Research article

Does apparent temperature modify the effects of air pollution on respiratory disease hospital admissions in an industrial area of South Africa?

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Abstract

Background: Temperature and air pollution are often treated as separate risk factors and very few studies investigated effect modification by temperature on air pollution, and the impact of this interaction on human health in Africa. This study therefore investigated the modifying effects of temperature on the association between air pollution and respiratory disease (RD) hospital admissions in South Africa.

Methods: RD admission data (ICD10 J00-J99) were obtained from two hospitals located in Secunda, South Africa beween 1 January 2011 to 31 October 2016. Ambient NO_2, SO_2, PM_{10}, $PM_{2.5}$, temperature and relative humidity data were obtained from the South African Weather Services. A case-crossover epidemiological study design was applied and lag0-1 was used. Models were adjusted for public holidays and apparent temperature (Tapp). Days were classified as warm (Tapp>75th percentile), cold (Tapp<25th percentile) and normal (Tapp 25th-75th percentile).

Results: Of the 14 568 RD admissions, approximately an equal number of females and males were admitted. The average daily NO_2, SO_2, $PM_{2.5}$ and PM_{10} levels were 12.4 µg/m^3, 8.5 µg/m^3, 32.3 µg/m^3 and 68.6 µg/m^3, respectively. Overall, a 10 µg/m^3 increase in SO_2 on warm days was associated with an increase in RD hospital admissions: 8.5% (95% Conf. Int: 0.4%, 17.2%) and 8.4% (95% Conf. Int: 0.3%, 17.1%) after adjustment for $PM_{2.5}$ and PM_{10}, respectively. However, increasing $PM_{2.5}$ or PM_{10} levels was associated with an increase in RD hospital admissions on normal days,after adjusting for SO_2. On cold days there were significant associations between the SO_2 and RD admissions among the 0-14 year age group, after adjusting for either $PM_{2.5}$ (6.5%; 95% Conf.Int: 0.9%, 12.4%) or PM_{10} (5.5%; 95% Conf.Int: 0.3%, 11.1%).

Conclusions: These results indicate that the risk of RD hospital admission due to ambient air pollution exposure is different on cold, normal and warm days in Secunda.

Keywords

Particulate matter, SO_2, apparent temperature, respiratory disease, hospital admissions, South Africa, case-crossover.

Introduction

Many epidemiological studies have demonstrated the independent effects of air pollution and temperature on health (Zhang et al., 2018; Chen et al., 2017; Wichmann, 2017). Rising temperature is one of the key climatic change indicators which affects human health directly and indirectly leading to deaths, illnesses and the aggravation of respiratory diseases (Wichmann, 2017). Cardiovascular diseases such as ischemic heart disease have been attributed to high temperature (Zacharias et al., 2014). Studies have shown that increase in temperature can lead to increased mortality (Li et al., 2013; Petkova et al., 2013). It has also been shown that both low temperature and high temperature can increase the risk of respiratory diseases (Michelozzi et al., 2009; Zhao et al., 2018; Su et., 2014).

Air pollution also affects human health, especially the respiratory system which is usually the first point of contact in the human body (Dadbakhsh et al., 2015). In urban areas, anthropogenic emissions give rise to high levels of air pollution and the commonly found anthropogenic and natural air pollutants are SO_2, NO_x, O_3, volatile organic compounds and suspended particulate matter (PM) (Rahman, 2016; Norman et al., 2007).

Exposure to ambient levels of air pollution is an important determinant of emergency room visits and hospital admissions for acute and chronic respiratory symptoms (Szyszkowicz et al., 2018). There has been significant increase in ischemic heart disease deaths attributable to heat wave of 1.9-fold (685 deaths per year) in 2021–2050, and 5.1-fold (1801 deaths per year) in 2069–2098 compared to baseline years of 2000–2010 (Zacharias et al., 2014). Increases from 1980 baseline in heat-related mortality of approximately 22.2, 49.4, and 91 % in 2020s, 2050s, and 2080s, respectively, using the A2 scenario (Li et al.,2013). Increase in heat-related mortality to six to nine times present rates in 2080s using RCP 8.5 (Petkova et al., 2013).

Respiratory morbidity in South Africa

In South Africa, evidence suggests that the prevalence of respiratory morbidity is increasing (Masekela et al., 2018). A study on the epidemiology of asthma in South Africa reports an approximate 5% increase in lifetime and 12-month wheeze amongst children and adolescents between 1995 and 2002 (Zar et al., 2007). The increase in respiratory symptoms was associated with deteriorating air quality (Naidoo et al., 2013).

In Durban, children living in industrial areas with higher levels of ambient air pollution have more asthma and hyper-reactive airways than children living further away from industrial areas (Naidoo et al., 2013).

Similarly, people living close to mine-dumps in South Africa have poorer respiratory health outcomes compared to people living further away (Nkosi et al., 2015; Nkosi et al., 2015b).

However, the modification effects of ambient temperature on the association between respiratory morbidity and air pollution in South Africa have not be explored.

An earlier study observed an association between daily ambient apparent temperature and daily all cause mortality between 2006 and 2010 with almost half a million deaths out of a population of about 12 million in Cape Town, Durban and Johannesburg (Wichmann, 2017).

Another study showed that there was a modification effect of temperature on air pollution associated with CVD hospital admissions in Cape Town (Lokotola et al., 2020).

It is therefore important to explore the modification effect of ambient temperature on the association between respiratory morbidity and air pollution in South Africa.

This is also important because the mean annual temperature in South Africa increased by at least 1 °C during the last 50 years which is 1.5 times the global average (Engelbrecht et al., 2015; Ziervogel G et al., 2014; MacKellar et al., 2014).

