures from local gas manufacturers (Secondary reference materials)
  - Analysis of tedlar bags and other sampling vessels
- **Proficiency Testing Schemes**
  - Ambient air monitoring
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- **Calibration of ozone instruments**
- **Calibration of gas monitors**
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Please contact us at **gas@nmisa.org** or **+27 12 947 2818**

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Research Projects

Environmental and ambient air gases
Development of the following reference gas mixtures:

- **Greenhouse gases**
  - Carbon dioxide, methane, Sulphur hexafluoride, nitrous oxide
- **Low amount fraction reactive gases**
  - Nitrogen monoxide, nitrogen dioxide, hydrogen sulphide
  - Preparation of calibration gas mixtures using dynamic volumetric methods
- **Volatile organic compounds**
  - Non-methane hydrocarbons (NMHCs), Hazardous Air Pollutants (HAPs), oxygenated VOCs, benzene, toluene, ethyl benzene, (o,m,p) xylenes
- **Sulphur compounds**
  - Sulphur dioxide, Ethyl mercaptans, Dimethyl sulphide, Tetrahydrothiophene

Industrial emission and energy gases
Development of the following reference gas mixtures:

- **Stack emission gases**
  - Nitrogen monoxide, sulphur dioxide, carbon dioxide
- **Automotive exhaust gases**
  - Carbon monoxide, carbon dioxide, propane, oxygen
- **Natural gases**
  - Ethane, propane, n-butane, n-pentane, i-pentane
- **Refinery gases**
  - Carbon dioxide, carbon monoxide, methane, ethane, propane, 1,3-butadiene, oxygen nitrogen and helium (balance)
- **Development of the Biogas gas mixture**
  - Methane, carbon dioxide and hydrogen sulphide


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Environmental Projects

News

Adoption of Artificial Intelligence Tools and Resources Policy

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The Clean Air Journal has adopted a new policy on the use of Artificial Intelligence (AI) tools and resources for all submissions to Clean Air Journal. This policy was written with the view that transparency about the use of AI is necessary to ensure trust between authors, reviewers, editors and readers. In addition, we believe that appropriate use of AI can support authors and research and be a great resource. The policy is available online at Artificial Intelligence tools and resources policy and is detailed below.

Artificial Intelligence (AI) Tools and Resources Policy

The purpose of this policy is to guide Clean Air Journal authors on the use of content generated by AI applications in research publication.

Appropriate use of AI

The CAJ supports the appropriate use of AI tools and resources in the preparation of manuscripts, provided ethics and scientific integrity are upheld. The appropriate uses are detailed in Table 1.

How to declare use of AI

The use of AI and the extent thereof must be declared at the time of submission in the cover letter.

In addition, the use of AI that was used in the methods of the study have to be detailed in the methods section of the manuscript.

The use of AI not included in the methods should be declared at the end of the manuscript.

The declaration of AI usage in the cover letter and the manuscript should include the name, version, and manufacturer of the tool used, and the date on which it was accessed, for example:
(JenniAI, Version 02 July 2022, Open AI, accessed 16 May 2024)

If authors declare their use of AI, it creates transparency and trust between them and their reviewers, editors and readers.

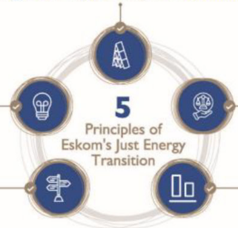
Any submission found to include inappropriate use of AI will be declined [or retracted if already published] and the Clean Air Journal's Ethics and Malpractice Statement will come into effect.

Table 1: *Guidelines for appropriate use of AI tools and resources*

Task	AI can be used	AI use must be disclosed
Writing or generating any part of the manuscript	No	N/A
Creating images (excluding graphs based on study data provided by the author (see data analysis below))	No	N/A
Modifying data images e.g. remote sensing images, SEM images, model outputs	No	N/A
Conception and design of the study e.g. “Evaluate the study protocol to identify possible confounding factors”.	Yes	Yes
Editing, translating and summarising papers or large reports e.g. “Provide recommendations to improve text readability, and paragraph enhancement.” e.g. “Edit text to reduce to 250 words while preserving content, intention and clarity”	Yes	Yes
Editing, translating and summarising papers or large reports e.g. “Provide recommendations to improve text readability, and paragraph enhancement.” e.g. “Edit text to reduce to 250 words while preserving content, intention and clarity”	Yes	Yes
Data analysis (e.g. asking AI to create graphs from data collected in the study and provided to AI by the author)	Yes	Yes
Editing non-data images	Yes, provided the integrity of the image is retained	No
Grammar and spell checking and copyediting	Yes	No
Similarity checking tools (e.g. using Turnitin to check before submission)	Yes	No
Reference managers	Yes	No

Our vision for a Just Energy Transition enables job creation and growth

Our JET strategy has five underlying principles



Balancing all elements of energy trilemma: energy security, access, and sustainability

Decoupling Repurposing and Repowering initiatives from decommissioning schedules

Embodying principles of Distributive, Restorative and Procedural Justice

Making decisions flexibly and dynamically to respond to changing context

Aligning with both national and Eskom priorities to ensure success

Our JET vision will enable growth, create jobs and increase competitiveness in a future net-zero world

Demand side response

Distribution grid enabled for consumer responses to fluctuations in supply, and for sale of consumer-owned RE back to the grid

Firm capacity

Wind and PV constructed with storage, and grid network adapted to increase stability

Seasonal peaking power

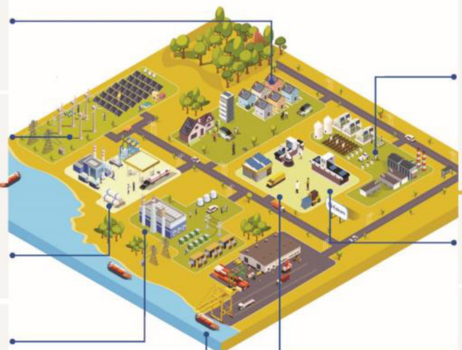
Gas used as transitional peaking fuel until cleaner technologies emerge (e.g. SMR nuclear)

Daily peaking power

Batteries and pumped hydro for short term power storage

Trade

Export industries receive low-carbon power, allowing them to complete globally despite globally increasing carbon-border taxes



Older generation

Residual traditional nuclear and newer coal plants maintained until replaced, but ultimately phased out

Decommissioned coal plants **repurposed** (e.g. agrivoltaics, training facilities, new manufacturing centres etc.) or **repowered** (into new RE plants) bringing new, jobs to communities

Industry

Industry and commerce grows with access to reliable, abundant and affordable power

Socio-Economic Development

New training centers prepare the workforce for new jobs created in the economy, supporting innovative small businesses creating local value

Our JET strategy will create new, high quality jobs in South Africa, such as:

RE plant operator operates and maintains power producing equipment

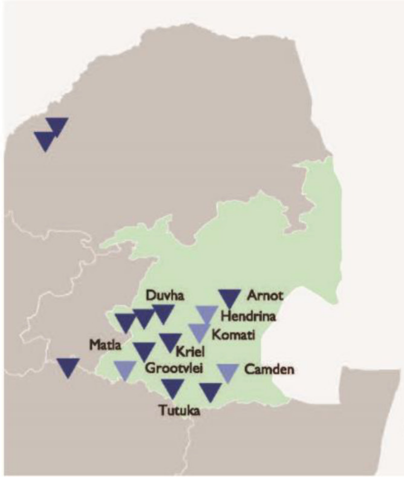
Solar water system plumber installs, repairs, and maintains water systems

Laboratory assistant supports tests and research for bioenergy solutions

Horticulture specialist helps develop agrivoltaics, aquaponics, hydroponics

Eskom is making progress towards a Just Energy Transition for South Africa

We will repower and repurpose to create local opportunities



Starting with Mpumalanga's oldest coal plants, we will...

