Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 22 | No. 1 | pp. 1-13 | 2023

Original Research Paper

https://doi.org/10.46488/NEPT.2023.v22i01.001

Open Access Journal

Spatial Distribution of PM_{10} and NO_2 in Ambient Air Quality in Cape Town CBD, South Africa

O. Ndletyana*, B. S. Madonsela* and T. Maphanga*†
*Cape Peninsula University of Technology, Faculty of Applied Sciences, Department of Environmental and Occupational Studies, Corner of Hanover and Tennant Street, Zonnebloem, Cape Town 8000, RSA
†Corresponding author: T. Maphanga; maphangat@cput.ac.za

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 28-07-2022
Revised: 12-09-2022
Accepted: 15-09-2022

Key Words:
Air quality
PM_{10}
NO_2
Spatial distribution
Seasonal variation
Geographic information system

ABSTRACT

Fixed air quality monitoring stations generally monitor the air quality in developing countries. However, this practice, in addition to being costly, inherently contains drawbacks associated with the inability to capture the spatial distribution of air pollutants. Against this limitation, it is necessary to employ flexible and dynamic monitoring techniques that are fundamental and influential in comprehending the spatial distribution of pollutants. Because of this, in recent times, the application of GIS as a monitoring technique has proved to be more efficient than using fixed monitoring stations. Therefore, to this end, the current study mapped the spatial distribution of PM_{10} and NO_2 pollutants in Cape Town CBD using the GIS technique. Subsequently, the GIS monitoring technique revealed that both pollutants had high spatial distribution between 2017 and 2018, irrespective of the season. Furthermore, high exposure concentrations of PM_{10} were generally observed across the CBD in contrast to NO_2 exposure levels, which were relatively low. To contextualize the findings, compared with other studies, the current research discovered that spatial distribution of air pollution is associated with meteorological conditions, such as wind speed and temperature, that traditional techniques of monitoring exposure can't capture.

INTRODUCTION

Air pollution is one of the most important environmental problems, mainly concentrated in cities. Monitoring atmospheric pollution is a difficult problem, especially for particulate matter and nitrogen oxides. Southern Africa faces difficulty in measuring air quality, and as a result, South Africa is the only country with more advanced ambient air quality monitoring equipment (Coker & Kizito 2018). Mainly because South Africa's spheres of government are entrusted with exposure assessment of ambient air pollutants (DEADP 2017). Therefore, to fulfill this mandate, the different spheres of government have erected automated fixed-air quality monitoring stations across the country (Gwaze & Mashele 2018). The fixed monitoring stations are designed to collect regulatory pollutants, such as nitrogen oxides (NO_x, NO, NO_2) and particulate matter (PM_{10}, $PM_{2.5}$), which have been internationally recognized as environmental priority air pollutants since they can constitute a threat to human health and the Environment (Mustafić et al. 2012, Castell et al. 2017). These fixed monitoring stations capture accurate measurements that are used to understand long-term air quality levels and indicate the status of compliance with prescribed national ambient air quality standards. The policymakers must take the necessary and suitable actions to lower the level of air pollution for the citizens' welfare in light of the detected air quality concentrations. In essence, monitoring presents the air quality data contributing to understanding air pollution exposure levels and potential health risks.

For this reason, monitoring air pollution is fundamental in ensuring compliance with prescribed air quality standards that seek to mitigate the risks of exposure. Hence air pollution exposure monitoring efforts are associated with protecting human health and the environment (Zheng et al. 2015). Given that monitoring ensures that management of air quality is adequate and the potential negative impacts to the Environment and human health linked with poor air quality are understood and mitigated as early as possible (Forbes 2016).

However, in as much as the South African government is proactive in managing air quality by monitoring exposure through continuous assessment, they should be conscious that fixed monitoring stations only measure air pollution at a shallow spatial resolution (Sajani et al. 2004). Due to the limited number of available monitoring stations (Castell et al. 2017). This is due to the exuberant costs associated with

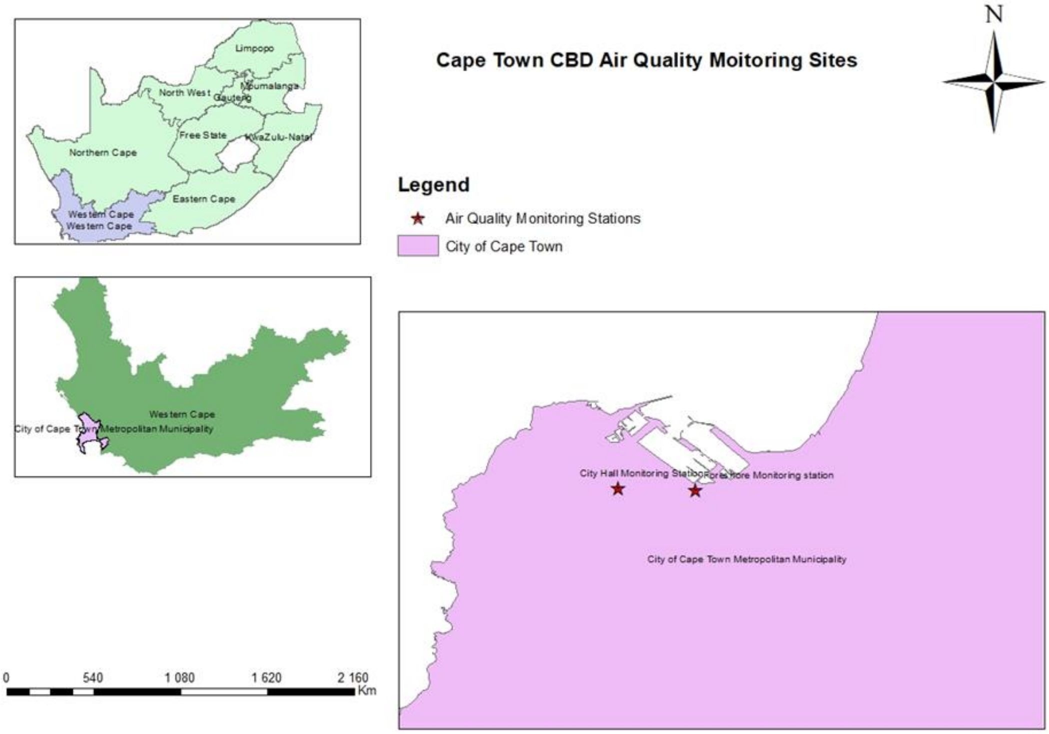

Fig. 1: The study area map of Cape Town monitoring stations in the CBD.

installing, operating, and maintaining fixed monitoring stations. These drawbacks influence the conventional fixed air quality monitoring station's ability to capture the spatial variability of pollutants. Even though understanding spatial and temporal variability in pollutants concentration is essential to air quality management and health risk assessment (Marshall et al. 2008, Wei et al. 2020).

