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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Received: 29 May 2024 - **Reviewed:** 5 November 2024 - **Accepted:** 15 November 2024
https://doi.org/10.17159/caj/2024/34/2.18784

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.

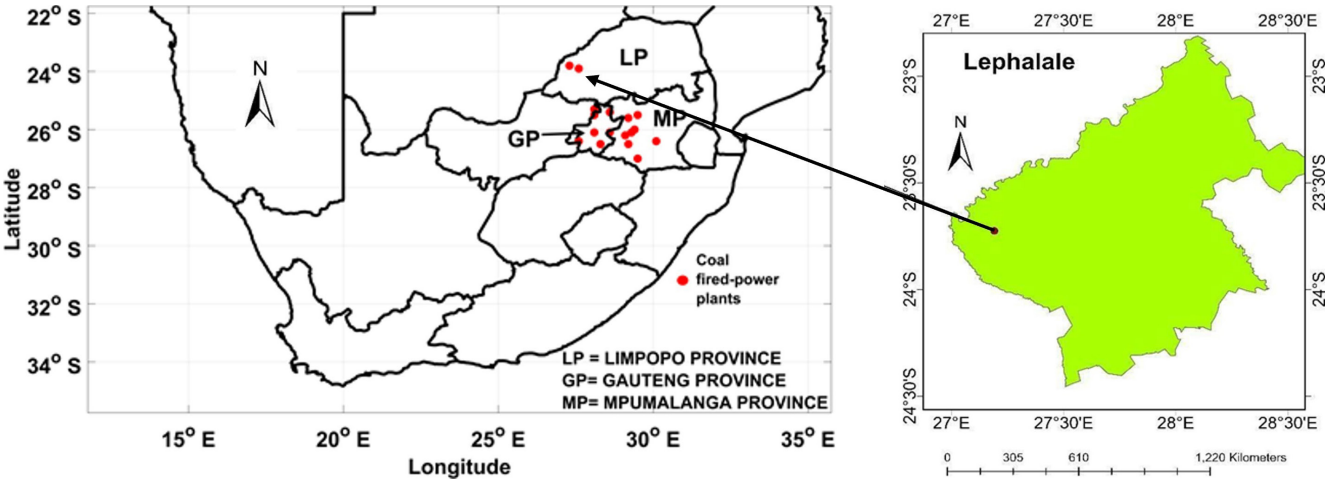

Figure 1: *Map showing the coal-fired power stations that serve as SO_2, NO_2, CO and CO_2 emitters in Limpopo and South Africa*

