Estimating the burden of disease attributable to ambient air pollution (ambient $PM_{2.5}$ and ambient ozone) in South Africa for 2000, 2006 and 2012

R A Roomaney,[1] MPH; **E Cairncross,**[1] PhD; **M Tesfaye,**[2] PhD; **T Kapwata,**[3] PhD; **N Abdelatif,**[4] MSc; **C Olivier,**[2] BSc Hons; **K Mathibela,**[2] BSc Hons; **A Cois,**[1,5] PhD; **I Neethling,**[1,6] PhD; **J Botai,**[2] PhD; **E B Turawa,**[1] MSc; **O F Awotiwon,**[1] MBBS, MSc; **K Chetty,**[7] BSc Hons; **B Nojilana,**[1] PhD; **C Y Wright,**[3,8] PhD; **R Pacella,**[6] PhD; **D Bradshaw,**[1,9] DPhil; **V Pillay-van Wyk,**[1] PhD

[1] *Burden of Disease Research Unit, South African Medical Research Council, Cape Town, South Africa*
[2] *Department of Research and Innovation, South African Weather Service, Centurion, South Africa*
[3] *Environment and Health Research Unit, South African Medical Research Council, Pretoria, South Africa*
[4] *Biostatistics Research Unit, South African Medical Research Council, Cape Town, South Africa*
[5] *Division of Health Systems and Public Health, Department of Global Health, Faculty of Medicine and Health Sciences, Stellenbosch University, South Africa*
[6] *Institute for Lifecourse Development, University of Greenwich, London, UK*
[7] *Air Quality Services, South African Weather Service, Centurion, South Africa*
[8] *Department of Geography, Geoinformatics and Meteorology, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa*
[9] *School of Public Health and Family Medicine, Faculty of Health Sciences, University of Cape Town, South Africa*

Corresponding author: *R A Roomaney (rifqah.roomaney@mrc.ac.za)*

Background. Globally, a growing body of research has shown that ambient air pollution is one of the most critical environmental issues, especially in relation to human health. Exposure to ambient air pollution leads to serious health conditions such as lower respiratory infections, cancers, diabetes mellitus type 2, ischaemic heart disease, stroke and chronic obstructive pulmonary disease.
Objectives. To estimate the burden of disease attributable to ambient air pollution in South Africa (SA) for the years 2000, 2006 and 2012.
Methods. Comparative risk assessment method was used to determine the burden of disease due to two pollutants (particulate matter ($PM_{2.5}$) and ambient ozone). Regionally optimised fully coupled climate chemistry models and surface air pollution observations were used to generate concentrations of $PM_{2.5}$ and ozone for each SA Census Small Area Level, for the year 2012. For 2000 and 2006, population-weighted $PM_{2.5}$ and ozone were estimated, based on the 2012 results. Following the identification of disease outcomes associated with particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$) and ozone exposure, the attributable burden of disease was estimated for 2000, 2006 and 2012. Furthermore, for the year 2012, the burden of disease attributable to ambient air pollution exposure was computed at provincial levels.
Results. In 2012, approximately 97.6% of people in SA were exposed to $PM_{2.5}$ at levels above the 2005 World Health Organization guideline: 10 μg/m³ annual mean. From 2000 to 2012, population-weighted annual average $PM_{2.5}$ increased from 26.6 μg/m³ to 29.7 μg/m³, and ozone 6-month high 8-hour daily maximum increased from 64.4 parts per billion (ppb) to 72.1 ppb. At a national scale, in the year 2000, 15 619 (95% uncertainty interval (UI) 8 958 - 21 849) deaths were attributed to $PM_{2.5}$ exposure, while 1 326 (95% UI 534 - 1 885) deaths were attributed to ozone. In 2006, an estimated 19 672 deaths (95% UI 11 526 - 27 086) were attributed to $PM_{2.5}$, and a further 1 591 deaths (95% UI 651 - 2 236) to ozone exposure. In 2012, deaths attributed to $PM_{2.5}$ were 19 507 (95% UI 11 318 - 27 111), and to ozone 1 734 (95% UI 727 - 2 399). Additionally, population-weighted provincial scale analysis showed that Gauteng Province had the highest number of attributable deaths due to both $PM_{2.5}$ and ozone in 2012.
Conclusion. The study showed that ambient air pollution exposure is an important health risk in SA, requiring both short- and long-term intervention. In the short term, the SA Ambient Air Quality Standards and industrial minimum emissions standards need to be enforced. In the longer term, to reduce air pollution and the associated disease burden, the combustion of fossil fuels as a source of energy for power generation and transportation, as well as industrial and domestic uses, needs to be replaced with clean renewable energy sources. In addition to local measures, when the southern African prevalent anticyclonic air dynamics that transport regionally emitted pollutants into SA (especially from biomass burning) are considered, it is also advisable to establish long-term regional co-operation in reducing air pollution.

S Afr Med J 2022;112(8b):705-717. https://doi.org/10.7196/SAMJ.2022.v112i8b.16483

The article in context

The South African Comparative Risk Assessment Study 2000 (SACRA1) calculated the burden of disease due to outdoor air pollution in selected urban areas in SA for the year 2000. It assessed the attributable burden for three diseases, namely cardiopulmonary disease, lung cancer and acute respiratory infections (in children). The population-weighted particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$) concentration was estimated to be 26.6 μg/m³ in selected urban areas, leading to 4 637 deaths or 0.9% (95% uncertainty interval (UI) 0.3 - 1.5) of all deaths in the country in 2000.

Added value of this study. The present study used updated methods to estimate the burden of disease due to ambient air pollution in SA for 2000, 2006 and 2012. $PM_{2.5}$ and ozone were chosen as the main indicators of ambient air pollution, and their concentrations were computed at SA Census Small Area Level using an aggregated approach that combined a regionally optimised fully coupled climate chemistry model and air pollution observations. Besides computing exposure at a higher resolution, this study also used death data from the second SA National Burden of Disease Study (SANBD2). For diseases attributable to $PM_{2.5}$ exposure, relative risks were generated from integrated exposure response relative risk curves for lower respiratory infections (LRIs), trachea, bronchus and lung cancers, diabetes mellitus type 2, ischaemic heart disease (IHD), stroke and chronic obstructive pulmonary disease (COPD). For both $PM_{2.5}$ and ozone, population-attributable fractions (PAFs) were computed at a high resolution. Following these, the burden of disease attributable to ambient air pollution exposure was analysed and presented at both national and provincial scales.

Implications of the available evidence. There is a significant burden of disease due to ambient air pollution in SA. Efforts are needed to reduce harmful concentrations of ambient air pollution in the country. In the short term, proactive enforcement of air quality regulations and emissions standards is needed, while in the long term, the country needs to employ alternative strategies to eliminate reliance on fossil fuels, to ensure industrial and domestic energy needs are met in an environmentally sustainable manner.

Air pollution is a threat to human health, well-being and sustainable development.[1] Ambient air pollution is associated with significant excess mortality and ill health.[2] In 2019, ambient air pollution was responsible for an estimated 4.5 million deaths worldwide.[3,4] Recent studies show that even short-term exposure to ambient air pollution leads to slight but statistically significant increases in the relative risk of all-cause mortality (from 0.41% - 0.72% increases for different pollutants).[5]

Ambient air pollution comprises a complex mixture of pollutants that includes particulate matter (PM), ozone, carbon monoxide, nitrogen oxides, sulphur dioxide, hydrocarbons, lead compounds and others.[6] Generally, fine PM ($PM_{2.5}$ – particulate matter with aerodynamic diameter<2.5 μm) has a variety of both primary and secondary, stationary and mobile sources. Primary $PM_{2.5}$ particles are emitted directly from sources, while secondary $PM_{2.5}$ particles are formed in the atmosphere through the chemical reactions of precursor gaseous pollutants. Usually, fine- and coarse-mode particles are generated by different processes, experience different atmospheric physicochemical transformations and are removed from the atmosphere through different mechanisms.[7] Various combustion activities account for significant sources of anthropogenic gaseous and particulate emissions that lead to the primary and secondary formation of $PM_{2.5}$, whereas emissions from mechanical and non-combustion activities such as mining, construction and agriculture lead to a higher proportion of coarse-mode particles (particles within the size range PM_{10} - $PM_{2.5}$, and PM_{10} (particulate matter <10 μm in aerodynamic diameter).[7] Hence the main anthropogenic sources of $PM_{2.5}$ emissions are mobile sources (exhaust emissions due to the combustion of petrol and diesel in cars and trucks), stationary sources (coal-burning power plants, industrial boilers burning coal and oil, metallurgical plants), the combustion of coal and wood for domestic energy, mechanical grinding during industrial processes and windblown dust off coal and ash stockpiles, mine tailings dumps and aeolian dust.[8-10] Ground-level (ambient) ozone is a secondary pollutant formed in the atmosphere through a complex series of reactions involving volatile organic compounds (VOCs – hydrocarbons, nitrogen oxides (NO_x – nitric oxide (NO) and nitrogen dioxide (NO_2)) and ultraviolet sunlight.[11] Anthropogenic sources contribute to the precursors of ozone formation (NO_x, VOCs).[12] NO_x is produced from combustion sources (power plants, industries, vehicle emissions), and VOCs arise from emissions from vehicles, petroleum industries, solvent utilisation, industrial processes, fuel distribution and biogenic (plant) emissions.[12]

Exposure to ambient air pollution leads to a significant burden of disease.[1] Several studies have focused on the health effects on children[13-17] and adults living close to mines or industrial areas in SA.[18] Norman *et al.*[19] estimated that 4 637 deaths and 42 000 years of life were lost to outdoor air pollution (specifically $PM_{2.5}$) in urban areas in SA in the year 2000. Compared with PM_{10}, exposure to $PM_{2.5}$ gets more attention because the associated health outcomes are more serious.[20] Larger particles are filtered in the nose and throat, but smaller $PM_{2.5}$ particles may penetrate to the gas exchange regions of the lung. The smallest particles pass the epithelial and subepithelial barriers to affect other organs of the body.[21] $PM_{2.5}$ exposure is associated with the development of many conditions, including LRIs,[22-24] trachea, bronchus and lung cancers,[25] diabetes mellitus type 2, COPD,[25,26] IHD,[27] stroke[27] and adverse birth outcomes[28,29] such as low birthweight, preterm birth and stillbirth. When ambient ozone is inhaled, it is absorbed in the upper respiratory tract and moves into the intrathoracic airways, reaches the lower respiratory tract and dissolves into the epithelial lining fluid.[30] Both short-term and long-term exposure to ozone have been linked to ill-health effects (such as lung function decrements, susceptibility to respiratory tract infections, asthma attacks and COPD)[30] and premature mortality.[5]