Repower coal plants by leveraging existing infrastructure to build new generation capacity including solar, wind, gas turbines, or synchronous condensers

Repurpose coal plants into new centres of economic activity including training centres, water treatment facilities, manufacturing plants, microgrid assembly and modern farms

Unlock transmission and distribution capacity by investing in sub-stations and transformers in a province where solar resources are high by global standards

Ensure a Just Transition for local communities through the Repurposing and Repowering activities that will help to retain economic activity, creating jobs and new economic opportunities

▼ Coal plant operation post 2035 ▼ Coal plant to be R&R'ed by 2035

The largest just repowering and repurposing project in the developing world is already underway at Komati Power Station

Three projects in progress

- **Komati Training Facility** capacitates local community and Eskom with renewable energy capabilities and diversified jobs
- **Agrivoltaics Plant** combines solar power, battery storage, and agricultural activities, acting as an incubator for agriculture SMMEs
- **Containerised Microgrid Assembly** creates a broad array of new jobs, including welders, painters, electricians and more

New project in development

- **Copper Recycling Facility** extracts copper from existing coal plants to recycle and beneficiate for use in renewable energy

Impact by 2030

~660 — **Direct, sustainable jobs** created in repowering and repurposing work at Komati Power Station

~8700 — **Additional temporary jobs** created mainly in work related to construction and decommissioning

~300 — **MW Generation Capacity** added, replacing 100 MW of Komati operational capacity when decommissioned

~R1.3b — **Total contribution so South Africa's economy** from Komati Repurposing and Repowering can be achieved

~$0.5b — **Funding** secured from the World Bank for Komati Repurposing and Repowering initiatives

Note: Precise figures may vary between now and 2030

Eskom

Research brief
Africa's greenhouse gas emissions exceeding its sink capacity

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Abstract
Rising greenhouse gas (GHG) emissions in Africa is a cause for concern. With a growing population and its associated requirements for energy, food and socio-economic development, climate change impacts will further exacerbate the current trend. A recent greenhouse gas budget for Africa synthesised the most current and comprehensive modelling and observational data available for the period 2010-2019 (Ernst et al. 2024), showing that the continent has likely become a net carbon source to the atmosphere. In this Research brief, the key findings of the GHG budget for Africa is highlighted.

The most recent GHG budget for the African region, as part of the Regional Carbon Cycle Assessment and Processes Phase II project (RECCAP2) aimed to interrogate the most recent GHG flux estimates using bottom-up approaches and reconciling these estimates with top-down atmospheric inversion estimates. This synthesis improved on the previous budget through incorporating novel methodologies, new African-specific data sets and including improved estimates of the contributing component fluxes. The components with improved estimates included (among others) geological and aquatic fluxes, emissions from termites, peatland loss rates, fire emission estimates and lateral fluxes, but the final estimates highlighted that emissions from land use change (1.7 (0.8/2.7) $PgCO_2eq\ yr^{-1}$) and fossil fuels (1.74 (1.53/1.96) $PgCO_2eq\ yr^{-1}$) were the most influential components impacting the budget.

Despite terrestrial ecosystems continuing to support a large CO_2 sink of an average of 0.8 billion tons of carbon (~20% of the global land CO_2 sink), land conversion in the form of agricultural expansion and intensification has increased substantially. As this key component is expected to contribute significantly into the future and is still associated with high uncertainty, it will require directed effort to improve categorisation of land use and land cover data at finer spatial and temporal resolutions, and increased field observations to verify satellite products.

Closely associated with the land component, emissions from wildfire (46% and 65% contribution to the global fire emissions) decreased over the period, but the authors point out that land conversion for agricultural purposes and increasing methane emissions from livestock (0.48 (0.248/0.585) $PgCO_2eq\ yr^{-1}$) could substitute the estimated decrease. Importantly, fuelwood burning has increased over the period and is expected to continue to grow while African countries struggle to meet energy demands.

The updated GHG budget is key to identify the most important aspects for mitigation and management. Shifts to carbon neutral energy sources can possibly remove up to 30% of the current fossil fuel emissions, but emissions from land use change are more challenging to reduce. For Africa to meet its own climate responsibilities and unlock potential from the increasing international carbon trade demand (e.g. Jones, 2023; Yang et al., 2023), the continents' development trajectory will have to move swiftly towards carbon-neutrality. This will however require policy development and implementation, as well as global commitment for financial and technical support to address the socio-economic challenges that hinder climate mitigation progress. Coupled with this, the uncertainties in the budget highlight the need for the expansion of the GHG observation network across Africa, intensifying field observations and empirical studies, development of models specific to the African context and enabling more consistent reporting in national data inventories.

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Research article

Monitoring the trends in emissions from coal-fired power stations in Lephalale (Limpopo) during the 2010-2022 period using remotely sensed data

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Abstract

This study uses datasets from the Sentinel-5P, Modern Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), Ozone Monitoring Instrument (OMI) and Goddard Earth Observing System with Chemistry Model (GEOS-Chem) to investigate the spatial and temporal distribution of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon dioxide (CO_2) and carbon monoxide (CO) in the town of Lephalale, South Africa. Lephalale has two active coal-fired power stations which continuously releases SO_2, NO_2, CO_2 and CO. Within the 2010-2022 period of the study, it was found that SO_2 and NO_2 had the most significant trend of increase from 2010-2019, and decreased from 2020-2021 due to the COVID-19 global pandemic. CO_2 and CO kept a fluctuating trend between the 2010-2022 study period. The results of the study showed that the poor air quality in Lephalale is consequential of these emissions by coal combustion. Most importantly, if no mitigation measures are taken and strictly followed by coal mines and electricity generators, the lives of the people in and around Lephalale and Limpopo province will be severely affected.

Keywords

emission, Sentinel-5P, MERRA-2, air quality, coal-fired power station

Introduction

Global emissions from fossil fuel use, mainly coal combustion, have been one of the most significant causes of environmental and atmospheric damage, significantly impacting human health (Farzad et al., 2021). A notable amount of these emissions are greenhouse gasses (GHG) and particulate matter (both $PM_{2.5}$ and PM_{10}) that are a result of the generation of electrical power (Duncan et al., 2014; Albers et al., 2015). In 2020, there were 18 coal-fired power stations in South Africa, all owned by Eskom, the country's sole electricity producer and generating over 80% of the national grid's electricity (Winning, 2021). With so many coal-fired power stations, Winning (2021) denotes that the country holds the 12th position in the world's list of greenhouse gas emitters. In addition, Shikwambana et al. (2020) noted that South Africa and other countries, including India and Brazil, were among the top 20 on the list of greenhouse gas emitters. Amongst these 18 coal power stations, a prominent number are in the Highveld region and thus serve as hotspots for the country's most significant greenhouse gas emissions (Shikwambana et al., 2020). One of these coal-fired power stations is located in the Waterberg-Bojanala Priority Area (WBPA) in the Limpopo province, outside the town of Lephalale. The very first construction of the power station began in 2007, and according to Marcatelli (2020), it was to be completed in 2020. Still, its completion and full use were only a year after the estimated completion. The WBPA was initially designated as an air quality priority area due to the potential risks of future air pollution. It has since become a recognized air pollution hotspot. The primary sources of emissions in this area include mining, industry, residential activities, motor vehicles, and biomass burning (Wernecke et al., 2023).

GHG emissions caused by the complete and incomplete coal combustion for electricity generation have been a notable problem in South Africa and other global countries and promise to persist if there are no reductions to emissions and a shift to cleaner energy sources (Barnes et al., 2009; Jiang et al., 2022). Power stations worldwide have struggled to develop ameliorative measures to better the scourge of pollutants. This greatly affects communities near and around these coal-fired stations and, to a greater extent, the world. If not adequately mitigated, the combustion and subsequent gasses and particulate matter pose dangerous health risks to human health. These risks are significant and lead to morbidity and premature mortality among the young and the old as they are more vulnerable to respiratory, brain and lung death-related illnesses (Gupta et al., 2006; Lelieveld et al., 2019). As significant as these are, research centred on the main study – the Medupi Power Station – is quite limited and does not give extensive evidence to account for the station's impact on air quality in surrounding communities.

Arowosegbe et al. (2022) and the World Health Organization's report of 2012 noted that 87% of the 3 million deaths that same year were due to air pollution in low and middle-income countries as these had higher air polluting emissions. Africa is no exception to these high rates as it is a less developed continent with few resources to rehabilitate and manage the environment repeatedly to reduce the effects over time. Reports urging for the transition from fossil fuel energy to clean, renewable energy sources have termed Algeria, Nigeria, Morocco, Egypt and South Africa as 'Africa's Big Five', as these five countries are the biggest consumers of fossil fuels, particularly coal, for energy generation (Mutezo and Mulopo, 2021). Furthermore, South Africa is regarded as the continent's biggest greenhouse gas emitter because it is the most industrialised country in Africa, which has put a toll on the atmospheric environment and people's lives (Shikwambana et al., 2020).

The objectives of this study are (1) to assess the long-term time-series trends of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon dioxide (CO_2) and carbon monoxide (CO) emissions in the Limpopo province for the period 2010 to 2022, (2) to map the spatial distribution of SO_2, NO_2, CO and CO_2 in the Limpopo province, and (3) to provide recommendation of the transitional shift from non-renewable to cleaner energy, thereby protecting the environment.

