Research article

Temperature modifies the association between air pollution and respiratory disease hospital admissions in an industrial area of South Africa: The Vaal Triangle Air Pollution Priority Area

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Abstract

Background: Epidemiological studies reported independent effects of air pollution and temperature on health, yet these two exposures are often treated as separate risk factors. Few studies investigated temperature effect modification on the health effects of air pollution in Africa and none examined the effects of black carbon on respiratory disease (RD) hospitalisations. The aim of this study was to determine whether the association between RD hospitalisations and air pollution in the Vaal Triangle Air Pollution Priority Area was modified by apparent temperature (Tapp) during January 2013 to February 2020.

Methods: RD admission data (ICD10 J00-J99) were obtained from two hospitals located in Vanderbijlpark and Vereeniging. Ambient PM_{10}, $PM_{2.5}$, BC, NO_2, SO_2 and O_3, temperature and relative humidity data were obtained from six monitoring stations. A case-crossover epidemiological study design was applied. Lag0-1 was investigated, i.e. the average air pollutant level on the day and the day before hospitalisation. Models were adjusted for public holidays and Tapp. Effect modification was investigated by stratifying days into low, moderate and high Tapp days. Susceptibility by age and sex was investigated.

Results: Of the 43 386 hospital admissions, 50.9% (n=22 092) were women and 51.4% (n=22 304) were 0-14-year olds. Air pollutants exceeded the daily WHO air quality guidelines generally on more than 50% of the days. In general, moderate Tapp worsened the effects of $PM_{2.5}$, PM_{10}, SO_2 and BC, whilst the effects of NO_2 and O_3 were most pronounced on days with high Tapp. The elderly and females were more vulnerable to air pollution, especially on days with moderate Tapp.

Conclusions: These results indicate that the risk of RD hospitalisation due to ambient air pollution exposure is different on low, moderate and high Tapp days in Vanderbijlpark and Vereeniging.

Keywords

Air pollution, PM_{10}, $PM_{2.5}$, NO_2, SO_2, O_3, black carbon, apparent temperature; respiratory disease; hospital admissions; South Africa; heat effects; case-crossover

Introduction

The World Health Organization (WHO) concluded that the burden of disease attributable to air pollution is on a par with other major global health risks such as tobacco smoking and unhealthy diet (WHO, 2021). Therefore, air pollution is now acknowledged as the single biggest environmental threat to human health. 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). It is estimated that the majority of these deaths occur in low– and middle–income countries (LMIC), however these estimates are based mostly on exposure-response functions derived from epidemiology studies conducted in developed countries (Cohen et al., 2017; Ostro et al, 2018; WHO, 2021). More air pollution epidemiological studies need to be conducted in LMIC, such as South Africa (Ostro et al. 2018).

Ambient temperature is another major environmental risk factor of human health (Romanello et al., 2022). Climate change is projected to have dangerous effects on weather patterns and temperature globally in the near future (Romanello et al., 2022). Both heat and cold exposure are risk factors for human health, but most studies focused on heat (Ryti et al., 2016; Song et al., 2017; Vicedo-Cabrera et al., 2018). Epidemiological studies in Africa and other LMIC on the human health effects of heat and cold are lacking (Amegah et al., 2016; Wichmann, 2017; Green et al., 2019). LMIC populations are more susceptible to temperature extremes due to inadequate infrastructure, healthcare services, technology (Green et al., 2019). It is projected that by 2080, temperature increases greater than 4°C will be observed across South Africa (Department of Environment, Forestry and Fisheries, 2020).

Most air pollution epidemiological studies adjust for ambient temperature as a confounder in regression models (Atkinson et al., 2014; 2015; Chen et al., 2017; Li et al., 2017; Abed et al., 2020; Orellano et al., 2020; Grigorieva, & Lukyanets, 2021; Areal et al., 2022). During the last decade research emerged on whether the effects of air pollution on human health are modified by temperature (Chen et al., 2017; Li et al., 2017). Most of these studies focused on cause-specific mortality, such as respiratory, cerebrovascular diseases and specific cardiovascular diseases. Fewer studies globally investigated cause-specific hospital admissions (Abed Al Ahad et al., 2020; Lokotola et al., 2020; Olutola and Wichmann, 2021; Areal et al., 2022). The evidence so far is ambiguous and studies are lacking in LMIC. The WHO recommended more epidemiological studies that investigate temperature effect modification of air pollution along with more studies that focus on BC, NO_2 and SO_2 exposure (WHO, 2021).

To address the gaps in understanding the human health effects due to the interaction between ambient air pollution and temperature exposure, this study investigated respiratory disease hospital admissions during a study period of just over seven years in one of the most polluted areas in South Africa, namely the Vaal Triangle Air Pollution Priority Area (VTAPA). Susceptibility by sex and age groups (0–14, 15–64 years and ≥65 years) was also investigated.

Material and methods

Study area

Vereeniging and Vanderbijlpark are located in the VTAPA (Figure 1). The two cities border each other directly. Air pollution priority areas are air pollution hot spot areas of concentrated industrial activities (Naiker et al., 2012).These air pollution hot spot areas are declared as priority areas according to the National Environmental Management: Air Quality Act, 2004, i.e. if the Minister of Environmental Affairs or Member of the Executive Committee reasonably believes that: ambient air quality standards are being, or may be, exceeded in the area, or any other situation exists which is causing, or may cause, a significant negative impact on air quality in the area; and the area requires specific air quality management action to rectify the situation (Department of Environmental Affairs 2005). Three National Priority Areas have so far been declared: The VTAPA, the Highveld and the Waterberg-Bojanala Priority areas in 2006, 2007 and 2012, respectively.

Study design

The associations between air pollution and respiratory disease hospital admissions were investigated with the case-crossover epidemiological design, as done in numerous other studies globally (Chen et al., 2017; Li et al., 2017; Song et al., 2017) and in South Africa (Lokotola, Wright and Wichmann, 2020; Olutola and Wichmann, 2021; Thabethe, Voyi & Wichmann 2021; Wichmann & Voyi 2012, Shirinde and Wichmann, 2022).

The case-crossover epidemiological study design was developed as a variant of the case-control epidemiological design to study the effects of transient exposures on emergency events, comparing each person's exposure in a time period just prior to a case-defining event with each person's exposure at other times (Maclure, 1991). If the control days are chosen close to the event day, personal characteristics that vary slowly over a short time period of 24 hours are controlled by matching. Such characteristics may include co-morbidities (e.g. HIV status, hypertension, smoking status and so forth). Nevertheless, such characteristics may be potential effect modifiers, i.e. indicate susceptibility. However, information on such characteristics is not provided by hospital registers.

The time-stratified approach was applied to select the control days, defining the day of hospital admission as the case day and the same day of the week in the same month and year as control days (i.e. theoretically 3 to 4 control days per case day) (Carracedo-Martínez et al., 2010). The incidence of hospital admissions is likely to be influenced by time-varying factors, such as day of the week, public holidays, long-term trend and seasonality. In case-crossover study design, day of the week, long-term trend and seasonality are controlled by design.

Hospital admission data

Respiratory disease hospital admission data (International Classification of Disease, 10th version [ICD-10] (J00–J99) were obtained from two hospitals located in Vereeniging and Vanderbijlpark after ethical approval had been obtained (Reference 132/2018 and 433/2021, Research Ethics Committee, Faculty of Health Sciences, University of Pretoria) (Figure 1). Data from the two hospitals were available electronically from 1 January 2013 – 29 February 2020.

Air pollution and weather data

$PM_{2.5}$, PM_{10}, BC, NO_2, SO_2 and ground-level O_3 were investigated for the study period 1 January 2013 to 29 February 2020 and downloaded as daily averages from the SAAQIS website. The South African Weather Services (SAWS) manages the data that are deposited in the South African Air Quality Information System. The air pollution data source is the same as the very large study of 682 cities (Liu et al., 2019) and other local studies (Adebayo-Ojo et al., 2022; Olutola and Wichmann, 2021, Shirinde and Wichmann, 2022). A network of six air pollution monitors were assigned to the VTAPA (South African Air Quality Information System 2022) and these continuously assess real-time concentrations of the criteria air pollutants using equivalent methods of the United States Environmental Protection

Agency and in accordance with ISO 17025 guidelines (National Environmental Management: Air Quality Act, 2004) (Figure 1). This Act requires the monitoring of criteria air pollutants.