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

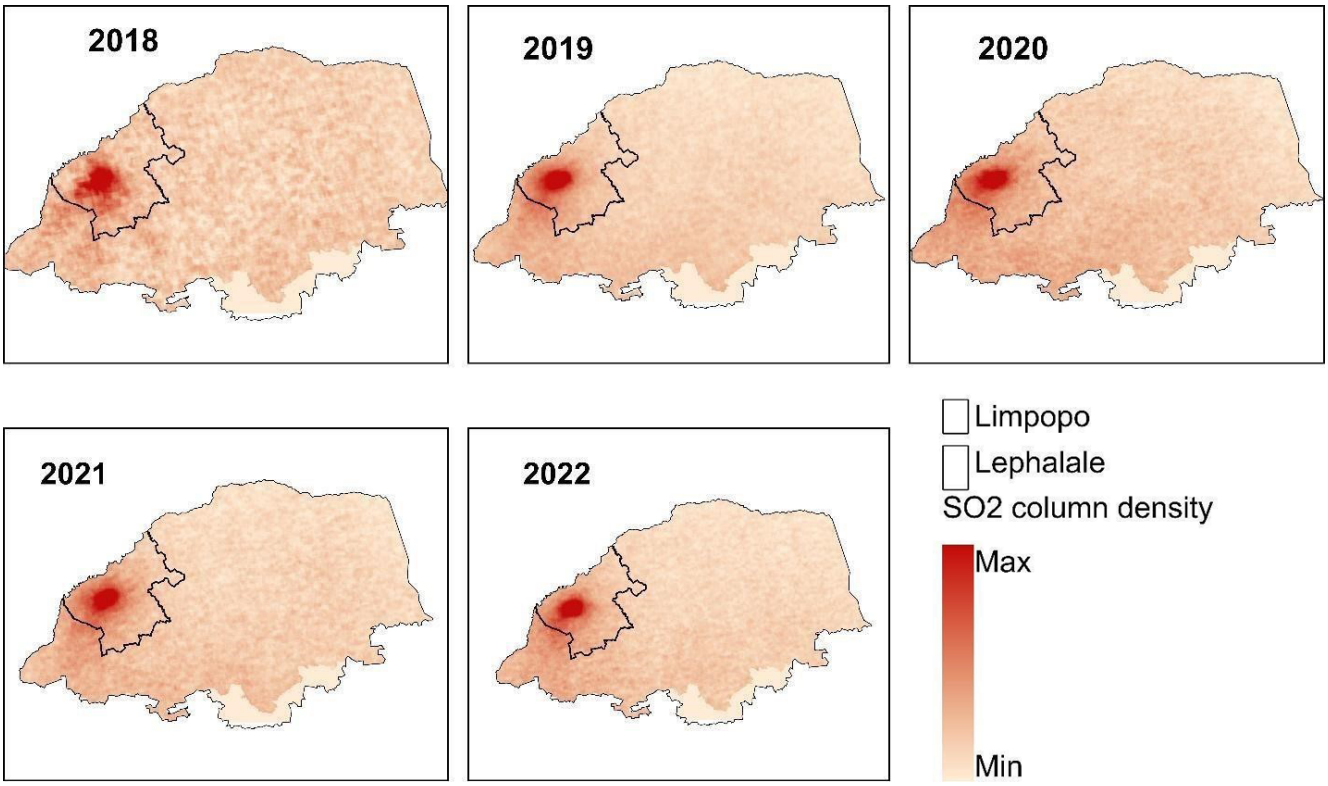

Figure 2: *SO_2 column density (mol/m²) trends over Lephalale from 2018-2022 from Sentinel-5P.*