To this end, Pavani & Rao (2017) substantiate that conventional fixed air quality monitoring systems cannot provide air pollution data of high spatiotemporal resolution due to non-scalability and limited data availability. Hence, the gaps in monitoring the spatial variability of pollutants. Therefore because of the limitation in monitoring techniques such as the fixed stations, the application of GIS has been introduced to alternate the traditional monitoring methods. The use of GIS as a monitoring system is advantageous in estimating the spatial distribution of air quality rather than relying on conventional methods, i.e., fixed monitoring station that limits the understanding of the spatial distribution of pollutants. As Somvanshi et al. (2019) state, GIS has proved to be a crucial tool for monitoring, serving various purposes, from spatially monitoring a region's air quality to creating spatial models for predicting future air quality conditions of the region of study. Considering the above, it makes sense that in recent times, a small but growing number of scientists have started experimenting with the use of GIS in monitoring air quality, and others have looked at the spatial distribution of air pollution in Beijing (Li et al. 2019) and Weifang (Song et al. 2019). Keeping this in view, the current study aimed to map the spatial distribution of PM and NO_2 pollutants in Cape Town CBD using GIS. The following objectives were pursued: (a) investigate and map the spatial distribution of PM_{10} and NO_2 in the CBD; (b) determine the spatial behavior of PM_{10} and NO_2 concentration in the CBD and (c) assess the seasonal (summer and winter) distribution of PM_{10} and NO_2.

MATERIALS AND METHODS

Study Area

Cape Town is one of SA's capital cities which falls under the legislative capital. It is normally referred to as the Mother City. Cape Town is the largest city on the western cape, situated southwest coast beneath the imposing Table Mountain with GPS coordinates -33°55'29.64" S and 18°25'26.75" E. The city occupies an area of about 2461 km^2 with an average elevation of 1590.4 m above sea level. It is bordered by the Table Mountain range along the west coast, influencing airflow within the region. The Cape Town climate is the Mediterranean, with warm, dry summers and mild, moist winters. It has a wind force called "Cape doctor," which helps blow away smog and impurities to clear the skies and provide fresh air (World Weather and Climate Information 2019). According to Census (2011), the Cape Town population is about 374,0026. Increased urbanization and economic activities have resulted in many people in the area. This has consequently increased the number of potential users of public transport (taxis, buses, and trains); private transport is also included (Walton 2005). According to CoCT (2002), the CBD experiences massive traffic congestion during peak hours, i.e., in the morning and afternoon. Thus, Cape Town experiences high pollution levels from motor vehicle exhaust emissions, which is characterized as the primary contributor to the formation of brown haze (Walton 2005). The brown haze is noticeable from April to September due to strong temperature inversions and calm conditions experienced during this period. The haze extends over most of the City of Cape Town (CCT) and shifts according to the prevailing wind direction (Keen & Altier 2016, Wicking-Baird et al. 1997).

Air Pollution Monitoring Stations

The City of Cape Town (CoCT) municipality monitors the Cape Town CBD's ambient air quality through a network of 2 Air Quality Monitoring (AQM) Stations (DEADP 2016) (Fig. 1). Therefore, these two monitoring stations have been selected to analyze the spatial distribution of air quality in Cape Town CBD. The first monitoring station is located at City Hall CBD. As the name suggests, it is in the central business district on the grand parade west of the Castle of Good Hope center.

Data Collection

The ambient air quality data was retrieved from the City of Cape Town Municipality air quality monitoring stations. These stations are located in Cape Town CBD to measure ambient air quality exposure concentrations. Amongst the measured pollutants substances are Particulate Matter (PM_{10}) and Nitrogen Dioxide (NO_2), which are pollutants of concern since they are associated with traffic emissions. To this end, each station is designed to collect data on a particular pollutant. For instance, the Foreshore monitoring station is designated to measure PM pollutants, while the City Hall monitoring station measures the (NO_2) pollutants. However, these stations collected data intermittently. As a result, the current data obtained from the CoCT municipality mostly covered the years 2017 to 2018 for both pollutants.

Data Analysis

GIS spatial analysis was used in this study to determine the distribution of ambient air quality levels in Cape Town CBD. Therefore, the results of this research were presented and analyzed using ArcGIS 10.8 pro, a product of ESRI. This software can be used in mapping and analytics application to examine spatial relationships, predicts outcomes, and make better data-driven decisions. Moreover, this software handles multiple tables and easily relates them to each other. Additionally, the study used ArcGIS for statistical purposes to model the pollution surface based on measurements at air quality monitoring sites. IDW modeling technique was deployed as it provides heat maps of pollution surfaces based on point measurements. IDW was more suitable for this study as it uses the existing monitoring station data. Therefore, the development of a regression model and testing of a regression-mapping approach was carried out in all three centers using ArcGIS pro-10.8. In each center, a GIS was established, containing four main sets of data: main roads (e.g., road network, road type), altitude monitored data NO_2 and PM_{10} concentrations. The geostatistical analysis functions in ArcMap pro 10.8 database development are either non-spatial (tubular) or spatial (containing locations). Therefore, graphs and heat maps were produced using the mean concentration of geostatistical analysis called the IDW interpolation method. The conceptual model below outlines the methodology adopted for exploring the spatial patterns of air pollution.

RESULTS AND DISCUSSION

Seasonal Spatial Behaviour Concentration of PM_{10} and NO_2 in Cape Town CBD, 2017-2018

During the rapid development of Cape Town's economy and society, urbanization has accelerated, and energy consumption has increased steadily. As a result, air pollution in cities has become a significant threat to both physical and mental health. The seasonal spatial behavior analysis for the concentration of PM_{10} and NO_2 in Cape Town CBD is represented in bar and line graphs. The bar graphs in Fig. 2 and 3 show the seasonal (winter and summer months) dataset of monthly average concentration (Tables 1 and 2) of Cape Town CBD from 2017 to 2018. The line graphs in Fig. 4 and 5 show the daily concentration exposure level of PM_{10} and NO_2 during the winter and summer months of 2017 and 2018. The x-axis in the graphs shows the seasonal variation (winter and summer months), while the y-axis demonstrates the pollutant concentration exposure level. The seasonal behavior concentration demonstrates high levels of PM_{10} and NO_2 pollutants during winter, which might be influenced and exacerbated by meteorological conditions such as low temperatures and low wind speed.

Seasonal Spatial Behavior Concentration of PM_{10} at Cape Town CBD

Despite the importance of understanding and controlling air pollution in highly populated areas, interpreting levels of gaseous pollutants and particulates in the atmosphere is complicated by several factors, including dominant natural and anthropogenic emissions, micro-meteorological processes, and chemical reactions that occur directly in the atmosphere. Therefore, to better explore and determine the seasonal (winter and summer) spatial distribution and behavior characteristics of PM_{10} in Cape Town CBD during 2017- 2018, table 1 and Fig. 2 were used to show the concentration exposure levels. Both Fig. 2 and Table 2 illustrate readings from Foreshore AQM, which display the seasonal spatial behavior of PM_{10} pollutants during winter (Jun, Jul, and Aug) and summer (Dec, Jan, and Feb) months within the years 2017 and 2018.