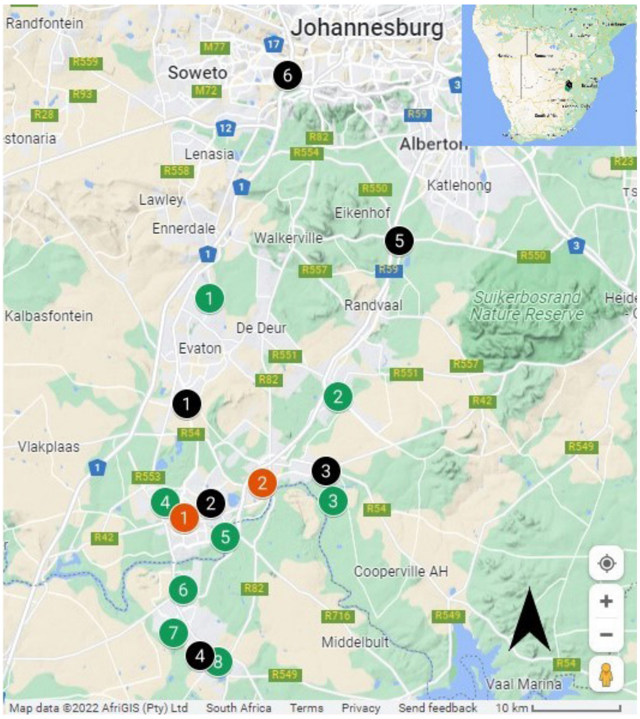

Figure 1: Map of the location of the air pollution stations in the Vaal Triangle Air Pollution Priority Area and the two hospitals
Red symbols are the hospitals (1) Vanderbijlpark and (2) Vereeniging.
Black symbols are the pollution monitoring stations of the VTAPA: (1) Sebokeng, (2) Sharpeville, (3) Three Rivers, (4) Zamdela, (5) Kliprivier, (6) Diepkloof.
Green symbols are the pollution monitoring stations of the City of Johannesburg:(1) Orange Farm, (2) Meyerton, (3) Randwater, (4) Vanderbijlpark, (5) North West University, (6) Bongani Mabaso Eco Park, (7) AJ Jacobs, (8) Leitrim.

Data of all six air pollution monitoring stations of the VTAPA (Kliprivier, Diepkloof, Zamdela, Sebokeng, Sharpeville and Three Rivers) were applied in the study as people are mobile and are not just based all the time in the area where the two hospitals are located. In addition, measurements are also collected by the six stations for meteorological data such as wind speed, wind direction, ambient temperature, relative humidity and rainfall. This study applied applied temperature and relative humidity to calculate apparent temperature (Tapp).

In order to minimise exposure misclassification, eight other air pollution monitoring stations in the vicinity of the VTAPA, managed by City of Johannesburg (see Figure 1), were also considered. However, these stations had missing data for several years and the data were not applied in this study.

This study investigated Tapp, which reflects the physiological experience of combined exposure to humidity and temperature and thereby better capture the response on health than temperature alone (Steadman, 1984). Song et al 2017 in a recent review stated that Tapp is considered to be a better temperature exposure metric than temperature, especially for the effects of heat exposure on morbidity or mortality.

The following equations were used to calculate the Tapp (Steadman 1984)

$$\text{Saturation vapour pressure} = 6.112 \times 10^{(7.5 \times \text{temperature °C}/\,(237.7 + \text{temperature °C})} \quad (1)$$

$$\text{Actual vapour pressure} = (\text{relative humidity (\%)} \times \text{saturation vapour pressure})/100 \quad (2)$$

$$\text{Dew point temperature °C} = (-430.22 + 237.7 \times \ln(\text{actual vapour pressure}))/-\ln(\text{actual vapour pressure}) + 19.08) \quad (3)$$

$$\text{Apparent temperature °C} = -2.653 + (0.994 \times \text{temperature °C}) + 0.0153 \times (\text{dew point temperature °C}) \quad (4)$$

Statistical analysis

Missing air pollution and meteorological data were imputed with the missing data imputation by chain equations (MICE) method, which is commonly applied in air quality studies (Gómez-Carracedo et al., 2014; Hadeed et al., 2020; Hajmohammadi & Heydecker 2021; Van Buuren & Groothuis-Oudshoorn, 2011).

The data were assumed to be missing at random. This means the missing data being observed within a variable is independent of the value of itself, however, it is dependent on other variables which are included in the data set (Allison, 2009). According to the monthly SAAQIS reports some of the reasons for missing data were power failures, station vandalism and faulty instruments (SAAQIS, 2020). MICE is a particular multiple imputation method that can only be used under the missing at random assumption of missing data (Azur et al., 2011).

The ‘mice’ package in the R statistical programme was applied. The mice predictive mean algorithm imputation option was used, which draws imputations from the observed data, imputed values had the same gaps as in the original data, and were always within the range of the original dataset (Karahalios et al., 2012). This method ensures that no imputations are outside the original data range, which produces more reliable results (Chinomona and Mwambi, 2015). Each air pollutant was imputed individually from each of the six air monitoring stations. Pollution data from one station was used to impute each pollutant. Thereafter overall averages for the VTAPA area were calculated for each pollutant.

The correlations between the air pollutants and Tapp were investigated using Spearman rank correlation analyses. As in other studies on temperature or Tapp as a modifier, the results in the present study focused on lag0-1. i.e. mean of lag0 (same day of exposure as day of hospitalisation) and lag 1 (day prior to day of hospitalisation) (Chen et al., 2017; Li et al., 2017, Song et al., 2017, Lokotola et al., 2020; Olutola and Wichmann, 2021;

Thabethe et al. 2021; Shirinde and Wichmann, 2022; Adebayo-Ojo et al., 2022).

Daily and yearly air pollution levels were compared to the daily and yearly WHO air quality guidelines (WHO, 2021) and South African air quality standards (National Environmental Management: Air Quality Act, 2004).

Stratified analyses were used to investigate the modification effects of lag0-1 of Tapp. High and low Tapp days were defined as days when Tapp was higher than the 75th percentile level in the study period (19.5°C) and lower than the 25th percentile level (11.7°C), respectively. Moderate Tapp days were those equal or higher than the 25th percentile level, but lower or equal to the 75th percentile level. A similar approach was followed in other studies (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022).

The association between the air pollutants and respiratory disease hospital admissions was investigated using conditional logistic regression models. Only single pollutant models were investigated as pollutants were all significantly correlated with each other ($p<0.05$). Models were adjusted for public holiday variable (binary variable) and Tapp.

The shape of the association between Tapp and respiratory disease hospital admissions was investigated. Tapp was included as a natural spline with 3 degrees of freedom (df) (non-linear term) in the models, as done in other studies (Wichmann et al. 2014, 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Thabethe et al. 2021; Shirinde and Wichmann, 2022). Whether the non-linear term of Tapp improved the model was checked with log likelihood ratio tests, i.e. compared it to a model that included Tapp as a linear term. It was observed that the non-linear term of Tapp was not significantly associated with the hospital admissions and also did not add value to the model. Hence, Tapp was included as a linear term in the models. Air pollutants were added as linear terms in the model, as done in many studies (Chen et al. 2017; Li et al. 2017, Wichmann, 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Thabethe et al. 2021; Shirinde and Wichmann, 2022; Adebayo-Ojo et al., 2022).

The associations were presented as the percent excess risk in hospital admissions per 10 $\mu g.m^{-3}$ increase in an air pollutant level, except for BC. The range of BC levels was small, hence an increase per 1 $\mu g.m^{-3}$ was applied. This approach is commonly applied in other studies (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022).

Susceptibility by sex and age groups (0–14 years, 15–64 years and ≥65 years) on low, moderate and high Tapp days was also investigated.

Results and discussion

Descriptive statistics

Table 1 summarises the characteristics of the respiratory disease hospital admissions and Supplementary Figure 1 illustrates the time-series of the daily admissions. In total 43 386 admissions were included in the study and between 1 and 55 respiratory disease hospital admissions were recorded daily. Males and females had similar number of admissions, whilst more than half occurred amongst the youngest age group (0–14 years). Clear seasonal trends were observed with more admissions during the colder months (May to August) than during the warmer months (September to April) (Figure 1). The majority of respiratory disease hospital admissions occurred on moderate Tapp days (50%), followed by 31% and 19% on days with low and high Tapp, respectively.