It has been projected that by 2100, warming will reach around 3-4°C along the South African coast, and 6-7°C inland, thus higher than the global average warming (Department of Environmental Affairs, 2010).

Many studies have reported on the interaction between ambient temperature and air pollution on repiratory morbidity (McCormack et al., 2016; Iranpour et al., 2020). However,

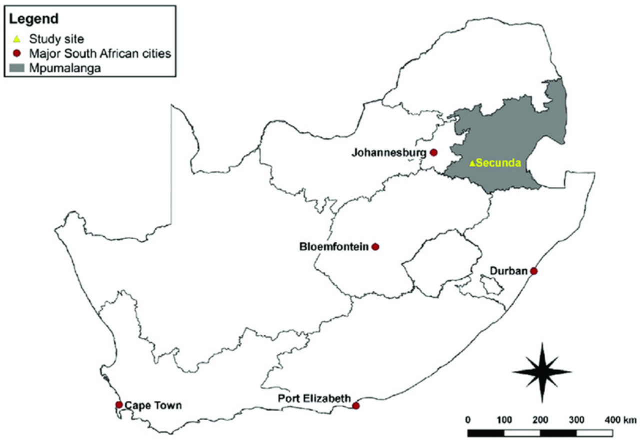

Figure 1: *Map of South Africa showing the location of the study site, Secunda. Courtsey: Emslie et al.2020*

there is accumulating evidence that the warm/hot increasing temperature effects are enhanced by high pollution levels (especially PM_{10} and ozone) and vice versa and that effects of pollutants are enhanced by the presence of high temperature (Analitis et al.,2018).

In Hefei, China, a study found synergy between PM_{10} concentrations and temperature in their effects on mortality (Qin et al., 2017). Given the frequent simultaneous exposure to ambient temperature and air pollution, one can expect to see the synergistic effects of these factors in human physiology (Analitis et al., 2018). It has been shown that high temperature could modify the effects of air pollution on daily mortality and high air pollution might enhance the air temperature effects (Chen et al., 2018).

The knowledge of the modifying effects of temperature on the association between RD hospital admission and air pollution will help policy makers, and inform risk assessments (Kan et al., 2008). Therefore, we investigated the effects of apparent temperature on the association between air pollution and respiratory disease (RD) hospital admissions in Secunda, which is situated in the inland part of South Africa.

Secunda is located in the Highveld Priority Area (HPA), which was declared 14 years ago in 2007 as such to manage and address the poor air quality in the area (NEMA, 2004; http://www.saaqis.org.za/documents/Highveld%20Priority%20Area%20Declaration.pdf). Air quality in the HPA consistently exceeds national ambient air quality standards (NAAQS) due to both industrial and non-industrial sources (NEMA, 2004).

The Highveld area in South Africa is characterised by poor ambient air quality and elevated concentrations of criteria pollutants due to the concentration of industrial and non-industrial sources (Held et al., 1996).

Secunda was identified to be an air quality hotspot in the Highveld Priority Area Air Quality Management Plan due to frequent exceedances of the SO_2 standards.

The main emissions in Secunda are from the petrochemical industry and energy sector in the region. Others agriculture, domestic fuel burning, mining activities, veld fires, and power stations which are sources of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 (SSI Environmental, 2013).

Secunda lies at the heart of South Africa's coal mining industry and still experiences high air pollution levels (NEMA, 2004). (Figure 1). Secunda produces the most polluting liquid fuels in the world through the Sasol's Synfuels facility (Myllyvirta, 2020). To improve air quality in the HPA, an Air Quality Management Plan (AQMP) was developed in accordance with the National Environmental Management Air Quality Act 2004.

Material and methods

Ethical approval (reference 132/2018) was obtained from the Research Ethics Committee, Faculty of Health Sciences, University of Pretoria in 2018.

Study design

In this study, a case-crossover epidemiology study design was used to explore the modifying effects of temperature on the association between major air pollutants, including sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter less than 10 microns in diameter (PM_{10}) and 2.5 microns in diameter ($PM_{2.5}$) and hospital admissions for RD in Secunda, South Africa. (Carracedo-Martínez et al., 2010).

This study design was developed as a variant of the case-control 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 the person's exposure at other times (Carracedo-Martínez et al., 2010). 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 for by matching (Carracedo-Martínez et al., 2010). 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 was not provided by the hospitals.

A time-stratified approach was applied to select the control days, defining the day of RD 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).

Hospital admission data

Individual-level RD hospital admission data (International Classification of Disease, 10th version [ICD-10] (J00–J99)) were obtained from two private hospitals in Secunda, after ethical approval. The two hospitals are from the same hospital group. Data were available electronically from 1 January 2011 to 31 October 2016.

Air pollution and weather data

Hourly $PM_{2.5}$, PM_{10}, NO_2 and SO_2 data from 2011-2016 were obtained from the South African Weather Services through the South African Air Quality Information Systems (SAAQIS) for the study period, after signing a data agreement. A network of air pollution monitors in Secunda continuously measures 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).

Hourly temperature (°C) and relative humidity (%) data were obtained from the South African Weather Service (SAWS) for the study period 1 January 2011 – 31 October 2016, after signing a data agreement. The Secunda monitoring station is 11.8km and 16.9km in relation to the two hospitals.

Apparent temperature

Models were adjusted for apparent temperature (Tapp) which reflects the physiological experience of combined exposure to humidity and temperature and thereby better captures the response on health than temperature (Steadman, 1984).