Fig. 2 demonstrated that the high concentration exposure levels of PM_{10} in 2017 peaked in Jun (winter) at 38.9 $\mu g.m^{-3}$. While in 2018, during the same season, the concentration of the pollutant peaked in July at 40.91 $\mu g.m^{-3}$. The occurrence of high concentration levels of PM_{10} in different months of the year might be influenced by a couple of factors, for example, the type of climate, changing state of the weather, and anthropogenic activities in that particular year. This resulted in a distinct variation of PM_{10} concentration in ascending order from 2017 to 2018. Moreover, the seasonal variation concentration of PM_{10} in Fig. 6 shows that high concentration levels were observed in winter and low concentrations in summer months. Thus,

Table 1: Seasonal concentration variation of PM_{10} for Foreshore monitoring station.

Monthly average concentration data of Foreshore AQM for PM_{10} ($\mu g.m^{-3}$), 2017-2018				
Air Quality Monitoring station	Year	Season	Months	Average concentration
Foreshore AQM	2017	Winter	Jun	38.92
			Jul	33.83
			Aug	29.00
		Summer	Jan	26.61
			Feb	30.32
			Dec	28.06
	2018	Winter	Jun	32.35
			Jul	40.91
			Aug	23.08
		Summer	Jan	29.56
			Feb	33.87
			Dec	0.00

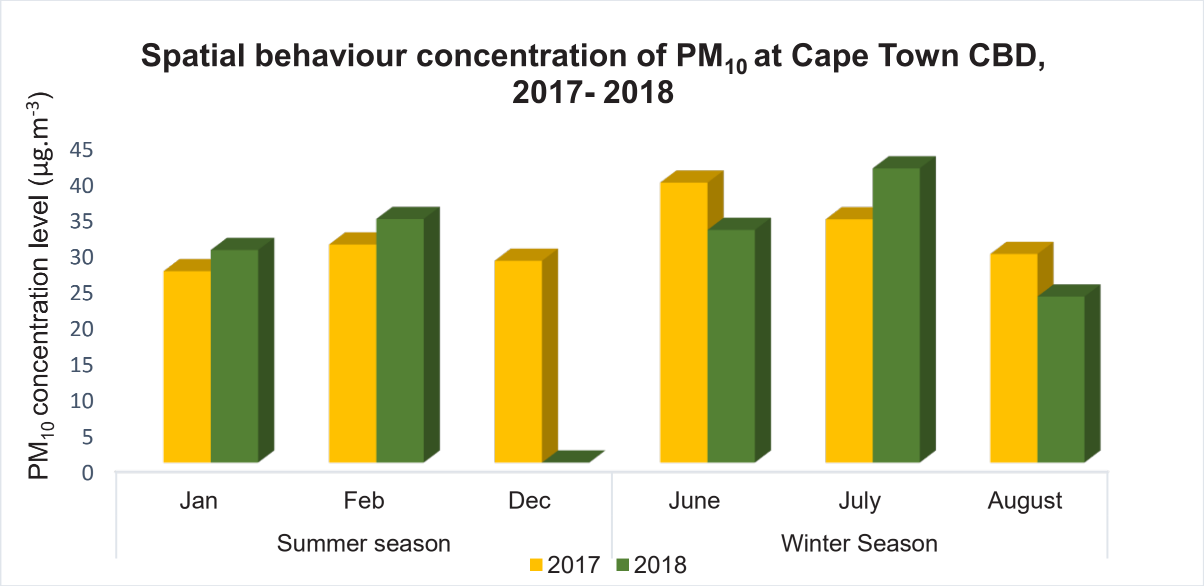

Fig. 2: Seasonal spatial behavior concentration of PM_{10}, 2017-2018.

the strong temperature inversion during the winter combined with prevailing windless conditions is attributed to the high concentration levels of PM_{10} Kelly et al. (2012). The findings of this study are consistence with previous studies done in cities in China which included Beijing (Jiang & Bai 2018), Weifang (Li et al. 2019), and Jiangsu (Song et al. 2019), observed high concentration levels during the winter season and low concentration levels during the summer season. The studies further demonstrated that low temperatures and windless conditions worsened the high concentration levels observed in winter. Cichowicz et al. (2017) corroborate the findings that the high concentration levels of PM_{10} in winter may be exacerbated by an increase in emission from local furnaces and the inversion temperature that may result in smog events in most cities around the world. Literature has supported that meteorological conditions such as temperature during the winter season may result in air pollutants not being easily dispersed, which might lead to high concentration levels of PM (Wei et al. 2020, Jiang & Bai 2018, Li et al. 2019, Song et al. 2019).

Seasonal Spatial Behavior Concentration of NO_2 at Cape Town CBD

Increasing ambient NO_2 concentrations can have significant effects on respiratory health, particularly for children, the elderly, and individuals who are susceptible to asthma, pneumonia, bronchitis, etc. It can even cause death at extremely high levels and long-term exposure. Table 2 and Fig. 3 shows the seasonal concentration variation behavior of NO_2 pollutant during winter (June, July, and August) and summer (Jan, Feb, and Dec) months within the years 2017 and 2018.

Fig. 3 shows a seasonal variation in the concentration behavior of NO_2 from 2017 to 2018. It was noted that the winter season in both years recorded the highest concentration of NO_2, 38.41 $\mu g.m^{-3}$ (2017) and 35.61 $\mu g.m^{-3}$ (2018), all for the month of August. Furthermore, the results illustrate that the average concentration of NO_2 was low for the summer period (2017 and 2018) compared to the winter average this might be attributed to Cape Town's dry summer subtropical climate (Mediterranean). More people use private cars as opposed to summer as winter is characterized by heavy wind and rainfall. It was also observed that during summer, the maximum concentration level peaked in February, reaching a concentration level of 33.51 $\mu g.m^{-3}$ in 2017 and 32.65 $\mu g.m^{-3}$ in 2018. This study's findings align with the results of the study done in Jiangsu city, where high concentrations of NO_2 were reported during the winter season, reaching 54 $\mu g.m^{-3}$ concentration and low in the summer season with an average of 40 $\mu g.m^{-3}$ (Wang et al. 2021). The study further discussed that Jiangsu's climate influenced the high concentration levels of NO_2 during winter; in winter, the city experiences a strong vertical temperature inversion layer which makes air pollutants not easily dispersed.