Both regionally and globally, the concentrations of fine PM and ambient ozone are indicators of ambient air pollution, and are monitored for regulatory purposes.[1,31] In SA, the National Environmental Management Act No. 39 of 2004[32] governs the standard-setting processes for a range of pollutants. Ambient air quality standards for most pollutants were gazetted in 2009, while the standard for $PM_{2.5}$ was gazetted in 2012.[33,34] The $PM_{2.5}$ annual average standard was 25 μg/m^3 in 2012, decreasing to a more protective 20 μg/m^3 in 2016. For ambient ozone, the national ambient air quality standard is 61 ppb or 120 μg/m^3 for an 8-hour running mean concentration.[35] In 2005, the World Health Organization (WHO) ambient air quality guideline (AQG) recommended an annual mean of 10 μg/m^3 for $PM_{2.5}$, and a 100 μg/m^3 (51 ppb) 8-hour mean for ozone.[36] In 2021, updated AQGs were released by the WHO where the $PM_{2.5}$ AQG was reduced from 10 to 5 μg/m^3 for the annual mean, and for ozone, it was set to a short-term value of 100 μg/m^3 8-hour daily maximum, and a new long-term guideline of 60 μg/m^3 8-hour mean for the seasonal peak value.[31] While the establishment of these ambient air pollution standards was undoubtedly an important step for SA, their enforcement remains tentative.[34] Although every municipality in SA should be monitoring and reporting air quality data to the SA Air Quality Information System (SAAQIS), many are not doing so,[34] contributing to weak air quality data availability.[37]

Where monitoring data are available, air pollution standards are being exceeded at many sites in SA.[34,38,39] This may be in part due to the country's heavy reliance on its mining, petrochemical and

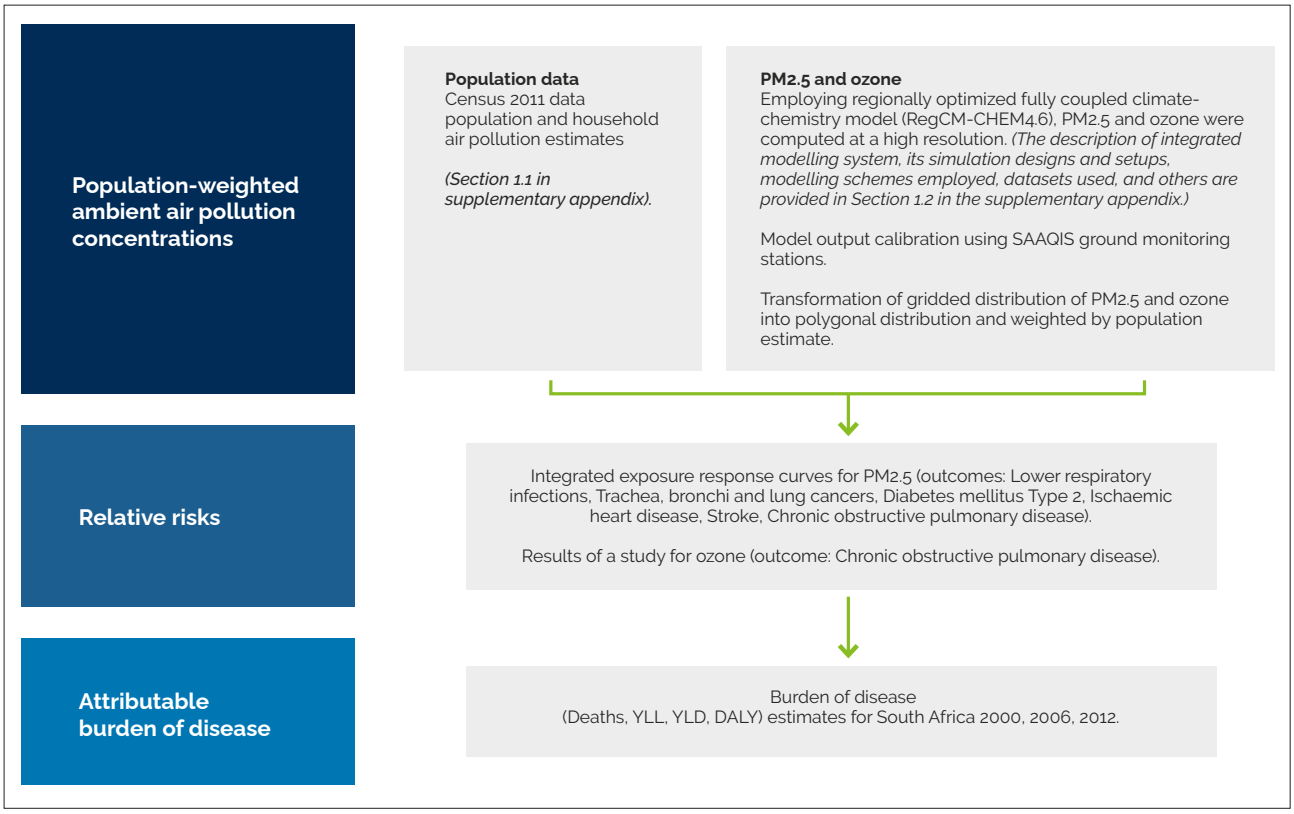

Fig. 1. Data sources for calculating the burden of disease attributable to ambient air pollution ($PM_{2.5}$ and ozone) for 2012. (HAP = household air pollution; SAAQIS = South African Air Quality Information System; YLL = year of life lost, YLD = year of life lived with a disability, DALY = disability-adjusted life year.)

metallurgical industries, along with poorly regulated coal-fired power stations,[42] with coal being used to generate 82% of the country's electricity.[41] These activities affect the region,[42] especially in hotspot locations (priority areas) such as the Vaal Triangle Airshed Priority Area, the Highveld Priority Area and the Waterberg-Bojanala Priority Area. These regions are considered priority areas because of emissions from industrial activities such as mining, electricity production, industrial activities and domestic solid-fuel burning resulting in widespread exceedances of ambient air quality standards.[43-46] At an individual level, it is difficult to control the quality of the ambient air we breathe, but government regulation and enforcement of air quality and source emission standards can play a pivotal role in reducing the burden of disease caused by exposure to ambient air pollution. To generate evidence to inform the reduction and management of ambient air pollution and its health impacts, this study aimed to estimate the burden of disease attributable to ambient air pollution ($PM_{2.5}$ and ozone) for the years 2000, 2006 and 2012.

Methods

This study used comparative risk assessment methodology[47] to estimate the burden of disease attributable to ambient air pollution using the counterfactual scenario of the theoretical minimum risk exposure level (TMREL). Calculating the burden of disease entailed computing the concentrations of $PM_{2.5}$ and ozone, identifying health outcomes and calculating the PAFs (Fig. 1).

Following the Global Burden of Diseases, Injuries, and Risk Factors Study 2017 (GBD 2017)[48] approach, the health risks from ozone and $PM_{2.5}$ were calculated separately. The study also made the assumption that the entire population was exposed to ozone. For $PM_{2.5}$, it was assumed that in each SA Census Small Area Level (SAL), the proportion of the population not using solid fuels is exposed to $PM_{2.5}$ at the modelled ambient concentration, and that the proportion using solid fuels is exposed at a higher exposure level applicable to households using solid fuels for cooking (household air pollution (HAP)). The $PM_{2.5}$ disease burden due to HAP is reported separately,[49] thereby ensuring that the $PM_{2.5}$ risks for the entire population are accounted for.

Exposure definitions

Consistent with the GBD 2017[48] definitions, exposure to $PM_{2.5}$ was defined as the annual average exposure to outdoor air concentrations of $PM_{2.5}$. Similarly, following GBD 2017, exposure to ozone was defined as the mean of the 6-month period with highest mean 8-hour daily maximum ozone concentrations (July - December 2012), henceforth abbreviated to 6-mo-high-8h-daily-max.[48]

Estimating exposure to $PM_{2.5}$ and ozone in SA for 2012

Online integrated climate chemistry model

Computational advances have allowed for the two-way interactive coupling of atmospheric chemistry with various static and dynamic components of the climate system.[49,50] These advanced numerical modelling systems are known as fully coupled or 'online integrated' climate chemistry models.[50,51] Despite their computational demands, fully coupled climate chemistry models become crucial tools for addressing the issues of atmospheric composition, as well as climate chemistry interactions.[50,51] Rather than coarse-resolution global-scale models, online integrated regional models are known to deploy sub-grid scale model physics, locally resolved dynamical

information, atmospheric physicochemical processes and so on.[50,51] Hence fine-scale regional models allow the generation of more realistic small-scale climate information, chemical processes and patterns at a higher resolution than the global-scale models.[52]

Accordingly, to model the concentration and spatiotemporal distributions of $PM_{2.5}$ and ozone for the whole of SA (section 1.1 in appendix: https://www.samedical.org/file/1932) at a higher resolution for the year 2012, the present study deployed the International Center for Theoretical Physics fully coupled regional climate chemistry model (RegCM-CHEM4.6).[53] Previous studies have shown the regional optimisation and capabilities of RegCM-CHEM in reproducing the state of the atmosphere (both meteorology and chemistry) over southern Africa.[53-55] A detailed description of the RegCM-CHEM modelling system, simulation set-ups, modelling schemes employed and datasets used are provided in section 1.2 of the appendix. The model outputs were calibrated using SAAQIS ground monitoring data.

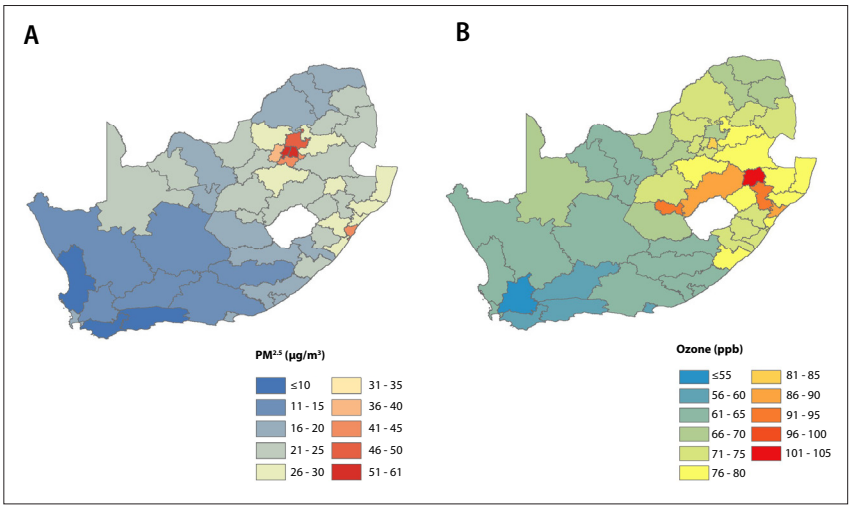

Fig. 2. Population-weighted (A) annual mean concentration of $PM_{2.5}$ ($\mu g/m^3$), (B) mean of the 6-month period with highest mean 8-hour daily maximum ozone concentrations ambient ozone concentrations (ppb), at district scale in South Africa for 2012.