Table 1: *Daily descriptive statistics of respiratory disease hospital admissions in Vereeniging and Vanderbijlpark, South Africa and air pollutants and weather conditions in the Vaal Triangle Air Pollution Priority Area, South Africa, 1 January 2013 – 29 February 2020 (2616 days).*

Variable	Mean	Min	P25	Median	P75	Max
Hospital admissions						
All ages and both sexes (n=43 386)	16.6	1	11	15	21	55
Females (n=22 092)	8.4	0	5	8	11	35
Males (n= 21 294)	8.1	0	5	7	11	30
0–14 year olds (n=22 304)	8.5	0	5	8	11	37
15–64 year olds (n=15 810)	6.0	0	4	6	8	27
≥65 year olds (n=5 272)	2.0	0	1	2	3	16
Exposure						
PM_{10} ($\mu g.m^{-3}$)	51.7	12.5	38.2	48.3	62.4	131.8
$PM_{2.5}$ ($\mu g.m^{-3}$)	30.4	7.3	22.7	28.5	36.0	80.6
Black carbon ($\mu g.m^{-3}$)	3.2	0.4	1.9	2.7	4.0	9.6
NO_2 ($\mu g.m^{-3}$)	30.7	8.0	23.4	28.9	36.0	80.8
SO_2 ($\mu g.m^{-3}$)	15.6	2.4	9.6	13.6	19.4	63.6
O_3 ($\mu g.m^{-3}$)	50.2	14.3	40.0	49.3	59.3	103.9
Tapp (°C)	15.6	-2.2	12.5	16.3	19.1	28.1
Temperature (°C)	17.1	0.4	14.0	17.7	20.5	29.8
Relative humidity (%)	49.9	13.1	40.7	50.3	59.6	85.1

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than $_{2.5}$ µm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature

Table 1 also summarises the descriptive statistics for daily air pollutant and Tapp levels, whilst Supplementary Figures 2 to 9 present the time-series of the exposure variables. The mean Tapp was 15.6°C and ranged between -2.2°C to 28.1°C.

The highest PM_{10}, $PM_{2.5}$, BC, NO_2, SO_2 and O_3 levels were 131.8 $\mu g.m^{-3}$, 80.6 $\mu g.m^{-3}$, 9.6 $\mu g.m^{-3}$, 80.8 $\mu g.m^{-3}$, 63.6 $\mu g.m^{-3}$ and 103.9 $\mu g.m^{-3}$, respectively. The daily PM_{10}, $PM_{2.5}$ and SO_2 and NO_2 levels exceeded the daily WHO air quality guidelines of 45 $\mu g.m^{-3}$, 15 $\mu g.m^{-3}$, 40 $\mu g.m^{-3}$ and 25 $\mu g.m^{-3}$ on 1 532, 2 544, 47 and 1 771 days of the 2616 days, respectively (Figure 2) (World Health Organization, 2021). There is no daily WHO guideline for O_3. The more lenient South African daily air quality standards of 75 $\mu g.m^{-3}$, 40 $\mu g.m^{-3}$ and 125 $\mu g.m^{-3}$ were exceeded on 332, 452 and zero days, respectively for PM_{10}, $PM_{2.5}$ and SO_2 (National Environmental Management: Air Quality Act, 2004). There is no daily South African air quality standard for NO_2 or O_3.

Agbo et al (2021) reviewed 211 journal articles from air pollution exposure assessment studies that were conducted in 27 of the 54 African countries, including South Africa. These were published between 2006 and 2018. Outdoor PM_{10} daily levels ranged from 0.06 $\mu g.m^{-3}$ in Rukomechi, Zimbabwe (Nyanganyura et al., 2007; Agbo et al., 2021) to 7154 $\mu g.m^{-3}$ in Nouna, Burkina Faso (Yamamoto et al., 2014; Agbo et al., 2021). Daily and yearly mean PM_{10} levels exceeded the WHO guidelines for the majority of the 24 African cities that had available PM_{10} data. Thabethe et al. (2020) and Adebayo-Ojo et al. (2022) reported daily PM_{10} levels in three large South African cities that ranged from 6.9 to 121.5 $\mu g.m^{-3}$ in Cape Town, 5.8 to 146.4 $\mu g.m^{-3}$ in Durban and 7.7 to 273.3 $\mu g.m^{-3}$ in Johannesburg during 2006–2016. Data for the three cities were obtained from the air quality monitoring networks of the municipalities. Outdoor PM_{10} daily levels at industrial areas across Africa ranged from 14.9 $\mu g.m^{-3}$ at Sour El Ghozlane, Algeria (Khedidji et al., 2017; Agbo et al., 2021) to 1780.2 $\mu g.m^{-3}$ in Illorin, Nigeria (Adeniran et al., 2017; Agbo et al., 2021). Daily PM_{10} levels ranged from 0 to 496.9 $\mu g.m^{-3}$ during 2011-2016 in the Highveld Airshed Priority Area, a heavily industrialised region in the Mpumalanga province, South Africa (Olutola & Wichmann, 2021). A large study reported a yearly mean PM_{10} level (56 $\mu g.m^{-3}$) in 24 countries worldwide, whilst the lowest mean was observed in Sweden (14 $\mu g.m^{-3}$) and the highest in China (89 $\mu g.m^{-3}$) (Liu et al., 2019). The only country from Africa that was included in this large global study was South Africa with a mean of 59 $\mu g.m^{-3}$.

The range of daily $PM_{2.5}$ levels in the VTAPA during 1 January 2013 – 29 February 2020 was higher than those recorded by the South African government at 21 ambient air quality monitoring stations in 5 provinces in 2012 (4.9 to 43.3 $\mu g.m^{-3}$) (Altieri and Keen (2019). $PM_{2.5}$ levels were also lower during April 2017 to April 2018 in Cape Town, a large coastal city in the country, and Thohoyandou, a rural non-industrial town in the north of the country (Novela et al., 2020; Williams et al., 2021). $PM_{2.5}$ levels were lower in Pretoria, the administrative capital of South Africa during April 2017 to February 2020 (Adeyemi et al., 2022; Howlett-Downing et al., 2022). Outdoor $PM_{2.5}$ daily levels ranged from 0 to 535 $\mu g.m^{-3}$ in Jinja and Kampala, Uganda (Kirenga et al., 2015). Daily $PM_{2.5}$ data were available for 22 cities across Africa and exceeded the corresponding WHO guideline (15 $\mu g.m^{-3}$) in nearly all towns (Agbo et al 2021). Lower $PM_{2.5}$ levels were reported during July 2015 to June 2016 in the Greater Tubatse Municipality, Limpopo province, South Africa. Three ferrochrome smelters and over fifteen operational chromium, platinum and silica mines are located in this municipality (Tshehla and Djolov, 2018). A similar $PM_{2.5}$ mean level (32 $\mu g.m^{-3}$) was reported during January 2011 to October 2016 in the Highveld Airshed Priority Area, a heavily industrialised region in the Mpumalanga province, South Africa, (Olutola and Wichmann, 2021). Daily mean $PM_{2.5}$ levels in industrial locations ranged from 8.2 to 384 $\mu g.m^{-3}$ in Kampala (Kirenga et al., 2015). The yearly mean level in 16 countries worldwide was 35.6 $\mu g.m^{-3}$, whilst the lowest mean was observed in Australia (7 $\mu g.m^{-3}$) and the highest in China (52 $\mu g.m^{-3}$) (Liu et al., 2019). The study reported a mean of 31 $\mu g.m^{-3}$ for South Africa.

There is a lack of studies in Africa that reported on BC levels and their health effects. The mean BC level (1.28 $\mu g.m^{-3}$) in Thohoyandou was lower (Novela et al. 2020). A study from Nairobi, Kenya reported a higher mean of 2.7 $\mu g.m^{-3}$ for BC (Gaita et al. 2014). A study estimated BC levels in Africa and reported the lowest level in South Africa (2.1 $\mu g.m^{-3}$) and the highest level in Benin (16 $\mu g.m^{-3}$) (Bachwenkizi et al. 2021). A study from London, UK reported a lower mean BC level (1.5 $\mu g.m^{-3}$) during 2011–2012 (Samoli et al., 2016), whilst a study from the Uzice region, Serbia observed a higher mean BC level (33.9 $\mu g.m^{-3}$) during 2012–2014 (Tomic-Spiric et al., 2019).

Daily NO_2 levels in three large South African cities ranged from 3.4 to 59.8 $\mu g.m^{-3}$ in Cape Town, 9.9 to 131.1 $\mu g.m^{-3}$ in Durban and 0.9 to 123.1 $\mu g.m^{-3}$ in Johannesburg during 2006–2016 (Thabethe et al. 2020; Adebayo-Ojo et al., 2022). In the review by Agbo et al (2021), data on NO_2 were available for 14 countries from 26 studies and indicated that traffic and industrial activities impacts NO_2 levels. Yearly mean levels of outdoor NO_2 ranged between 0.6 $\mu g.m^{-3}$ in Okaukuejo, Namibia (Martins et al., 2007) and 5 $\mu g.m^{-3}$ (Botsalano, South Africa) (Aurela et al., 2016) at background sites. Yearly mean NO_2 levels at industrial sites ranged from 5 $\mu g.m^{-3}$ (Amersfoort, South Africa) (Martins et al., 2007) to 19 $\mu g.m^{-3}$ (Kuraymat Egypt) (Hindy and Abdelmaksoud, 2016). A lower mean NO_2 level (12 $\mu g.m^{-3}$) was reported during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area in South Africa (Olutola & Wichmann, 2021). The yearly mean NO_2 level in 19 countries worldwide was 30.4 $\mu g.m^{-3}$, whilst the lowest mean was observed in Australia (7 $\mu g.m^{-3}$) and the highest in China (52 $\mu g.m^{-3}$) (Liu et al., 2019). The study did not report a mean for South Africa.