Daily Concentration Exposure Level of PM_{10} and NO_2 at Cape Town, 2017-2018

To make predictions, selecting the appropriate time series models for the data is important. Using these time series models, environmental quality managers can estimate parameters according to evolving information needs. As well as providing early warnings to the respective population, related bodies can also use the developed models. Fig. 4 and Fig. 5 demonstrate the daily time series dataset for PM_{10} and NO_2 pollutants during winter (Jun, Jul, and Aug) and summer (Jan, Feb, and Dec) months at Cape Town CBD within the years 2017 to 2018. Specifically, it shows the

Table 2: Seasonal concentration variation of NO_2 for City Hall monitoring station.

Monthly average concentration data of City Hall AQM for NO_2 ($\mu g.m^{-3}$), 2017-2018				
Air Quality Monitoring Station	Year	Season	Months	Average concentration
City Hall AQM	2017	Winter	Jun	34.43
			Jul	37.37
			Aug	38.41
		Summer	Jan	29.64
			Feb	33.51
			Dec	24.94
	2018	Winter	Jun	20.74
			Jul	31.65
			Aug	35.61
		Summer	Jan	26.97
			Feb	32.65
			Dec	21.36

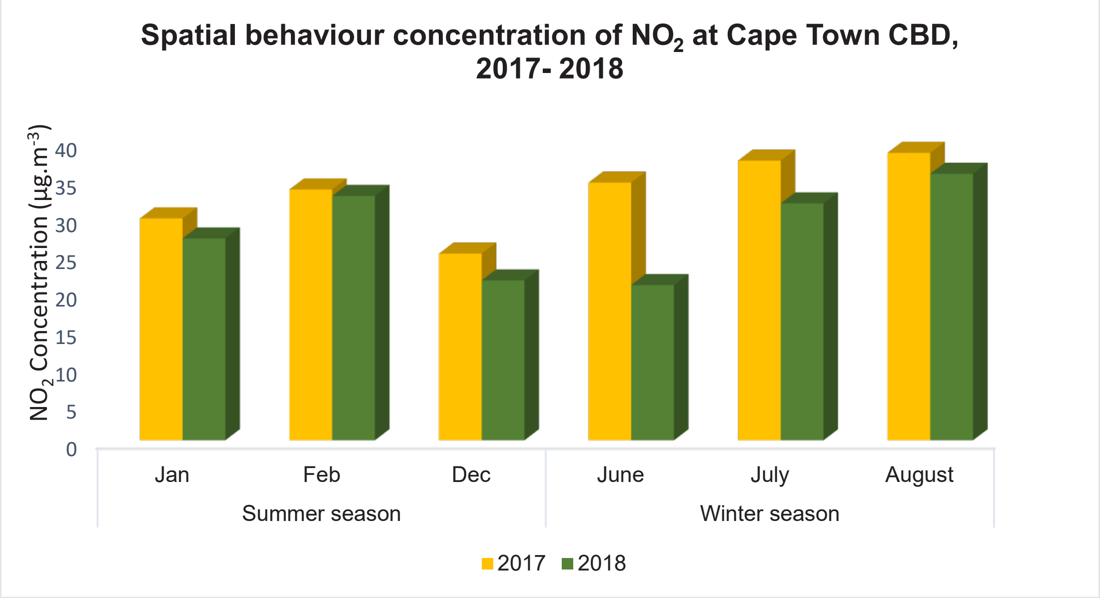

Fig. 3: Seasonal spatial behavior concentration of NO_2, 2017-2018.

daily concentration exposure levels of Cape Town CBD from foreshore AQM (PM_{10}) and City Hall AQM (NO_2) measurements from 2017 to 2018.

According to Fig. 4, the PM_{10} pollutant has high concentration exposure levels that reach 140 $\mu g.m^{-3}$ during the winter months (Jul 2018). On other months and days, the concentration levels of PM_{10} and NO_2 almost behave the same, with the lowest concentration levels of less than 20 $\mu g.m^{-3}$. In corroboration with the results found by Tui et al. (2021), similar behavior was found; the variation of the daily concentration of PM_{10} and NO_2 fluctuated significantly and had a high degree of similarity. In comparison with the winter months (Fig. 4), NO_2 pollutant has high concentration exposure levels that reach 94 $\mu g.m^{-3}$ during the summer season (Jan 2017). Notably, the high concentration exposure level of NO_2 was more severe in 2017 during the summer compared to 2018. Although the NO_2 pollutant concentration peaked during summer days in 2017, the observation indicates that summer (Fig. 5) concentration exposure levels are low compared to winter concentration readings (Fig. 4). Additionally, according to observation (Fig. 5), during summer, some days the concentration exposure level on NO_2 and PM_{10} have similar behavior with the lowest readings of less than 10 $\mu g.m^{-3}$. This indicates better air quality in summer, while the levels in winter imply risky air pollution levels in the CBD. Moreover, the observations (Fig.4 and 5) indicate that PM_{10} is the main pollutant of concern, with high concentrations recorded in the CBD, particularly during winter. The above results can collaborate with the previous results from Fig. 2 and Fig. 3, which depicted that winter had higher concentration levels.

Spatial Distribution of PM_{10} and NO_2 During Summer and Winter Seasons in Cape Town CBD, 2017 To 2018

Considering the spatial characteristics of air pollution in cities can give us a better understanding of how the city as a whole is affected by air pollution, help identify the sources of urban air pollution, and help develop practical policies to control air pollution. As a result, such research has a significant impact on urban sustainability. Spatial interpolation maps were used to illustrate the air pollution exposure to PM_{10} and NO_2. The heat maps show how pollutants varied across the CBD of Cape town during the summer and winter months of 2017 and 2018. An elevated concentration of the pollutant of concern indicates the hazardous zones, indicated by the color red on the heat maps. In contrast, yellow indicates an exposure level of an average to middle concentration, whereas green indicates a low concentration of a pollutant, which identifies a zone that does not constitute a hazardous situation.

Spatial Distribution of PM_{10} During the Summer Season in Cape Town CBD

High traffic volume and excessive pollutant emissions have been associated with the rapid development of Cape Town's economy and urbanization process, resulting in serious air pollution issues and hindering sustainable development. Fig. 6 shows that the seasonal variations in PM_{10} concen-

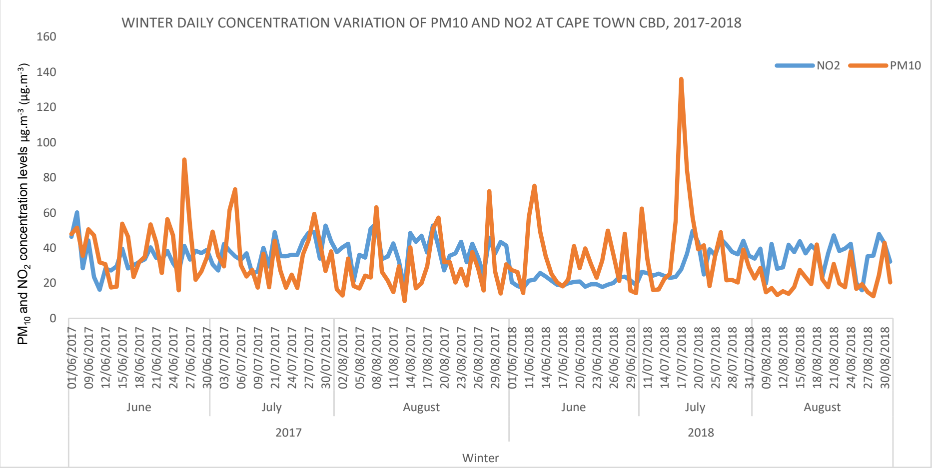

Fig. 4: Daily concentration of PM_{10} and NO_2 pollutants during winter months at Cape Town CBD.