Saturation vapour pressure

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

Actual vapour pressure

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

Dew point temperature °C

$$= (-430.22 + 237.7 \times \ln(\text{actual vapour pressure}))/(-n(\text{actual vapour pressure}) + 19.08) \quad (3)$$

Apparent temperature °C

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

Statistical analysis

Correlation between the air pollutants and Tapp were investigated using Spearman correlation analyses. Most studies on temperature as a modifier of the health effects of air pollution selected short lags, e.g. lag0 (same day of exposure as day of hospital admission), lag1 (day prior to day of hospital admission) or lag0-1 (mean of lag0 and lag1). The results in the present study will focus on lag0-1, as done in other studies (Li et al., 2017; Chen et al., 2017).

The association between the air pollutants and RD hospital admissions was investigated using conditional logistic regression models (R Development Core Team, 2019). Two pollutant models were investigated, which included $PM_{2.5}$ and SO_2, $PM_{2.5}$ and NO_2, PM_{10} and SO_2 and PM_{10} and NO_2 as the air pollutants were not strongly correlated with each other ($p < 0.05$). Models were adjusted for a public holiday variable (binary variable) and Tapp. The shape (i.e. linear or non-linear) of the association between the Tapp and RD hospital admissions was investigated. First Tapp was included as a natural spline with 3 degrees of freedom (df) (non-linear term) in the models. 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 did not add value to the model and Tapp was then included as a linear term. Air pollutants were added as linear terms in the model, as done in many studies (Li et al., 2017; Chen et al., 2017).

The associations are presented as the percent excess risk in RD hospital admissions per 10µg.m^{-3} increase in an air pollutant level. This approach is commonly applied in other studies (Li et al., 2017; Chen et al., 2017). Susceptibility of age groups (<15 years, 15–64 years and ≥65 years) and sex (male/female) on warm and cold days was investigated in stratified analyses followed by models with interaction terms.

Intra-individual factors cannot be examined as effect modifiers due to the nature of the case-crossover design. However inter-individual variation using an interaction term between the effect modifier and an air pollutant in the conditional logistic regression model, can detect a p-value for interaction.

Stratified analyses were conducted to examine the interactive effects of temperature and air pollution on RD hospital admission. Temperature was divided into three levels –warm, normal and cold days. Warm and cold days were defined as days when Tapp was higher than the 75th percentile of Tapp of the study period and lower than the 25th percentile of Tapp, respectively. Normal days were those equal or higher than the 25th percentile of Tapp, but lower or equal to the 75th percentile of Tapp. Other studies have used a similar approach (Chen et al., 2017; Li et al., 2017; Chen et al., 2013).

Results

Descriptive statistics

Of the 14 568 RD hospital admissions in this study, 49.3% (n=7 179) were males and the highest number of patients admitted for RD in a day was 26 (Table 1a). The mean Tapp for the study period was 14.2°C, PM_{10} peaked at 496.9 µg.m^{-3} and $PM_{2.5}$ peaked at 262.4 µg.m^{-3} (Table 1b). During the study period, daily PM_{10} and $PM_{2.5}$ levels exceeded the daily WHO air quality guidelines on 721 (34%) and 1081 (51%) of the 2131 days, respectively. The daily WHO air quality guidelines for $PM_{2.5}$ and PM_{10} are 25 µg.m^{-3} and 50 µg.m^{-3}, respectively. The annual PM_{10} mean concentrations were above the annual WHO guideline (20 µg.m^{-3}), except in 2015. However, the annual mean values of SO_2 and NO_2 in Secunda between 2011 and 2016 were significantly lower than their NAAQS and WHO annual means.

All air quality variables were positively correlated (Table 2). PM_{10} and $PM_{2.5}$ were strongly correlated (r=0.946, $p < 0.05$), whilst SO_2 and NO_2 were weakly correlated (r = 0.085, $p < 0.05$). Air quality variables were negatively correlated with temperature and relative humidity (r=-0.483 to -0.120) (Table 2).

Table 1a: *Summary statistics of health outcomes in Secunda, 1 January 2011 – 31 October 2016 (2 131 days).*

Variable	Mean	Min	25%	Median	75%	Max
Respiratory disease hospital admissions						
All ages and both sexes	6.8	0.0	3.0	6.0	10.0	26.0
Female patients (n=7 389)	3.5	0.0	1.0	3.0	5.0	17.0
Male patients (n=7 179)	3.4	0.0	1.0	3.0	5.0	15.0
0-14 year olds (n=6 915)	3.2	0.0	1.0	2.0	5.0	20.0
15-64 year olds (n=6 531)	3.1	0.0	1.0	2.0	4.0	16.0
≥65 year olds (n=1 122)	0.5	0.0	0.0	0.0	1.0	4.0

Table 1b: *Summary statistics of air pollutants and meteorological conditions in Secunda, 1 January 2011 – 31 October 2016 (2 131 days).*

Variable	Mean	Min	25%	Median	75%	Max
PM_{10} (µg.m^{-3})	68.6	0.0	19.4	43.3	97.9	496.9
$PM_{2.5}$ (µg.m^{-3})	32.3	0.0	10.7	19.9	41.8	262.4
SO_2 (µg.m^{-3})	8.5	0.0	3.8	6.7	10.9	73.2
NO_2 (µg.m^{-3})	12.4	0.5	6.7	11.0	16.7	73.8
Tapp (0C)	14.2	-1.0	9.4	14.9	18.9	26.4
Temperature (0C)	15.6	1.7	11.7	16.5	19.3	26.5
Relative humidity (%)	58.5	16.6	47.3	60.3	70.3	94.1

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter of less than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter of less than 2.5 µm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide, Tapp: apparent temperature

