environmental affairs

Department:
Environmental Affairs
REPUBLIC OF SOUTH AFRICA

The Second Generation Vaal Triangle Airshed Priority Area Air Quality Management Plan: Draft Baseline Assessment Report

Abbreviations, Symbols, Units

Abbreviations	
AADT	Average annual daily traffic
AEL	Atmospheric emissions license
AIR	Air impact report
AQM	Air quality management
AQMP	Air quality monitoring plan
AQMS	Air quality monitoring stations
AQO	Air quality officer
ASTM	American Society for Testing and Materials
Cal-EPA	California Environmental Protection Agency
CAMx	Comprehensive Air Quality Model with Extensions
CDSM	Chief Directorate Surveys and Mapping
COJ	City of Johannesburg
DEA	Department of Environmental Affairs
DM	District Municipality
DMR	Department of Mineral Resources
DOE	Department of Energy
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
eNATIS	Electronic National Administration Traffic Information System
FAO	Food and Agricultural Organization of the United Nations
GAE	Global Energy Assessment
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies
GAUTRANS	Gauteng Department of Roads and Transport
GHG	Greenhouse gas(es)
HH	Household
HHRA	Human Health Risk Assessment
HQ	Hazard quotient
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
IPCC	Intergovernmental Panel on Climate Change
ITTs	Implementation Task Teams
LM	Local Municipality
LPG	Liquid Petroleum Gas
MEC	Member of the Executive Council
MSRG	Multi-Stakeholder Reference Group
MVEI	Motor Vehicle Emission inventory
NAAQS	National Ambient Air Quality Standards
NAEIS	National Atmospheric Emission Inventory System
NEM:AQA	National Environmental Management: Air Quality Act
NDCR	National Dust Control Regulations
NHTS	National Household Travel Survey
NOAA ARL	US National Oceanic and Atmospheric Administration Air Resources Laboratory
PFT	Plant functional type
PSC	Project Steering Committee
RCP	Representative Concentration Pathways
RDP	Reconstruction and Development Programme (in reference to housing programmes)
SAL	Small area level
SANRAL	South African National Roads Agency Limited
SP	Sub-place
SARCAMM	South African Road Classification and Access Management Manual

TSF	Tailing storage facility
TAZ	Travel Analysis Zone
US EPA	United States Environmental Protection Agency
VKT	Vehicle kilometres travelled
VTAPA	Vaal Triangle Airshed Priority Area
WHO	World Health Organization
WLTP	World Harmonised Light Duty Vehicle Test Procedure
WRF	Weather Research and Forecasting Model
Symbols	
BVOC	Biogenic volatile organic compounds
CO	Carbon monoxide
C_6H_6	Methane
NMVOC	Non-methane volatile organic compounds
NO_X	Oxides of nitrogen
NO_2	Nitrogen dioxide
NH_3	Ammonia
O_3	Ozone
Pb	Lead
PM	Particulate matter
$PM_{2.5}$	Inhalable particulate matter (aerodynamic diameter less than 2.5 µm)
PM_{10}	Thoracic particulate matter (aerodynamic diameter less than 10 µm)
SO_2	Sulfur dioxide
VOC	Volatile organic compounds
Units	
°C	Degree Celsius
g	Gram(s)
g/m^2	Grams per square metre
g/s	Grams per second
$g/s.m^2$	Grams per second per square metre
kg	Kilograms
kg/day	Kilograms per day
km	Kilometre
kPa	Kilopascal
K	Temperature in Kelvin
1 kilogram	1 000 grams
m	Metre
m/s	Metres per second
mamsl	Metres above mean sea level
µg	Microgram(s)
$\mu g/m^3$	Micrograms per cubic metre
m^2	Square metre
m^3	Cubic metre
m^3/hr	Cubic metre per hour
$mg/m^2.day$	Milligram per square metre per day
mg/Nm^3	Milligram per normal cubic metre (normalised at 273 K; 101.3 kpa)
MW	Mega Watt
ppm	Parts per million
t/a	Tonnes per annum

Executive Summary

The Vaal Triangle Airshed was declared a priority area in April 2006 (Government Gazette Notice No. 365 of 21 April 2006, as amended by Notice 711 of 17 August 2007) and was the first Air Quality Priority Area in South Africa due to concern for elevated pollutant concentrations within the area, specifically particulates. A medium-term review was conducted in 2013. The objective of the second generation AQMP (Air quality management plan) is to characterise the baseline after seven years and determine the improvement, if any, that resulted from the implementation of the 2009 AQMP. This second generation AQMP aims to establish new strategies and intervention plans, based on a better understanding of the cause and effect relationships that will ensure further improvement and eventual compliance within the area.

Baseline characterisation is needed to assess compliance with ambient air quality standards and subsequently understand the potential risk to human health and environmental degradation. The baseline characterisation provides the foundation for the development of the AQMP; informing the detailed strategies and interventions of the set clean air objectives within a specific timeframe.