Daily SO_2 levels in three large South African cities ranged from 0.8 to 53.5 $\mu g.m^{-3}$ in Cape Town, 3.1 to 76.9 $\mu g.m^{-3}$ in Durban and 1.2 to 90.7 $\mu g.m^{-3}$ in Johannesburg during 2006–2016 (Thabethe et al. 2020; Adebayo-Ojo et al., 2022). In the review by Agbo et al (2021), data on SO_2 were available for 14 countries from 23 studies. The yearly mean SO_2 levels ranged from 2–35 $\mu g.m^{-3}$ at various locations in South Africa (Martins et al., 2007, Adon et al., 2010, Morakinyo et al., 2017; Laakso et al., 2012; Aurela et al., 2016; Lourens et al., 2011). The yearly mean SO_2 levels ranged from 0.8 $\mu g.m^{-3}$ in Zoetele, Cameroon (Adon et al., 2010) to 10 $\mu g.m^{-3}$ in Kuraymat, Egypt (Hindy and Abdelmaksoud, 2016). A lower mean SO_2 level (9 µg.m^{-3}) was reported during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area in South Africa (Olutola & Wichmann, 2021). The yearly mean SO_2 level in 16 countries worldwide was 20.2 µg.m^{-3}, whilst the lowest mean was observed in Estonia (3 µg.m^{-3}) and the highest in China (29 µg.m^{-3}) (Liu et al., 2019). The study did not report a mean for South Africa.

In the review by Agbo et al (2021), data on O_3 were available for 35 cities in 14 countries across Africa. The day time O_3 levels ranged from 0.3 µg.m^{-3} to 1.2 µg.m^{-3} in Lagos, Nigeria was (Olajire et al., 2011). The yearly mean levels ranged from 31 to 53 µg.m^{-3} at industrial locations and 69 to 71 µg.m^{-3} at background locations in South Africa (Agbo et al., 2021). O_3 levels are higher at background locations due to atmospheric chemistry. The yearly mean O_3 levels in other parts of Africa ranged from 8 µg.m^{-3} in Bomassa Congo (Adon et al., 2010) to 45 µg.m^{-3} in Okaukuejo, Namibia (Martins et al., 2007). The yearly mean O_3 level in 22 countries worldwide was 65.4 µg.m^{-3}, whilst the lowest mean was observed in Colombia (25 µg.m^{-3}) and the highest in Brazil (83 µg.m^{-3}) (Liu et al., 2019). The study did not report a mean for South Africa.

Table 2 shows the correlation between the air pollutants and temperature. PM_{10}, $PM_{2.5}$, BC, NO_2 and SO_2 had moderate positive correlations (r = 0.384 to 0.875). O_3 had inverse correlations with the other air pollutants (r= –0.258 to –0.455). Meteorological conditions can diffuse, dilute and accumulate air pollution. All the air pollutants were inversely correlated with temperature, except O_3. There was no significant correlation between temperature or Tapp and relative humidity (p>0.05). A large study of 15 African countries reported a weaker correlation between estimated $PM_{2.5}$ and BC levels (0.67) (Bachwenkizi et al. 2021). $PM_{2.5}$ and PM_{10} had a stronger correlation than those observed in 652 cities from 24 countries (0.78). A study from Cape Town reported a weaker correlation between $PM_{2.5}$ and PM_{10} (0.481) (Williams et. al.) whilst a study in the industrialised Highveld Airshed Priority Area in South Africa reported a stronger correlation (0.95) (Olutola & Wichmann, 2021). Liu et. al. (2019) reported weaker correlations between $PM_{2.5}$ and NO_2 (0.48) and between $PM_{2.5}$ and SO_2 (0.40) in 652 cities from 24 countries. Weaker correlations between $PM_{2.5}$ or PM_{10} and NO_2 or SO_2 were observed in the industrialised Highveld Airshed Priority Area (Olutola & Wichmann 2021).

Exposure-response estimates

Insignificant associations were observed between lag0-1 of PM_{10}, $PM_{2.5}$ or BC and respiratory disease hospitalisations in the unstratified analyses, i.e. entire Tapp range and all ages and sexes combined: 0.6% (95% CI -0.2%; 1.5%), 1.0% (95% CI -0.3%; 2.4%) and 1.1% (95% CI -0.1%; 2.3%), respectively (Table 3). PM_{10}, $PM_{2.5}$ and BC also did not influence hospital admissions for the different age and sex groups across the entire Tapp range, except that an increase in BC (per 1 µg.m^{-3}) lead to a significant increase of 3.6% (95% CI 0.3%; 7.0%) in hospital admissions among the elderly.

Table 2: *Spearman rank correlation coefficients between air pollution and weather variables in the Vaal Triangle Air Pollution Priority Area, South Africa, 1 January 2013 – 29 February 2020 (2616 days).*

Variable	$PM_{2.5}$	BC*	NO_2	SO2	O_3	Tapp	Temp	RH
PM_{10}	0.875	0.726	0.586	0.384	-0.258	-0.315	-0.309	-0.320
$PM_{2.5}$		0.721	0.624	0.410	-0.281	-0.320	-0.318	-0.122
BC			0.796	0.431	-0.455	-0.548	-0.539	-0.388
NO_2				0.516	-0.379	-0.433	-0.427	-0.269
SO_2					-0.335	-0.329	-0.323	-0.267
O_3						0.728	0.731	-0.111
Tapp							1.000	0.028
Temp								0.006

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than 2.5 µm; BC: Black carbon; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature; Temp: Temperature; RH: relative humidity
All correlations were significant ($p < 0.001$), except between temperature and RH (p=0.771), and Tapp and RH (p=0.158)

In contrast to the findings of the current study, a study from Cape Town reported a stronger association between PM_{10} and respiratory disease hospitalisations, namely a 1.9% increase in hospitalisations (95% CI 0.5%; 3.2%) per 12 µg.m^{-3} increase in lag0-1 of PM_{10}, even though the PM_{10} levels were lower than in the current study. Renzi et al. (2022) reported a weaker association between PM_{10} and daily respiratory hospitalisations than in the current study; in the entire Italy: 0.39% (95% CI 0.21%; 0.56%) per 10 µg.m^{-3} increase in lag0-1 of PM_{10}. PM_{10} levels ranged from 2 to 290 µg.m^{-3} in their study. A meta-analysis on studies conducted in LMIC reported the same percentage increase in daily respiratory disease hospitalisation per 10 µg.m^{-3} increase in lag0-1 of PM_{10} as the study from Italy (Newell et al., 2017). Most of these studies were from East Asia and the Pacific region.

Atkinson et al (2014) conducted the most recent systematic review and meta-analyses on the effects of $PM_{2.5}$ on daily respiratory disease hospitalisations. They reviewed 43 time-series epidemiological studies; none were from Africa. An excess risk of 0.96% (95% CI –0.63%; 2.58%) was reported per 10 µg.m^{-3} increase in lag0-1 of $PM_{2.5}$, which is similar to our result. A lower increase in daily respiratory disease hospitalisation per 10 µg.m^{-3} increase in lag0-1 of $PM_{2.5}$ was observed in LMIC, namely 0.42% (95% CI –0·93; 1·77) (Newell et al., 2017).

Very few studies globally and none from Africa investigated the short-term effects of BC on respiratory disease hospital admissions. Song et al (2021) reported a 1.2% (95% CI 0.7%; 3.1%) increase in respiratory disease hospital admissions per 1 µg.m^{-3} increase in BC (10 studies), which is similar to our observation.