Table 2: *Spearman correlation coefficients between air pollution and weather variables.*

Variable	$PM_{2.5}$	SO_2	NO_2	Tapp	Temp	RH
PM_{10}	0.946	0.235	0.216	-0.446	-0.398	-0.483
$PM_{2.5}$		0.238	0.259	-0.507	-0.477	-0.406
SO_2			0.085	-0.180	-0.176	-0.200
NO_2				-0.263	-0.261	-0.120
Tapp					0.983	0.242
Temperature						0.106

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter of less than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter of less than 2.5 µm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; Tapp: apparent temperature; RH: relative humidity. All correlations were significant ($p < 0.05$)

Exposure - response estimates

In the unstratified analysis (i.e. entire Tapp range), there was no association between any of the pollutants and RD hospital admission. In the stratified analysis, a 10 µg.m^{-3} increase in SO_2 was associated with a significant increase in hospital admissions for RD among the 0-14 year age-group (4.9% (0.3%, 9.7%)) on cold days. Also, a 10 µg.m^{-3} increase in NO_2 led to an increase (8.0% (1.3%, 15.1%)) in RD hospital admissions among males on normal days. However, there was no association between either $PM_{2.5}$ or PM_{10} and RD hospital admission. (Table 3).

In the second model, for all ages combined, a 10 µg.m^{-3} increase in $PM_{2.5}$ and PM_{10} was associated with a 3.5% (0.1%, 7.0%) and 1.7% (0.3%, 3.1%) increase in RD hospital admissions after adjusting for SO_2 on normal days. Also, for all ages combined, a 10 µg.m^{-3} increase in SO_2 on warm days was associated with 8.5% (0.4%, 17.2%) and 8.4% (0.3%, 17.1%) increase in RD hospital admission after controlling for $PM_{2.5}$ and PM_{10}, respectively. Conversely, on cold days, a 10 µg.m^{-3} increase in SO_2 was associated with increased hospital admissions among the 0-14 year age-group after controlling for the two types of particulate matter- $PM_{2.5}$ (6.5% (0.9%, 12.4%) and PM_{10} (5.5% (0.3%, 11.1%). (Table 4).

Sensitivity analysis

Median Tapp used to classify days

The only robust result was found with SO_2. Similar to the main analysis (Tables 3 and 4), a 10µg.m-3 increase in the level of SO_2 increased RD hospital admission in the 0-14 year olds on cold days in both the two level models (Tables 5 and 6). Also, a 10 µg.m^{-3} increase in SO_2 was associated with an increase in hospital admisions among the female participants on warm days after adjusting for $PM_{2.5}$ as in the two pollutant model of the main analyses. The effect estimates for SO_2 in the sensitivity analysis were lower than those of the main analysis except in the one-pollutant level (9.0% (0.3%, 18.4%)-Table 5) where it was higher than in the main analysis (4.9% (0.3%, 9.7%) (Table 3).

Discussion

This study explored the modifying effects of temperature on the association between NO_2, SO_2, $PM_{2.5}$ and PM_{10} and RD hospital admission over a five-year period in Secunda, South Africa.

RD hospital admissions associated with SO_2 concentrations were affected by temperature extremes while the particulate matters ($PM_{2.5}$ and PM_{10}) had effect on RD admission during normal temperature. Overall, SO_2 was significantly associated with increased hospitalizations on warm days after adjusting for $PM_{2.5}$ or PM_{10}. The same applied to children between 0 and 14 years old. During normal temperature, $PM_{2.5}$ and PM_{10} were associated with increased hospitalizations after adjusting for SO_2. There was an increase in the hospital admissions of the female participants when exposed to a 10 µg.m^3 increase in PM_{10} (adjusted for SO_2) and SO_2 (adjusted for $PM_{2.5}$) on normal and warm days respectively. With either of the particulate matters (PM_{10} and $PM_{2.5}$), there was an increase in the RD hospital admission during normal temperature. These findings highlight the need to effectively manage air pollutants especially SO_2 in areas where temperature extremes are common.

The Highveld Priority Area, within which Secunda is located, is the home of many coal mining operations and coal fired power stations which are the main sources of SO_2 emissions. SO_2 is a gas produced by fuel combustion and one of the major sources of combustion pollution is traffic (Enkh-Undraa et al., 2019). Overall, SO_2 was associated with increased RD hospital admission during the warm periods in this study. This is probably because high temperature leads to an increase in sulphate aerosols due to faster SO_2 oxidation (Jacob and Winner, 2009; Luhana et al., 2007) and sulphate aerosols are considered to be the most irritating acid aerosol for the respiratory tract (Duarte et al., 2014). This is an important finding because in the next 100 years, the average temperature of South African inland where Secunda is located is projected to increase by 6-7°C (Department of Environmental Affairs, 2010) and this means that more RD hospital admissions should be expected in the future.

Furthermore, a 10 µg.m^3 increase in SO_2 could lead to an increase in RD hospital admissions among female patients on warm days, but no effect of temperature was observed among their male counterparts. Different studies have shown that female patients show higher susceptibility to SO_2 than male patients (Zhou et al., 2019; Zhang et al., 2014). The increase in RD hospital admissions among the female patients might be due to females having smaller lung tissue and trachea than males (Oiamo and Luginaah, 2013) resulting in a greater deposition of inhaled particles in their lungs. Females have fewer red blood cells than males, and thus may be more sensitive to the toxicological influences of SO_2 (Chen et al., 2005). Men and women also differ in their response to extreme temperatures. Women sweat less, have a higher working metabolic rate, and have thicker subcutaneous fat that prevents them from cooling themselves as efficiently as men. This shows that women, as a population, are less tolerant of an imposed heat stress (Duncan, 2006).