A background assessment, evaluation of ambient air quality in the VTAPA, an emission inventory representing the year 2017 and associated dispersion modelling results are covered in the baseline assessment report. The assessment provided a good understanding of the current state of air quality within the VTAPA and to some extent, the source contributions to the ambient pollution levels. The source apportionment results, currently being conducted, will provide the link between source and receptor to allow for the identification of desired intervention strategies.

Background Assessment

The background assessment used existing information to assess the current state of air in the VTAPA, as well as to understand the geographical context of the priority area; the drivers of air quality; and how the air quality has changed since the 2009 AQMP and 2013 medium term review.

The current study made use of the 2011 Census data and the 2016 Community Survey statistics, where the 2009 VTAPA AQMP study made use of the 2001 Census data. In 2001 the population was reported to be 2 532 362, increasing to 2 848 140 in 2011 and by a further 10% in 2016 (3 127 907).

Emission Inventory

The emission inventory for VTAPA assessed available emissions data, quantified fugitive emission sources, and identified gaps in the emission inventory. Two emission inventories were developed: one for the VTAPA and one as a regional emission inventory. The focus of the emission inventory was on criteria pollutants, especially for the industrial sources. The VTAPA emission inventory was used for management purposes, and the regional emission inventory was used for dispersion modelling.

Emissions were quantified for all main sources within the VTAPA, as well as sources from the surrounding areas to form input into air quality modelling. The emission inventory reported on here is for the sources within the VTAPA. These include:

- ***Industrial Sources***: sources of air pollutants represent mostly stationary facilities operating under licenses or registration, of which the emissions are reported to the authorities annually (Section 21 and Section 23 sources). A total of 452 individual point sources were identified, across 117 facilities in the VTAPA, mostly in the Emfuleni Local Municipality, of which 40 facilities operate listed activities under Section 21 of NEM: AQA and 48 individual point sources are classified as Section 23 Controlled Emitters. Data reported on in NAEIS for the 2017 calendar year was used.

- ***Mining Sources***: including opencast and underground mines and quarries. Two opencast mines (one dolomite and one coal) and one underground coal mine were identified. Activity data reported on in NAEIS for the calendar year 2017 was used.
- ***Mobile Sources***: accounting for vehicles traveling on arterial- and main roads, national freeway, secondary roads, slipways, off- and on ramps and streets. Use was made of SANRAL national counts for 2016 and GAUTRANS Gauteng Manual counts for 2015. A top-down and bottom-up approach was followed.
- ***Domestic Fuel Burning***: fuel combustion for energy use in the domestic environment in VTAPA. Both a top-down (for gas, paraffin and coal) and bottom-up (for wood) approach was used for domestic fuel use emissions. Community Survey 2016 and Census 2011 data were used to proportionally disaggregate national fuel consumption to provincial and then SAL geographic units.
- ***Waste***: open burning in residential areas was quantified based on available information (no information was available on landfills and waste water treatment facilities to quantify these emissions).
- ***Windblown Dust***: from mine waste facilities, product stockpiles, as well as ash storage facilities for large combustion sources. Windblown dust from denuded areas was not included.
- ***Biogenic VOC Emission***: plants emitting numerous VOC compounds, primarily isoprene, due to stress responses were included due to the important role of the VOCs in the atmospheric chemistry.
- ***Biomass Burning***: large scale agricultural burning and natural fires. FINN data was extracted for the year 2016 and processed, with erroneous fires due to surface coal mines removed.
- ***Airfields:*** there are no major commercial airports within the VTAPA and the occasional use of airstrips in the area was not regarded to result in significant emissions.
- ***Agriculture***: including mainly for its contribution to ammonia emissions used in the dispersion model.

Based on the quantified emissions, industrial sources were the main contributors of SO_2 (99.8%) and NOx (93%) emissions within the VTAPA. Mobile sources were the only other significant contributors to NOx emissions at 7%. Total PM_{10} emissions were mainly a result of mining operations (49%) followed by industrial sources (31%), with windblown dust the third most significant contributing source group at 16%. For the sources for which $PM_{2.5}$ emissions were reported and/or quantified, mining was the main contributing source (39%) followed by windblown dust (33%) and domestic fuel burning (17%). CO emissions were a result of domestic fuel burning (28%), mobile sources (27%), biomass burning (26%) and industrial sources (19%). Biogenic VOC emissions were unsurprisingly the main contributor to NMVOC emissions followed by biomass burning. Ammonia (NH_3) emission sources were mainly (soil) biogenic, with contributions from agriculture (87%) and to a lesser extent mobile sources (11%).

Compared to the 2009 and 2013 medium-term review inventories, the total emissions within the VTAPA remained similar for SO_2 but reduced significantly for NOx. This is primarily a result of lower estimated mobile source emissions and domestic fuel burning emissions. PM_{10} emissions increased from the 2009 and 2013 inventories mainly due to the high PM_{10} emissions reported for the opencast coal mine, but also likely due to more sources included in this inventory. Industrial PM_{10} emissions reduced from the 2009 VTAPA, and even though the cause of this reduction is not clear, it could be an actual reduction in industrial PM_{10} emissions since the 2017 emission inventory is regarded more comprehensive than the one for 2009.