Study area

The province of Limpopo is located in the northern-east of South Africa (see Figure 1) and is the fifth biggest in the country. According to Köppen and Geiger, the province is classified as Cwc, as it is temperate with summer rainfall and hot summers between October and April (Peel et al., 2007; Rapolaki et al., 2021). Lephalale (23.66°S, 27.74°E) is located northwest of the Limpopo province. It is found in the Waterberg-Bojanala Priority Area and is home to two power stations: the Medupi Power Station and the Matimba Power Station. A coal mine, Exxaro Groogeluk, provides coal to both power stations through a conveyor belt (Muthige, 2013). Unfortunately, Medupi and Matimba Power Stations are located in a rural location where most of the population is uneducated about their hazardous surroundings to the byproduct emissions in Lephalale (Shamuyarira & Gumbo, 2014)

Data and method

Sentinel-5P (Precursor)

The Sentinel-5 Precursor (Sentinel-5P) was developed by the European Space Agency (ESA) and launched on 13 October 2017 (Shami et al., 2022). The Tropospheric Monitoring Instrument (TROPOMI) is the instrument on board the Sentinel-5P satellite. Its role is to detect trace gasses using three streams: near-real-time (NRTI), offline (OFFL) and reprocessing (RPRO). TROPOMI has a spatial resolution of 3.5 × 7 km^2 and a swath width of 2600 km, allowing global atmospheric coverage (Shikwambana et al., 2020). In addition, it comprises a temporal resolution of less than a few hours, passing by an area and providing data on it twice a day (Theys et al., 2019). TROPOMI is made up of seven spectral bands being: ultraviolet (UV-1) (270-300 nm) and (UV-2) (300-370 nm), visible (VIS) (370-500 nm), near-infrared (NIR-1) (685-710 nm) and (NIR-2) (745-773 nm), shortwave (SWIR-1) (1590-1675 nm) and (SWIR-3) (2305-2385 nm) (Theys et al., 2019). Before and after its launch, its mission is to monitor ultraviolet (UV) radiation, the incidence of ozone (O_3) in the atmosphere, atmospheric air quality and climate. TROPOMI measurements include SO_2, NO_2, CO, O_3, CH_4 and formaldehyde (CH_4O) (Shami et al., 2022). More details on sentinel-5P are found in Theys et al. (2019), Tilstra et al. (2020) and Verhoelst et al. (2021). The data used in this study is between 2018 and 2022.

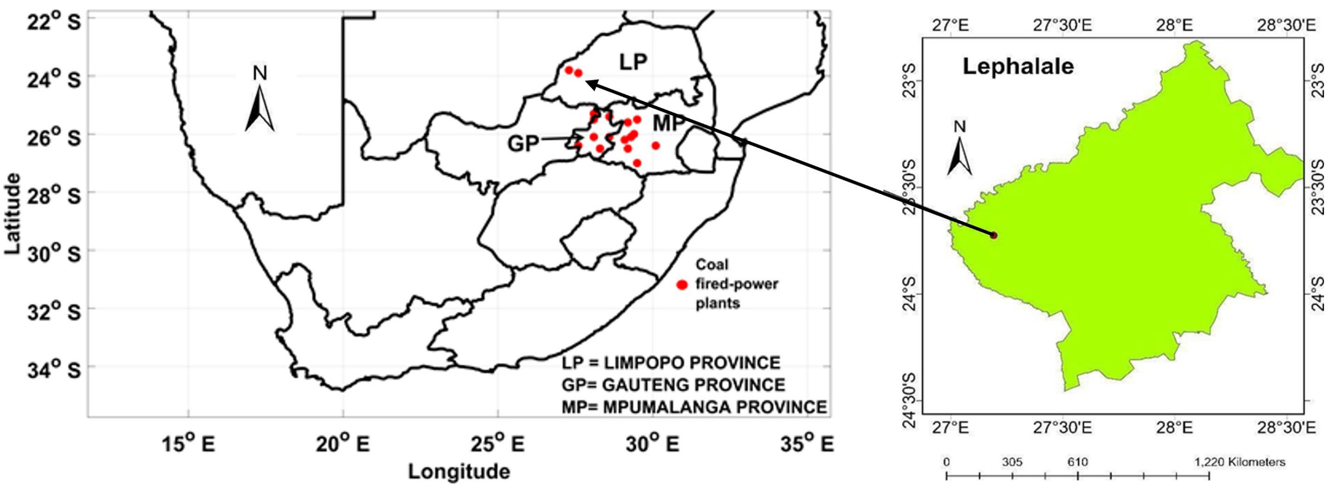

Figure 1: *Map showing the coal-fired power stations that serve as SO_2, NO_2, CO and CO_2 emitters in Limpopo and South Africa*

MERRA-2

Modern Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) is a reanalysis of the modern satellite era launched by NASA's Global Modeling and Assimilation Office (GMAO) on 1 January 1980. For its full function, it includes the Goddard Earth Observing System, version 5 (GEOS-5) and the Atmospheric Data Assimilation System (ADAS), version 5.12.4 satellites, and using these sustains GMAO's commitment to near-real-time (NRTI) climate analysis (Shikwambana et al., 2020). It can separate different aerosols from one another, especially GHGs, and measures surface temperature, air temperature and wind speed (Gelaro et al., 2017; Shikwambana et al., 2020). The MERRA-2 satellite uses a cubed-sphere latitude by longitude spectral resolution of 0.5° × 0.625° and 72 hybrid-eta layers from the Earth's surface for configuration (Gelaro et al., 2017). More details on MERRA-2 can be found in Gelaro et al. (2017), Buchard et al. (2017) and Randles et al. (2017). The data used in this study is between 2018 and 2022.

OMI

The Ozone Monitoring Instrument (OMI) is a satellite instrument launched aboard the Earth Observing System (EOS) on 15 July 2004. It is driven by the European Global Ozone Monitoring Experiment (GOME) and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) (Levelt et al., 2006). It measures solar radiation that is reflected using spectral bands ultraviolet (UV-1) (270-310 nm), (UV-2) (310-365 nm) and visible (VIS) (365-500 nm) (Levelt et al., 2006). Through these spectral bands, this satellite sensor can measure trace aerosol gasses like SO_2, NO_2, HCHO, O_3 and UV radiance (Mokgoja et al., 2023). OMI has a spatial resolution of 13 × 25 km^2 and a daily temporal resolution. More details on the OMI can be found in Boersma et al. (2002), Bucsela et al. (2006), Levelt et al. (2006), and Levelt et al. (2018). The data used in this study is between 2018 and 2022.

GEOS-Chem

The Goddard Earth Observing System with Chemistry Model (GEOS-Chem) is a global 3-D model of atmospheric chemistry driven by meteorological inputs. The model output is a set of quantities, such as tracer concentrations in every grid cell (Miatselskaya et al., 2022). The near-real-time GEOS Forward Processing (GEOS FP) output provides data globally at a horizontal resolution of 0.25°×0.3125° (Fritz et al., 2022). Bey et al. (2001) describe the standard application of the GEOS-Chem model. The data used in this study is between 2015 and 2021.

SQMK test

Sneyers first used the Sequential Mann-Kendall (SQMK) test in the 1990s to detect any change between a significant trend's starting and ending period (Sneyers, 1990). This test has two series of analyses, a progressive $u(t)$ and a retrograde $u'(t)$ series. With these, the test detects the beginning of a significant change and trend (Mosmann et al., 2004). More details on the SQMK test can be found in Mosmann et al. (2004) and Lu et al. (2004). The SQMK test has the following steps:

I. At each comparison, the number of cases $x_i > x_j$ is counted and indicated by n_i, where x_i $(i=1,2,...,n)$ and x_j $(j=1,2,...,n)$ are the sequential values in a series, respectively.

II. The test statistic t_i is calculated by

$$t_i = \sum_{j=1}^{i} n_j \quad (1)$$

III. The mean $E(t)$ and the variance $\mathrm{var}(t_i)$ of the test statistic are calculated by

$$E(t) = \frac{n(n-1)}{4}, \quad (2)$$

$$\mathrm{var}(t_i) = \frac{i(i-1)(2i+5)}{72}. \quad (3)$$

IV. Sequential progressive value can be calculated as

$$u(t) = \frac{t_i - E(t)}{\sqrt{\mathrm{var}(t_i)}}. \quad (4)$$

Similarly, the values of u'(t) are computed backwards, starting from the end of the series.