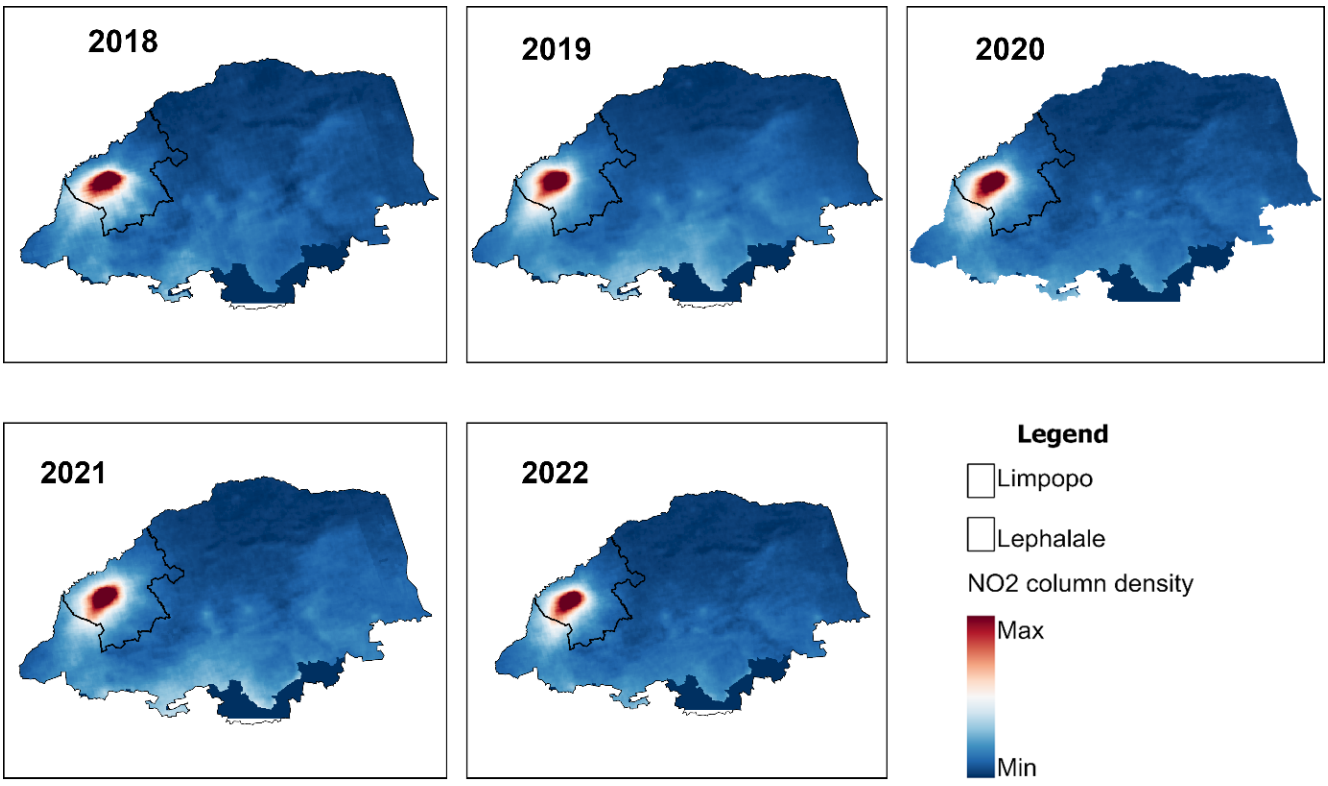

Figure 3: *NO_2 column density (mol/m²) trends over Lephalale from 2018-2022 from Sentinel-5P.*

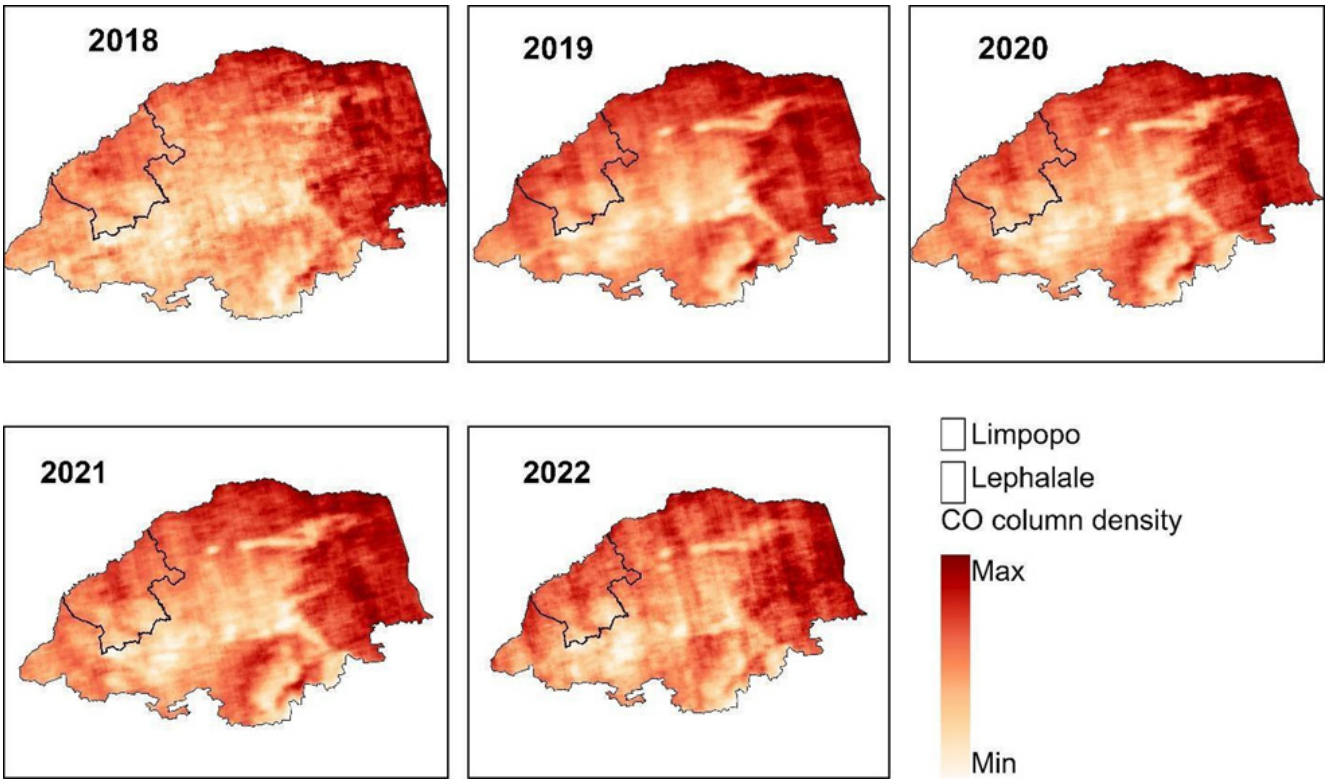

Figure 4: *CO column density (mol/m²) trends over Lephalale from 2018-2022 from Sentinel-5P.*