Ambient Air Quality Assessment

The ambient air quality assessment made use of available ambient air quality data from SAAQIS (South African Air Quality Information System), from District Municipalities and from industries. The DEA operates six ambient monitoring stations within the VTAPA, located at Diepkloof, Sharpeville, Three Rivers, Zamdela, Kliprivier and Sebokeng. These stations record meteorological parameters and ambient air quality concentrations for SO_2, NOx, PM_{10} and $PM_{2.5}$. Data was obtained from these stations for the period 2013-2015 to determine dispersion conditions and for the period 2007-2016 to assess ambient air quality trends. In addition, data from the three Sasol ambient monitoring stations was obtained for the same period as well as from the Eskom station and the four ArcelorMittal stations. The Sedibeng DM stations were not included since data were only available for one year (2017).

The main findings were:

- There was some variability in wind fields across the VTAPA monitoring stations, however a predominance of wind from the north-easterly and north-westerly sectors was evident at all stations, with possible exception of Eco Park, where a south-easterly flow was dominant. Winds exceeding 4 m/s were more frequently recorded at Sharpeville, Leitrim, and Eco Park. The Leitrim station recorded the least calm conditions (6%), while calm periods were most frequent at the AJ Jacobs station (30%).
- Long term trends, from 2007 to 2016, in SO_2 concentrations showed compliance with the NAAQSs at most of the stations for most of the time. Trends in SO_2 concentrations over the 10 years showed small decreases at Diepkloof, Zamdela, Randwater and Eco Park but slight increases over time at Kliprivier, Three Rivers and AJ Jacobs. Concentrations at Sebokeng, Sharpeville and Leitrim showed more annual variability and no distinct long-term trends.
- Annual average NO_2 concentrations were non-compliant with the NAAQSs at Diepkloof (all the years except 2011), Kliprivier (2009 and 2010), Sebokeng (2015) and Sharpeville (2015). Hourly NO_2 concentrations were also non-compliant with NAAQS at Sebokeng in 2015, with the lowest concentrations recorded at the Randwater station. Monthly NO_2 concentrations have decreased slightly at the Leitrim station, while concentrations have increased at Diepkloof; Three Rivers; Zamdela; and AJ Jacobs stations. At the other stations ambient NO_2 concentrations remained the same.
- PM_{10} concentrations were in exceedance of the NAAQS at most of the stations for most of the years assessed except at Eco Park where annual PM_{10} has been compliant with NAAQS since establishment of the station. The highest concentrations were recorded at Zamdela.
- Annual average $PM_{2.5}$ concentrations were in non-compliance with NAAQS, for most of the period assessed, except for AJ Jacobs where no annual exceedances were noted between 2014 and 2016. AJ Jacobs and Three Rivers had the lowest annual average concentrations whereas Leitrim, Sharpeville, Kliprivier, and Sebokeng had the highest. Annual average concentrations seem to have decreased at Diepkloof and Sebokeng but monthly average $PM_{2.5}$ concentrations did not show substantive improvements with slight increases at Kliprivier, Sharpeville, Zamdela and AJ Jacobs stations.

Dispersion Modelling and Scenario Assessment

The CAMx chemical air quality model was used to simulate ambient air quality concentrations over the VTAPA, including background sources outside the VTAPA boundary. The model also allows for primary and secondary pollutant tracking. The same modelling domain was used as for the 2009 VTAPA AQMP, including the topographical data with an update on the land-use data including all air quality sensitive receptors within the study area.

NO_2

- The modelling results generally provided a good comparison to the measured values.
- The model under-estimated at Diepkloof (Ben Naude Street traffic) as the model did not capture micro-scale emissions activity on roads around the monitoring station.
- It over-estimated at AJ Jacobs due to enhanced turbulence leading to Lethabo power-station and Sasol Sasolburg plumes impacting ground level concentrations.
- The best performance was at Eco Park.
- Higher concentrations were modelled around Sasolburg and south CoJ, with exceedance of the annual average NAAQS near Sasolburg.

O_3

- Generally, the modelled results indicted a good comparison to the measured values.
- The evening simulated concentrations were higher than the observed.
- Peak day-time modelled concentrations resulted in a very slight under-estimation.
- The simulated 8hr 99th percentile concentrations showed widespread exceedances (note that this averaging period may be seen as a maximum).
- There was a zone of titration around Sasolburg where the concentrations were lower.

SO_2

- The model showed overall moderate performance with over-estimated SO_2 concentrations compared to measured results due to over-estimated wind speed – tall stack impacts tend to dominate due to enhanced turbulence.
- General exceedances of the NAAQS around Lethabo power station and Sasolburg were modelled.
- Simulation results showed exceedances around point sources; and not near air quality monitoring stations.

PM_{10}

- PM_{10} concentrations were in general under-estimated compared to measured concentrations, primarily due to the potential impact of much localized sources near stations.
- High exceedances of the NAAQS (for both 24hr and annual averages) were still simulated around industrial facilities, mines and the old tailings areas in CoJ.
- Lower exceedances of the NAAQS were located around high emitting residential fuel combustion areas.