Results

Sentinel 5P-spatial distribution

Figure 2 shows the presence and incidence of SO_2 in Lephalale, with 2018 showing a more increased gas dispersion. The year 2019 shows a slight increase from the previous year, caused by the high demand for electricity throughout the year and the cold weather during the winter months (Shikwambana et al., 2020). Between 2020 and early 2022, the world was riddled with the COVID-19 pandemic, affecting South Africa and halting many economic activities and movements (Kganyago and Shikwambana, 2020). This affected the production and distribution of electricity, thus decreasing the spatial distribution of SO_2 by the two most productive coal-fired power stations in Limpopo. Although no real column density values in mol/m^2 are presented (the units of measurement for gas column densities), these are replaced by the "minimum" and "maximum values", which essentially show how highly concentrated the municipality of Lephalale, the province of Limpopo and regions nearby are by NO_2, SO_2 and CO. Based on Figure 2, it is clearly evident that all the years between 2018 and 2022 have had varying concentrations of SO_2, with 2018 showing more spatial distribution than the other four years preceding it. We anticipate that meteorological parameters like high wind speeds or slightly higher temperatures could be responsible for the higher spatial distribution of SO_2 in 2018.

In Figure 3, 2018 and 2019 depict a fluctuation trend, with a slight difference in their column densities. Similar to SO_2, the spatial distribution of NO_2 is slightly higher in 2018 than in 2019. Again meteorological parameters are the possible drivers for this. Succeeding these are 2021 and 2022, both having picked up their NO_2 emission rates rapidly after the 2020 lockdown period, where there was little need and usage of electricity

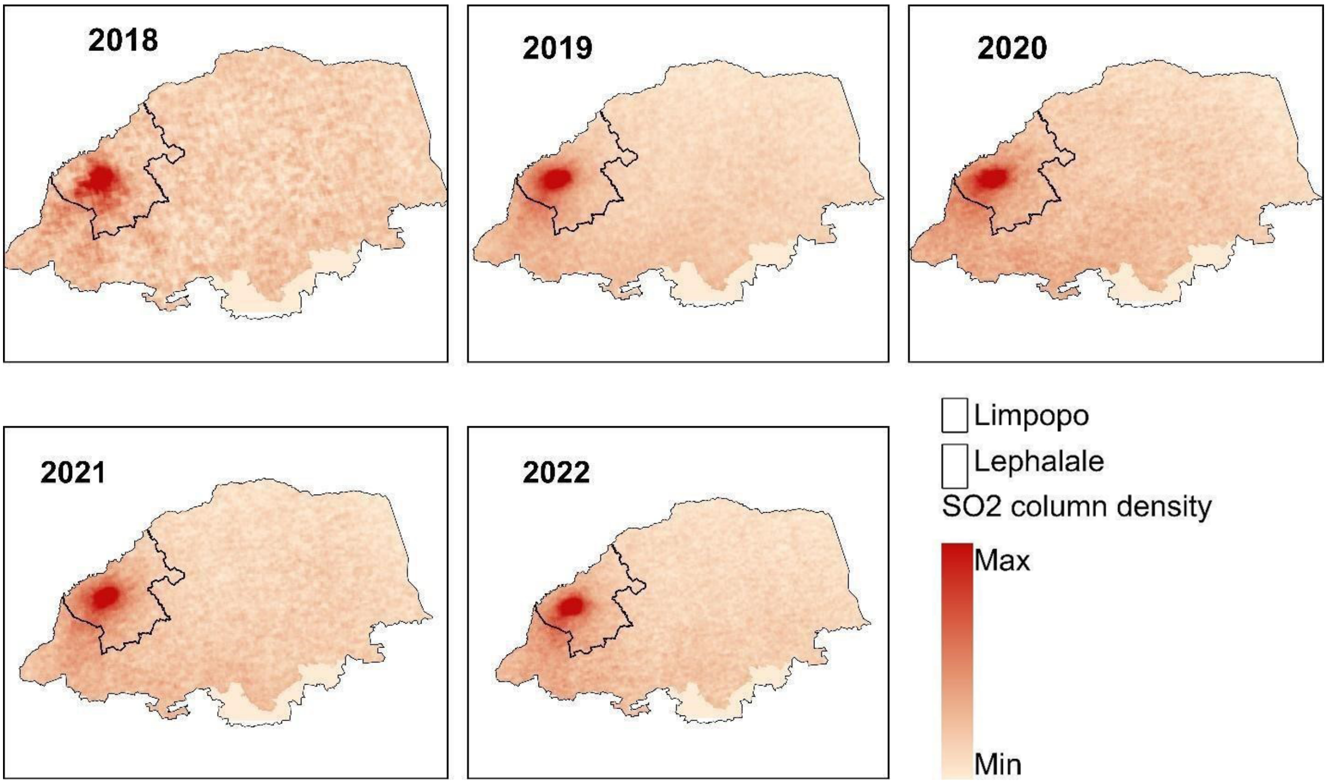

Figure 2: *SO_2 column density (mol/m^2) trends over Lephalale from 2018-2022 from Sentinel-5P.*

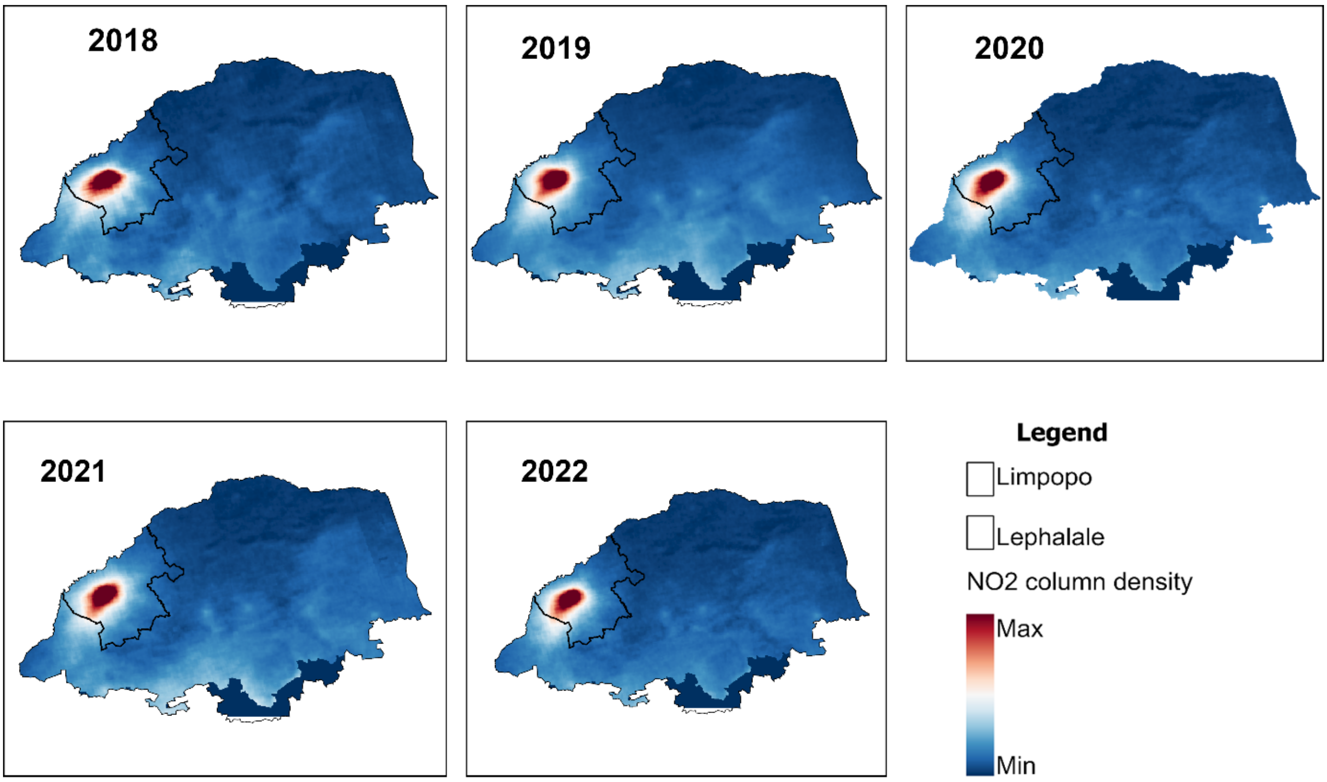

Figure 3: *NO_2 column density (mol/m^2) trends over Lephalale from 2018-2022 from Sentinel-5P.*