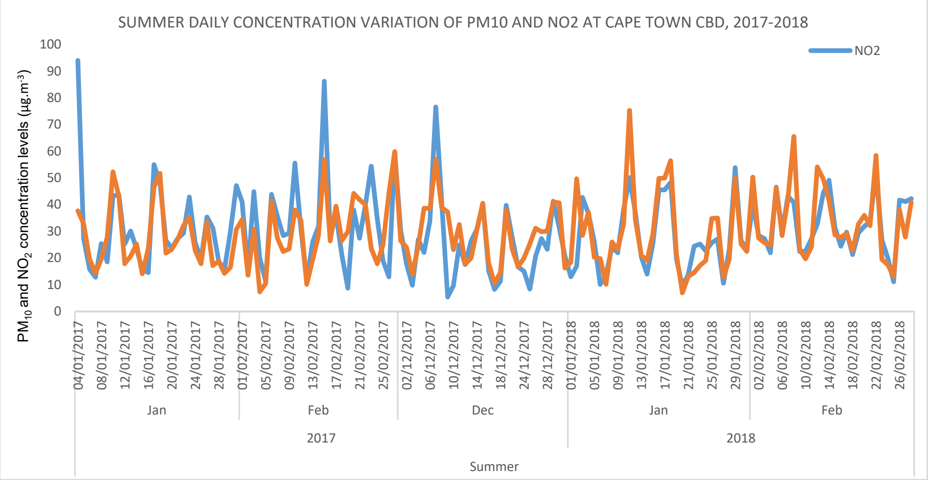

Fig. 5: Daily concentration of PM10 and NO_2 pollutants during summer months at Cape Town CBD.

trations are essentially similar, and the seasonal variations' characteristics are as follows.

Fig. 6 demonstrate mapping of the spatial distribution of PM_{10} concentration recorded at Foreshore AQM station within the Cape Town CBD from 2017 to 2018. The mapping outcome of summer PM_{10} pollutants generally indicates variability in spatial distribution. According to Fig. 6, the Foreshore monitoring station recorded low exposure concentrations (23.94 µg.m^{-3}) of $PM_{10.}$ It was observed that there was an increase in concentration when moving the north and eastern parts of the map. It was also noted that the high concentration of PM_{10} was found close to national highways and traffic intersections entering CBD, which recorded 37.78 µg.m^{-3}. This demonstrates that the national freeways, main roads, and traffic intersections entering CBD can be described as hazardous delineated zones. The findings of this study are in line with a study conducted in the areas of Bengaluru City, where it was established that national highways and traffic intersections recorded high spatial distribution concentrations of PM_{10} due to high traffic volume (Begum et al. 2006, Song et al. 2020, Cichowicz et al. 2020).

A similar observation was found in a study done at Coimbatore City by Tharani et al. (2021) that PM_{10} pollutants were spatially distributed nearby of major roads. The study further demonstrated the spatial distribution of high PM_{10} concentration was mostly accredited to increased vehicular movement and the presence of high buildings. Tshehla &

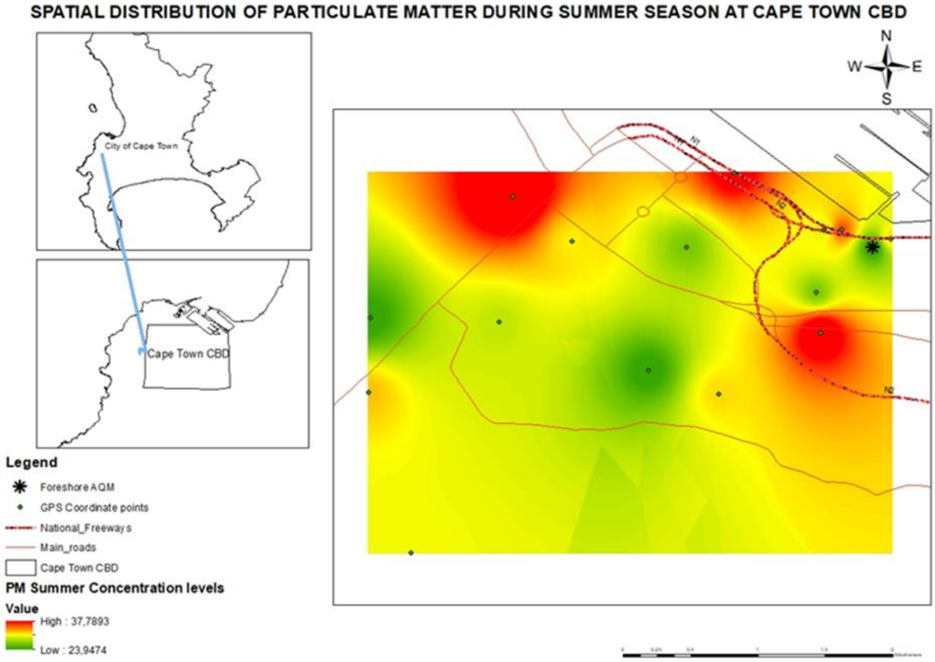

Fig. 6: Spatial distribution of PM_{10} during the summer season.

Wright (2019) did a study on the spatiotemporal distribution of air pollutants and corroborated that the high concentration levels of PM_{10} were observed closer to the source of pollution. According to CoCT (2012), approximately 60% of vehicular traffic movements from Cape Metropolitan Areas are heading to Cape Town CBD. Thus, traffic emissions might be the source of air pollution in the CBD because of the ongoing and coming traffic congestion (Kandlikar 2007, Khan et al. 2020). As presented, for instance, by the analysis in Fig. 6, the hazardous delineated zone is found near the traffic intersection and national highway entering the CBD.

Moreover, Cape Town experiences a wind force called ‘Cape Doctor’ during the period that is said to clear all air pollutants in the city, offering an amazingly clear sky (World Weather and Climate Information 2019). The direction of this wind force is from South to East (‘South Eastern wind’) during warm summer seasons (Kelly et al. 2012). Therefore, wind can be a factor that spatially distributes the air pollutants due to the wind force and direction that blows from False Bay and funnels through Cape Town City Bowl to Blouberg. Consequently, Kandlikar (2007) corroborates that meteorological factors such as wind speed and direction have the aptitude to spatially disperse air pollutants. Thus, the variability in the spatial distribution of pollutants at Foreshore AQM.