Ground monitoring station data

Ground-based air quality observations were used to compare and correct modelled surface concentration of $PM_{2.5}$ and ozone. Hourly observations of $PM_{2.5}$ and ozone were obtained from SAAQIS. During the analysis, there were 62 PM- and 38 ozone-monitoring stations that reported to SAAQIS (section 1.3 in appendix). However, after applying multi-data quality screening criteria, this study used 46 PM and 31 ozone sites (additional details available in appendix

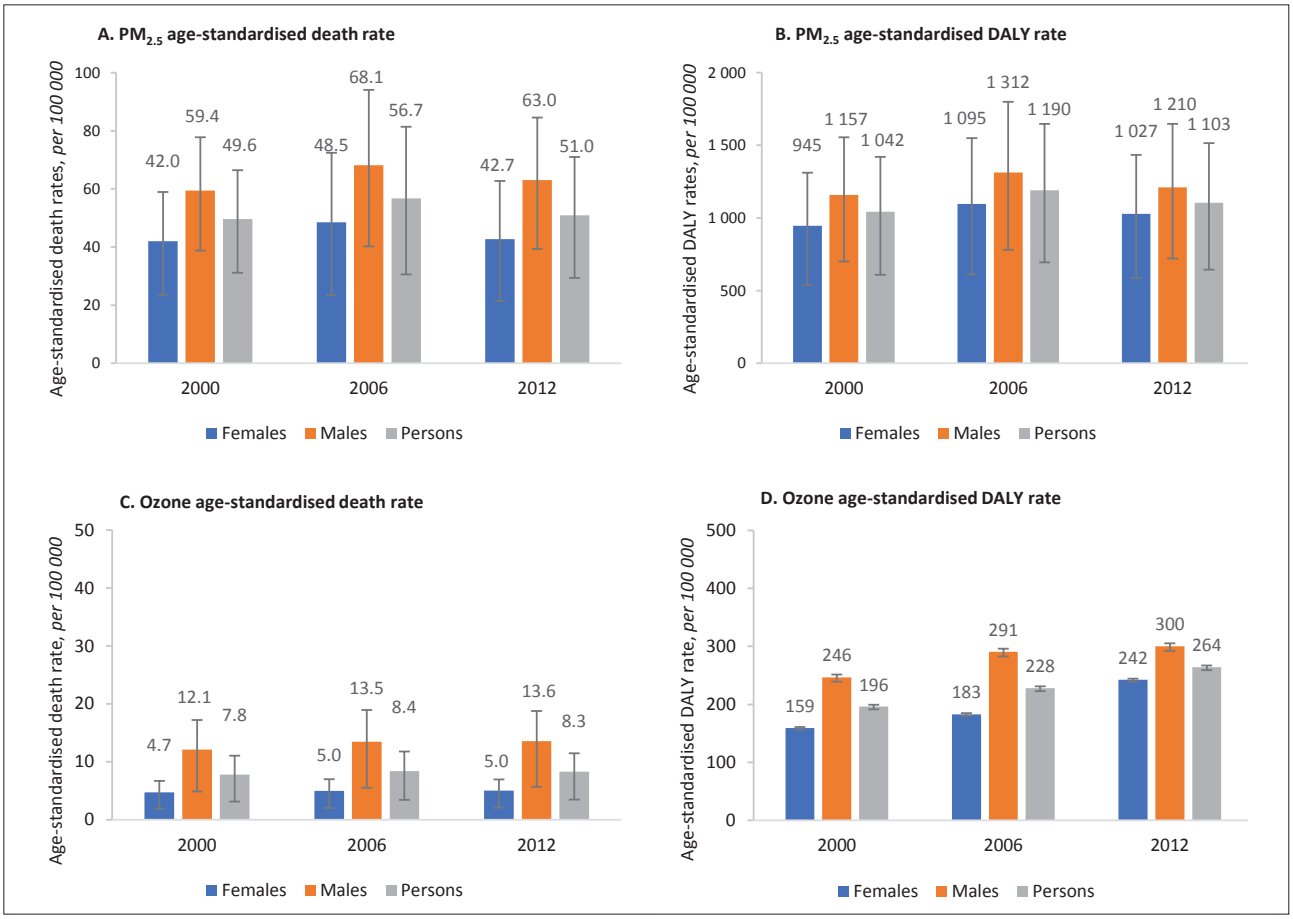

Fig. 3. $PM_{2.5}$ age-standardised (A) death and (B) disability-adjusted life year (DALY) rates per 100 000 population. Ambient ozone age-standardised (C) death and (D) DALY rates per 100 000 population. (All graphs exhibit the national outcomes for South Africa for 2000, 2006 and 2012.)

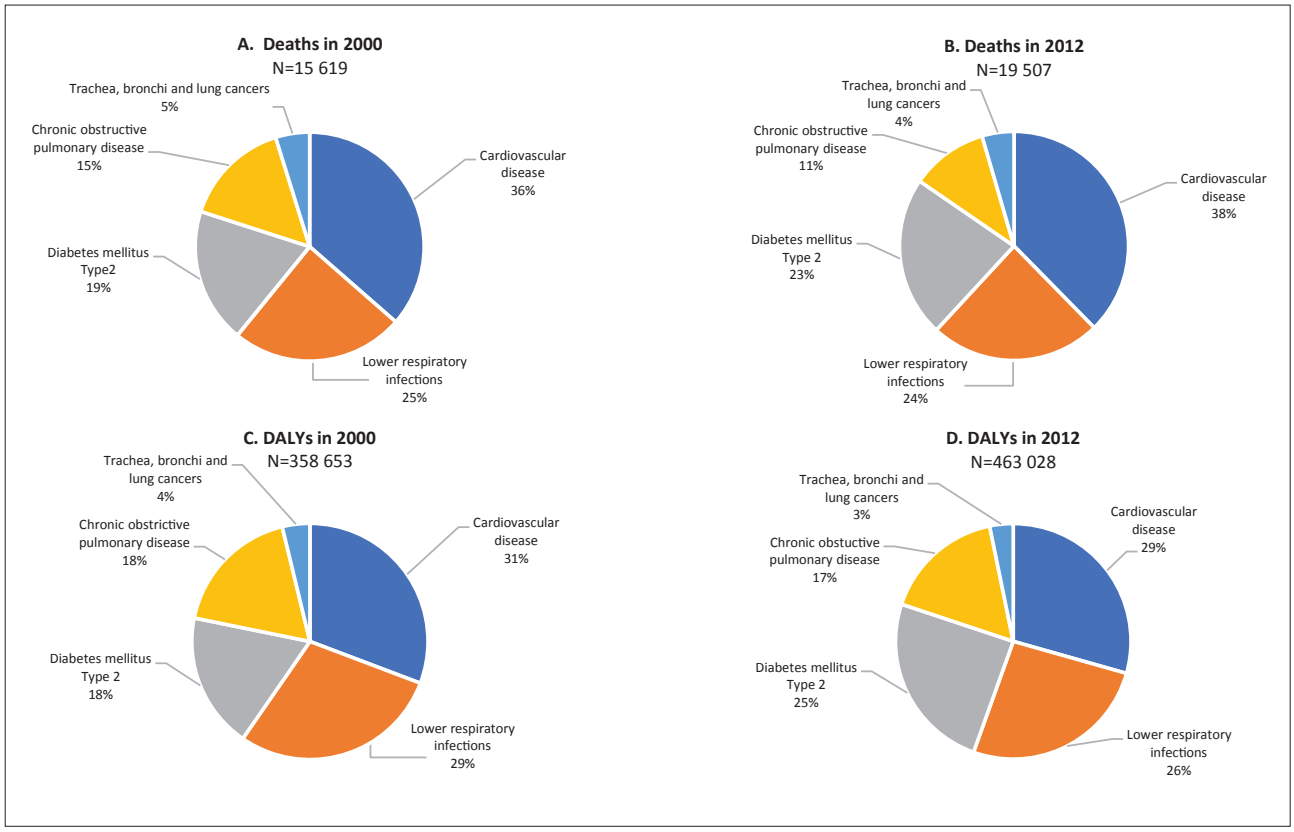

Fig. 4. Deaths attributable to $PM_{2.5}$ by disease condition for (A) 2000 and (B) 2012. Disability-adjusted life years (DALYs) attributable to $PM_{2.5}$ by disease condition for (C) 2000 and (D) 2012. (Cardiovascular disease is the addition of ischaemic heart disease and stroke. Lower respiratory tract infections were a disease outcome for all ages.)

Fig. S5, and Tables S3 and S4: https://www.samedical.org/file/1810). The multi-data quality screening criteria applied in this study are: (*i*) exclusion of data points that exhibited values outside the minimum (i.e. <3 μg/m^3 for $PM_{2.5}$ and <1 ppb for ozone) and maximum (i.e. >500 μg/m^3 for $PM_{2.5}$ and >350 ppb for ozone) concentration thresholds; (*ii*) for $PM_{2.5}$, over monitoring stations that report both $PM_{2.5}$ and PM_{10}, if the $PM_{2.5}$ levels reported exceed concurrent co-located PM_{10} levels as well as if the station registers the same concentrations for 3 or more consecutive hours, those $PM_{2.5}$ data points are omitted; (*iii*) after applying the aforementioned criteria, stations with a valid data recovery efficiency with a benchmark of 75% were used. In 2012, among the total stations that reported PM parameters to SAAQIS, 21 monitoring stations reported both $PM_{2.5}$ and PM_{10} (14 sites with valid data points), and the remaining 41 stations (32 sites with valid data points) reported only PM_{10} (appendix Fig. S6). For sites only reporting PM_{10}, their $PM_{2.5}$ values were estimated following the approach detailed in section 1.3 in the appendix.

Most of the observational stations that reported to SAAQIS are concentrated in the northern and eastern parts of the country, where anthropogenic sectors (e.g. urban, residential, biomass burning and industrial activities), as well as population density, are higher (appendix Fig. S3: https://www.samedical.org/file/1810). This provided the opportunity to produce optimal bias-corrected values of $PM_{2.5}$ and ozone, throughout industrially active and densely populated areas of SA.

Model calibration

The initial comparison of modelled hourly values with quality-controlled observations from SAAQIS showed that the model adequately captured both the magnitude and spatiotemporal distributions of $PM_{2.5}$ and ozone. However, to enhance the quality of modelled values and ensure their reliable applicability for regional exposure studies, quantile mapping-based bias correction was performed.[56,57] Region of influence-specified quantile functions were constructed in order to transform modelled outputs into quality-controlled hourly observations of $PM_{2.5}$ (over 46 sites: appendix Fig. S5A: https://www.samedical.org/file/1810) and ozone (over 31 sites: appendix Fig. S5B), for the entire year of 2012. The quantile transformation functions were applied within their region of influence in terrestrial parts of SA to generate bias-corrected $PM_{2.5}$ and ozone distributions. Afterwards, at the local scale, bias-corrected $PM_{2.5}$ and ozone were compared with observations of individual sites. The comparison showed the bias-corrected 8-hour running average ozone annual mean bias (AMB) is within the range of ~–2.2 - 2.9 ppb, while over 91% of the stations' ozone AMBs are within the range of ~–0.04 - 0.59 ppb. Also, for the $PM_{2.5}$, the AMBs are within the range of ~–2.8 - 3.4 μg/m^3, with over 87% of the stations' $PM_{2.5}$ AMBs within the range of ~–0.91 - 0.5 μg/m^3. Further information on monitoring sites and statistics are tabulated in appendix Tables S3 and S4 (https://www.samedical.org/file/1810).