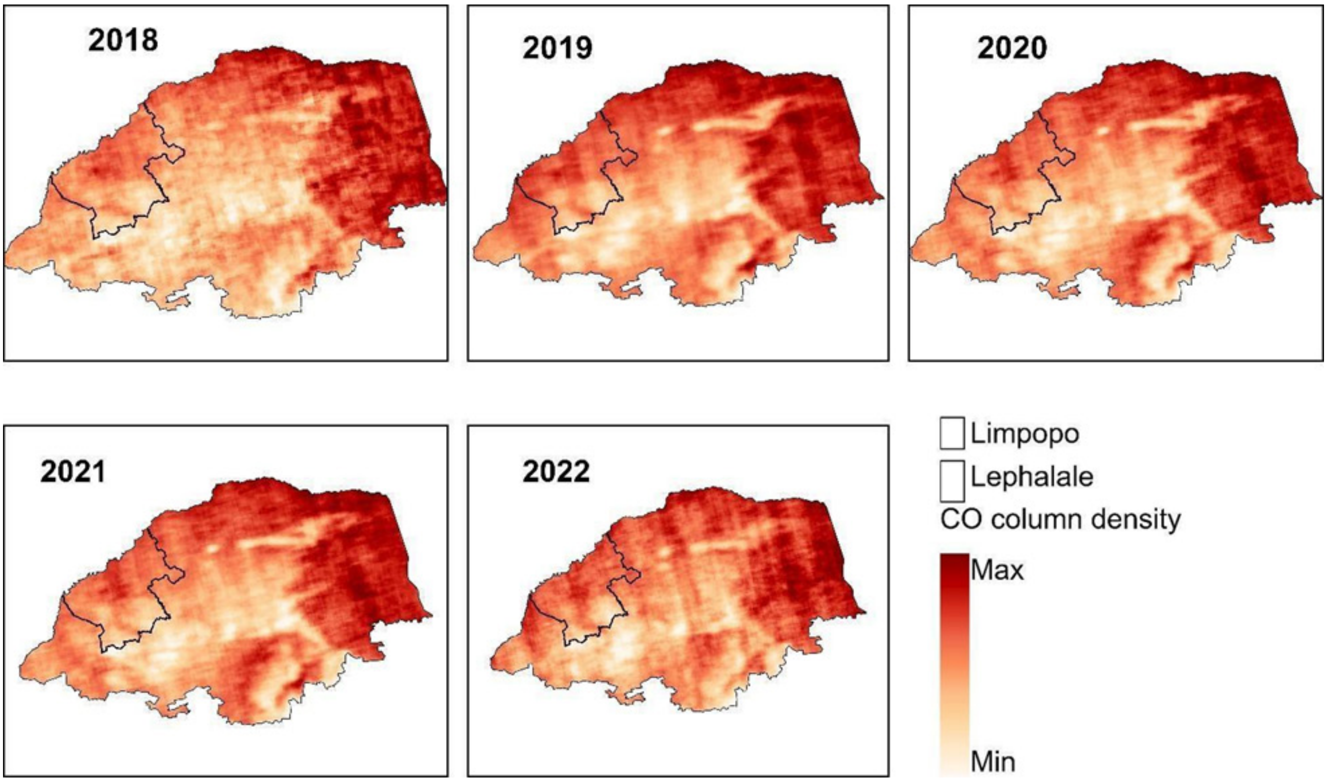

Figure 4: *CO column density (mol/m²) trends over Lephalale from 2018-2022 from Sentinel-5P.*

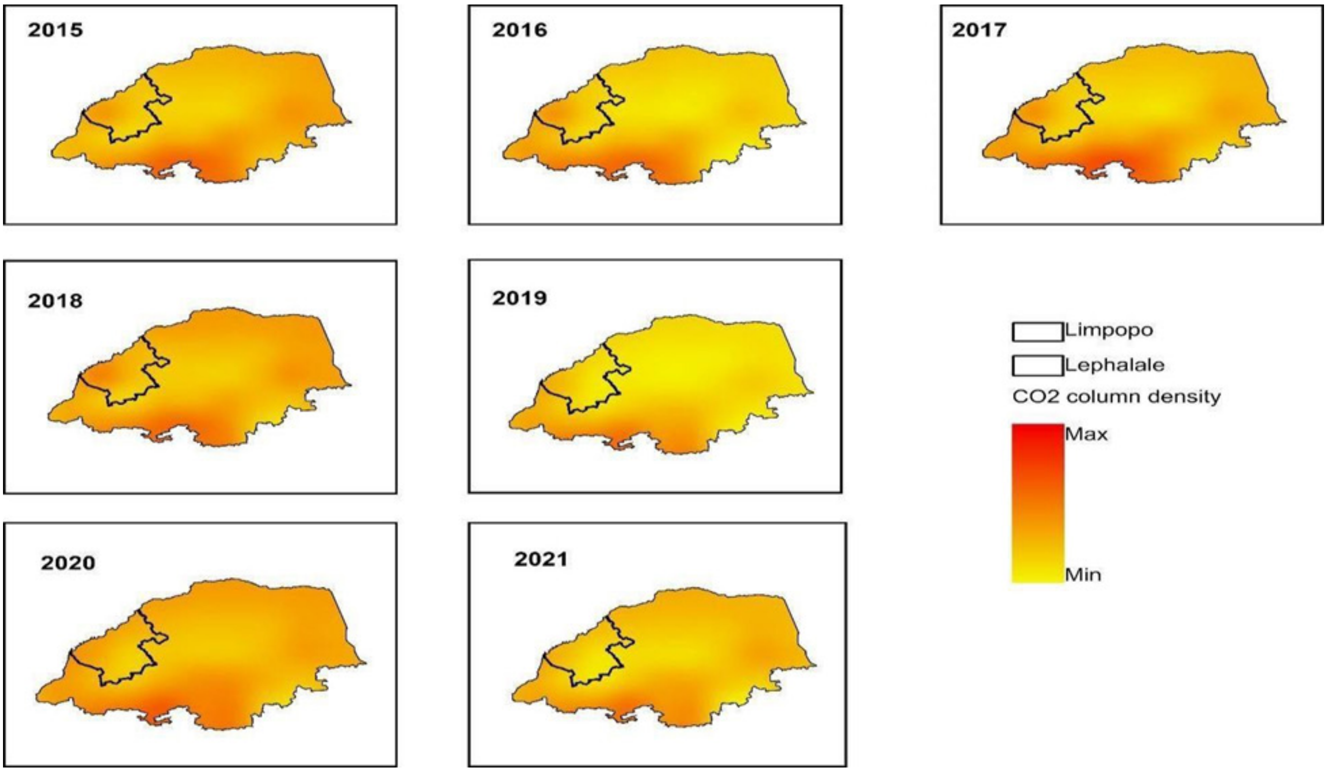

Figure 5: *CO_2 column density (mol CO_2/ mol dry) trends over Lephalale from 2015-2021, as observed by GEOS-Chem.*

for any economic activity, and traffic was controlled, but more emissions from the burning of biomass agricultural land (Kganyago and Shikwambana, 2020). These are displayed by the column densities, seen in the minimum and maximum descriptions in Figure 3. The year 2018 is seen to have a greater maximum value of NO_2, followed by 2019. During the same 5-year period, 2020 and 2021 had a lower column density caused by the halting of economic activities due to the global pandemic. However, fossil fuels were still being burnt in households as winters and autumns in Limpopo were harsh (Rapolaki et al., 2021). Overall, compared to the incidence of SO_2, NO_2 column density decreased due to the possible change to low NO_x coal for less and safer emissions (Shikwambana et al., 2020).

Figure 4 shows the spatial distribution of CO in Lephalale. The years 2020 and 2021 have an equal distribution of CO in and around the study area and its broader location. The years with the highest column density range between 0.0256614 mol/m^2 and 0.0314215 mol/m^2 (not shown in Figure 4). The year 2018 has the least CO column density, followed by 2019 and 2022. A cause of these fluctuations could be due to meteorological factors like wind and temperature. But 2018-2022 had little wind and rain, and 2020-2021 were drought years, these factors might have contributed towards the concentrations and spatial distribution of the CO. Overall, there is no significant presence of CO in Lephalale from the power stations.