Spatial Distribution of PM_{10} During the Winter Season in Cape Town CBD

The spatial distribution analysis in air quality studies is essential and helpful in predicting seasonal variations in the concentration of air pollutants due to changes in meteorology. Mapping the spatial distribution will help us understand the distributed pollutants across the city and the investigation of movement and their influential factors. Fig. 7 shows the winter seasonal variation characteristics of PM_{10} concentration.

The Fig. 7 shows the analysis of the winter spatial distribution of PM_{10}. The heat map illustrates the outcome of the pollutant that the Foreshore monitoring station recorded during the winter months from 2017 to 2018. The Winter spatial distribution of PM_{10} shows a distinctive spatial distribution compared to the summer season. In this season, the pollutant maximum concentration exposure level increase is almost double (46.81 $\mu g.m^{-3}$) the records of the summer season. Chen et al. (2013) reported a similar trend whereby particulate matter significantly increased over the winter seasonal period. Another recent study undertaken in the Western Cape neighborhoods observed that the change of season generally affects pollution exposure levels (Madonsela et al. 2022). The results from this current study indicate that in contrast to summer observations, the maximum concentration levels were relatively higher

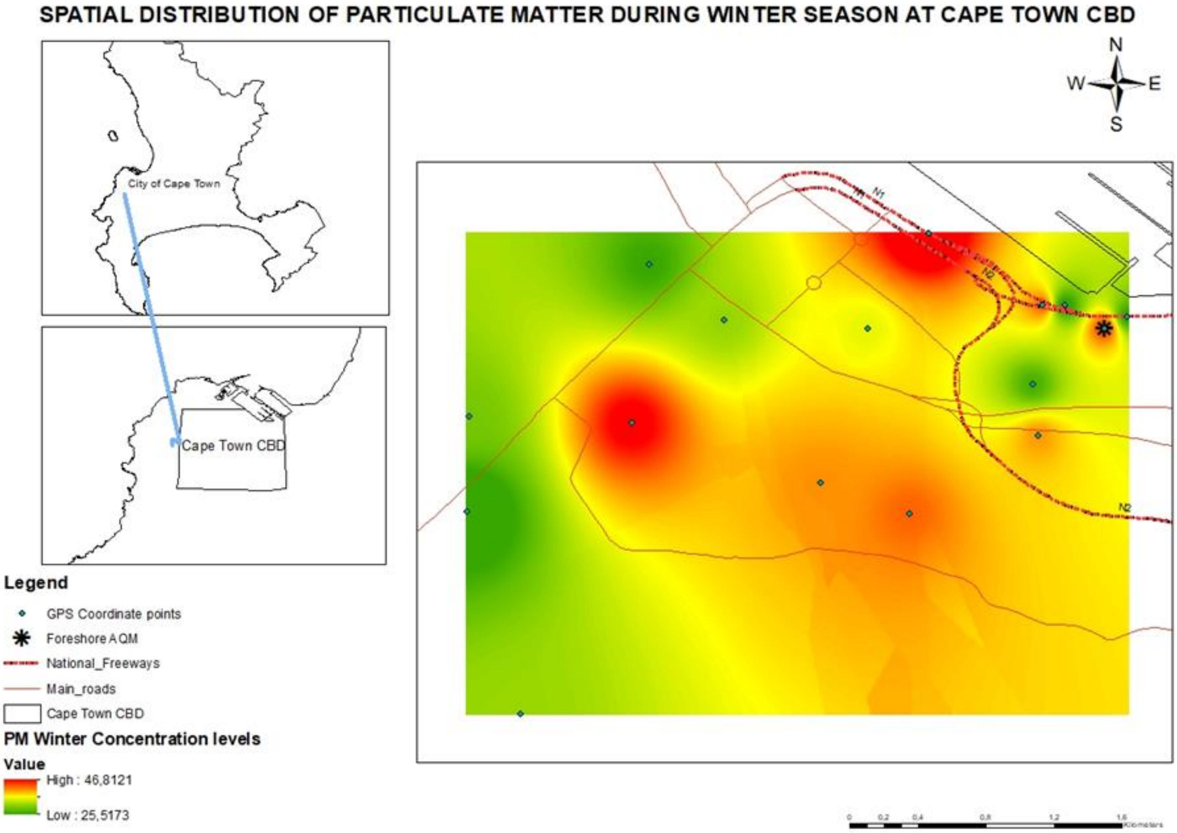

Fig. 7: Spatial distribution of PM_{10} during the winter season.

in the Foreshore air quality monitoring station during the winter season, with an increase observed when moving to the southeastern side of the map. Thus, in winter, the PM_{10} high concentration exposure levels are spatially distributed on the inland side closer to residential and high buildings. Song et al. (2019) studied the spatiotemporal distribution of air pollution characteristics in Jiangsu Province, China; the results showed a similar trend of the highest readings of PM_{10} pollutants on the inland side.

The study corroborated that the northwest wind prevails in winter can be attributed to the spatial distribution of the air pollutants in the northern part of Jiangsu, which is close to the inland. Furthermore, Jiangsu has rainy conditions during the winter season, which results in a strong vertical temperature inversion layer, making air pollutants difficult to disperse (Song et al. 2019). Thus, Jiangsu's winter condition is similar to Cape Town's winter conditions, with strong temperature inversion that combines with prevailing windless conditions that prevent air pollutants from dispersing upwards (Kelly et al. 2012). These high levels of air pollution are primarily responsible for brown haze episodes in the CBD, resulting in poor visibility. The distribution of pollutants can be attributed to low wind speed and direction, favoring the accumulation of pollutants mostly experienced during winter (Cichowicz et al. 2020). In the summer, the opposite situation occurred where the temperature was high with a high wind speed called "cape doctor' therefore, the PM_{10} pollutant was also reduced and behaved differently compared to the winter season. In a nutshell, the high concentration levels of PM_{10} during winter in the CBD are likely to be influenced by pollution from motor vehicles as source pollution and meteorological factors (i.e., wind speed and temperature).

Spatial Distribution of NO_2 During the Summer Season in Cape Town CBD

Considering the location of the air quality monitoring station, NO_2 concentrations are lower in the west and higher in the east, as illustrated in the Fig. 8. It shows that the seasonal NO_2 concentrations are essentially similar to PM_{10}, and the seasonal variations' characteristics are as follows.