$PM_{2.5}$

- The model showed reasonable performance even though $PM_{2.5}$ concentrations were in general under-estimated in comparison to measured results.
- Exceedances over most of VTAPA were simulated even with the under-estimation.
- Long term averages showed areas of impact around mines, tailings facilities and areas of heavy domestic fuel combustion.
- Model simulations did not reflect the annual exceedances recorded at Sebokeng and Three Rivers.
- The model did not simulate late evening and early morning peaks – this may be related to the over-estimate in wind speed.

Model simulations indicated widespread exceedances of O_3 and PM over the majority of the VTAPA.

Source tracking was done for industry sources within and outside the VTAPA. PM_{10} impacts within VTAPA were primarily due to industries within VTAPA. There is a regional aspect to O_3 formation when related to the precursor contributing sources and for the VTAPA there was a mixed contribution from local industry and those outside, but the outside sources seem to play a larger role in O_3 formation within the VTAPA.

VTAPA Health Study

A baseline health assessment study was conducted in the VTAPA during 2013 and 2014. The study comprised of a community survey in four communities and a child respiratory health study (including lung function tests) in four schools within the community study areas, as well as an assessment of human health risks resulting from exposure to air pollution.

The main findings of the study may be summarised as follows:

- Ambient concentrations measured at DEA/SAWS stations in 2013 indicated no risk from SO_2 but indicated risk from NO_2 in Zamdela. PM_{10} was found to be a concern with highest concentrations of PM_{10} recorded in Sharpeville during 2013.
- From the community survey, risk factors for respiratory illnesses were mostly associated with energy use (coal for cooking and paraffin for heating), overcrowding and hygiene practices (burning or burying of refuse or failure to regularly remove refuse) as well as lifestyle (active and passive smoking and alcohol use).
- The main conditions affecting vulnerability of areas to the effects of air pollution involved socio-economic conditions and energy use. The main vulnerable areas were north of the Sebokeng and Sharpeville monitoring stations and south-east of the Zamdela monitoring station.
- Although the socio-economic conditions and exposure at the schools were similar, the odds of having chronic symptoms (such as cough, wheeze and phlegm and asthma) were significantly higher at the school in Sharpeville.

There is reason for concern that air pollution in the VTAPA may be affecting child health.

VTAPA Source Apportionment Study

Preliminary findings indicated that PM_{10} and $PM_{2.5}$ concentrations were higher in the winter at sampling sites compared to summer. Preliminary XRF analyses of the summer samples showed inorganic content from crustal and anthropogenic activities.

Way forward

The VTAPA Source Apportionment study is currently being conducted with results expected by the end of February 2019. These results, as indicated, will be integrated into the baseline assessment to inform the cause and effect relationship.

In parallel to the Source Apportionment study, the GAINS model will be run for a set of intervention scenarios. These scenarios are based on the same emission inventory used in this study. Up to three scenarios were selected for each source group. These results are also expected to be available by the end of February 2019. The aim with the GAINS model intervention scenarios is that it will provide an indication of the expected air quality improvement associated with a specific intervention, as well as the cost benefit thereof. These selected interventions will then be modelled using the VTAPA CAMx model.

The strategy analysis will be conducted during a workshop once the preferred interventions have been identified. The outcome will be action plans for implementation within a set timeframe.

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1 INTRODUCTION

The Vaal Triangle Airshed was declared a priority area in April 2006 (Government Gazette Notice No. 365 of 21 April 2006, as amended by Notice 711 of 17 August 2007) by the then Minister of Environmental Affairs and Tourism and was the first Air Quality Priority Area in South Africa due to concern for elevated pollutant concentrations within the area, specifically particulates (Figure 1-1). An Air Quality Management Plan (AQMP), providing detailed intervention strategies, was developed for the Vaal Triangle Priority area between 2007 and 2009, with the final plan published on 29 May 2009 (Government Gazette No. 32254). In 2013, the AQMP was reviewed with the objective to establish an updated understanding of the air quality status in the Vaal Triangle Airshed Priority (VTAPA) Area and to inform strategies that will ensure improvement in air quality in the area. The aim of the second generation AQMP is to characterise the baseline after seven years and determine the improvement, if any that resulted from the implementation of the 2009 AQMP. This second generation AQMP aims to establish new strategies and intervention plans, based on a better understanding of the cause and effect relationships, that will ensure further improvement and eventual compliance within the area,

The Vaal Triangle Airshed Priority Area encompasses: a portion of the City of Johannesburg Municipality, as well as Emfuleni, Midvaal, and Metsimaholo Local municipalities (Figure1-2).