However, on cold days, a 10 µg.m^3 increase in SO_2 increased hospital admissions in children of 0-14 years but not in the older age-groups. SO_2 is a highly reactive gas whose concentration is very seasonal, peaking in the winter period (Morakinyo et al., 2020). It has been observed that children are more vulnerable than adults to air pollutants such as SO_2 by virtue of their increased susceptibility and the higher doses received (Mielzynska-Svach et al., 2013; Kochi et al., 2017) as they breathe higher volumes of air, their body systems are still developing and they have little control over their environment unlike adults (Salvi, 2007; Heinrich et al., 2002; Pikhart et al., 2001). Furthermore, exposure to cold temperatures reduces the functions of the nasal epithelium and reduces the capacity to protect the lower respiratory tract. This causes disorganization of the epithelium, nasal muciciliary defence mechanisms and leaving the distal acinar airways more vulnerable to air pollutants (Lowen et al., 2007).

In this study, the effects of $PM_{2.5}$, PM_{10} and NO_2 on respiratory disease hospital admissions were not robust enough as effects were different in the main analyses and the sensitivity analyses- the temperature effects depended on the categorization and levels of Tapp. In the main analysis, $PM_{2.5}$ and PM_{10} increased RD hospital admission during normal temperature on adjusting for SO_2, showing that extremes of temperature did not affect the effects of the particulate matters on RD hospital admissions in Secunda. This is contrary to the results of the 2 level Tapp and other studies that did not use similar classification of Tapp or temperature in cold, normal and warm/hot and when there was no adjustement for SO_2. In the 2 level Tapp, $PM_{2.5}$, PM_{10} and SO_2 had effects during the warm temperature and this is similar to many studies (Zhang et al., 2018).

Tapp has been shown to be the most important predictor of heat-related mortality (Zhang et al; 2014). This is contrary to the findings of Barnett et al. (2010) which showed that there was no single temperature measure that is superior to others. Tapp has been applied in several studies (Wichmann et al., 2012; Wichmann et al., 2011; Lokotola et al., 2020). For example, in the warm period, an inter-quartile range increase in maximum apparent temperature (Tappmax) was associated with an increase of 7% (95% CI: 1%, 13%) in RD admissions in Greater Copenhagen, Denmark (Wichmann et al., 2011). Also, in South Africa,

This study is limited by the use of patient records from private hospitals. In South Africa, users of private hospitals are more likely to have high incomes, white-collar occupations and be gainfully employed. These factors are significant predictors of health insurance ownership (Kiriga et al., 2005). In South Africa, only the wealthiest 16% of the population can afford private health insurance to cover the costs of private-sector services (McIntyre and van den Heever, 2007). Therefore, the results cannot be extrapolated to the general South African population as the results represent the middle and upper socio-economic classes. It was postulated that including data from public hospitals would include people from the lower socio-economic class as people living in poor socio-economic conditions generally live closer to industrial areas and suffer more from the ill effects of air pollution (Naidoo et al., 2013), and could potentially show stronger associations with hospitalisation and air pollution levels. However, South African public hospitals have poor state of records management. Medical records are not being managed properly, resulting in a lack of effective systems for opening, tracking and indexing files (Marutha and Ngoepe, 2017).

It was assumed that air quality and temperature were homogenous for Secunda, which might give rise to measurement error. There might also be a potential lagged effects among participants who were not admitted immediately with the appearance of the symptoms, missing the milder cases that are not admitted to the hospital at all. Also, this study did not consider factors such as socioeconomic status, physical activities and pre-existing diseases as potential confounders because these factors would not change within the month of case and control days.

Conclusion

SO_2 was associated with RD hospital admission in children aged 0-14 years during cold temperature but in females during warm temperatures. Both $PM_{2.5}$ and PM_{10} were associated with RD hospital admissions when the temperature was normal. This epidemiological evidence will help policy makers in South Africa to accept that policy interventions are needed to improve air quality as well as address the climate change-related health risks.

Author contributions

B.G.O. and J.W: Research design, methodology, statistical analyses, interpretation of results and writing the manuscript.

Financial interests' declaration

None declared.

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Conflicts of interest

The authors declare no conflict of interest.

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***Table 3:** Percentage change (95% CI) in daily respiratory disease hospital admissions per 10 μg/m³ increase in an air pollutant level (lag0-1) in Secunda, South Africa on normal, warm and cold days by age groups and sex.*