Increases in the three gaseous air pollutants (NO_2, SO_2 and O_3) significantly increased hospital admissions across the entire Tapp range and for all population groups combined: 3.0% (95%

CI 1.3%; 4.7%), 1.7% (95% CI 0.1%; 3.4%) and 2.5% (95% CI 0.9%; 4.3%) per 10 µg.m^{-3} increase in lag0-1 levels, respectively. A study from Cape Town reported similar associations between NO_2 or SO_2 and respiratory disease hospitalisations, namely a 2.3% (95% CI 0.6–4%), and 1.1% (95% CI −0.2–2.4%) increase per 7.3 µg.m^{-3} or 3.6 µg.m^{-3} increase in lag0-1 of NO_2 or SO_2, respectively. NO_2 and SO_2 levels were lower in Cape Town. Across the entire Tapp range, the elderly was significantly most at risk for hospitalisation when NO_2 increased (8.2% 95% CI 3.4; 13.2) whilst this was the case for the 15–64 year old group when O_3 increased (3.8% 95% CI 1.0; 6.7).

In general, an increase in the air pollutants on days with moderate Tapp significantly lead to more admissions compared those on low and high Tapp days, except for NO_2 and O_3 that resulted in significantly more admissions on days with warm Tapp (Table 3). An unexpected result was the 1.3% and 1.9% reduction in respiratory disease hospital admissions with increasing levels of PM_{10} on days with low Tapp for all groups combined and the youngest age group, respectively. The elderly was more vulnerable when the air pollutants increased, especially with increases in SO_2 on days with moderate Tapp that lead to a significant 17.1% increase in hospitalisations. Females were more at risk to be hospitalised than males when PM_{10}, $PM_{2.5}$ or BC increased on days with moderate Tapp. Males were more at risk than females when NO_2 or SO_2 increased on days with moderate Tapp or when O_3 increased on days with warm Tapp.

NO_2 and SO_2 in general had stronger associations with hospital admissions compared to PM_{10}, $PM_{2.5}$ and BC on days with moderate Tapp. In general, $PM_{2.5}$ and PM_{10} are regarded to be the most hazardous of the criteria air pollutants as they infiltrate to the lower airways and consist of many toxic components that trigger a variety of adverse health responses such as inducing oxidative stress in the airways, inflammatory responses and impairing the immune system (Li et al., 2022). A plausible reason for the higher hospitalisation risks of NO_2 compared to PM_{10} may be due to the fact that NO_2 is a precursor for ions of water-

Table 3: *Percentage change (95% CI) in daily respiratory disease hospital admissions in Vereeniging and Vanderbijlpark, South Africa following an increase in an air pollutant level (lag0-1) in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 – 29 February 2020 (2616 days).*

Air pollutant	Tapp	All	0–14 years	15–64 years	≥65 years	Females	Males
PM_{10}	Entire range	0.6 (-0.2; 1.5)	0.9 (-0.3; 2.1)	-0.3 (-1.7; 1.2)	2.0 (-0.4; 4.4)	0.6 (-0.6; 1.8)	0.6 (-0.6; 1.9)
	Low	**-1.3 (-2.4; -0.1)**	**-1.9 (-3.5; -0.3)**	-0.6 (-2.5; 1.3)	-0.7 (-3.7; 2.5)	-1.3 (-2.8; 0.3)	-1.3 (-2.9; 0.3)
	Medium	**3.3 (1.7; 5.0)**	**4.2 (2.0; 6.5)**	0.5 (-2.1; 3.3)	**7.7 (2.8; 13.0)**	**3.5 (1.2; 5.8)**	**3.1 (0.8; 5.5)**
	High	-1.9 (-5.2; 1.6)	-0.2 (-5.0; 4.7)	-2.9 (-8.1; 2.6)	-3.0 (-12.1; 7.0)	-2.5 (-7.1; 2.3)	-1.2 (-5.9; 3.7)
$PM_{2.5}$	Entire range	1.0 (-0.3; 2.4)	1.0 (-0.8; 2.9)	0.3 (-1.9; 2.5)	3.4 (-0.4; 7.3)	1.3 (-0.5; 3.2)	0.8 (-1.1; 2.7)
	Low	-1.1 (-2.8; 0.6)	-2.2 (-4.6; 0.2)	-0.2 (-3.0; 2.7)	0.7 (-4.0; 5.6)	-0.8 (-3.2; 1.7)	-1.5 (-3.9; 1.0)
	Medium	**4.2 (1.5; 6.9)**	**5.2 (1.5; 9.0)**	0.4 (-3.9; 5.0)	**10.7 (2.3; 19.8)**	**4.6 (0.9; 8.6)**	3.6 (-0.2; 7.6)
	High	1.1 (-4.0; 6.5)	3.5 (-3.9; 11.5)	0.2 (-7.7; 8.9)	-1.8 (-15.2; 13.8)	3.7 (-3.6; 11.5)	-1.4 (-8.3; 6.0)
Black carbon	Entire range	1.1 (-0.1; 2.3)	1.4 (-0.3; 3.0)	-0.1 (-2.0; 1.8)	**3.6 (0.3; 7.0)**	1.3 (-0.3; 3.0)	0.8 (-0.8; 2.5)
	Low	-1.5 (-3.0; 0.0)	-2.7 (-4.9; -0.6)	-0.8 (-3.2; 1.7)	1.4 (-2.7; 5.6)	-0.9 (-3.0; 1.3)	-2.1 (-4.2; 0.1)
	Medium	**4.9 (2.6; 7.2)**	**6.8 (3.7; 9.9)**	1.0 (-2.7; 4.8)	**7.8 (1.0; 15.1)**	**5.0 (1.9; 8.3)**	**4.7 (1.5; 8.0)**
	High	1.5 (-4.4; 7.7)	5.8 (-2.8; 15.1)	-3.4 (-12.2; 6.4)	2.8 (-13.4; 22.1)	2.9 (-5.3; 11.9)	-0.1 (-8.3; 8.8)
NO_2	Entire range	**3.0 (1.3; 4.7)**	**3.5 (1.2; 5.9)**	0.5 (-2.1; 3.3)	**8.2 (3.4; 13.2)**	**2.7 (0.4; 5.1)**	**3.2 (0.8; 5.6)**
	Low	-1.3 (-3.5; 1.1)	-3.4 (-6.6; 0.0)	-0.3 (-4.0; 3.6)	4.1 (-2.2; 10.9)	0.0 (-3.3; 3.3)	-2.5 (-5.7; 0.9)
	Medium	**7.8 (4.9; 10.8)**	**9.8 (5.8; 14.0)**	3.2 (-1.4; 8.0)	**14.2 (5.4; 23.6)**	**6.7 (2.8; 10.9)**	**8.9 (4.8; 13.3)**
	High	**8.7 (0.9; 17.1)**	**14.5 (3.1; 27.2)**	2.9 (-8.8; 16.1)	6.4 (-14.5; 32.4)	2.8 (-7.4; 14.1)	**15.4 (3.7; 28.4)**
SO_2	Entire range	**1.7 (0.1; 3.4)**	2.0 (-0.3; 4.3)	1.2 (-1.5; 3.9)	2.2 (-2.4; 7.1)	1.5 (-0.8; 3.8)	1.9 (-0.4; 4.3)
	Low	-1.5 (-3.9; 1.1)	-1.4 (-4.9; 2.2)	-0.1 (-4.1; 4.1)	-5.3 (-11.7; 1.6)	-0.5 (-4.0; 3.1)	-2.5 (-5.9; 1.1)
	Medium	**6.5 (3.4; 9.6)**	**5.6 (1.5; 9.9)**	4.6 (-0.4; 9.9)	**17.1 (7.5; 27.4)**	**5.1 (0.9; 9.5)**	**7.9 (3.5; 12.4)**
	High	-0.1 (-5.1; 5.1)	2.8 (-4.4; 10.5)	-2.2 (-9.8; 5.9)	-4.4 (-18.1; -11.6)	-4.0 (-10.5; 3.1)	4.2 (-3.1; 12.0)
O_3	Entire range	**2.5 (0.9; 4.3)**	1.9 (-0.4; 4.3)	**3.8 (1.0; 6.7)**	1.5 (-3.2; 6.5)	**2.6 (0.3; 5.1)**	2.4 (0.0; 4.9)
	Low	1.0 (-2.9; 4.9)	0.5 (-4.9; 6.3)	0.3 (-5.8; 6.7)	5.2 (-5.5; 17.0)	0.4 (-5.0; 6.0)	1.5 (-3.9; 7.3)
	Medium	1.1 (-1.5; 3.7)	0.9 (-2.6; 4.5)	1.3 (-3.0; 5.9)	0.7 (-6.6; 8.4)	2.6 (-1.0; 6.4)	-0.6 (-4.2; 3.2)
	High	**5.2 (1.6; 9.0)**	5.1 (-0.1; 10.5)	5.5 (-0.3; 11.6)	4.8 (-5.6; 16.4)	4.9 (-0.2; 10.2)	**5.6 (0.4; 11.1)**

High: Apparent temperature > 75th percentile; Low: Apparent temperature < 25th percentile; Medium: Apparent temperature >= 25th and <= 75th percentile. Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than 2.5 µm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature; Bold text: Significant ($p < 0.05$)

soluble inorganic salts, such as nitrate, that can partition to the particulate-phase, thus generating PM (WHO, 2013). A review reported that all-cause non-accidental mortality increased by 17% per 1 $\mu g.m^{-3}$ increase in nitrate (Atkinson et al. 2015), compared to a 0.4% increase per 10 $\mu g.m^{-3}$ increase in PM_{10} (Orellano et al., 2020). SO_2 is converted to sulphate- during the afternoon when sunlight is brightest (He et al. 2014). Sulphate leads to a substantial increase in the bioavailable metals and soot in PM (WHO, 2013). A review concluded that natural-cause mortality increased by 15% per 1 $\mu g.m^{-3}$ increase in sulphate (Atkinson et al. 2015).