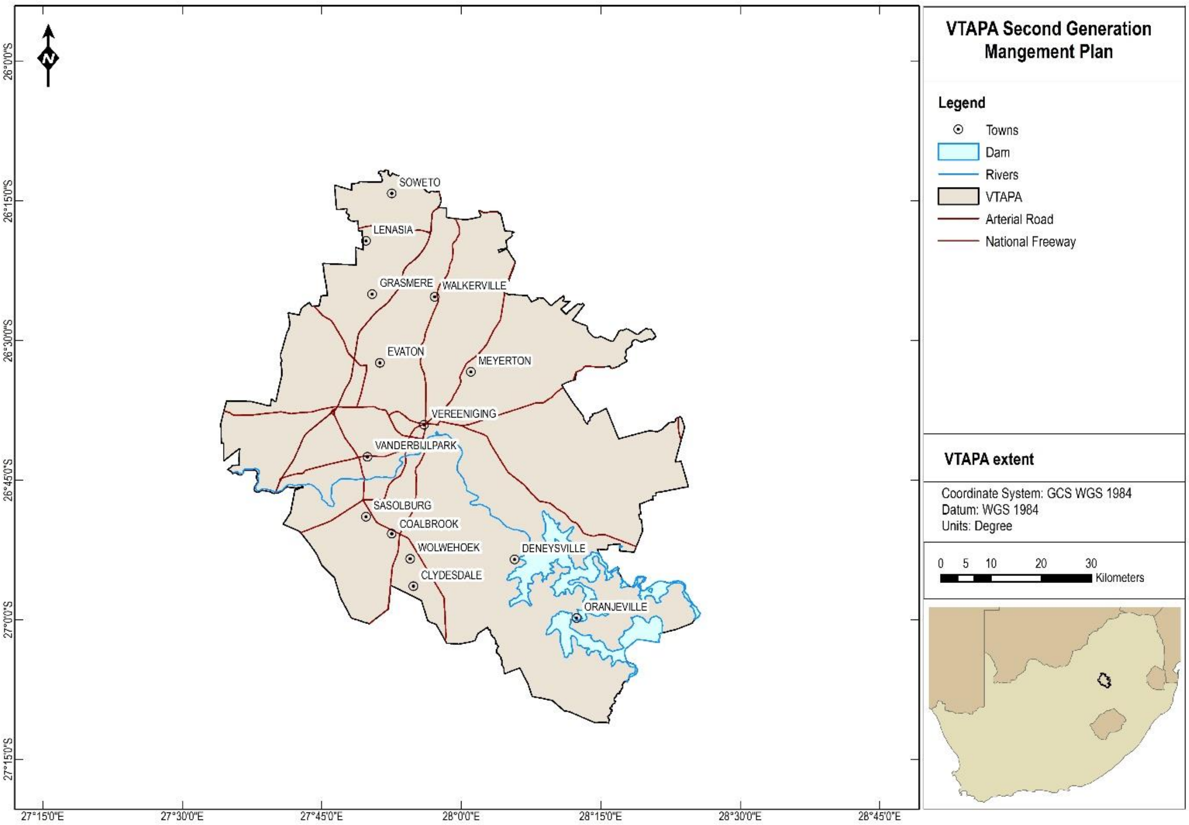


Figure 1-1: Demarcation of the Vaal Triangle Air-shed Priority Area

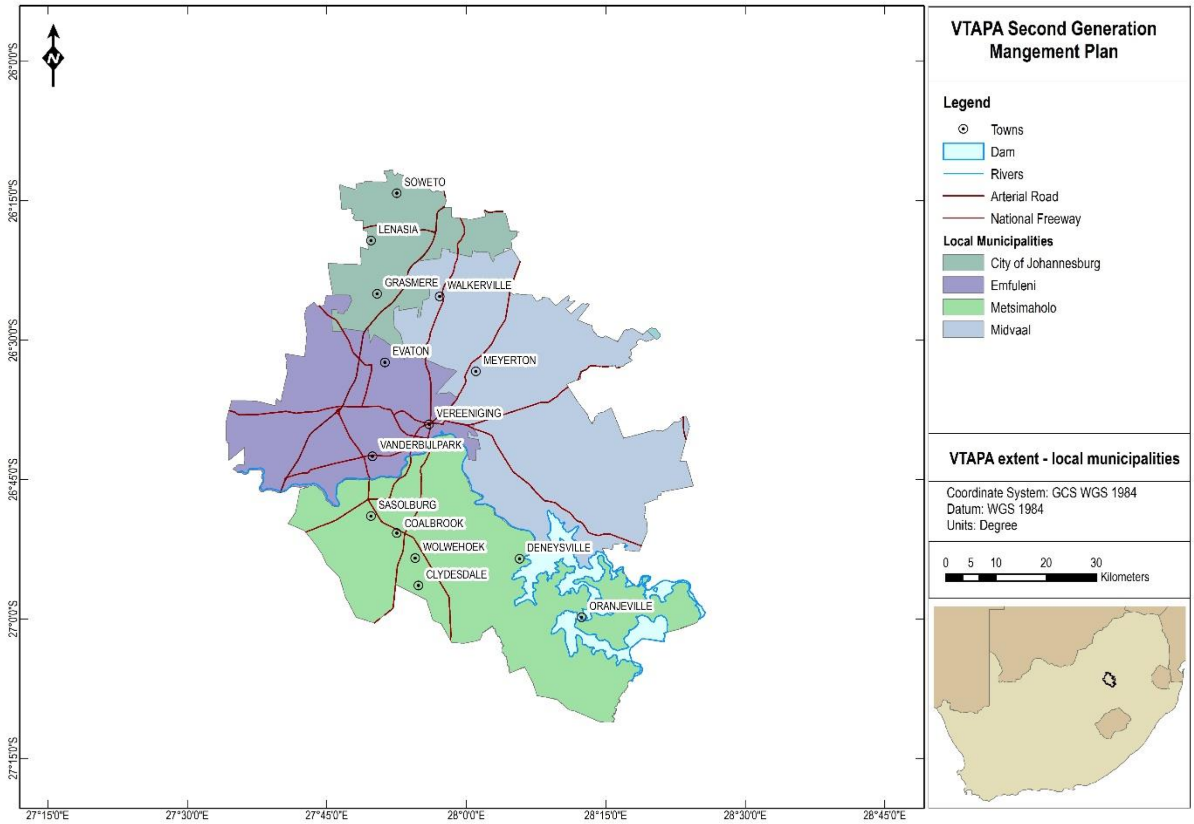


Figure 1-2: Local, District, and Metropolitan Municipalities included in the VTAPA

1.1 Output B: Baseline Assessment Report

The baseline characterisation is needed to assess compliance with ambient air quality standards and subsequently understand the potential risk to human health and environmental degradation. The baseline characterisation provides the foundation for the development of the AQMP; informing the detailed strategies and interventions of the set clean air objectives within a specific timeframe. It also provides the basis for emission reduction strategy assessment and to determine the implications of reduction measures.

In the process of developing an AQMP that can assist in effectively managing air quality in the Priority Area, the project looked at what has already been done, evaluated the current situation and assessed what is needed going forward. The project also assessed and made comparisons between the (i) current situation, (ii) 2013 situation (medium term review) and (iii) 2009 situation (2009 AQMP) to provide a narrative of circumstances that may have led to changes in air quality.

1.1.1 Activity B1: Background Assessment

The background assessment used existing information to assess the current state of air in VTAPA, as well as to understand the geographical context of the priority area; the drivers of air quality; and how the air quality has changed since the 2009 AQMP and 2013 medium term review. The tasks in Activity B1, the approach followed and the sections of the report where these are addressed are provide in Table 1-1.

Table 1-1: Tasks in Activity B1

Task	Deliverable	Approach, Assumptions and Limitations	Reported in:
i	Describing the **geographic background** of the area (topography, land use, etc.);	Map showing the terrain elevation, the geographical extent and populated areas	Section 3
ii	Describing of **meteorology** and climate of the area	Meteorological data from the DEA air quality monitoring stations in the VTAPA was obtained for the period 2013-2015/6	Section 4
iiii	Summarising the **population statistics** of the area	Description of the population according to the 2001 and 2011 Census data as well as the 2016 Community Survey	Section 3
iv	Describing **sources** of air pollution	All main pollution sources were identified, and the associated emissions quantified. Source identification and quantification were limited by available information. Sources not included are: vehicle entrained dust from unpaved roads (especially within residential areas), windblown dust from denuded areas, agricultural activities and airports. Waste burning was limited to informal waste burning within residential areas. The emission inventory capture sources within the VTAPA as well as regional sources. Ammonia emissions were also included.	Section 5.1