Air pollutant	Tapp	All	0-14 year olds	15-64 year olds	≥65 year olds	Females	Males
$PM_{2.5}$	Warm	5.2 (-5.3, 16.9)	11.5 (-3.3, 28.5)	-1.7 (-17.2, 16.7)	-2.1 (-33.4, 43.8)	-0.4 (-14.7, 16.5)	10.0 (-4.6, 26.9)
	Normal	2.3 (-0.2, 5.0)	2.2 (-1.4, 6.1)	2.9 (-0.9, 6.9)	-0.8 (-10.3, 9.6)	1.5 (-1.9, 5.0)	3.4 (-0.4, 7.4)
	Cold	0.1 (-1.3, 1.5)	-0.1 (-2.0, 1.9)	0.0 (-2.0, 2.1)	1.4 (-3.3, 6.3)	0.4 (-1.5, 2.3)	-0.2 (-2.1, 1.8)
PM_{10}	Warm	0.8 (-1.7, 3.3)	3.0 (-0.3, 6.5)	-2.1 (-6.0, 1.9)	0.1 (-10.5, 11.9)	-0.5 (-4.1, 3.3)	1.8 (-1.6, 5.3)
	Normal	0.9 (-0.1, 2.0)	1.0 (-0.6, 2.6)	0.8 (-0.8, 2.3)	1.9 (-2.4, 6.5)	0.9 (-0.6, 2.4)	1.0 (-0.6, 2.6)
	Cold	-0.1 (-0.8, 0.7)	-0.1 (-1.2, 1.0)	0.0 (-1.2, 1.1)	0.1 (-2.5, 2.7)	0.0 (-1.0, 1.1)	-0.1 (-1.2, 1.0)
NO_2	Warm	3.8 (-4.4, 12.8)	0.0 (-12.0, 13.6)	5.7 (-5.9, 18.7)	13.9 (-16.0, 54.5)	1.5 (-9.6, 14.0)	6.3 (-5.6, 19.6)
	Normal	1.2 (-3.2, 5.8)	1.3 (-4.8, 7.7)	1.0 (-5.7, 8.2)	1.9 (-16.1, 23.6)	-5.2 (-11.0, 1.0)	**8.0 (1.3, 15.1)**
	Cold	-0.7 (-4.4, 3.2)	-2.2 (-7.4, 3.2)	0.2 (-5.6, 6.3)	5.4 (-7.9, 20.6)	-1.6 (-6.9, 3.9)	0.2 (-5.0, 5.8)
SO_2	Warm	6.3 (-1.3, 14.5)	9.4 (-2.4, 22.6)	4.7 (-5.9, 16.4)	0.1 (-23.1, 30.2)	10.5 (-0.5, 22.8)	2.5 (-7.7, 13.8)
	Normal	-0.4 (-3.8, 3.2)	0.9 (-4.2, 6.3)	-1.0 (-5.9, 4.1)	-4.6 (-16.9, 9.5)	-0.9 (-5.6, 4.1)	0.2 (-4.7, 5.4)
	Cold	1.5 (-1.4, 4.5)	**4.9 (0.3, 9.7)**	-0.9 (-5.1, 3.4)	-0.9 (-9.9, 9.0)	-0.2 (-4.3, 4.1)	3.3 (-0.9, 7.6)

Warm: Apparent temperature > 75th percentile; Cold: Apparent temperature < 25th percentile; Normal: Apparent temperature >= 25th and <= 75th percentile

***Table 4:** Percentage change (95% CI) in daily respiratory disease hospital admissions per 10 μg/m³ increase in an air pollutant level (lag0-1) in Secunda, South Africa on normal, warm and cold days by age groups and sex.*