Polygonal transformation

For exposure analysis, the bias-corrected gridded distribution of $PM_{2.5}$ and ozone were transferred into a polygonal distribution based on the population census 2011 SAL polygons from Statistics SA.[58] The transformation of gridded to polygonal distribution was performed using a polygonal size-dependent multi-grid point weighted average matrix. To verify the transformation accuracy, the gridded values were interpolated into the centroid of each of the polygons and compared with the corresponding polygonal values of ozone and $PM_{2.5}$. The transformation analysis showed

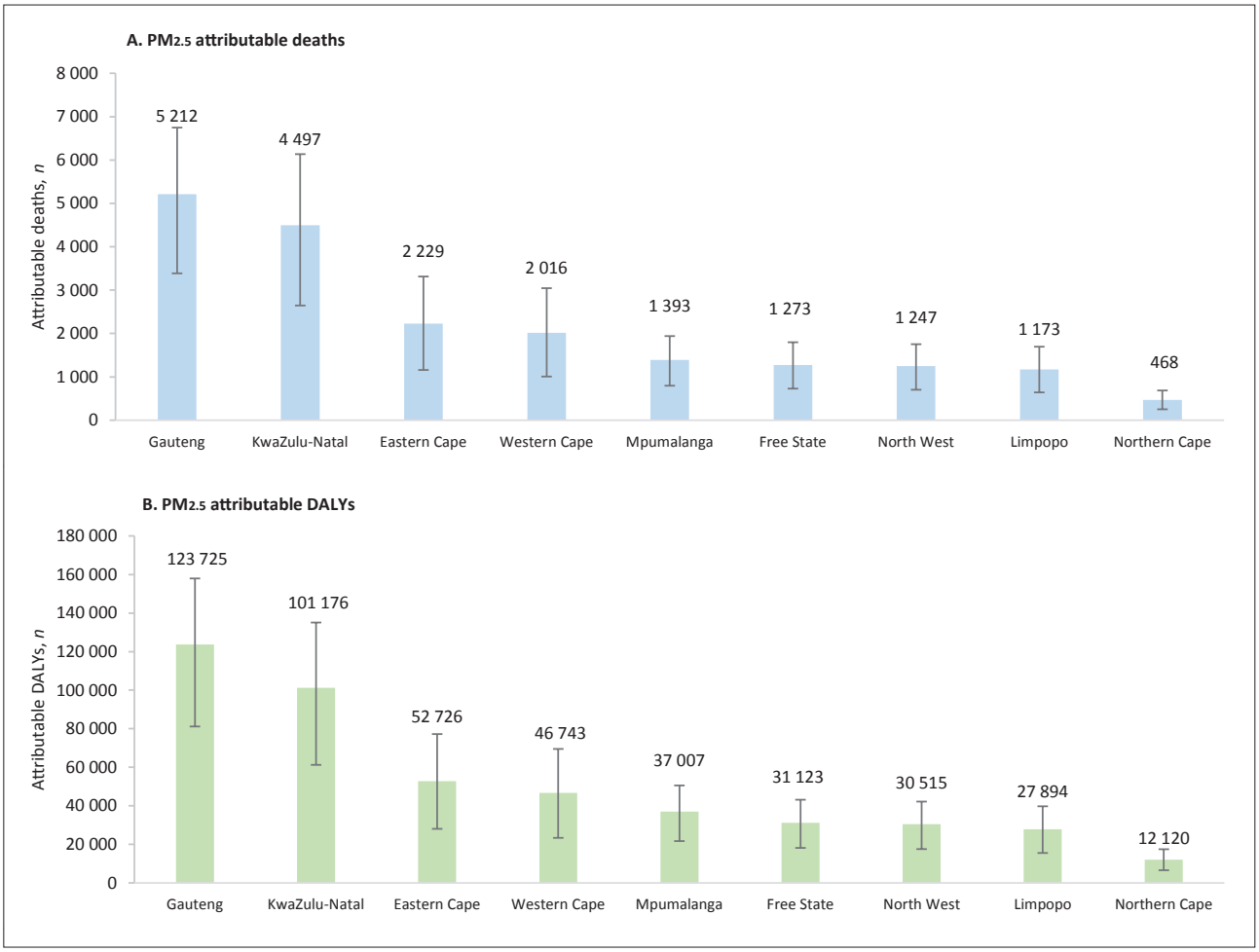

Fig. 5. $PM_{2.5}$ attributable (A) deaths and (B) disability-adjusted life years (DALYs) by province for 2012.

99.6% and 99.2% of polygonal values have less than 1 ppb of ozone and 1 μg/m³ of $PM_{2.5}$ absolute difference, respectively, when compared with the gridded values that are interpolated into the centroid of each of the polygons.

Adjustment for HAP

Although HAP and ambient air pollution are related, since both are indexed against annual $PM_{2.5}$ exposure, we analysed the disease burden due to these risk factors separately. To estimate total $PM_{2.5}$ risks and burden of disease, we assumed in each SAL that modelled ambient concentrations applied to the total population minus the population exposed to HAP. The estimates of HAP due to cooking with solid fuels were made using the Census 2011 data.[58]

Population weighting air pollution estimates

After mapping the calibrated $PM_{2.5}$ and ozone concentrations onto 90 271 SAL polygons of the SA Census 2011, the shape files were exported into Excel (Microsoft Corp., USA). The exported files contained $PM_{2.5}$ and ozone concentrations for each SAL and their corresponding small-area geographical information. The national and provincial population-weighted average values were computed based on the SAL values within their respective boundaries.

The population-weighted $PM_{2.5}$ and ozone concentrations were calculated using ArcGIS software (ArcGIS, USA). The $PM_{2.5}$ and ozone SAL layers were overlaid onto their corresponding population layers, then following equation 1, the population-weighted annual mean concentrations of $PM_{2.5}$ and population-weighted 6-mo-high-8h-daily-max ambient ozone concentrations were calculated:[60-61]

$$\frac{\sum (P_i x C_i)}{\sum P_i}$$

where P_i is the population in SAL i, and C_i is its corresponding pollutant concentration.

Estimating exposure to PM2.5 and ozone in South Africa for 2000 and 2006

For 2000, the estimate of population-weighted mean $PM_{2.5}$ used by Norman *et al.*[19] was adopted (26.6 μg/m³). A linear interpolation was done between the 2000 and 2012 values to calculate an estimate of $PM_{2.5}$ for 2006. For ozone, the 2012 modelled estimate was used, together with a 20% (95% confidence interval: 15 - 25) increase per decade based on a study by Thompson *et al.*,[62] to calculate values for 2000 and 2006.

Disease outcomes and relative risks

Generally, particulates differ in physical properties, size distribution and chemical composition, depending on their emission sources and formation processes, and lead to different impacts on human health. However, the present study, consistent with other studies,[48] assumes that the relative risks associated with $PM_{2.5}$ depend only on the mass concentration of $PM_{2.5}$, irrespective of the relative contributions of different sources or of differing chemical

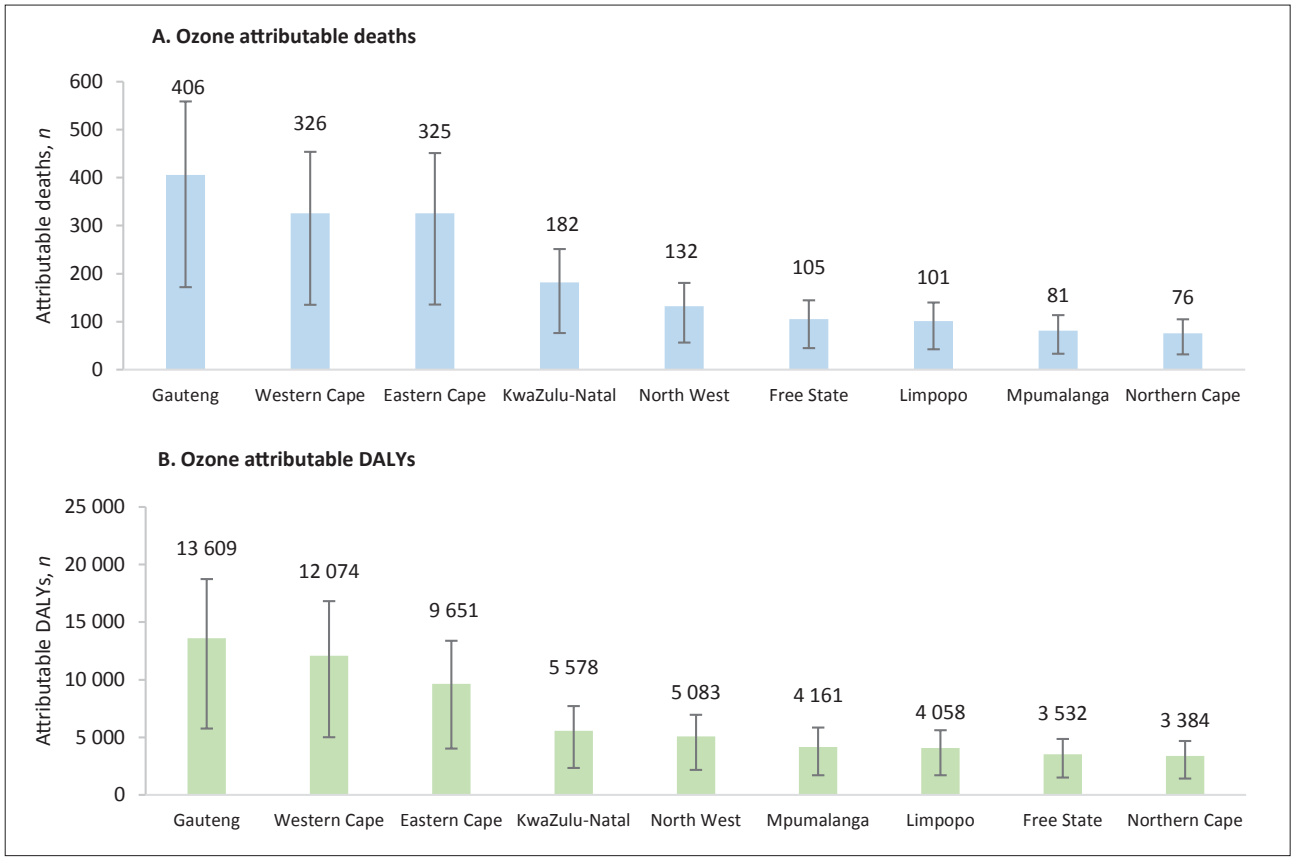

Fig. 6. Ozone-attributable (A) deaths and (B) disability-adjusted life years by province for 2012.

compositions. Thus both primary and secondary $PM_{2.5}$ arising from anthropogenic activities (such as coal power plants, road traffic, industries, open biomass burning, the use of solid fuels in households), and natural events (such as windblown dust, biogenics), are assumed to have the same exposure-response relationship, based only on the mass concentration.[31]

GBD 2017[48] was referenced for appropriate disease outcomes and relative risks associated with $PM_{2.5}$ and ozone (Table 1). For $PM_{2.5}$, integrated exposure response (IER) relative risk curves were derived using available evidence to estimate the relative risks of exposure over the entire global range of exposures (appendix section 1.4: https://www.samedical.org/file/1810).[63,64] IER relative risk curves were used to generate relative risks at each SAL corresponding to computed $PM_{2.5}$ concentrations using R statistical software version 3.6.0 (R core Team, Austria). For ambient ozone exposure, COPD in adults ≥25 years was a risk-outcome pair.[65]

Computation of population attributable fractions

For computing population attributable fractions, Excel spreadsheets were developed for each year of interest. For $PM_{2.5}$, the relative risks (mean, lower bound and upper bound) for each disease outcome and age group were calculated for each concentration of $PM_{2.5}$ in each SAL, using the IER relative risk tables and calculation procedure. We calculated the population exposed to ambient air by taking the total population in each SAL and subtracting the people using solid fuels for cooking.