Figure 5 shows the CO_2 spatial distribution for the years 2015 to 2022. The years 2015-2018 have the most negligible column density of CO_2, ranging between 0.00039853 mol/m^2 – 0.00040602 mol/m^2 of the maximum value and 0.000398252 mol/m^2 – 0.000405739 mol/m^2. These could be owing to a stable atmosphere and fewer economic activities, thus affecting the country's GDP. Table 1 also provides evidence that during these years, access to electricity and the amount of CO_2 emissions in South Africa, as provided by the World Bank, were amongst the lowest. From 2019-2021 onwards, there is a steady rise in these emissions, with column density ranging between 0.00040861 mol/m^2 – 0.000413503 mol/m^2 of the maximum and 0.000409091 mol/m^2 – 0.000412969 mol/m^2.

Trend analysis

The Sequential Mann–Kendall (SQMK) trends are presented in Figures 6–9, with the red line representing the progressive series, whereas the blue line represents the retrograde series. The confidence interval for this test is set at $\alpha = 0.05$ (± 1.96). The solid black line represents the upper bound (+1.96), whereas the lower bound (-1.96) is represented by the square dotted black line. The point at which the red and light blue lines intersect indicates an abrupt change and the year in which the change occurred. A significant trend is observed when the progressive series crosses the lower or upper bounds. In contrast, an insignificant trend is observed when the progressive series is within the upper and lower bounds. The SQMK trends are over the Lephalale region.

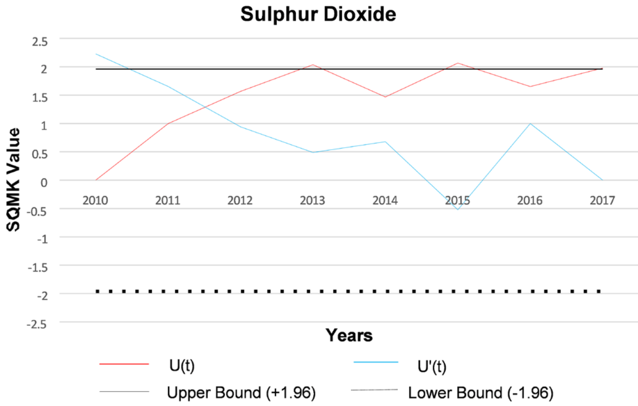

Figure 6: *SQMK trends for SO_2 column density in Lephalale between 2010 and 2017.*

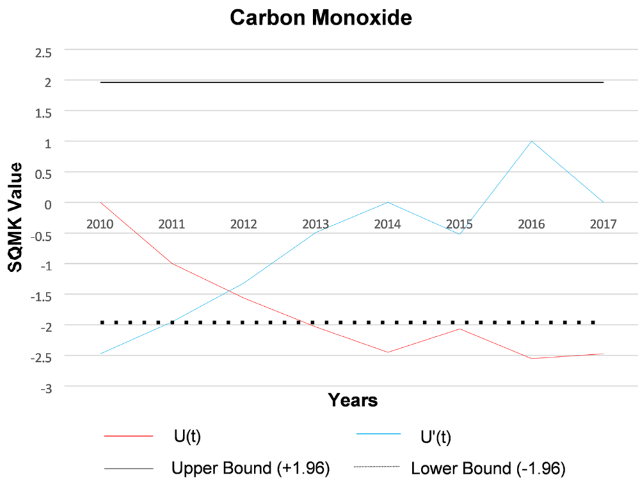

Figure 7: *SQMK trends for CO column density in Lephalale between 2010 and 2017.*

Figure 6 shows a trend of the SO_2 column density from 2010 to 2017 in Lephalale. It shows an increasing trend from the later months of 2010 until 2013. From 2014 onwards, there has been a fluctuating trend in the emission of SO_2: a gradual decline in 2014, a gradual increase in 2015, a decline from then into 2016, and then emissions pick up again into 2017. This steady rise between 2010 and 2013, as having been mentioned before, may strongly have been due to the transfer of emissions between Mpumalanga and Limpopo, affecting the presence of GHGs in both provinces. Fluctuations between 2013 and 2017, wherein

Table 1: *Yearly rates of the percentage of the population with access to electricity and the amount of CO_2 emissions in a thousand tons in South Africa from 2010-2021 (World Bank, 2023).*

Indicator	2015	2016	2017	2018	2019	2020	2021
Access to electricity (% of population.)	85.3	83.9	84.4	84.7	85	90	89.3
CO_2 emissions (kt)	425063	425683	435215	439645	446626	393242	------

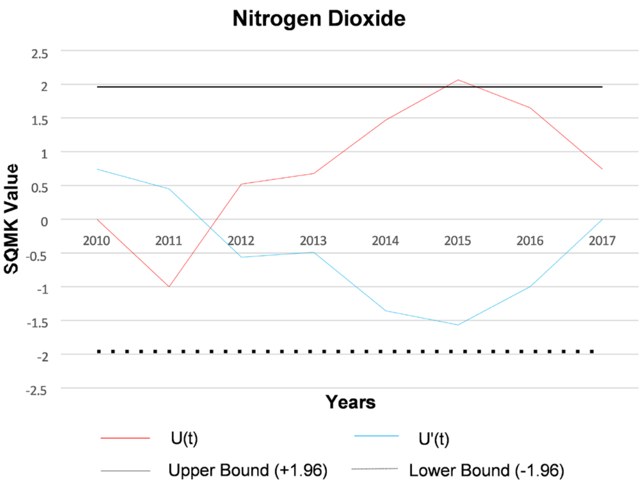

Figure 8: *SQMK trends for NO_2 column density in Lephalale between 2010 and 2017.*

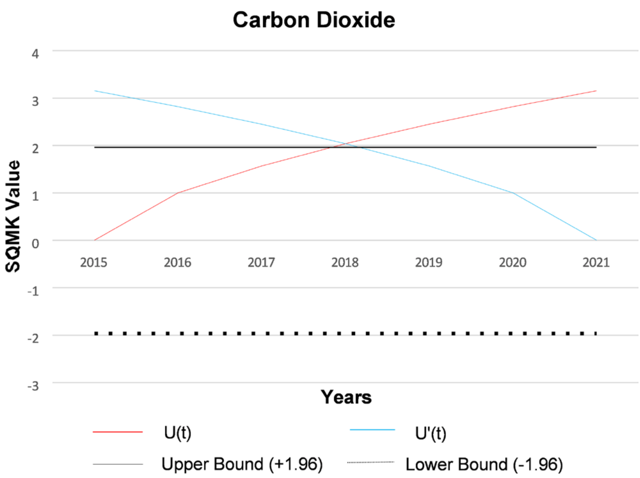

Figure 9: *SQMK trends for CO_2 column density in Lephalale between 2010 and 2017.*

their column densities and trend lines are still higher than pre-2013, are a result of the full electricity generation of coal-fired power stations and the full operation of coal mines, the Grootegeluk in particular (Shikwambana et al., 2021). Thus, change seems to contradict itself as the *u(t)* and *u'(t)* intersect within the two boundary layers, showing insignificant change in the emissions of SO_2, while the years 2013 and 2015 cross over a little beyond the upper boundary layer, which is interpreted as significant change.

The spatial distribution of carbon monoxide, as shown in Figures 5 and 7, is not quite apparent, especially within Lephalale, where the Medupi Power Station is located. However, it is quite noticeable within just Limpopo. That said, a large amount of CO present within the study area is undoubtedly due to the burning of biofuel and biomass more than it is due to fossil fuel burning (Kumar et al., 2011; Shikwambana & Tsoeleng, 2020). As it stands, there is no evident trend change of CO in Lephalale because, even though both progressive and retrograde intersect within boundary layers (insignificant change), only the retrograde series extends beyond the (lower) boundary layer; there is no clear beginning of a trend or significant change in its occurrence.

Figure 7 shows no evident trend change of CO in Lephalale. Even though both progressive and retrograde intersect within boundary layers (insignificant change), only the retrograde series extends beyond the (lower) boundary layer, and there is no clear beginning of a trend or significant change in its occurrence. A large amount of CO present within the study area is undoubtedly due to the burning of biofuel and biomass more than it is due to fossil fuel burning (Kumar et al., 2011; Shikwambana & Tsoeleng, 2020).

Figure 8 shows the column density trend of NO_2 in Lephalale between 2010 and 2017. It shows considerable significant changes in column densities within the study period. Between 2010 and 2011, a significant decline dropped in 2011. The years 2011 to 2012 show a steep increase in the emissions of NO_2, followed by a gradual increase in 2013 and a significant increase between 2013 and 2015. This is followed by a trend of insignificance resulting from coal combustion and agricultural fires, just like SO_2 (Opio et al., 2021). Overall, an insignificant change in the emissions and presence of NO_2 is detected.