Air pollutant	Tapp	All	0-14 year olds	15-64 year olds	≥65 year olds	Females	Males
$PM_{2.5}$ adjusted NO_2	Warm	1.9 (-8.7, 13.8)	9.5 (-6.1, 27.6)	-5.7 (-20.9, 12.5)	-4.2 (-35.5, 42.4)	-3.6 (-18.3, 13.7)	6.6 (-8.2, 23.6)
	Normal	2.0 (-1.1, 5.3)	4.1 (-0.5, 8.8)	0.3 (-4.3, 5.1)	-1.3 (-12.6, 11.5)	2.1 (-2.1, 6.5)	2.2 (-2.4, 7.1)
	Cold	-0.2 (-1.9, 1.5)	-0.4 (-2.8, 2.1)	-0.1 (-2.6, 2.4)	0.8 (-5.1, 7.0)	0.2 (-2.1, 2.5)	-0.6 (-3.0, 1.9)
NO_2 adjusted $PM_{2.5}$	Warm	4.8 (-4.1, 14.5)	-0.1 (-12.8, 14.3)	6.1 (-6.4, 20.3)	25.7 (-10.9, 77.3)	3.7 (-8.7, 17.7)	6.0 (-6.3, 20.0)
	Normal	-2.4 (-8.4, 4.0)	-2.1 (-10.2, 6.7)	-4.3 (-13.6, 6.0)	1.4 (-22.2, 32.1)	-9.5 (-17.3, -0.8)	5.2 (-4.0, 15.2)
	Cold	-1.0 (-4.8, 3.1)	-2.3 (-7.7, 3.3)	-0.4 (-6.4, 6.0)	5.1 (-8.6, 20.8)	-2.0 (-7.4, 3.8)	0.0 (-5.4, 5.7)
$PM_{2.5}$ adjusted SO_2	Warm	-2.2 (-15.3, 13.0)	1.5 (-17.9, 25.3)	-0.6 (-19.8, 23.3)	-27.6 (-57.9, 24.8)	-8.8 (26.3, 13.0)	3.8 (-14.7, 26.3)
	Normal	**3.5 (0.1, 7.0)**	2.8 (-1.9, 7.7)	5.9 (**0.5, 11.6**)	-4.7 (-16.1, 8.3)	2.8 (-1.8, 7.6)	4.4 (-0.7, 9.6)
	Cold	-0.3 (-2.6, 2.0)	-1.5 (-4.7, 1.9)	0.6 (-2.9, 4.23)	0.6 (-6.9, 8.8)	1.6 (-1.6, 4.9)	-2.1 (-5.3, 1.2)
SO_2 adjusted $PM_{2.5}$	Warm	**8.5 (0.4, 17.2)**	12.1 (-0.5, 26.2)	6.8 (-4.3, 19.3)	-1.6 (-26.2, 31.2)	**11.6 (0.0, 24.6)**	5.5 (-5.4, 17.8)
	Normal	-2.2 (-5.9, 1.7)	-1.3 (-6.9, 4.6)	-3.0 (-8.3, 2.7)	-3.2 (-16.6, 12.4)	-1.8 (-7.0, 3.7)	-2.5 (-7.9, 3.2)
	Cold	1.6 (-1.9, 5.2)	**6.5 (0.9, 12.4)**	-2.2 (-7.0, 2.9)	0.3 (-10.9, 13.0)	-1.3 (-6.2, 3.7)	4.6 (-0.4, 9.9)
PM_{10} adjusted NO_2	Warm	-0.3 (-3.0, 2.4)	2.9 (-0.7, 6.6)	-4.2 (-8.3, 0.1)	-2.4 (-13.3, 9.8)	-2.2 (-6.1, 1.8)	1.2 (-2.4, 5.0)
	Normal	0.7 (-0.6, 2.0)	1.6 (-0.3, 3.6)	-0.4 (-2.4, 1.5)	2.2 (-2.9, 7.5)	0.9 (-0.9, 2.7)	0.4 (-1.5, 2.4)
	Cold	-0.2 (-1.1, 0.7)	-0.2 (-1.6, 1.2)	-0.1 (-1.5, 1.2)	-0.3 (-3.5, 2.9)	0.0 (-11.2, 1.3)	-0.4 (-1.7, 1.0)
NO_2 adjusted PM_{10}	Warm	5.0 (-4.0, 14.9)	-1.5 (-14.2, 13.1)	7.4 (-5.2, 21.7)	26.9 (-10.4, 79.5)	4.5 (-8.0, 18.8)	5.6 (-6.9, 19.7)
	Normal	-1.8 (-7.6, 4.4)	-0.8 (-8.6, 7.6)	-3.6 (-12.9, 6.5)	-2.1 (-24.3, 26.6)	-9.0 (-16.6, -0.7)	6.2 (-2.7, 16.0)
	Cold	-0.9 (-4.8, 3.1)	-2.3 (-7.7, 3.3)	-0.4 (-6.3, 6.0)	5.9 (-7.9, 21.7)	-1.9 (-7.3, 3.9)	0.1 (-5.3, 5.8)
PM_{10} adjusted SO_2	Warm	-0.7 (-3.6, 2.3)	1.4 (-2.8, 5.8)	-2.4 (-6.7, 2.0)	-3.5 (-16.6, 11.7)	-2.0 (-6.2, 2.4)	0.4 (-3.6, 4.6)
	Normal	**1.7 (0.3, 3.1)**	1.5 (-0.5, 3.6)	1.6 (-0.4, 3.7)	3.5 (-2.2, 9.5)	**2.2 (0.2, 4.2)**	1.2 (-0.8, 3.2)
	Cold	-0.2 (-1.3, 1.0)	-0.3 (-2.0, 1.5)	0.1 (-1.7, 1.9)	-1.2 (-5.0, 2.7)	0.3 (-1.3, 2.0)	-0.6 (-2.3, 1.1)
SO_2 adjusted PM_{10}	Warm	**8.4 (0.3, 17.1)**	12.3 (-0.3, 26.4)	6.7 (-4.5, 19.1)	-1.4 (-26.1, 31.6)	11.5 (-0.1, 24.5)	5.7 (-5.3, 17.9)
	Normal	-2.5 (-6.3, 1.4)	-1.7 (-7.4, 4.3)	-2.4 (-7.8, 3.2)	-7.8 (-21.1, 7.8)	-2.9 (-8.1, 2.6)	-2.1 (-7.5, 3.6)
	Cold	1.6 (-1.8, 5.0)	**5.5 (0.3, 11.1)**	-1.8 (-6.4, 3.0)	2.5 (-8.1, 14.4)	-0.5 (-5.1, 4.4)	3.6 (-1.1, 8.6)

Warm: Apparent temperature > 75th percentile; Cold: Apparent temperature < 25th percentile; Normal: Apparent temperature >= 25th and <= 75th percentile. Bold text: Significant ($p < 0.05$)

Table 5: *Percentage change (95% CI) in daily respiratory disease hospital admissions per 10 μg/m³ increase in an air pollutant level (lag0-1) in Secunda, South Africa on warm and cold days by age groups and sex.*

Air pollutant	Tapp	All	0-14 year olds	15-64 year olds	≥65 year olds	Females	Males
$PM_{2.5}$	Warm	**8.2 (1.3, 15.6)**	**12.0 (2.0, 23.0)**	4.0 (-6.2, 15.2)	10.7 (-13.8, 42.1)	9.4 (-0.4, 20.3)	7.0 (-2.5, 17.5)
	Cold	0.7 (-0.4, 1.8)	0.2 (-1.4, 1.8)	1.0 (-0.7, 2.7)	2.2 (-1.7, 6.4)	1.1 (-0.4, 2.6)	0.2 (-1.4, 1.8)
PM_{10}	Warm	1.6 (0.0, 3.2)	**3.0 (0.8, 5.3)**	-0.2 (-2.7, 2.3)	2.7 (-3.6, 9.4)	**2.7 (0.4, 5.0)**	0.6 (-1.6, 2.9)
	Cold	0.4 (-0.2, 1.0)	0.2 (-0.6, 1.1)	0.5 (-0.3, 1.4)	1.0 (-1.1, 3.1)	0.6 (-0.2, 1.4)	0.2 (-0.6, 1.1)
NO_2	Warm	-0.2 (-11.0, 11.8)	-6.2 (-20.7, 11.0)	2.6 (-13.1, 21.2)	23.7 (-20.8, 93.2)	-6.3 (-20.4, 10.2)	6.2 (-9.6, 24.6)
	Cold	2.6 (-2.7, 8.3)	2.1 (-5.2, 9.9)	1.6 (-6.6, 10.5)	14.2 (-6.7, 39.9)	-0.4 (-7.7, 7.4)	5.8 (-1.9, 14.2)
SO_2	Warm	**13.5 (0.4, 28.3)**	**25.3 (4.8, 49.7)**	8.4 (-9.5, 29.7)	-24.4 (-54.2, 24.7)	**19.9 (0.8, 42.7)**	7.7 (-9.5, 28.0)
	Cold	4.5 (-1.2, 10.5)	**9.0 (0.3, 18.4)**	1.8 (-6.3, 10.5)	-3.0 (-19.6, 17.0)	2.2 (-5.5, 10.6)	6.8 (-1.3, 15.6)
Warm: Apparent temperature ≥ 50th percentile; Cold: Apparent temperature < 50th percentile. Bold: $p < 0.05$							