v	Clearly describing the **current ambient air quality** in the area and compare this to NAAQS	Ambient air quality data was obtained from the DEA monitoring stations within the VTAPA, as well as from District Municipality and Industry stations. Data reported on range within the period 2007 to 2017. The ambient pollutant concentrations were evaluated against the NAAQSs (reported on in Section 2.2)	Section 5.2
vi	Describing the **cause and effect relationships** that give rise to the significant sources of air pollution	Initial cause and effect relationships were taken from the 2009 VTAPA AQMP and the 2013 medium-term review. These two studies identified the main sources of concern within the VTAPA and these then formed the basis for emissions quantification and dispersion modelling. Air quality model simulations provided the link between the source of emission and the receiving environment.	Section 5
vii	Providing details on any **future threats** to air quality in the area	Current and future threats were informed by the findings from the baseline modelling results and from other studies conducted such as the VTAPA 2013 Health Study. These threats will further be informed by the VTAPA Source Apportionment study currently being undertaken	Section 5.4 Section 5.5
viii	Identifying and reviewing recent and current **air quality studies** in the study area	The VTAPA 2013 Health Study was reviewed as well as the VTAPA Source Apportionment Study currently being undertaken. The results from the Source Apportionment study will be incorporated into the baseline report as soon as it becomes available.	Section 5.4 Section 5.5
ix	Summarising **available capacities** in the different spheres of government	Available government capacities are briefly listed. These capacities and who will be responsible for what, will be identified once the intervention strategies and implementation requirements are known.	Section 2.9
x	Listing structures that are available to encourage **participatory governance and stakeholder engagements**	The current platforms for participatory governance and stakeholder engagement are listed.	Section 2.9

1.1.2 Activity B2: Emission inventory

The emission inventory for VTAPA assessed available emissions data, quantified fugitive emission sources, and identified gaps in the emission inventory. Two emission inventories have been developed: one for the VTAPA and one as a regional emission inventory. The focus of the emission inventory is on criteria pollutants, especially for the industrial sources. The VTAPA emission inventory is used for management purposes, and the regional emission inventory is used for dispersion modelling.