BC and $PM_{2.5}$ had stronger associations than PM_{10} with hospital admissions on days with moderate Tapp (Table 3). On a mass basis, BC has a greater relative toxicity compared to $PM_{2.5}$ (Janssen et al., 2011; Thomas et al., 2017), and this was also observed in our study with BC having, in general, stronger associations with respiratory disease hospital admissions compared to $PM_{2.5}$. BC make up a small proportion of total $PM_{2.5}$ mass and air pollution abatement strategies targeted at lowering BC sources may assist to diminish the health effects attributed to $PM_{2.5}$, although only to a small extent (Thomas et al., 2017). $PM_{2.5}$ penetrate deeper into the lungs than PM_{10}, which is a possible explanation for the higher risks observed for hospitalisation. Another possible reason is that the two air pollutants often have different sources which influences the chemical composition. $PM_{2.5}$ is also a subfraction of PM_{10}. $PM_{2.5}$ derive from combustion sources or from atmospheric chemistry reactions, whilst the coarse fraction of PM_{10} derive from dust. A review included in the 2021 WHO AQ Guideline report, also observed higher risks for $PM_{2.5}$ than PM_{10} in terms of daily all-cause non-accidental mortality (Orellano et al., 2020).

More studies investigated effect modification of temperature indicators, such as Tapp, on the effects of air pollution on mortality than hospitalisations (Chen et al., 2017; Li et al., 2017; Lokotola et al., 2020; Grigorieva and Lukyanets, 2021; Areal et al., 2022). Studies that focused on mortality mostly defined days with cold, moderate and warm Tapp as done in this study, i.e. used the 25th and 75th percentiles of Tapp as cut-off points (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022). However, the selection of the cut-off points is arbitrary. Five studies applied different percentile cut-off values (10th, 15th, 20th, 25th, 50th, 75th, 80th, 85th, 90th) to define days with low, moderate and high temperature (Wang et al., 2013; Qui et al., 2018; Yitshak-Sade et al., 2018; Lokotola et al., 2020; Olutola & Wichmann, 2021; Areal et el., 2022). Some studies focused on specific respiratory disease hospital admissions such as chronic obstructive pulmonary disease (COPD), and none of the studies investigated BC or O_3. The range of air pollutant and temperature levels also varied across studies. Comparing results is therefore a challenge.

Wang et al (2013) conducted a study in Lanzhou City, China and focused on respiratory disease hospitalisations amongst all ages, PM_{10}, SO_2 and NO_2 during 2001–2005. The strongest associations for all three pollutants were observed on days with low temperature (<15th percentile), followed by days with moderate temperature and high temperature (>85th percentile). Wang et al (2013) did not investigate $PM_{2.5}$, O_3 or BC. Air pollution levels were higher in Lanzhou City than in the current study, as PM_{10} levels ranged from 16 to 2561 $\mu g.m^{-3}$, NO_2 from 4 to 260 $\mu g.m^{-3}$ and SO_2 from 2 to 371 $\mu g.m^{-3}$. Lower temperatures were reported than in the current study, whilst the maximum was similar (range -12 to 30°C).

Qui et al (2018) investigated COPD hospitalisations amongst all ages in urban areas of Chengdu, China during 2015–2016. The strongest associations for PM_{10}, $PM_{2.5}$, NO_2 and SO_2 were observed on days with low temperature (<20th percentile), followed by days with high temperature (≥80th percentile) and moderate temperature. Qui et al (2018) did not investigate O_3 or BC. Air pollution levels were higher in the urban areas of Chengdu than in the current study, as PM_{10} levels ranged from 13 to 339 $\mu g.m^{-3}$ and NO_2 from 14 to 106 $\mu g.m^{-3}$. Similar temperature levels were reported than in the current study, namely from -1 to 30°C.

As in the study by Wang et al (2013), the current study also observed the higher hospitalisation risks for PM_{10} and SO_2 on days with moderate Tapp compared to days with high Tapp. However, our results differ from Qui et al (2018) and Wang et al (2013) as the strongest associations between hospitalisations and air pollutants were not observed on days with cold Tapp, but on days with moderate Tapp.

Yitshak-Sade et al (2018) investigated the association between $PM_{2.5}$ and respiratory disease hospitalisations amongst the elderly (≥65 years) in New-England, USA during 2001–2011. They observed the strongest association on days with high temperature (>90th percentile). In contrast the strongest association was observed on days with moderate Tapp in the current study. The $PM_{2.5}$ and temperature levels were higher in the current study than in New England as the interquartile range of $PM_{2.5}$ was 5 to 11 $\mu g.m^{-3}$ and for temperature 6 to 15 °C.

Olutola & Wichmann (2021) and Lokotola et al. (2020) investigated the association between respiratory disease hospitalisations amongst all ages and PM_{10}, NO_2 and SO_2 during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area and in Cape Town, respectively. In both studies the effects of the three air pollutants on hospitalisation were more pronounced on days with high Tapp (>75th percentile), as was the case in the study by Yitshak-Sade et al (2018).

None of the studies that focused on respiratory disease hospital admissions investigated BC or O_3, whilst the few studies that investigated mortality assessed O_3, but not BC. Three studies conducted in the China, UK and US reported stronger associations between O_3 and all-cause non-accidental or respiratory disease mortality on days with high temperature compared to days with low or moderate temperature (Pattenden et al., 2010; Qian et al., 2008; Ren et al., 2008). This is in agreement with the results of the current study.

Meteorology, toxicity of air pollutants, atmospheric chemistry, human behaviour or physiology are plausible reasons why temperature indicators may modify the effects of air pollution on health outcomes. The likelihood to be exposed to outdoor air pollution may be higher on days with moderate and high Tapp levels as people may spend more time outdoors or may open windows more resulting in more outdoor air pollution infiltrating indoors. Similarly, the likelihood of exposure to outdoor air pollution may be lower on days with low Tapp levels as people may spend more time indoors and may keep windows closed. The sources and composition of air pollution may fluctuate with outdoor temperature. A greater fraction of more toxic forms of PM at higher temperature were reported by studies (Li et al., 2017; Chen et al., 2017). The possible biological mechanisms for the synergistic effects between air pollution and high temperature on human health were summarised in a review (Grigorieva and Lukyanets, 2021). Mechanisms of thermoregulation may play a role to increase the inhaled dose of air pollutants and increased dose absorbed by the skin. A combination of air pollution and heat exposure is associated with systemic inflammation and lung tissue damage (Grigorieva and Lukyanets, 2021).

Inconsistent results were reported for risks by age and sex. In the current study the elderly (≥65 years) and females were in general more vulnerable to air pollution exposure. Females have smaller lung tissue and trachea than males, which may lead to a greater inhaled dose (Oiamo and Luginaah, 2013). Women have a higher working metabolic rate, sweat less and may have thicker subcutaneous fat that may hamper thermoregulation (Kazman et al., 2015). In contrast, Olutola & Wichmann (2021) and Lokotola et al. (2020) observed the youngest group (0-14 years) to be more at risk to air pollution exposure, whilst Qui et al (2018) reported the elderly (≥80 years) to be more vulnerable. Wang et al (2013) noted that the <65 year old group was more at risk than the older age group. All the other studies reported that males were more vulnerable to air pollution.

This study is not without limitations. As in similar studies, the assumption that the ambient air pollution and meteorological variables measured at a few sites are the same across the entire area might have resulted in a measurement error. This exposure misclassification is non-differential and bias associations to be insignificant (i.e. bias effect estimates towards the null) (Hatch and Thomas, 1993). This study cannot be extrapolated to the general South African population as the study applied private hospital data and the patients belong to the middle and upper socio-economic classes. Only the wealthiest 16% of the South African population make use of the private-sector services (Barber et al., 2018). Perhaps effects may be even worse if data from public hospitals were available as mostly patients in the lower socio-economic classes make use of public hospitals. Poverty and malnutrition may make them more susceptible to the health risks of air pollution.