Table 6: *Percentage change (95% CI) in daily respiratory disease hospital admissions per 10 μg/m³ increase in an air pollutant level (lag0-1) in Secunda, South Africa on normal, warm and cold days by age groups and sex.*

Air pollutant	Tapp	All	0-14 year olds	15-64 year olds	≥65 year olds	Females	Males
$PM_{2.5}$ adjusted NO_2	Warm	3.2 (-4.2, 11.2)	**11.5 (0.4, 23.9)**	-6.1 (-16.4, 5.4)	10.0 (-16.6, 45.0)	2.3 (-8.2, 14.0)	-0.1 (-2.0, 2.0)
	Cold	0.4 (-1.0, 1.7)	-0.4 (-2.3, 1.6)	1.0 (-1.1, 3.0)	1.8 (-3.1, 7.0)	0.7 (-1.1, 2.6)	4.0 (-6.1, 15.3)
NO_2 adjusted $PM_{2.5}$	Warm	0.6 (-6.0, 7.7)	-4.5 (-13.8, 5.8)	3.2 (-6.4, 13.8)	22.6 (-6.8, 61.1)	-3.6 (-12.6, 6.4)	4.7 (-4.8, 15.1)
	Cold	0.6 (-2.8, 4.1)	1.2 (-3.4, 6.1)	-1.2 (-6.5, 4.3)	5.8 (-6.6, 19.8)	-0.4 (-5.1, 4.6)	1.5 (-3.3, 6.6)
$PM_{2.5}$ adjusted SO_2	Warm	4.6 (-3.3, 13.3)	7.9 (-3.8, 21.1)	1.4 (-9.9, 14.1)	6.9 (-20.8, 44.1)	4.9 (-6.2, 17.4)	4.3 (-6.8, 16.7)
	Cold	-0.3 (-2.1, 1.6)	-1.5 (-4.0, 1.2)	0.9 (-1.9, 3.7)	0.3 (-5.7, 6.8)	0.9 (-1.6, 3.5)	-1.6 (-4.2, 1.0)
SO_2 adjusted $PM_{2.5}$	Warm	4.3 (-1.0, 9.9)	5.0 (-2.8, 13.5)	5.5 (-2.1, 13.7)	-10.1 (-27.5, 11.4)	**7.9 (0.2, 16.1)**	1.0 (-6.2, 8.7)
	Cold	2.0 (-0.6, 4.6)	**4.7 (0.8, 8.7)**	-0.2 (-3.8, 3.6)	-0.4 (-8.7, 8.6)	0.6 (-2.9, 4.2)	3.4 (-0.2, 7.2)
PM_{10} adjusted NO_2	Warm	0.9 (-0.8, 2.7)	3.4 (1.0, 5.9)	-2.4 (-5.1, 0.4)	2.6 (-4.3, 10.0)	1.8 (-0.7, 4.4)	0.0 (-2.4, 2.5)
	Cold	0.3 (-0.4, 1.0)	0.1 (-0.9, 1.2)	0.4 (-0.6, 1.5)	0.8 (-1.8, 3.4)	0.4 (-0.5, 1.4)	0.1 (-0.9, 1.2)
NO_2 adjusted PM_{10}	Warm	0.3 (-6.4, 7.4)	-6.2 (-15.5, 4.0)	4.1 (-5.6, 14.8)	21.9 (-7.5, 60.7)	-4.5 (-13.5, 5.5)	5.1 (-4.6, 15.7)
	Cold	0.5 (-2.9, 3.9)	0.8 (-3.8, 5.5)	-1.0 (-6.3, 4.5)	6.2 (-6.1, 20.0)	-0.4 (-5.0, 4.5)	1.3 (-3.4, 6.3)
PM_{10} adjusted SO_2	Warm	0.9 (-0.8, 2.7)	2.4 (-0.1, 4.9)	-0.9 (-3.5, 1.8)	2.5 (-4.6, 10.0)	1.6 (-0.8, 4.2)	0.2 (-2.2, 2.6)
	Cold	0.1 (-0.8, 1.1)	-0.1 (-1.5, 1.2)	0.4 (-1.0, 1.8)	0.1 (-3.0, 3.3)	0.6 (-0.7, 1.8)	-0.3 (-1.6, 1.0)
SO_2 adjusted PM_{10}	Warm	4.5 (-0.7, 10.0)	5.1 (-2.6, 13.4)	6.0 (-1.6, 14.1)	-10.4 (27.7, 11.0)	**7.7 (0.1, 15.9)**	1.4 (-5.7, 9.1)
	Cold	1.6 (-0.8, 4.1)	3.7 (0.1, 7.5)	0.0 (-3.5, 3.6)	-0.3 (-8.2, 8.2)	0.6 (-2.7, 4.1)	2.6 (-0.8, 6.2)