The attributable fractions for each SAL were calculated using:

$$PAF = \frac{P\,[RR\,(x) - RR\,(TMREL)]}{P\,[RR\,(x) - 1]}$$

where P is the proportion of the population in each SAL exposed at the ambient air concentration value x and $RR(x)$ and $RR\,(TMREL)$ are the relative risks calculated at exposure level x and the counterfactual TMREL values, respectively. For the national and provincial geographies, the PAFs for each age group and risk factor were calculated as the age-group population (in each SAL)-weighted average.

Computation of attributable burden

The attributable fractions were multiplied by the estimates of deaths, years of life lost (YLLs), years of life lived with a disability (YLDs) and disability-adjusted life years (DALYs) from the second SA National Burden of Disease Study (SANBD2)[66,67] for the appropriate year. The national attributable burdens are the sum of the provincial attributable burdens for 2012. Age-standardised death and DALY rates were calculated by multiplying the attributable disease burden by the alternative mid-year population estimates[68] for each respective year, and dividing it by the WHO population standard.[69]

Uncertainty estimation

For $PM_{2.5}$ and ozone, we did not consider uncertainty around the exposure estimates. Uncertainty around the TMREL was included in the calculation of the relative risks. For $PM_{2.5}$ and ozone, we used the lower and upper 95% uncertainty levels of the relative risks to derive the lower and upper 95% uncertainty levels of the attributable fractions, and multiplied these by the burden estimates to produce lower- and upper-bound estimates of attributable burden.

Results

The 2005 WHO AQG for annual mean $PM_{2.5}$ was 10 μg/m^3,[36] and the SA National Air Quality Standard for annual $PM_{2.5}$ is 20 μg/m^3.[33] Results showed that in 2012, 97.6% of the total population of SA lived in areas that were exposed to population-weighted annual $PM_{2.5}$ concentrations above the 2005 WHO

Table 1. Description of ambient air pollution definitions, disease outcomes and relative risks

	Indicator pollutant	
Information	**$PM_{2.5}$**	**Ambient ozone**
Indicator definition	Annual average concentration of $PM_{2.5}$ in SA in μg/m³	Mean of the 6-month period (July - December) with highest mean 8-hour daily maximum ozone concentrations (ppb)
Theoretical minimum	Assigned a uniform distribution with lower/upper bounds (2.4 - 5.9 μg/m³)[48]	Assigned a uniform distribution with lower/upper bounds (29.1 and 35.7 ppb).[48]
Disease outcomes and ICD-10 codes	LRIs (J09-J18, J20-J22) Trachea, bronchus, and lung cancers (C33-C34) Diabetes mellitus type 2 (E11) IHD (I20-I25) Stroke (I60-I69) COPD (J40-J44, J47)	Chronic obstructive pulmonary disease (J40-J44, J47)
Disease outcomes by age group	People of all ages: • LRIs People aged ≥25 years: • Tracheal, bronchus and lung cancer • Diabetes mellitus type 2 • IHD • Stroke • COPD	People ≥25 years: • Chronic obstructive pulmonary disease • For every 10 ppb increase in ozone exposure, the risk of death from COPD increased linearly by 2.9% (RR: 1.06, 95% CI: 1.02 - 1.10).[65]

SA = South Africa; LRI = lower respiratory infection; IHD = ischaemic heart disease; COPD = chronic obstructive pulmonary disease; RR = relative risk; CI = confidence interval.

guideline (Figs 2A and B). Only 5.8% of districts, all located in the Western Cape Province, met this guideline. A total of 69.9% of the total population lived in areas exposed to $PM_{2.5}$ levels above the national standard of 20 μg/m³. Gauteng Province experienced the highest levels of $PM_{2.5}$ pollution, with an average population-weighted annual concentration of 52.3 μg/m³ and a peak of 65.0 μg/m³. Therefore Gauteng, with 24% of the total population, was exposed to high levels of pollution. In addition, the population-weighted mean $PM_{2.5}$ values (μg/m³) in KwaZulu-Natal (30.7), Mpumalanga (24.7), North West (23.5) and Free State (22.5) provinces all exceeded the national standard of 20 μg/m³.

The SA National Air Quality Standard for the daily maximum 8-hour running mean of ozone is 61 ppb. However, the 2005 WHO AQG is 100 μg/m³, which is equivalent to 50 ppb.[36] The analysis of the population-weighted 6-mo-high-8-h-daily-max ozone concentrations in SA found that in 2012, 93.8% of the total population lived in areas that exceed the national standard during the 6-month high-ozone season, while 100% of the areas exceeded the 2005 WHO ozone AQG. The highest mean 6-month high-ozone season values occurred in Free State and North West provinces (80.4 ppb and 80.1 ppb, respectively). The highest 8-hour running mean ozone values, >110 ppb, occurred in Free State, North West, Gauteng, KwaZulu-Natal and Eastern Cape provinces.

The 2012 national population-weighted annual average $PM_{2.5}$ concentration was estimated to be 29.7 μg/m³. For 2006, we estimated the population-weighted annual average $PM_{2.5}$ concentration was 28.2 μg/m³, and for 2000 we used a national population-weighted annual average of 26.6 μg/m³.[11] For ozone, the population-weighted 6-mo-high-8h-daily-max ambient ozone for 2012 was 72.1 ppb. It was estimated to be 64.4 ppb for 2006 and 58.1 ppb for 2000.

Burden of disease attributable to ambient air pollution exposure

At a national scale, the number of deaths attributable to $PM_{2.5}$ increased from 15 619 in the year 2000 to 19 507 in 2012, representing a 19.9% increase (Table 2). The number of deaths attributable to ozone increased by 23.5% from 2000 to 2012 (from 1 326 in the year 2000 to 1 734 in 2012) (Table 3).

While comparing the 2000 and 2012 national scale outcomes, the $PM_{2.5}$ age-standardised death rate increased by 2.7% and the DALY rate increased by 5.4% (Figs 3A and B). Similarly, the national scale analysis for ozone shows that the ozone age-standardised death rate increased by 6.0% and the DALY rate increased by 25.8% (Figs 3C and 3D). In the case of both pollutants, the age-standardised death and DALY rates were higher in males than females.

The results in Fig. 4 show that cardiovascular disease contributed to a large proportion of the mortality and morbidity burden attributable to $PM_{2.5}$ in 2000 and 2012. In terms of ozone exposure disease outcome, the study only considers the contribution of ozone to COPD, hence it is not displayed in a pie chart. The national scale analysis for age- and gender-categorised distribution of deaths attributable to $PM_{2.5}$ and ozone (for the years 2000, 2006 and 2012) are provided in section 2.2 of the appendix (https://www.samedical.org/file/1810). In terms of age-categorised impact, the deaths attributable to $PM_{2.5}$ exposure are higher within the age band of ≥70 years (for females) and 60 - 69 years (for males) (appendix Fig. S10). In terms of the deaths attributable to ozone exposure, the age-categorised analysis shows that the female and male populations within the age band of ≥80 years experience the highest impact (appendix Fig. S11).

Burden of disease due to ambient air pollution by province for 2012

The provincial variations on population-weighted annual $PM_{2.5}$ levels are provided in appendix Table S5 (https://www.samedical.org/file/1810). Gauteng (52.3 μg/m³), KwaZulu-Natal (30.7 μg/m³) and Mpumalanga (24.7 μg/m³) had the highest population-weighted concentrations of $PM_{2.5}$. The highest number of deaths and DALYS due to $PM_{2.5}$ exposure occurred in Gauteng, KwaZulu-Natal and Eastern Cape (Fig. 5). The provincial analysis determined that lower respiratory infections (in Gauteng) and diabetes mellitus type 2 (in KwaZulu-Natal) are the leading causes of deaths and DALYs attributable to $PM_{2.5}$ (appendix Fig. S12).

When the population structure and underlying cause of death are taken into account, the age-standardised death rates due to $PM_{2.5}$ were highest in Gauteng, KwaZulu-Natal and Free State provinces

Table 2. Burden of disease due to ambient $PM_{2.5}$ by health outcome and sex for 2000, 2006 and 2012

	Females			Males			Total		
Disease outcome	**AF (%)**	**Deaths, *n***	**DALYs, *n***	**AF (%)**	**Deaths, *n***	**DALYs, *n***	**AF (%)**	**Deaths, *n***	**DALYs, *n***
2000									
LRIs*	17	1 809	49 553	17	2 010	53 990	17	3 818	103 543
Trachea, bronchus and lung cancers	13	212	3 904	13	539	9 608	13	751	13 512
Diabetes mellitus type 2	25	1 833	40 721	25	1 151	25 891	25	2 983	66 612
IHD	12	1 263	24 064	12	1 579	30 910	12	2 842	54 973
Stroke	8	1 624	31 042	8	1 224	24 282	8	2 848	55 324
COPD	20	852	29 574	20	1 524	35 117	20	2 377	64 690
Total attributable burden	-	**7 592**	**178 857**	-	**8 027**	**179 796**	-	**15 619**	**358 653**
95% UI	-	4 293 - 10 624	103 288 - 246 865	-	4 665 - 11 225	106 109 - 248 658	-	8 958 - 21 849	209 397 - 495 523
% of total burden	-	**3.2**	**1.9**	-	**3.0**	**1.9**	-	**3.1**	**1.9**
95% UI (%)	-	1.8 - 4.5	1.1 - 2.6	-	1.8 - 4.2	1.1 - 2.6	-	1.8 - 4.2	1.1 - 2.6
2006									
LRIs*	19	2 361	61 579	19	2 489	65 246	19	4 851	126 824
Trachea, bronchus and lung cancers	15	272	4 836	15	575	10 013	15	847	14 848
Diabetes mellitus type 2	26	2 659	60 617	26	1 653	36 640	26	4 313	97 258
IHD	1	1 599	30 891	14	2 028	39 601	14	3 627	70 491
Stroke	9	2 044	38 831	9	1 465	28 317	9	3 509	67 148
COPD	22	896	33 886	22	1 629	40 906	22	2 525	74 793
Total attributable burden‡	-	**9 832**	**230 639**	-	**9 840**	**220 723**	-	**19 672**	**451 362**
95% UI	-	5 684 - 13 526	135 857 - 313 146	-	5 842 - 13 560	133 040 - 300 917	-	11 526 - 27 086	268 898 - 614 063
% of total burden	-	**2.9**	**1.8**	-	**2.9**	**1.8**	-	**2.9**	**1.8**
95% UI (%)	-	1.7 - 4.0	1.1 - 2.4	-	1.7 - 4.0	1.1 - 2.5	-	1.7 - 4.0	1.1 - 2.4
2012									
LRIs*	18	2 301	58 131	18	2 423	62 656	18	4 724	120 787
Trachea, bronchus and lung cancers	13	281	4 856	13	597	10 044	13	879	14 900
Diabetes mellitus type 2	24	2 683	72 380	24	1 748	41 706	24	4 431	114 086
IHD	15	1 580	29 462	15	2 045	39 543	15	3 625	69 005
Stroke	10	2 161	38 557	10	1 558	28 517	10	3 719	67 074
COPD	21	789	39 991	21	1 339	37 184	21	2 128	77 174
Total attributable burden	-	**9 797**	**243 378**	-	**9 710**	**219 650**	-	**19 507**	**463 028**
95% UI	-	5 603 - 13 637	142 103 - 332 147	-	5 715 - 13 475	131 319 - 300 791	-	11 318 - 27 111	273 422 - 632 937
% of total burden	-	**3.9**	**2.3**	-	**3.5**	**2.2**	-	**3.7**	**2.3**
95% UI (%)	-	2.2 - 5.4	1.4 - 3.2	-	2.1 - 4.9	1.3 - 3.0	-	2.1 - 5.1	1.3 - 3.1

AF = attributable fraction; DALY = disability-adjusted life year; LRI = lower respiratory infection; IHD = ischaemic heart disease; COPD = chronic obstructive pulmonary disease; UI = uncertainty interval.
*Lower respiratory tract infections were a disease outcome in all ages whereas other outcomes were for people aged >25 years.