The trend in Figure 9 shows CO_2 column densities between 2015 and 2021. The progressive trend line shows a steep increase in the emissions of CO_2 from 2015 to 2016. From there onwards, there will be an even steeper increase in these emissions up until 2021. This is quite interesting because economic activities, including trade and manufacturing, were halted from the end of 2019 until 2021 due to the global pandemic. However, a large portion of this change is due to burning natural gas, electricity production, and burning of biomass and fossil fuels as many people stay home, leading to more household activities than usual. There is an immense significant change in the time-series distribution of CO_2 in Lephalale. The increase in CO_2 is statistically significant from 2018 onwards.

Discussion

GHGs serve as proxies for economic growth and reflect the pace of a country's industrialization (Shikwambana et al., 2021). While this correlation may offer insights into the necessary adjustments for meeting economic objectives, it also highlights a significant risk to public health, particularly with regard to premature morbidity and mortality rates. Limpopo, home to the Medupi and Matimba Power Stations, has seen a rise in energy and transportation industries, contributing to elevated GHG emissions in the province and across South Africa (Seloa & Ngole-Jeme, 2022). Air quality data from Lephalale and Limpopo reveal high levels of NO_2, SO_2, CO_2, and CO, underscoring the environmental hazards associated with coal combustion. South Africa is not alone in facing these challenges; other countries experiencing economic growth also struggle with air pollution and its detrimental effects on public health (Mokgoja et al., 2023).

South Africa's reliance on fossil fuels and solid biomass for energy is well-established (Akinbami et al., 2021; Obileke et al., 2024), driven by a growing population and rapid urbanization, which increases the demand for energy and industrial development (Nuissl & Siedentop, 2021). A significant portion of emissions comes from the burning of coal for electricity generation, especially in urban and expanding rural areas in South Africa and worldwide (Runsten et al., 2018). For instance, Australia in the Global North generates over 70% of its electricity from coal, while South Africa relies on coal for more than 77% of its electricity needs (Ncipha & Sivakumar, 2022). The key difference lies in population density: while Australia's smaller population enjoys more widespread access to electricity, South Africa faces challenges in equitable distribution, as shown in Table 1.

Although emissions of NO_2, SO_2, CO_2, and CO exceed recently established environmental standards, significant disparities remain in electricity access across South African households (see Table 1). This indicates that efforts to reduce emissions must continue to close the gap in electricity distribution. Despite ongoing discussions on transitioning to green energy for over a decade, South Africa's environmental policies, such as the National Environmental Management: Air Quality Act (NEM: AQA) 39 of 2004, the National Environmental Management Act 107 of 1998, and the National Ambient Air Quality Standards (NAAQS), must be rigorously enforced and strengthened. These measures are crucial to ensure the protection of air quality for all citizens and reduce harmful emissions, ultimately safeguarding the atmosphere and public health (Mokgoja et al., 2023).

Conclusion

This study used remotely sensed data to investigate the spatial and temporal distribution of SO_2, NO_2, CO_2 and CO in Lephalale. This was to illustrate the impact coal-fired power stations have on Limpopo, particularly the Medupi Power Station. The spatial distribution maps showed that the pollutants were due to the operation of the Medupi and Matimba Power Stations. The SQMK trends show that the emissions fluctuate; the year 2010 for SO_2, NO_2 and CO_2 is the beginning of the rise in the atmospheric presence of these gases. Thus, it can be concluded that the air quality in Lephalale is a consequence of these emissions from coal combustion. In addition, if no mitigation measures are taken and strictly followed by coal mines and electricity generators, the lives of the people in and around Lephalale and Limpopo will be severely affected.

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Data statement

The data used in the study is freely available on the NASA Giovanni data portal.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

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Ethical approval

The University of the Witwatersrand granted the ethical approval for the research.

Consent to participate

No participants were involved in this research.

Consent to publish

No consent to publish is required for this research.

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The learning outcomes of this programme will allow graduates to successfully quip themselves with environmental management and air quality management skills especially those in the sector responsible for management, governance and strategic decision making.

MISSION STATEMENT

The programme aims to build capacity and skills within the air quality and climate change sectors. This is achieved through multi-disciplinary and international training collaboration.
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This course consists of 3 modules:

- **OMBO886:** Atmospheric Emissions and Impacts (40 Credits)
- **OMBO887:** Air Quality and Climate Change Law and Governance (40 Credits)
- **OMBO873:** Dissertation (100 Credits)

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- Two year part-time Programme.
- Three five-day contact sessions per year in Potchefstroom.

ENTRY REQUIRMENTS

- Appropriate honours degree or equivalent.
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Research article

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

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Abstract

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

Results: 24-hour $PM_{2.5}$ filter samples were collected manually every sixth day from 25 March 2021 to 25 January 2022 in Kimberley, Northern Cape Province, South Africa. The mean $PM_{2.5}$ concentration recorded in Kimberley was 6.3 µg/m^3 (range: 0.7 – 25 µg/m^3), slightly exceeding the World Health Organization (WHO) annual air quality guideline of 5 µg/m^3. Additionally, the daily WHO guideline of 15 µg/m^3 was exceeded on three occasions during the sampling period. The average soot (absorption coefficient), black carbon and organic carbon levels were 0.46 m-1 x 10-5, 0.6 µg/m^3 and 0.4 µg/m^3, respectively. Six geographic origins of air masses were identified after clustering 4476 generated 72-hour backward trajectories: North West (NW), North (N), East (E), South West (SW), South (S) and Long-range Indian Ocean (LRIO), suggesting diverse long-range transported air pollution from distant source areas.

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

Keywords

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

Introduction

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

The World Health Organization (WHO) and regulatory bodies of various countries established guidelines and standards for air pollutants, including $PM_{2.5}$. The WHO provides global yearly (5 µg/m^3) and daily (15 µg/m^3) guidelines for $PM_{2.5}$, to minimise health risks (WHO, 2022). South Africa is one of the few African countries that have an air quality act (UNEP, 2021; Department of Environment, Forestry and Fisheries, 2005). The Act enforces National Ambient Air Quality Standards (NAAQS) for various air pollutants since 2005 and for $PM_{2.5}$ since 2012: yearly NAAQS (20 µg/m^3) and daily NAAQS (40 µg/m^3) (Department of Environment, Forestry and Fisheries, 2012a). Altieri and Keen

(2019) estimated that 14 000 premature deaths could have been avoided in 2012 if yearly $PM_{2.5}$ levels in South Africa were below or at the yearly NAAQS (20 µg/m^3). Ideally, air pollution levels should be such that they do not pose any risk to human health. However, health effects have been observed for air pollution levels even below the more protective WHO guidelines (WHO, 2022; Brunekreef et al., 2021).

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

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

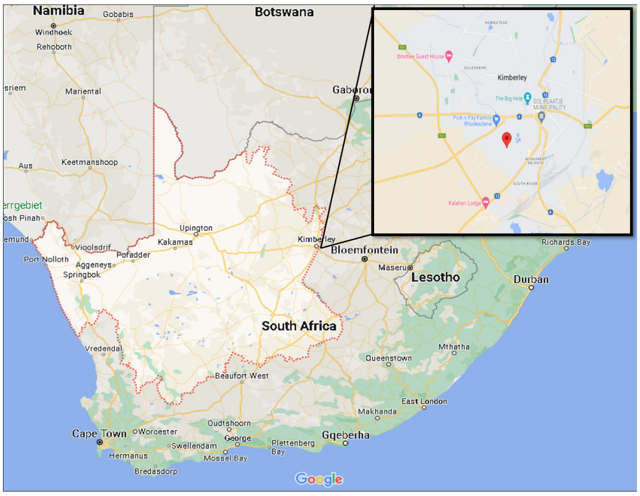

Figure 1: *Location of Kimberley in the Northern Cape province, South Africa. The sampling site is indicated by a red marker in the local map of Kimberley.*

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

Material and methods

Study area

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

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

$PM_{2.5}$ sampling and analysis

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

The choice of sampling equipment was determined by accessibility and cost-effectiveness compared to continuous real-time sampling instruments. A study from Pretoria indicated a good correlation between $PM_{2.5}$ sampling results obtained with the GilAir5 pump and continuous real-time sampling instruments (Spearman rank-ordered correlation coefficient 0.740; $p<0.0001$) (Figure 3 and Figure S1) (Mwase, 2020).