The tasks in Activity B2 included:

i. assessing of the number and types of industries within each of the municipalities;
ii. assessing the typical air pollutants emitted from these industries to ensure all criteria and Listed Activity pollutants are included;
iii. identify all existing mining operations and include emissions in the inventory;
iv. quantify domestic fuel burning based on recent statistical information;
v. identify and quantify other significant fugitive sources such as large tailings storage facilities prone to wind erosion (even though these fall under mining, it was assessed separately);
vi. assess data available for mobile sources, e.g. traffic flows and vehicle fleet composition, and verify against the national vehicle emission inventory;
vii. identify, and where possible quantify, waste treatment and disposal facilities;
viii. assess the degree of greenhouse gas emission data contained in the existing emission inventories;
ix. identify gaps even after update and revision and rank the significance of these gaps in order of importance.

Activity B2 is covered under Section 5.1 of the report, with a summary provided in Section 6.3.

1.1.3 Activity B3: Ambient Air Quality Assessment

This assessment was based on available ambient air quality data from SAAQIS, industries where possible, and any additional data from the on-going Source Apportionment Study.

The tasks in Activity B3 included:

i. assessment of the state of ambient air quality across the VTAPA in comparison to national standards and highlighting the compliance level of the VTAPA with NAAQS.
ii. assessment of the state of air quality in relation to sources, as well as in relation to changing sources over time – the source apportionment study is to provide key information on the contribution of different sources to areas across VTAPA.
iii. analyze trends in the air quality data from 2009 until present.
iv. identify Information and data gaps.

Activity B3 is covered under Section 5.2 with the summary of the findings under Section 6.3.

1.1.4 Activity B4: Dispersion Modelling and Scenario Assessment

A representative dispersion model, the CAMx chemical air quality model, was used to simulate ambient air quality concentrations over the VTAPA, including background sources outside the VTAPA boundary. The model also allows for primary and secondary pollutant tracking. The same modelling domain was used as for the 2009 VTAPA AQMP, including the topographical data with an update on the land-use data including all air quality sensitive receptors within the study area.

The air quality modelling methodology and results are provided in Section 5.3 and the main findings provided under Section 6.4.

1.2 Report Outline

This report sets out to provide information on the current situation by addressing the following aspects:

- current legislation with respect to ambient air quality standards;
- the geography and demographics of the province;
- the regional climate and atmospheric dispersion potential;
- a baseline characterisation of the emission sources and ambient air quality monitoring;
- air quality model simulations and model results validation;
- a summary of the VTAPA 2013 Health Study;
- a summary of the status of the VTAPA Source Apportionment Study, and
- main findings and way forward.

2 LEGISLATION AND REGULATORY REQUIREMENTS

The National Environmental Management: Air Quality Act (hereafter "the Act" or NEM: AQA) (Act No. 39 of 2004) commenced on the 11th of September 2005 and replaced the previous repealed Air Pollution Prevention Act of 1965. The National Framework (initially published under Notice No. 30284 of 11 September 2007 in terms of section 7 of NEM: AQA, updated in 2013 (Notice No. 36161 of 13 February 2013) and again in 2018 (Notice No. 41650 of 25 May 2018) is the underpinning document to NEM: AQA, providing national norms and standards and policies and procedures for air quality management to ensure compliance.

The Act is very specific to what an air quality management plan must achieve. These include improvement of air quality; reducing negative impacts on human health and the environment; addressing the effects of fossil fuels in residential applications; addressing the effects of emissions from industrial sources and from any point or non-point sources of air pollution; implementing the Republic's obligations in respect of international agreements; and giving effect to best practice in air quality management. The Act also provides for regulations that may be made for implementing and enforcing approved priority area AQMPs including, amongst others, funding arrangements; measures to facilitate compliance and regular review.

The NEM: AQA also makes provision for the declaration of controlled fuels and vehicles as controlled emitters, regulating dust and noise pollution and the development of municipal by-laws to regulate air pollution within the area of the municipality's jurisdiction.

The sections below summarise the legal and regulatory requirements based on current legislation.

2.1 National Environmental Management: Air Quality Act (Act No.39) of 2004

The Act makes provision for the declaration and setting of standards for controlled emitters and controlled fuels. The Act stipulates under Section 4:

- Controlled emitters (declaration of any appliance or activity as a controlled emitter) – The Minister or Member of the Executive Council (MEC) may declare any appliance or activity. It must follow a consultative process and must establish emission standards and prescribe monitoring methods. This should consider sound scientific information and health risk assessments. More information is provided in Section 2.1.4 below.
- Controlled fuels (declaration of fuels used in a combustion process as a controlled fuel) – The Minister or MEC may declare controlled fuels. This must follow a consultative process and may establish standards for use, manufacture, sale, or composition. This should consider sound scientific information and health risk assessments. No fuels have been declared controlled fuels to date.
- Control of dust, noise and offensive odours – The Minister or MEC may prescribe measured to control dust and/or noise. More information on the National Dust Control Regulations is provided in Section 2.1.2 below.