Table 3. Burden of disease due to ambient ozone by health outcome and sex for 2000, 2006 and 2012

	Females			Males			Total		
Disease outcome	**AF**	**Deaths, *n***	**DALYs, *n***	**AF**	**Deaths, *n***	**DALYs, *n***	**AF**	**Deaths, *n***	**DALYs, *n***
2000									
COPD	**11**	**476**	**16 497**	**11**	**850**	**19 589**	**11**	**1 326**	**36 086**
95% UI	-	(192 - 676)	(6 644 - 23 453)	-	(342 - 1 209)	(7 889 - 27 849)	-	(534 - 1 885)	(14 533 - 51 302)
% of total burden	**-**	**0.2**	**0.2**	**-**	**0.3**	**0.2**	**-**	**0.3**	**0.2**
95% UI (%)	-	(0.1 - 0.3)	(0.1 - 0.3)	-	(0.1 - 0.5)	(0.1 - 0.3)	-	(0.1 - 0.4)	(0.1 - 0.3)
2006									
COPD	**14**	**564**	**21 355**	**14**	**1 027**	**25 780**	**14**	**1 591**	**47 135**
95% UI	-	(231 - 793)	(8 743 - 30 015)	-	(420 - 1 443)	(10 554 - 36 234)	-	(651 - 2 236)	(19 297 - 66 249)
% of total burden	**-**	**0.2**	**0.2**	**-**	**0.3**	**0.2**	**-**	**0.2**	**0.2**
95% UI (%)	-	(0.1 - 0.2)	(0.1 - 0.2)	-	(0.1 - 0.4)	(0.1 - 0.3)	-	(0.1 - 0.3)	(0.1 - 0.3)
2012									
COPD	**17**	**643**	**31 781**	**17**	**1 090**	**29 350**	**17**	**1 734**	**61 130**
95% UI	-	(270 - 890)	(13 323 - 43 993)	-	(457 - 1 508)	(12 311 - 40 612)	-	(727 - 2 399)	(25 634 - 84 605)
% of total burden	**-**	**0.3**	**0.3**	**-**	**0.4**	**0.3**	**-**	**0.3**	**0.3**
95% UI (%)	-	(0.1 - 0.4)	(0.1 - 0.4)	-	(0.2 - 0.5)	(0.1 - 0.4)	-	(0.1 - 0.5)	(0.1 - 0.4)

AF = attributable fraction based on the numbers of attributable deaths; DALY = disability-adjusted life year; COPD = chronic obstructive pulmonary disease; UI = uncertainty interval.

(appendix Fig. S13: https://www.samedical.org/file/1932). The age-standardised DALY rate was highest in the Free State, which may be due to the large YLL contribution of LRIs to the cause of death profile in that province.[70]

The provincial variations on population-weighted 6-mo-high-8h-daily-max ambient ozone are provided in section 2.3 of the appendix. As shown in appendix Table S6 (https://www.samedical.org/file/1932), the highest values of population-weighted 6-mo-high-8h-daily-max ozone are found in the Free State (80.4 ppb), North West (80.1 ppb) and Gauteng (74.7 ppb). However, the highest number of deaths attributable to ambient ozone exposure occurred in Gauteng and the Western Cape (Fig. 6).

However, when the population structure and underlying cause of death are taken into account, the age-standardised death and DALY rates due to ozone were highest in the Northern Cape and Western Cape (appendix Fig. S14). With COPD being the only cause of death attributable to ozone, the high age-standardised rates in these two provinces are likely due to the high YLL burden of COPD to the cause of death profile in these provinces.

Discussion

This article has shown that in 2012, almost 51 million South Africans (97%) were exposed to harmful concentrations of $PM_{2.5}$ above 10 μg/m^3, and 35 million (67%) were exposed to concentrations above the national standard of 20 μg/m^3. For ozone, we estimated that >49 million South Africans (93.8%) were exposed above the 61 ppb SA 8-hour standard during the 6-month high-ozone season. For 2000 and 2012, the $PM_{2.5}$ concentrations increased by 12%, from 26.6 μg/m^3 to 29.7 μg/m^3. During the same period, ozone levels increased significantly. This indicates a widespread problem with ambient air pollution in SA.

$PM_{2.5}$ is a serious challenge in Gauteng, the most densely populated province in SA, with various urban and industrial activities in and around the province responsible for both primary and secondary particulates. In addition to these local sources, the predominance of anticyclonic circulation and strong subsidence over southern Africa promotes adiabatic warming and produces a stable atmospheric thermodynamic structure (as discussed by Tyson and Gatebe[71]). These conditions strongly favour the formation of tropospheric stable layers over southern Africa (usually within an altitude range of 700 - 600 hPa).[72] The semiarid nature of Gauteng, the higher level of gaseous pollutant emissions that are precursors of secondary aerosols, along with the atmospheric stable layers of the region – all these circumstances together facilitate the formation of secondary $PM_{2.5}$. Furthermore, the regional stable layers play an important role in inhibiting the vertical diffusion of particulates: as a result, both primary and secondary $PM_{2.5}$ over most areas of Gauteng are accumulated in the lower parts of the troposphere.

In addition to the local emission factors and the background atmospheric conditions, the mesoscale dynamics of the region play an important role in influencing the spatial distribution of ozone. As a result of the southern African subtropical region predominant anticyclone surface air circulation, most of the anthropogenic plume that originates from highveld zones of Gauteng and Mpumalanga disperses towards the central and eastern parts of SA before exiting the country over the Indian Ocean.[72,73] This plume usually contains hydrocarbons and NO_x that are precursors of ozone. Hence beside the local precursor sources, the abovementioned dynamical conditions of the region, along with the enhanced air temperature and moist meteorological conditions of the coastal regions, aggregately become important contributing factors for enhanced presence of ozone in the eastern parts of the country.

Several other studies[19,74,75] have estimated the burden of disease due to ambient air pollution in SA. SACRA1 estimated the burden of disease attributable to urban outdoor air pollution in SA for the year 2000.[19] The study focused on urban areas, and included six metropolitan areas and the Vaal Triangle area, seven areas with a population of 15 million, 33% of the total 2000 SA population. SACRA1 estimated that outdoor air pollution caused 4 637 deaths. We report a much higher number of deaths (15 619 deaths) due to ambient $PM_{2.5}$ in 2000. The SACRA1 estimate was very conservative, because only 33% of the population in metro areas was assumed to be at risk. In the present study, we estimated that 71% of the SA population were exposed to ambient $PM_{2.5}$ in the year 2000 (i.e. 31 million people were exposed to $PM_{2.5}$). Also, our study included updated relative risks and additional disease outcomes, as evidence has emerged to support the causality of ambient air pollution in various diseases, such as LRIs in people of all ages, diabetes mellitus type 2, stroke and IHD. These factors largely explain why our current estimates are higher.

The State of Global Air[74] (using GBD 2019[3] estimates) estimated exposure to $PM_{2.5}$ using various sources. Their study ascribed 25 500 deaths to ambient $PM_{2.5}$ in SA in 2012, which is higher than the number we estimated (19 507 deaths). The difference between the two studies could be ascribed to the methods used. We used a regionally optimised, fully coupled regional climate chemistry modelling system, with modelled outputs calibrated against SAAQIS air quality monitoring data, whereas the State of Global Air uses satellite observations, a global chemical transport modelling system and a more limited dataset of ground observations than ours (for SA).[74] We used IER relative risk curves (from GBD 2017[48]), whereas the State of Global Air used relative risk curves from GBD 2019.[3] In terms of ambient ozone in SA, we estimated a much higher population-weighted ozone than the State of Global Air (72.1 ppb v. 38.8 ppb), which explains why we estimated more deaths due to ozone (1 734 v. 512 deaths).[74]

Another study applied the BenMAP model to conduct a health impact analysis due to $PM_{2.5}$ in SA. Altieri and Keen[75] used similar inputs to our study but different TMREL values, relative risks and mortality data. They estimated that 14 000 deaths could be avoided if SA met the existing standard for $PM_{2.5}$ exposure of 20 μg/m^3, and that another 14 000 deaths could be avoided if the WHO standard of 10 μg/m^3 was met. We estimated fewer deaths compared with their study (19 507 v. 28 000), which could be due to the different inputs and the way in which HAP was accounted for.

Strengths and limitations

Various studies have used different techniques to determine the burden of disease attributable to air pollution, all indicating that ambient air pollution is a challenge in SA. To our knowledge, the present study represents the first time that a regionally optimised fully coupled regional climate chemistry model, along with observational calibration, has been applied in conjunction with a burden of disease assessment for $PM_{2.5}$ and ozone for SA. Generally, in terms of estimating $PM_{2.5}$ and ozone concentrations, owing to the computational demands and complexity of atmospheric physicochemical processes, global scale models are implemented at coarse spatial resolutions.[76] On the other hand, fine-scale regional climate models are known to deploy sub-grid scale model physics, locally resolved dynamical information, spatio-temporally variable chemical/photochemical processes and other data. Hence, the regional numerical models are crucial in obtaining more realistic regional (small-scale) chemical and meteorological information at a higher resolution than global scale models.[76,77] Also, the use of locally driven population and health information are important for more realistic estimates of the disease burden attributable to ambient air pollution. Considering the aforementioned, relative to the GBD, which deploys the global scale model with a coarse resolution, and uses indirectly driven or globally approximated model forcing datasets and coarse-resolution population and health information estimates, the present study has the following advances: (*i*) it applies a regionally optimised fully coupled climate chemistry model along with locally informed model forcing datasets – this enabled us to capture more realistically the physicochemical processes of the region; (*ii*) even though the model adequately captured both the magnitude and spatiotemporal distributions of $PM_{2.5}$ and ozone, to further enhance the quality of modelled values and ensure their reliable applicability for regional exposure studies, bias corrections were performed using regionally obtained and quality-controlled surface observations; (*iii*) unlike the GBD, in terms of population statistics and health information, this study uses locally driven, higher resolution and quality-controlled information from Statistics SA and the national health department for each province of SA.

Compared with the highveld industrial zones of SA, the availability of ground measurement data for coupled model calibration in eastern coastal areas and the south-eastern industrialised regions is limited. Also, the number of ozone observations is generally smaller when compared with the PM monitoring stations. In contrast, the spatial coverage of ground measurements in the northern and eastern parts of the country (particularly over the highveld industrial zones) was much better. This provided the opportunity to generate optimally calibrated $PM_{2.5}$ and ozone values in highly industrialised and densely populated areas of SA. Overall, applying various screening and optimisation techniques, the study applies the best available information at the time. It is also recommended that future assessments could be strengthened through additional monitoring stations and more reliable monitoring data.