Fig. 8 shows the spatial distribution of NO_2 during the summer season in Cape Town CBD from 2017 to 2018. Among two monitoring stations within the Cape Town CBD, one monitored the nitrogen dioxide pollutant for only

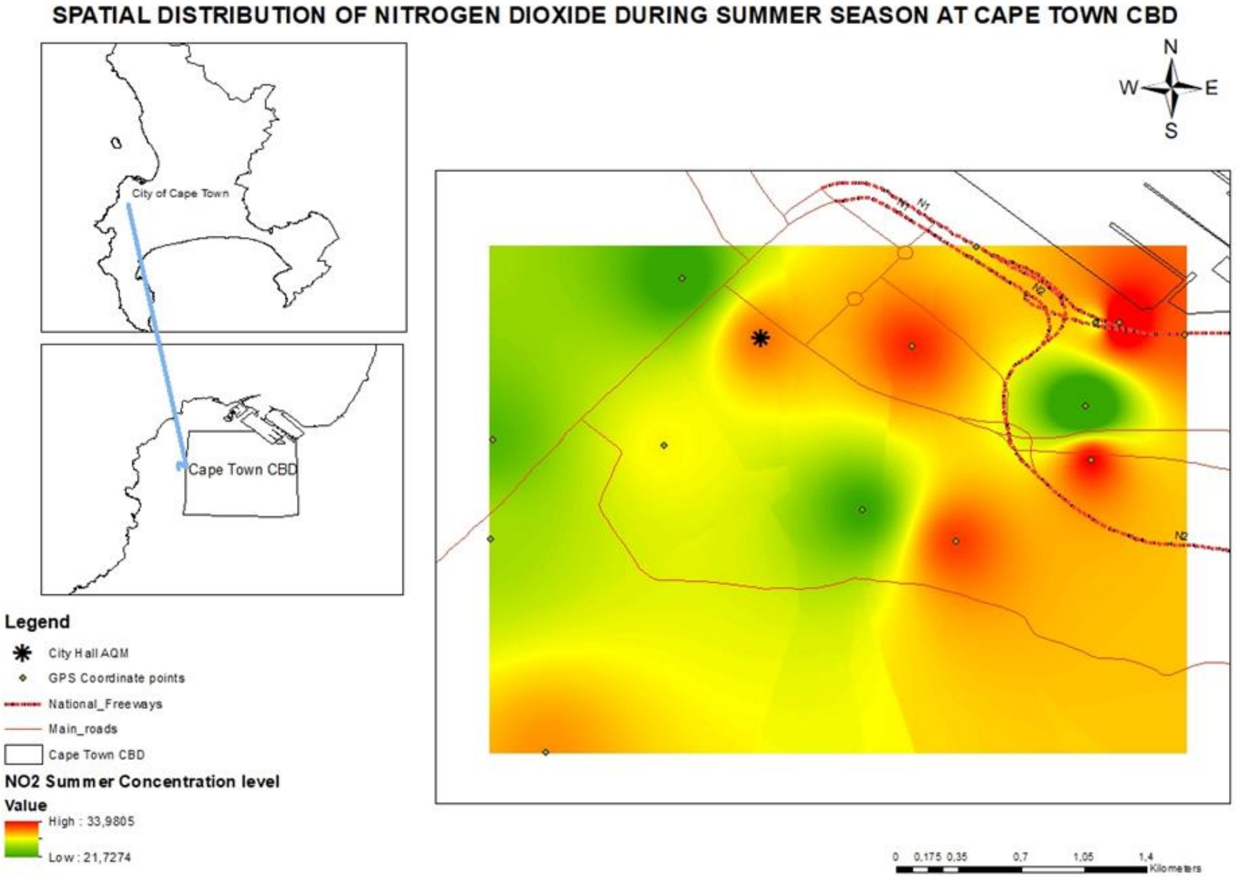

Fig. 8: Spatial distribution of NO_2 during the summer season.

January 2017 to December 2018. Therefore, the study used the measurements between these years for data accuracy for the winter and summer seasons. The heat map in Fig. 8 illustrates the outcome of the summer seasonal distribution of NO_2 concentration at City Hall AQM station within Cape Town CBD. The City Hall monitoring station recorded high exposure concentrations (33.98 $\mu g.m^{-3}$) of NO_2, with an increase in exposure concentration observed when the distance increases towards the northeastern and southeastern side of the monitoring station close to national highways and traffic intersections. The findings are similar to a study conducted by Adedeji (2016) in Nigeria, Metropolis, where the highest concentration of NO_2 was observed in the southeastern part near major roads that are attributed to high traffic volume. Nevertheless, in a study done in Jinan City determining the spatial characteristics of environmental air quality, the NO_2 pollutant was higher in the Northeastern and central parts of the map (Wang et al. 2021). The study further demonstrated that the direction of the pollutant distribution might be related to industrial production located in the northeastern part of the city.

In comparison with the PM_{10} summer spatial distribution demonstrated in Fig. 7, the spatial distribution of NO_2 (Fig. 8) almost behaves similarly to PM_{10} towards the national highways, traffic intersections, and main roads. That is, these two pollutants are both concentrated toward the traffic intersections. The discovery of a correlation reflected in similar behavior between PM_{10} and NO_2 pollutants validates a long-standing relationship between the two pollutants (Pineda & Cano 2021, Madonsela 2019). The observed correlation might be engendered by the fact that NO_2 has been identified as a secondary precursor for particulate matter (Pineda & Cano 2021, Madonsela et al. 2022), and these pollutants are both associated with traffic-related emissions primarily emitted from the combustion of motor engines (Keen & Altieri 2006). According to Fig. 8, national highways and major roads can be identified as hotspot areas during the summer season; the results of this study corroborate this finding.

Moreover, the south-easterly wind force is known as the 'Cape Doctor' that blows during the summer months and can be credited for spatially distributing the pollutants of PM_{10} and NO_2. Given the above, numerous scholars suggest that the most important constraints on air pollution dispersion throughout the summer are meteorological variables such as wind speed and topographically induced flows (Wei et al. 2021, Jiang & Bai 2018, Wang et al. 2021).

Spatial Distribution of NO_2 During the Winter Season in Cape Town CBD

The spatial distribution of transport emissions is of key concern. The meteorological patterns, high buildings, and street canyons will likely affect the concentration and spatial distribution of air pollution emissions from mobile sources.

Fig. 9 shows the results of the winter seasonal spatial distribution of NO_2 in the Cape Town CBD for the period of 2017 to 2018. The heat map outcome of winter NO_2 pollutants from the City Hall AQM station generally indicates variability in spatial distribution. Fig. 9 shows that the City Hall monitoring station recorded high exposure concentrations (38.59 $\mu g.m^{-3}$) of NO_2. It was observed that the is an increase in concentration when moving to the southwestern side of the map. Subsequently, high concentration exposure levels were also observed near the national highway (N1) and traffic intersections entering the CBD on the northeastern side of the map. The findings of this study are in line with a study done by Moja et al. (2019), which was conducted in the City of Tshwane, which identified that poor air quality is not evenly distributed throughout the city but localized in a few large residential areas and commercial activities, particularly in winter. Similarly, observations made by Moja et al. (2019) in Fig. 9 indicate that the hazardous delineated zones are mostly marked close to residential areas (Southwest side of the map) and the harbour industrial areas (Northeastern side of the map). This is partly because stable meteorological conditions in winter do not promote the distribution of pollutants (Lourens et al. 2011).