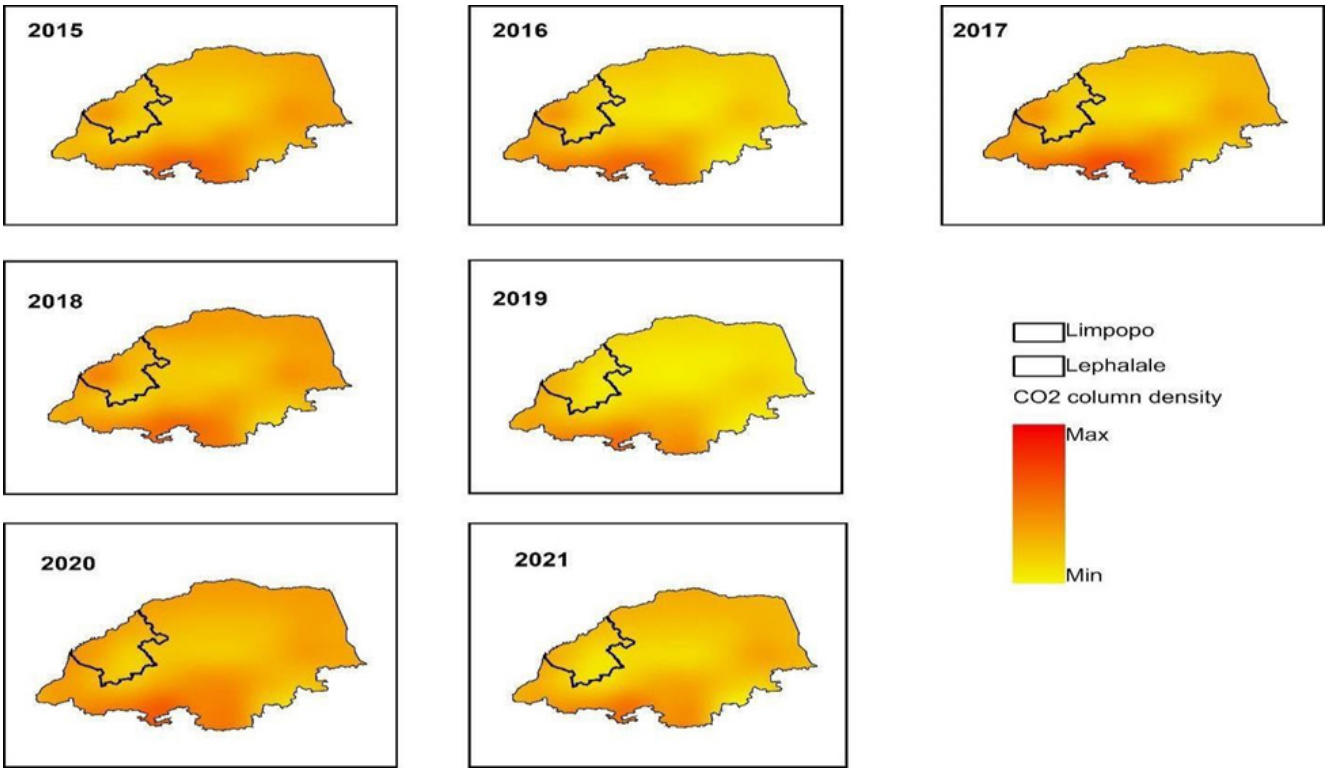

Figure 5: *CO_2 column density (mol CO_2/ mol dry) trends over Lephalale from 2015-2021, as observed by GEOS-Chem.*

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/m² and 0.0314215 mol/m² (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/m² – 0.00040602 mol/m² of the maximum value and 0.000398252 mol/m² – 0.000405739 mol/m². 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/m² – 0.000413503 mol/m² of the maximum and 0.000409091 mol/m² – 0.000412969 mol/m².

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 α= 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.