The flow rate of the GilAir5 pump (4 L/min) was verified using a field rotameter both before and after sampling. Calibration of the field rotameter was carried out using a GilAir calibrator. The filters were weighed using a Mettler-Toledo microbalance in

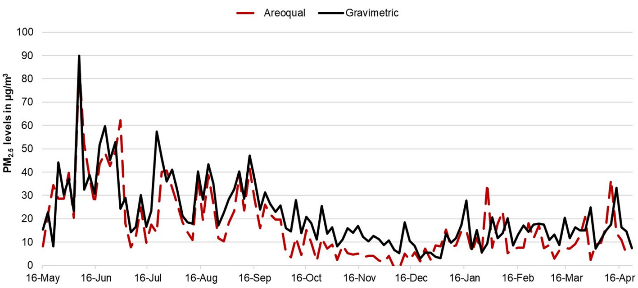

Figure 3: *Comparison between $PM_{2.5}$ levels obtained with gravimetric analysis against the continuous real-time sampling instrument, measured at the University of Pretoria from 19 April 2018 to 23 April 2019 (Mwase, 2020).*

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

Soot measurements

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

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

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

BC and OC analyses

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

Geographical origin of air masses

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

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

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

Meteorological data

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

Statistical analysis

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

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

Ethics approval

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

Results and discussion

$PM_{2.5}$ levels

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

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

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

The median $PM_{2.5}$ level on weekends were lower (2.9 µg/m³) than on weekdays (5.9 µg/m³) ($p>0.05$) (Table S1). The highest median $PM_{2.5}$ level was recorded on a Wednesday (9.0 µg/m³) and the lowest on a Saturday (2.7 µg/m³), although the median levels did not differ significantly by day of the week ($p > 0.05$) (Table S2).

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

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

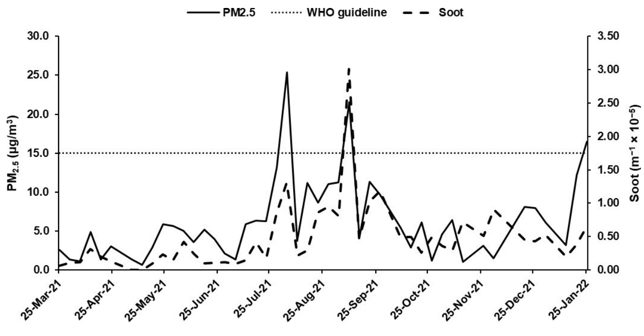

Figure 4: *Time-series graph of $PM_{2.5}$ and soot levels during 25 March 2021 and 25 January 2022 in Kimberley, South Africa.*

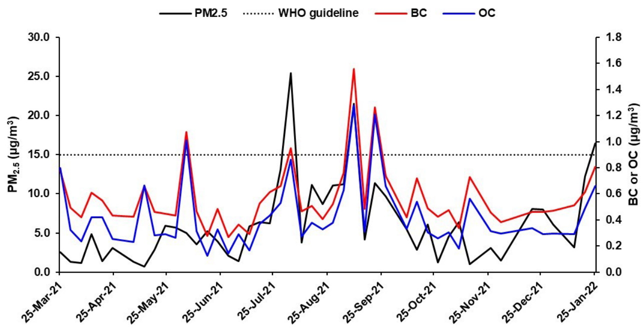

Figure 5: *Time-series graph of $PM_{2.5}$, BC and OC levels during 25 March 2021 and 25 January 2022 in Kimberley, South Africa.*

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

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

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

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

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

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

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

Bold indicates $p<0.05$

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

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

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

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

Soot, BC and OC levels

Studies on the ambient levels of soot, BC and OC and their health effects in Africa are scarce. There is currently no South African NAAQS or WHO air quality guidelines for soot, BC or OC. The median soot level was 0.33 $m^{-1} \times 10^{-5}$ during the study period (Table 1). The seasonal variation of soot levels is illustrated in Figure 4. The median soot level in spring (0.50 $m^{-1} \times 10^{-5}$) was significantly higher ($p<0.05$) compared to those in summer (0.45 $m^{-1} \times 10^{-5}$), winter (0.24 $m^{-1} \times 10^{-5}$) and autumn (0.11 $m^{-1} \times 10^{-5}$) (Table 1). Median soot levels on weekends (0.28 $m^{-1} \times 10^{-5}$) were not significantly different than on weekdays (0.56 $m^{-1} \times 10^{-5}$) ($p \geq 0.05$) (Table S1). The highest median soot level was recorded on a Thursday (1.01 $m^{-1} \times 10^{-5}$) and the lowest on a Friday (0.25 $m^{-1} \times 10^{-5}$), although the median levels did not differ significantly by days of the week ($p \geq 0.05$) (Table S2).

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

The median BC level was 0.49 µg/m³ during the study period (Table 1). Figure 5 indicates the seasonal variation of BC levels. The median BC levels did not differ significantly by season, weekday/weekend nor by days of the week ($p \geq 0.05$) (Table 1, Tables S1 and S2).

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

In terms of health effects due to ambient BC exposure, a study observed that the risk of infant mortality in 15 African countries increased significantly by 4% for every 6.6 µg/m³ rise in BC levels (Bachwenkizi et al., 2021). A review reported the following short-term effects per 10 µg/m³ increase in BC: increases of 0.7% in total mortality, 0.6% in cardiovascular disease mortality and 0.8% in respiratory disease mortality (Zhu et al., 2023). Long-term exposure to BC (per 10 µg/m³ increase) were associated with an increases of 29.8% in total mortality (Zhu et al., 2023). Song et al. (2022) found a 1.2% increase in respiratory disease hospital admissions per 1 µg/m³ increase in BC across 10 studies, which aligns with findings from the highly polluted Vaal Triangle Priority Area in South Africa (Mwase et al., 2022).

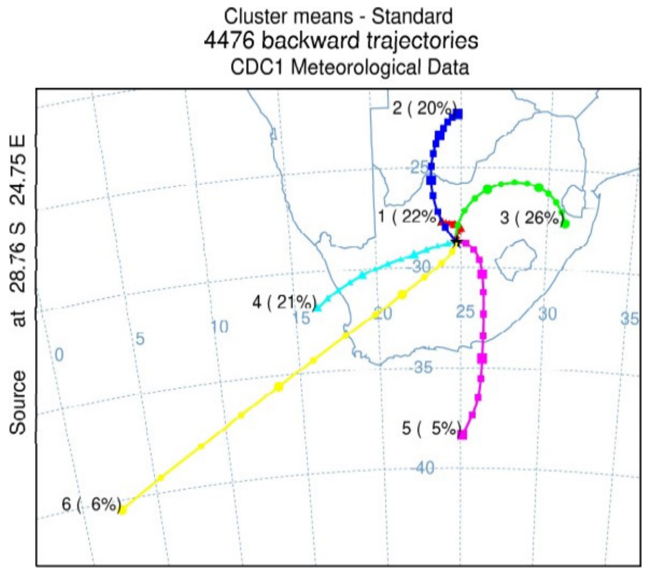

Figure 6: *Six geographical origins of air masses identified in the 72-hour backward trajectory model runs on all days during the study period March 2021 to January 2022 in Kimberley, South Africa. North West (NW) is indicated by the red line, North (N) indicated by the dark blue line, East (E) indicated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

The median OC level was 0.33 µg/m³ during the study period (Table 1). Figure 5 shows the seasonal variation of OC levels. The median OC levels did not differ by season (Table 1), weekdays/weekends nor by day of the week (Tables S1 and S2).

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

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

Meteorological conditions

The mean temperature during the study was 16.5 °C, with a range of 1.5 to 26.2 °C. The wind speed ranged from 2.5 to 39.5 km/hr, with the rainfall ranging from 0 to 23.8 mm (with rain on eight of the 46 sampling dates), and the relative humidity ranging from 12.7% to 81.7% (Table 1). Temperature, humidity and rainfall varied significantly by season, but not windspeed (Table 1). The predominant wind direction was from the north (19 sampling days) (Figure S2).

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

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

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

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

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

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

The 24-hour backward trajectory model runs revealed five geographical origins of air masses (Figure S3). These 24-hour clusters would indicate air pollution source areas that are closer than those indicated by the 72-hour clusters. Similar directions were observed as in the 72-hour model runs. As with the 72-hour clusters, no significant difference in the median $PM_{2.5}$, soot, BC and OC levels were identified ($p \geq 0.05$) (Table S3). This was also the case with wind direction ($p \geq 0.05$) (Table S4).

Conclusions

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

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Author contributions

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

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Supplementary material

Supplementary material can be accessed at
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