We used a previous iteration (GBD 2017[48]) of the IER relative risk curves and associated outcomes. The inclusion of the updated outcomes would likely have increased the attributable burden in our study. In GBD 2019,[3] the relative risk curves were updated with relevant studies at high $PM_{2.5}$ concentrations, studies on $PM_{2.5}$ due to smoking were excluded and meta-regression-Bayesian, regulated, trimmed spline fitting was used to generate risk curves. GBD 2019 also included low birthweight and short gestation as exposure outcomes due to $PM_{2.5}$, resulting in a 44% increase in DALYs compared with GBD 2017.[3] In addition, the IER relative risk curves are constructed using $PM_{2.5}$ from various different sources, and assume equitoxicity of particles, despite current evidence indicating that the source, size and chemical composition of particles impact health differentially.[48] The study is also limited by the assumption that the health effects of $PM_{2.5}$ and ozone are independent. Although this assumption is also made by other burden of disease studies,[48] the health risks due to $PM_{2.5}$ and ozone could be additive or multiplicative.

Conclusion

The burden of disease due to ambient air pollution, particularly due to $PM_{2.5}$, is large, especially when compared with other environmental risk factors such as HAP due to cooking with solid fuels. Research on the health risks associated with ambient air pollution continues to mount, showing that even low levels of exposure can have adverse health outcomes. Reducing the level of ambient air pollution to counterfactual levels in SA would reduce the burden of both non-communicable and infectious diseases.

It is vital that we sustain and amplify efforts to monitor and reduce ambient pollutant concentrations in the country. A comprehensive

system of monitoring stations measuring ambient air quality will provide important information in this effort. The urgent strengthening and enforcement of air-quality-related legislation is needed to reduce both the concentrations of pollutants and consequent burden of disease. In the longer term, the sources of pollution should be addressed: the combustion of fossil fuels for energy and transportation, the major source, should be phased out completely, and should be replaced with sustainable and clean energy sources, which do not produce emissions that are harmful to human health and the environment. Regionally, efforts should also be made to establish multi-country southern African co-operation to reduce air pollution.

Declaration. None.

Acknowledgements. We would like to acknowledge the SAAQIS for providing air quality observation datasets, Statistics SA for access to the population data, and the SA Centre for High Performance Computing for providing supercomputing facility. We would like to acknowledge Kate Causey for access to the data used for the IER curves. We would also like to thank Natashia Morris, Angie Mathee, Ali Dhansay, Pam Groenewald, Lyn Hanmer and Jané Joubert for their input. The survey review team, led by VPvW, conducted the risk of bias assessment of the national surveys. The following individuals are acknowledged for their contribution: DB, RR, OA, ET, Pam Groenewald, Andiswa Zitho, BN, Jané Joubert, Mmakamohelo Direko, Mweete Nglazi, Nomonde Gwebushe, Nomfuneko Sithole, AC, Linda Mbuthini, Lyn Hanmer, Akhona Ncinitwa, Nadine Nannan, Nada Abdelatif, Richard Matzopoulos, IN, Ali Dhansay and Ria Laubscher. The NBD team, led by VPvW, was responsible for mapping the NBD and GBD causes generating YLD and DALY estimates for national, provincial and population groups. The following individuals are acknowledged for their contribution: William Msemburi, OA, AC, IN, Tracy Glass, Pam Groenewald and DB.

Author contributions. Conceived and designed the study: RAR, EC, MT, KC, RP, DB, VPvW. Analysed the data: RAR, EC, MT, TK, NA, CO, KM, RP, DB, VPvW. Prepared data for analysis: RAR, EC, MT, NA, CO, KM, AC, JB, RP, DB, VPvW. Interrogated and interpreted results: RAR, EC, MT, TK, NA, IN, ET, OA, BN, RP, DB, VPvW. Drafted manuscript: RAR, EC, MT, TK, CW, RP, DB, VPvW. Senior authors: VPvW, DB, RP. All authors critically reviewed the manuscript for important intellectual content and agreed with the final version.

Funding. This research and the publication thereof were funded by the SA Medical Research Council's Flagships Awards Project (SAMRC-RFA-IFSP-01-2013/SA CRA 2).

Conflicts of interest. None.

1. Academy of Science of South Africa, Brazilian Academy of Sciences, et al. Air pollution and health – a science-policy initiative. Ann Glob Health 2019;85(1):140. https://doi.org/10.5334/aogh.2656
2. Owusu PA, Sarkodie SA. Global estimation of mortality, disability-adjusted life years and welfare cost from exposure to ambient air pollution. Sci Total Environ 2020;742:140636.
3. GBD 2019 Risk Factor Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990 - 2019: A systematic analysis for the Global Burden of Disease Study 2019. Lancet 2020;396(10258):1223-1249. https://doi.org/10.1016/S0140-6736(20)30752-2
4. Institute for Health Metrics and Evaluation. GBD compare. Seattle: IHME, University of Washington, 2015. http://vizhub.healthdata.org/gbd-compare (accessed 26 November 2021).
5. Orellano P, Reynoso J, Quaranta N, et al. Short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO^2), and ozone (O^3) and all-cause and cause-specific mortality: Systematic review and meta-analysis. Environ Int 2020;142:105876. https://doi.org/10.1016/j.envint.2020.105876
6. Farmer SA, Nelin TD, Falvo MJ, et al. Ambient and household air pollution: Complex triggers of disease. Am J Physiol Heart Circ Physiol 2014;307(4):H467-476. https://doi.org/10.1152/ajpheart.00235.2014
7. Seinfeld JH, Pandis SN. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. Hoboken, NJ: Wiley, 2016.
8. Molewa BEE. Highveld priority area air quality management plan. Government Gazette No. 35072, South Africa, 2012.
9. Department of Environmental Affairs, South Africa. The medium term review of the 2009 Vaal Triangle Priority Area: Air quality management plan final review report. n.d. https://saaqis.environment.gov.za/Pagesfiles/Final%20VTAPA%20Review%20Report_19-09-2013.pdf (accessed 18 August 2021).
10. Environment and Climate Change Canada. Air pollutant emission inventory report: 1990 - 2014. ECC, 2016. http://www.ec.gc.ca/Air/89ED82E9-CA92-424E-9FD1-C57235A04CE0/Air%20Pollutant%20Emission%20Inventory%20Report%201990-2014.pdf (accessed 18 August 2021).
11. Staehelin J. Ozone formation in the troposphere: Basic mechanisms and photooxidant air pollution. n.d. https://www.mao.kiev.ua/lao/presentation/staehelin_Ozone%20in%20Troposphere_Kiev%20SSch08.pdf (accessed 18 August 2021).
12. United States Environmental Protection Agency. Review of the National Ambient Air Quality Standards for ozone: Policy assessment of scientific and technical information. Triangle Park: USEPA Research, 2007. https://www3.epa.gov/ttn/naaqs/standards/ozone/data/2007_07_ozone_staff_paper.pdf (accessed 18 August 2021).
13. Morakinyo OM, Mokgobu MI, Mukhola MS, et al. Biological composition of respirable particulate matter in an industrial vicinity in South Africa. Int J Environ Res Public Health 2019;16(4):629. https://doi.org/10.3390/ijerph16040629
14. Mentz G, Robins TG, Batterman S, et al. Acute respiratory symptoms associated with short term fluctuations in ambient pollutants among schoolchildren in Durban, South Africa. Environ Pollut 2018;233:529-539. https://doi.org/10.1016/j.envpol.2017.10.108
15. Nkosi V, Wichmann J, Voyi K. Indoor and outdoor $PM(_{10})$ levels at schools located near mine dumps in Gauteng and North West Provinces, South Africa. BMC Public Health 2017;17(1):42. https://doi.org/10.1186/s12889-016-3950-8
16. Nkosi V, Wichmann J, Voyi K. Mine dumps, wheeze, asthma, and rhinoconjunctivitis among adolescents in South Africa: Any association? Int J Environ Health Res 2015;25(6):583-600. https://doi.org/10.1080/09603123.2014.989493
17. Naidoo RN, Robins TG, Batterman S, et al. Ambient pollution and respiratory outcomes among schoolchildren in Durban, South Africa. S Afr J Child Health 2013;7(4):127-134. https://doi.org/10.7196/sajch.598
18. Nkosi V, Wichmann J, Voyi K. Chronic respiratory disease among the elderly in South Africa: Any association with proximity to mine dumps? Environ Health 2015;14:33. https://doi.org/10.1186/s12940-015-0018-7
19. Norman R, Cairncross E, Witi J, et al. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000. S Afr Med J 2007;97(8):748-753.
20. Lu F, Xu D, Cheng Y, et al. Systematic review and meta-analysis of the adverse health effects of ambient $PM_{2.5}$ and PM_{10} pollution in the Chinese population. Environ Res 2015;136:196-204. https://doi.org/10.1016/j.envres.2014.06.029
21. Sturm R. Modelling the deposition of fine particulate matter ($PM_{2.5}$) in the human respiratory tract. AME Med J 2020;5:14. https://doi.org/10.21037/amj.2020.03.04
22. Gordon SB, Bruce NG, Grigg J, et al. Respiratory risks from household air pollution in low and middle income countries. Lancet Respir Med 2014;2(10):823-860. https://doi.org/10.1016/s2213-2600(14)70168-7
23. Dherani M, Pope D, Mascarenhas M, et al. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: A systematic review and meta-analysis. Bull World Health Org 2008;86:390-398. https://doi.org/10.2471/BLT.07.044529
24. Jary H, Simpson H, Havens D, et al. Household air pollution and acute lower respiratory infections in adults: A systematic review. PLoS ONE 2016;11(12):e0167656. https://doi.org/10.1371/journal.pone.0167656
25. Kurmi OP, Arya PH, Lam K-BH, et al. Lung cancer risk and solid fuel smoke exposure: A systematic review and meta-analysis. Eur Respir J 2012;40(5):1228-1237. https://doi.org/10.1183/09031936.00099511
26. Sood A, Assad NA, Barnes PJ, et al. ERS/ATS workshop report on respiratory health effects of household air pollution. Eur Respir J 2018;51(1):1700698. https://doi.org/10.1183/13993003.00698-2017
27. Fatmi Z, Coggon D. Coronary heart disease and household air pollution from use of solid fuel: A systematic review. Br Med Bull 2016;118(1):91-109. https://doi.org/10.1093/bmb/ldw015
28. Li Z, Tang Y, Song X, et al. Impact of ambient $PM_{2.5}$ on adverse birth outcome and potential molecular mechanism. Ecotoxicol Environ Saf 2019;169:248-254. https://doi.org/10.1016/j.ecoenv.2018.10.109
29. Sun X, Luo X, Zhao C, et al. The associations between birth weight and exposure to fine particulate matter ($PM_{2.5}$) and its chemical constituents during pregnancy: A meta-analysis. Environ Pollut 2016;211:38-47. https://doi.org/10.1016/j.envpol.2015.12.022
30. Nuvolone D, Petri D, Voller F. The effects of ozone on human health. Environ Sci Pollut Res 2018;25(9):8074-8088. https://doi.org/10.1007/s11356-017-9239-3
31. World Health Organization. WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: WHO, 2021. https://apps.who.int/iris/handle/10665/345329 (accessed 12 January 2022).
32. South Africa. National Environment Management: Air Quality Act No. 39 of 2004. https://www.gov.za/sites/default/files/gcis_document/201409/a39-04.pdf (accessed 12 January 2022).
33. Department of Environmental Affairs, South Africa. National ambient air quality standard for particulate matter with aerodynamic diameter less than 2.5 micron metres ($PM_{2.5}$). 2012. https://www.gov.za/sites/default/files/gcis_document/201409/35463gon486.pdf (accessed 12 January 2022).
34. Tshehla C, Wright CY. 15 years after the National Environmental Management Air Quality Act: Is legislation failing to reduce air pollution in South Africa? South Afr J Sci 2019;115(9-10):1-4. https://doi.org/10.17159/sajs.2019/6100
35. South Africa. National Environmental Management: Air Quality Act No. 39 of 2004. National ambient air quality standards. Government Gazette No. 32816:1210, 24 December 2009. https://www.environment.gov.za/sites/default/files/legislations/nemaqa_airquality_g32816gon1210_0.pdf (accessed 12 November 2020).
36. World Health Organization. WHO air quality guidelines: Global update 2005: Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. Geneva: WHO, 2006. http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf (accessed 25 November 2020).
37. Wright CY, Mathee A, Piketh S, et al. Global statement on air pollution and health: Opportunities for Africa. Ann Glob Health 2019;85(1):144. https://doi.org/10.5334/aogh.2667
38. Feig G, Garland RM, Naidoo S, et al. Assessment of changes in concentrations of selected criteria pollutants in the Vaal and Highveld priority areas. Clean Air J 2019;29(2):1-13. https://doi.org/10.17159/caj/2019/29/2.7464
39. Cairncross E. The state of South Africa's air quality monitoring network, and its air quality. Mbombela: National Association for Clean Air Conference, 2016.
40. Cairncross E, Dalvie A, Euripidou R, et al. Climate change, air pollution and health in South Africa. In: Akhtar R, Palagiano C, eds. Climate Change and Air Pollution: The Impact on Human Health in Developed and Developing Countries. Cham: Springer International Publishing, 2018:327-347.
41. Strambo C, Burton J, Atteridge A. The end of coal? Planning a 'just transition' in South Africa. SEI Report. Stockholm: Stockholm Environment Institute, 2019. http://www.sei.org/wp-content/uploads/2019/02/planning-a-just-transition-in-south-africa.pdf (accessed 18 July 2021).
42. Marais EA, Silvern RF, Vodonos A, et al. Air quality and health impact of future fossil fuel use for electricity generation and transport in Africa. Environ Sci Technol 2019;53(22):13524-13534. https://doi.org/10.1021/acs.est.9b04958
43. Department of Environmental Affairs and Tourism, South Africa. Notice of intention to establish the Vaal Triangle Air-shed Priority Area air quality management plan in terms of Section 19(1) of the National Environment Management: Air Quality Act, 2004 (Act No. 39 of 2004). Pretoria: DEAT, November 2008. https://www.environment.gov.za/sites/default/files/gazetted_notices/nemaqa_airqualityact_g31615gon1241_0.pdf (accessed 30 January 2022).