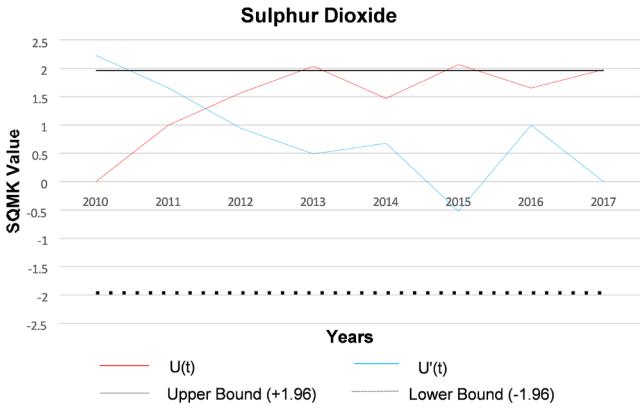

Figure 6: *SQMK trends for SO_2 column density in Lephalale between 2010 and 2017.*

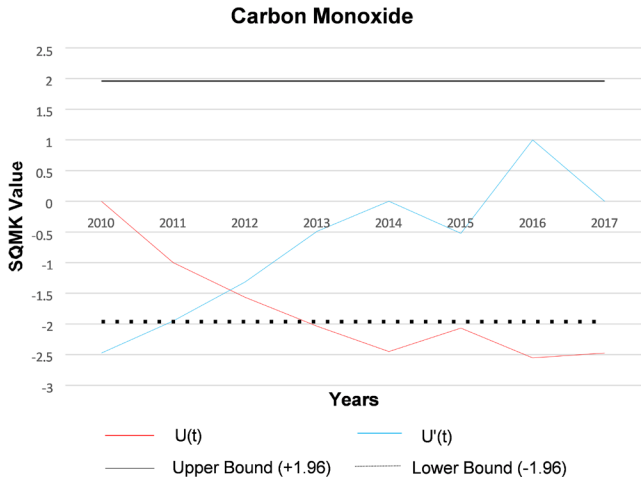

Figure 7: *SQMK trends for CO column density in Lephalale between 2010 and 2017.*

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	------

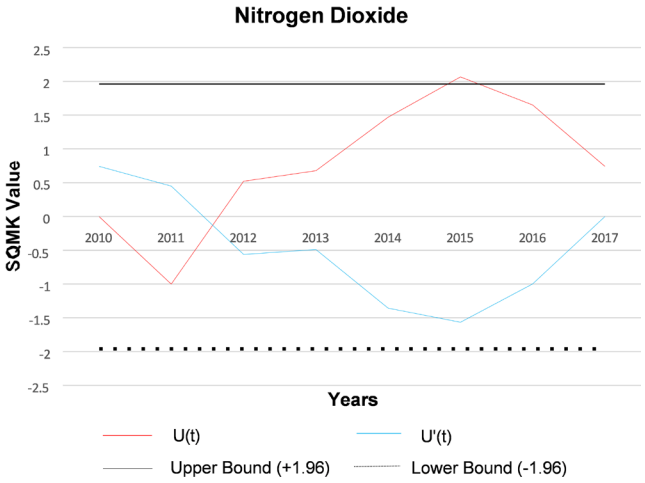

Figure 8: *SQMK trends for NO_2 column density in Lephalale between 2010 and 2017.*

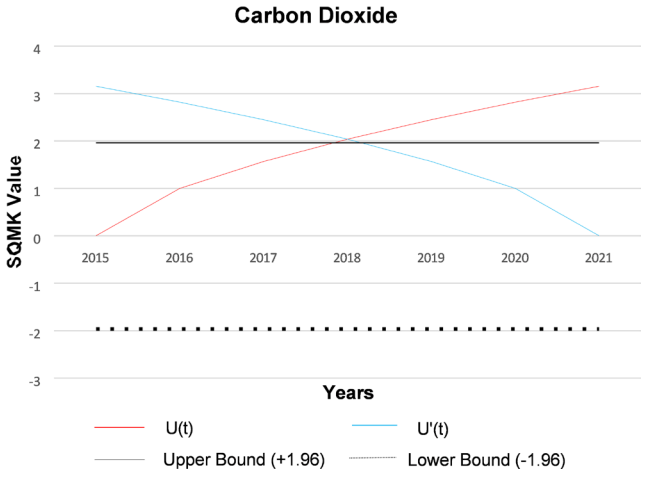

Figure 9: *SQMK trends for CO_2 column density in Lephalale between 2010 and 2017.*

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.

Acknowledgements

The author acknowledges the GES-DISC Interactive Online Visualization and Analysis Infra-structure (Giovanni) for providing the MERRA-2, OMI and GEOS-CHEM data. We further thank and acknowledge ESA for the Sentinel-5 P/TROPOMI data.

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

No funding was provided for this research.

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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