Conclusions

The aim of this study was to determine whether the association between RD hospitalisations and air pollution in the VTAPA was modified by Tapp during January 2013 to February 2020. It was observed that air pollution effects on respiratory disease hospitalisation were indeed modified by Tapp. In general, moderate Tapp worsened the effects of $PM_{2.5}$, PM_{10}, SO_2 and BC, whilst the effects of NO_2 and O_3 were most pronounced on days with high Tapp. The elderly and females were more vulnerable to air pollution, especially on days with moderate Tapp. Globally more epidemiological studies are needed on this topic.

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Author contributions

NSW: methodology; data collection; data analysis; data curation; writing. BGO: conceptualisation; methodology; writing. JW: conceptualisation; methodology; data collection; data analysis; data curation; writing.

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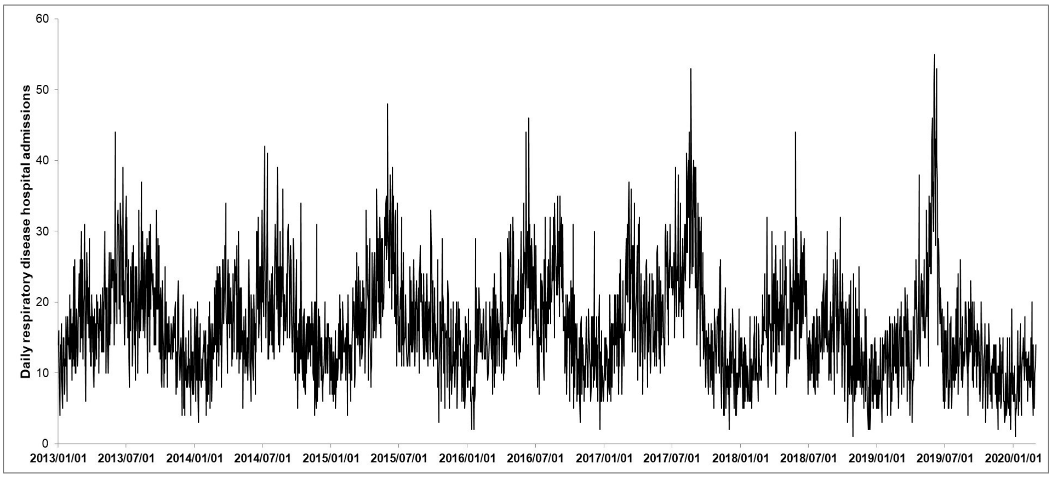
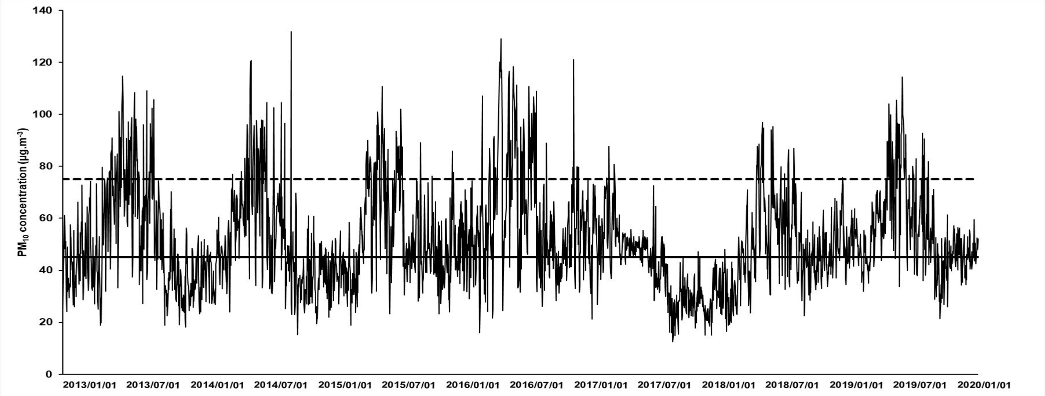


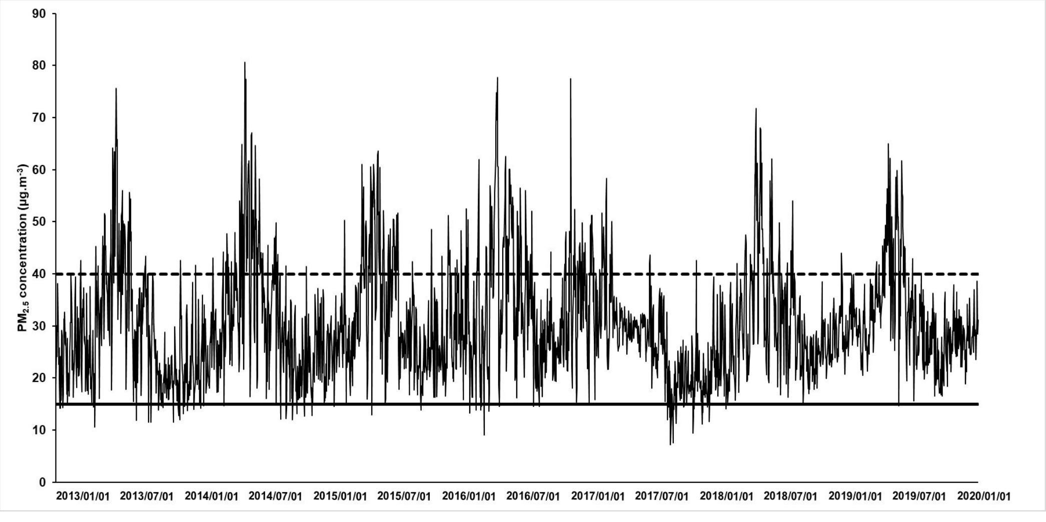
Supplementary Figure 1: *Time-series of the daily number of respiratory disease hospital admissions in Vanderbijlpark and Vereeniging in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*



Supplementary Figure 2: *Time-series of the daily levels of PM$_{10}$ in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

Solid line: Daily WHO guideline (45 µg.m^{-3})

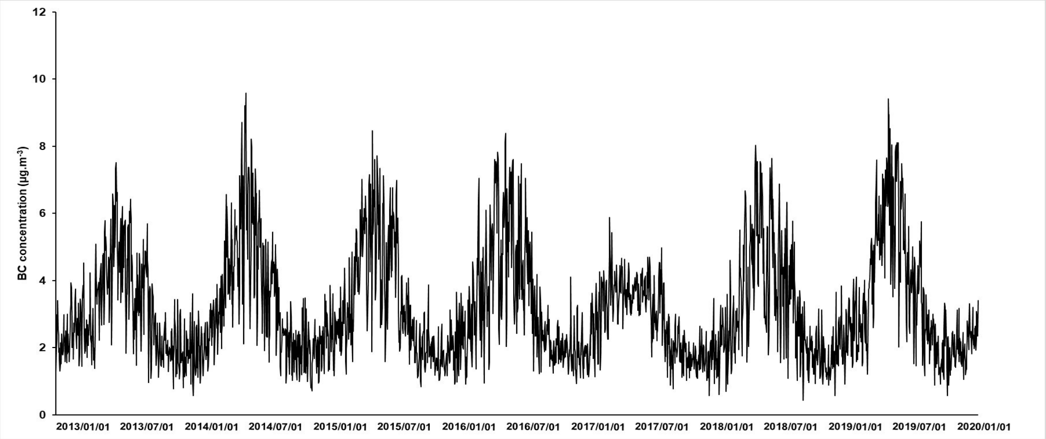
Dotted line: Daily South African standard (75 µg.m^{-3})



Supplementary Figure 3: *Time-series of the daily levels of PM$_{2.5}$ in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

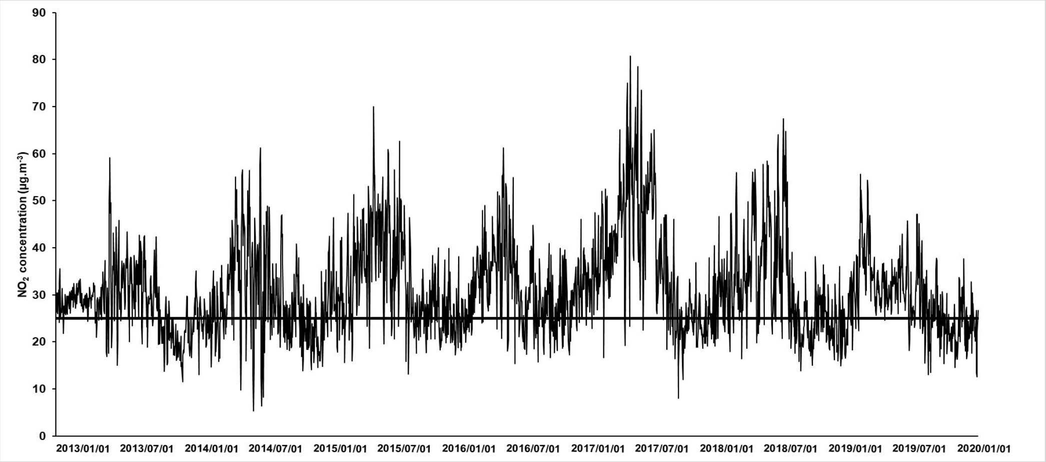
Solid line: Daily WHO guideline (15 µg.m^{-3})