44. South Africa. National Environmental Management: Air Quality Act No. 39 of 2004. Highveld Priority Area Air Quality Management Plan. 2012. https://www.gov.za/sites/default/files/gcis_document/201409/35072144.pdf (accessed 18 August 2021).
45. Department of Environmental Affairs and Tourism, South Africa. Vaal Triangle Airshed Priority Area Air Quality Management Plan. May 2009. https://www.naca.org.za/uploads/28%20May%202009.pdf (accessed 18 August 2021).
46. Department of Environmental Affairs. The Waterberg-Bojanala Priority Area Air Quality Management Plan: Baseline characterisation. October 2014. https://saaqis.environment.gov.za/Pagesfiles/Annexure%20A1%20-%20Waterberg%20Bojanala%20Priority%20Area%20AQMP%20Baseline%20assessment_24-04-2015.pdf (accessed 18 August 2021).
47. Murray CJ, Ezzati M, Lopez AD, et al. Comparative quantification of health risks: Conceptual framework and methodological issues. Popul Health Metr 2003;1(1):1.
48. GBD 2017 Risk Factor Collaborators. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990 - 2017: A systematic analysis for the Global Burden of Disease Study 2017. Lancet 2018;392(10159):1923-1994. https://doi.org/10.1016/S0140-6736(18)32225-6
49. Roomaney RA, Wright CY, Cairncross E, et al. Estimating the burden of disease attributable to household air pollution from cooking with solid fuels in South Africa in 2000, 2006 and 2012. S Afr Med J 2022;112(8b):718-728. https://doi.org/10.7196/SAMJ.2022.v112i8b.16474
50. Zhang Y. Online-coupled meteorology and chemistry models: History, current status, and outlook. Atmospheric Chem Phys 2008;8(11):2895-2932. https://doi.org/10.5194/acp-8-2895-2008
51. Baklanov A, Schluenzen KH, Suppan P, et al. Online coupled regional meteorology-chemistry models in Europe: Current status and prospects. Atmospheric Chem Phys Disc 2013;13(5):12541-12724. https://doi.org/10.5194/acpd-13-12541-2013
52. Tesfaye M, Tsidu GM, Botai J, et al. Mineral dust aerosol distributions, its direct and semi-direct effects over South Africa based on regional climate model simulation. J Arid Environ 2015;114(2015):22-40. https://doi.org/10.1016/j.jaridenv.2014.11.002
53. Tummon F, Solmon F, Liousse C, et al. Simulation of the direct and semidirect aerosol effects on the southern Africa regional climate during the biomass burning season. J Geophysical Research 2010;115(D19206):1-20. https://doi.org/10.1029/2009jd013738
54. Tesfaye M, Botai J, Sivakumar V, et al. Evaluation of regional climatic model simulated aerosol optical properties over South Africa using ground-based and satellite observations. ISRN Atmospheric Sciences 2013;2013:1-17. https://doi.org/10.1155/2013/237483
55. Tesfaye M. Application of RegCM-CHEM4.5 for dust storm and air quality forecast over southern Africa. In: World Meteorological Organization. Training Materials and Best Practices for Chemical Weather/Air Quality Forecasting – ETR-26 2020. WMO, 2020:500-5005. https://etrp.wmo.int/mod/url/view.php?id=14527 (accessed 31 May 2021).
56. Maraun D. Bias correction, quantile mapping, and downscaling: Revisiting the inflation issue. J Climate 2013;26(6):2137-2143. https://doi.org/10.1175/jcli-d-12-00821.1
57. Teutschbein C, Seibert J. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. J Hydrology 2012;456-457:12-29. https://doi.org/10.1016/j.jhydrol.2012.05.052
58. Statistics South Africa. Census 2011. http://www.statssa.gov.za/?page_id=3839 (accessed 18 August 2021).
59. Reis S, Liška T, Vieno M, et al. The influence of residential and workday population mobility on exposure to air pollution in the UK. Environ Int 2018;121(Pt 1):803-813. https://doi.org/10.1016/j.envint.2018.10.005
60. World Health Organization. Exposure to air pollution (particulate matter) in outdoor air, Fact Sheet 3.3. Geneva: WHO, 2011. https://www.euro.who.int/__data/assets/pdf_file/0018/97002/ENHIS_Factsheet_3.3_July_2011.pdf (accessed 24 January 2021).
61. Shakor A, Su'ad A, Pahrol MA, et al. Effects of population weighting on PM_{10} concentration estimation. J Environ Public Health 2020;2020(1561823):1-20. https://doi.org/10.1155/2020/1561823
62. Thompson AM, Balashov NV, Witte J, et al. Tropospheric ozone increases over the southern Africa region: Bellwether for rapid growth in Southern Hemisphere pollution? Atmospheric Chem Phys 2014;(14):9855-9869. https://doi.org/10.5194/acp-14-9855-2014
63. Institute for Health Metrics and Evaluation, World Bank. The cost of air pollution: Strengthening the economic case for action. Washington, DC: World Bank, 2016. https://openknowledge.worldbank.org/bitstream/handle/10986/25013/108141.pdf (accessed 30 January 2022).
64. Burnett RT, Arden Pope C, Ezzati M, et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ Health Perspect 2014;122(4):397-403. https://doi.org/10.1289/ehp.1307049
65. Jerrett M, Burnett RT, Pope CAI, et al. Long-term ozone exposure and mortality. N Engl J Med 2009;360(11):1085-1095. https://doi.org/10.1056/NEJMoa0803894
66. Pillay-Van Wyk V, Msemburi W, Laubscher R, et al. Mortality trends and differentials in South Africa from 1997 to 2012: Second National Burden of Disease Study. Lancet Global Health 2016;4(9):e642-653. https://doi.org/10.1016/s2214-109x(16)30113-9
67. Bradshaw D, Pillay van Wyk V, et al. 2nd Comparative Risk Assessment for South Africa (SACRA2) highlights need to strengthen health promotion and surveillance. S Afr Med J 2022. (This issue)
68. Dorrington R. Alternative South African mid-year estimates, 2013. Cape Town: Centre for Actuarial Research, University of Cape Town, 2013. http://www.care.uct.ac.za/sites/default/files/image_tool/images/561/Downloads/Mono11.pdf (accessed 22 December 2020).
69. Ahmad OB, Boschi-Pinto C, Lopez AD, et al. Age standardisation of rates: A new WHO standard. Geneva: World Health Organization, 2001. https://www.who.int/healthinfo/paper31.pdf (accessed 22 December 2020).
70. Msemburi W, Pillay-van Wyk V, Dorrington RE, et al. Second national burden of disease study for South Africa: Cause-of-death profile for South Africa, 1997 - 2012. Cape Town: South African Medical Research Council, 2016. https://www.samrc.ac.za/sites/default/files/files/2016-12-08/SouthAfrica2012.pdf (accessed 22 December 2020).
71. Tyson P, Gatebe C. The atmosphere, aerosols, trace gases and biogeochemical change in southern Africa: A regional integration: START Regional Syntheses. South Afr J Sci 2001;97(3):106-118.
72. Tyson PD, Preston-Whyte RA. Weather and Climate of Southern Africa. Oxford: Oxford University Press, 2000.
73. Tesfaye M, Sivakumar V, Botai J, et al. Simulation of anthropogenic aerosols mass distributions and analysing their direct and semi-direct effects over South Africa using RegCM4. Int J Climatology 2015;35(12):3515-3539. https://doi.org/10.1002/joc.4225
74. Health Effects Institute. State of Global Air 2020. Data source: Global Burden of Disease Study 2019. Institute for Health Metrics and Evaluation, 2020. https://www.stateofglobalair.org/data/#/air/plot (accessed 19 January 2020)
75. Altieri KE, Keen SL. Public health benefits of reducing exposure to ambient fine particulate matter in South Africa. Sci Total Environ 2019;684:610-620. https://doi.org/10.1016/j.scitotenv.2019.05.355
76. Emmons LK, Walters S, Hess PG, et al. Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). Geoscientific Mod Dev 2010;3(1):43-67. 10.5194/gmd-3-43-2010
77. Denis B, Laprise R, Caya D, et al. Downscaling ability of one-way nested regional climate models: The Big-Brother Experiment. Climate Dynamics 2002;18(8):627-646. https://doi.org/10.1007/s00382-001-0201-0
78. Tesfaye M, Sivakumar V, Botai J, et al. Simulation of anthropogenic aerosols mass distributions and analysing their direct and semi-direct effects over South Africa using RegCM4. Int J Climatol 2015;35(12):3515-3539. https://doi.org/10.1002/joc.4225

Accepted 2 March 2022.