These high concentration levels close to the harbour commercial areas may be influenced by the presence of shipping emissions and other sources, such as heavy-duty vehicles associated with port activities. A study by Tularam et al. (2020) in Durban, South Africa, highlighted the importance of the harbor variable, which serves as a proxy

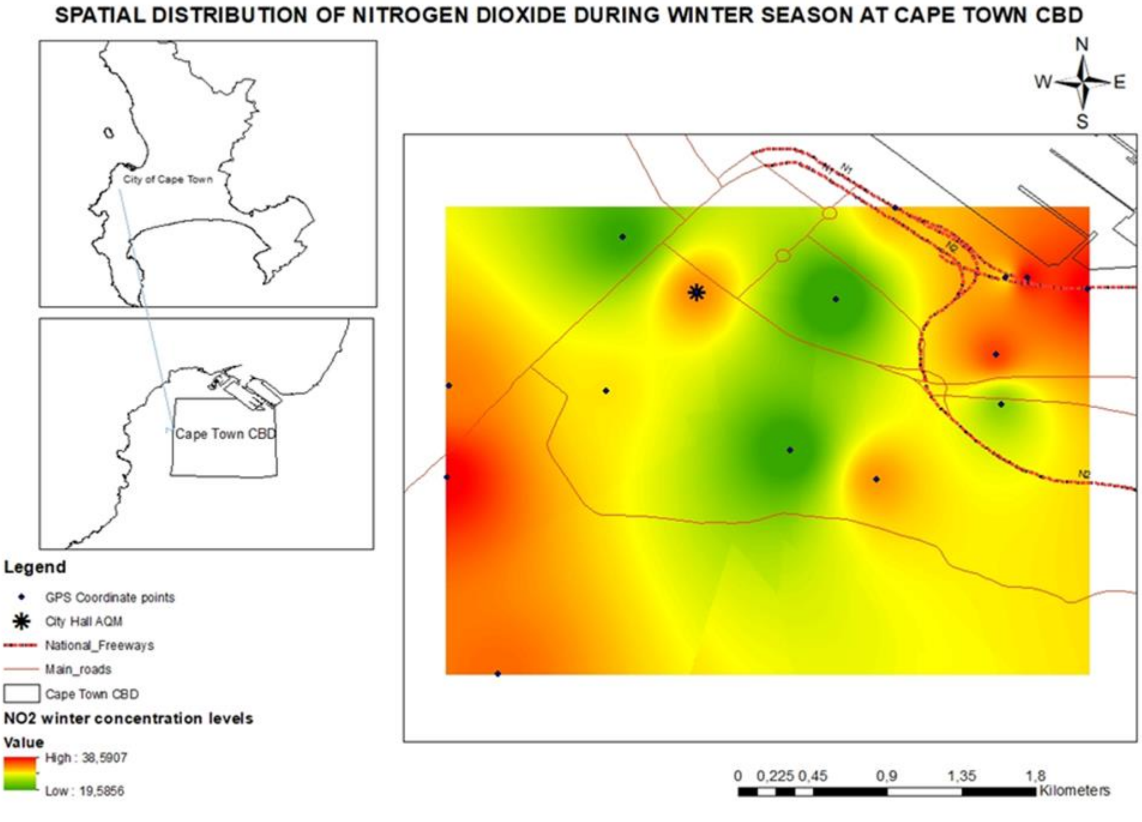

Fig. 9: Spatial distribution of NO_2 during the winter season.

for NO_2 concentration. In addition, the analysis in Fig. 8 indicated that the maximum concentration of ambient NO_2 levels was relatively higher in winter (38.59 $\mu g.m^{-3}$) than in summer (33.98 $\mu g.m^{-3}$). This can be attributed to the Table Mountain shielding properties and the climatic factors in winter that influence the accumulation and distribution of air pollutants Jury et al. (1990). Likewise, Kelly et al. (2012) substantiate that stable meteorological conditions contribute to pollutant level increases during the cold (winter) seasons.

The maximum concentration level results indicate that the NO_2 concentration level trend is comparable to results obtained elsewhere, where high exposure levels of NO_2 were discovered during the winter compared to the summer season (Levy et al. 2014, Rabiei-Dastjerdi et al. 2022). A study by Zheng et al. (2018, 2015) emphasized that in the winter, the pollutants are not easily washed away; hence some cities experience brown-haze smog episodes. Correspondingly, in a study of spatiotemporal variation characteristics of air pollutants in Shijiazhuang City, the distribution of NO_2 was more severe in the northeastern part of the map (Tui et al. 2021). The reason being in the north-eastern side, they are industrial activity sources and large vehicles.

CONCLUSION

The spatial distribution and behavior characteristics of ambient air quality (PM_{10} and NO_2) at Cape Town CDB were investigated utilizing ArcGIS to map spatial distribution. The study's findings show a distinct spatial variation in that PM_{10} was the main pollutant in the CBD, with a high concentration between summer and winter in 2017 and 2018, and the NO_2 pollutant was lighter. A large number of studies have shown that there are obvious seasonal differences in the distribution of air pollutants. The finding of this study indicated that meteorological conditions such as wind speed and temperature have a correlation close with the ambient air pollutants and play an important role in the spatial distribution of PM_{10} and NO_2. Although the meteorological factors are not studied in this study, the findings were comparable with others studies conducted globally. Moreover, the national traffic roads entering the CBD, industrial harbor, and dense residential areas with high buildings were considered the pollution hotspot in the CBD.

The monthly variation of atmospheric pollutant concentrations in Cape Town CBD's main urban area has obvious seasonal characteristics. The worse pollution was in winter, especially in August, which is in winter, and light (medium) pollution was noted in summer. Therefore, this paper is important because it provides an in-depth understanding of the spatiotemporal characteristics of air quality and the primary pollutants that have affected the AQI in Cape Town CBD. The study sheds light on future urban development and pollution control. Furthermore, air quality is affected by various factors, including weather and human activities, and this paper lacks other influential factors in wind speed. Future research should combine remote-sensed and ground-monitored data to reduce extrapolation errors/bias and investigate relationships between other driving factors and air pollutants for more urban sites.

ACKNOWLEDGEMENTS

We acknowledge Cape Peninsula, University of Technology for its support, and the City of Cape Town for providing us with raw data for analysis.

DATA AVAILABILITY

Raw data from the City of Cape Town, air quality management, were used in the study. The information can be requested from https://www.capetown.gov.za/City-Connect/Environmental-health/Apply-for-an-atmospheric

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