Dotted line: Daily South African standard (40 µg.m^{-3})



Supplementary Figure 4: *Time-series of the daily levels of BC in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

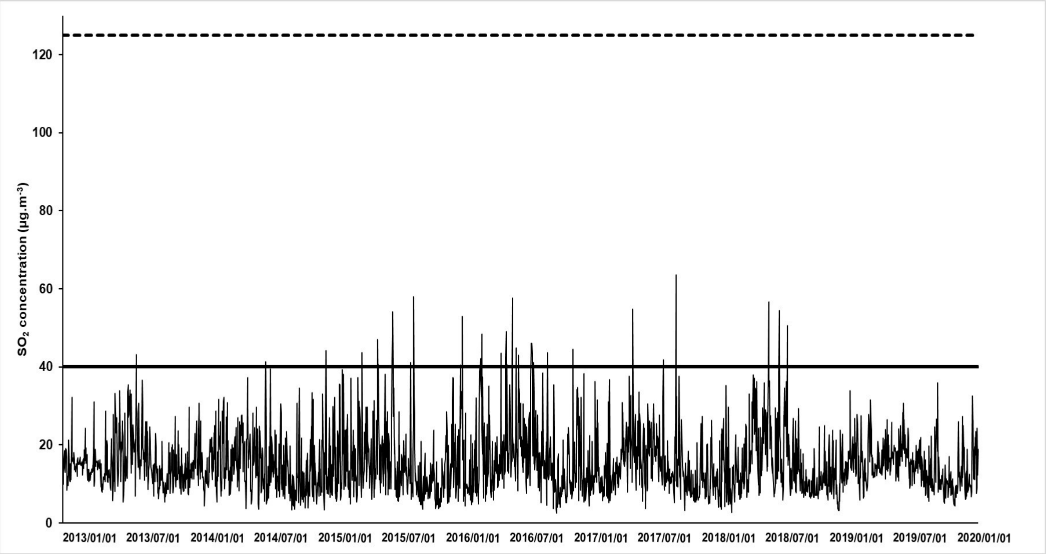
There is no daily WHO guideline or South African standard for BC



Supplementary Figure 5: *Time-series of the daily levels of NO_2 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

Solid line: Daily WHO guideline (25 µg.m^{-3})

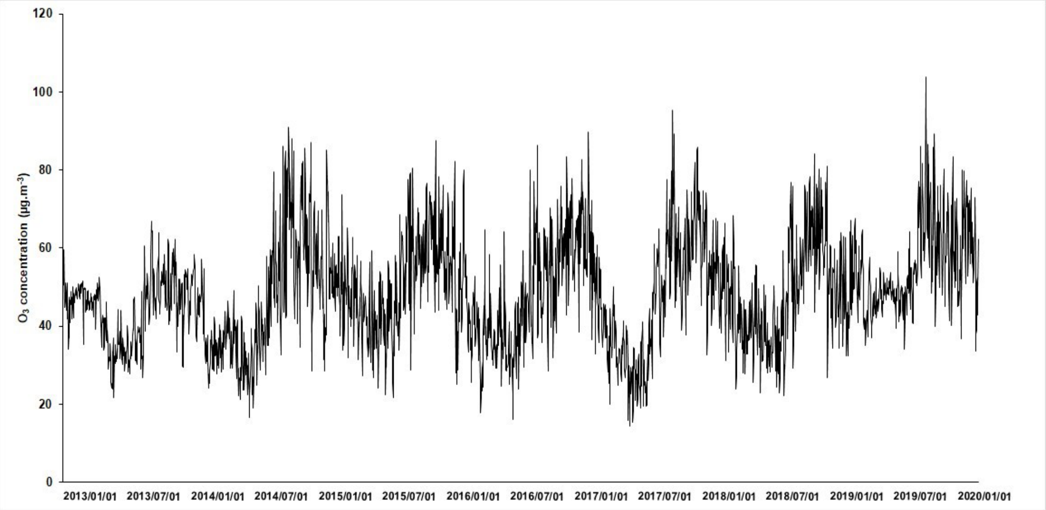
There is no daily South African standard for NO_2



Supplementary Figure 6: *Time-series of the daily levels of SO_2 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

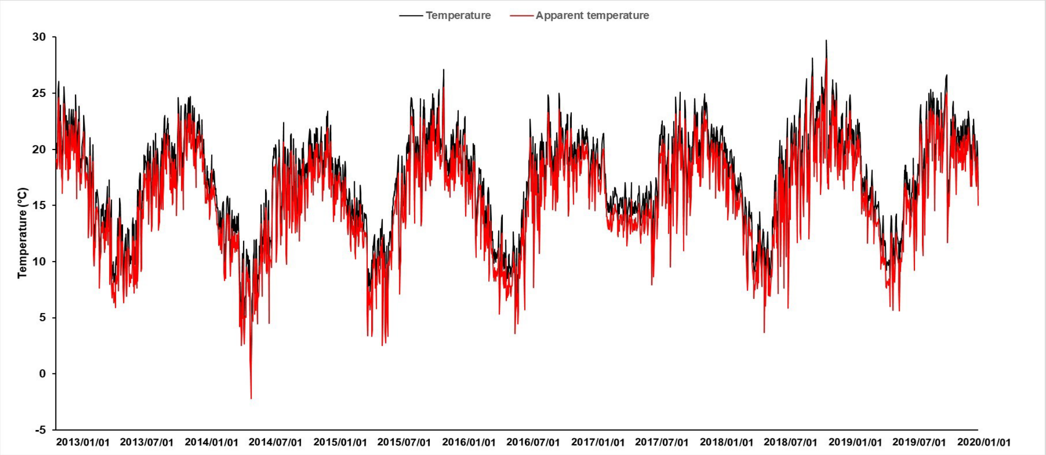
Solid line: Daily WHO guideline (40 µg.m^{-3})

Dotted line: Daily South African standard (125 µg.m^{-3})

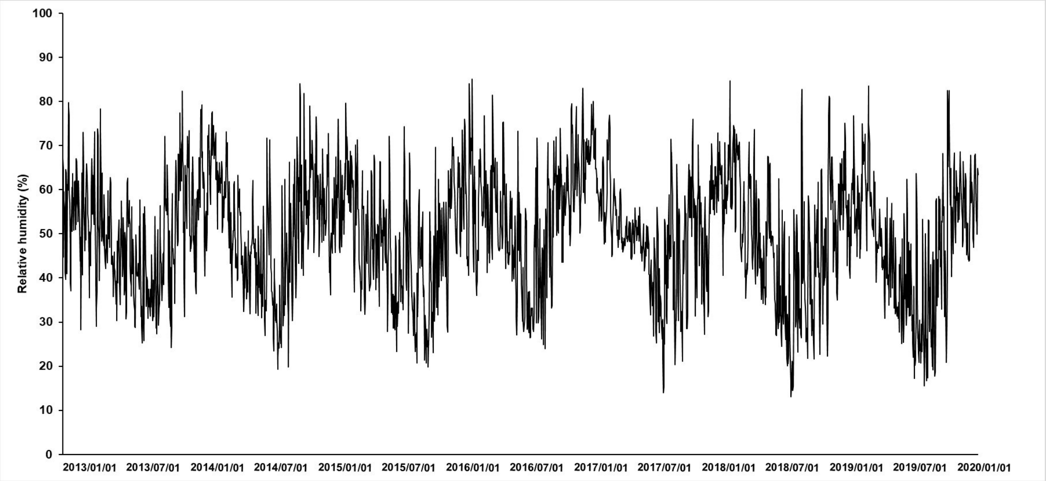


Supplementary Figure 7: *Time-series of the daily levels of O_3 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

There is no daily WHO guideline or South African standard for O_3



Supplementary Figure 8: *Time-series of the daily levels of temperature and apparent temperature in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*



Supplementary Figure 9: *Time-series of the daily levels of relative humidity in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*