The Department of Environmental Affairs (DEA) Manual for Air Quality Management Planning (2008) recommends that, in addition to the NEM: AQA, the following legislation be consulted in the goal setting processes of developing an AQMP:

- The Constitution of the Republic of South Africa, 1996
- National Environmental Management Act (No. 107 of 1998)
- National Health Act 61 of 2003
- Municipal Structure Act 117 of 1998 –Powers of (Executive) Mayors
- Municipal Systems Act 32 of 2000
- The National Framework for Air Quality Management in the Republic of South Africa as published in terms of Section 7 of NEM:AQA

2.1.1 National Ambient Air Quality Standards

Air quality guidelines and standards are fundamental to effective air quality management, providing the link between the source of atmospheric emissions and the user of that air at the downstream receptor site. The ambient air quality standards and guideline values indicate safe daily exposure levels for most of the population, including the very young and the elderly, throughout an individual's lifetime.

National Ambient Air Quality Standards (NAAQS) were determined based on international best practice for criteria pollutants that are most commonly found in the atmosphere and have proven detrimental health effects when inhaled (Table 2-1). The final revised NAAQS for criteria pollutants were published on 24 December 2009 (Government Gazette No. 32816) and 29 June 2012 (Government Gazette No. 35463).

Table 2-1: South African National Ambient Air Quality Standards

Substance	Molecular formula / notation	Averaging period	Concentration limit (µg m^{-3})	Frequency of exceedance[(a)]	Compliance date[(b)]
Sulfur dioxide	SO_2	10 minutes	500	526	Currently enforceable
		1 hour	350	88	Currently enforceable
		24 hours	125	4	Currently enforceable
		1 year	50	-	Currently enforceable
Nitrogen dioxide	NO_2	1 hour	200	88	Currently enforceable
		1 year	40	-	Currently enforceable
Particulate matter	PM_{10}	24 hours	75	4	Currently enforceable
		1 year	40	-	Currently enforceable
Fine particulate matter	$PM_{2.5}$	24 hours	40	4	1 Jan 2016 – 31 Dec 2029
			25		1 Jan 2030
		1 year	20	-	1 Jan 2016 – 31 Dec 2029
			15		1 Jan 2030
Ozone	O_3	8 hours (running)	120	11	Currently enforceable
Benzene	C_6H_6	1 year	5	-	Currently enforceable
Lead	Pb	1 year	0.5	-	Currently enforceable
Carbon monoxide	CO	1 hour	30 000	88	Currently enforceable
		8 hours (based on 1-hourly averages)	10 000	11	Currently enforceable

Notes:

(a) The number of averaging periods where exceedance of limit is acceptable.

(b) Date after which concentration limits become enforceable.

2.1.2 National Dust Control Regulations

The National Dust Control Regulations (NDCR) were gazetted on 1 November 2013 (No. 36974) with a draft update published on 25 May 2018 (No. 41650). The purpose of the regulations is to prescribe general measures for the control of dust in all areas including residential and light commercial areas. The standard for acceptable dustfall rate is set out in Table 2-2. The method to be used for measuring dustfall rate and the guideline for locating sampling points shall be ASTM D1739: 1970, or equivalent method approved by any internationally recognized body.

Table 2-2: Acceptable dustfall rates

Restriction Area	Dustfall Rate (mg/m².day, 30-day average)	Permitted Frequency of Exceeding Dustfall Rate
Residential area	D<600	Two in a year, not sequential months
Non-residential area	600<D<1200	Two in a year, not sequential months

2.1.3 Section 21 – Listed activities

Industrial and materials processing activities that are likely to, or currently, result in atmospheric emissions are required to apply for atmospheric emissions licenses (AEL). The activities are classified into ten categories (and sub-categories) in the Government Gazette No.: 37054 (2013):

- Category 1: Combustion Installations
- Category 2: Petroleum Industry, the production of gaseous and liquid fuels as well as petrochemicals from crude oil, coal gas or biomass
- Category 3: Carbonization and Coal Gasification
- Category 4: Metallurgical Industry
- Category 5: Mineral Processing, Storage and Handling
- Category 6: Organic Chemicals Industry
- Category 7: Inorganic Chemicals Industry
- Category 8: Thermal Treatment of Hazardous and General Waste
- Category 9: Pulp and Paper Manufacturing Activities, Including By-Products Recovery
- Category 10: Animal Matter Processing

2.1.4 Section 23 – Controlled Emitters

Controlled emitters, as per Section 23(1) of NEM: AQA, include:

- any small boiler with a design capacity exceeding 10 MW but less than 50 MW net heat input per unit, based on the lower calorific value used;
- any temporary asphalt plants producing mixtures of aggregate and tar (or bitumen) for road surfacing purposes; and
- any small-scale char or charcoal plants.

Section 23 of the Act provides for registration and reporting requirements; fuel use; emission standards for these controlled emitters; and appropriate operating conditions.

2.1.5 Reporting of Atmospheric Emissions

The National Atmospheric Emission Reporting Regulations (Government Gazette No. 38633) came into effect on 2 April 2015.

The purpose is to regulate the reporting of data and information from identified point, non-point and mobile sources of atmospheric emissions to an internet-based National Atmospheric Emission Inventory System (NAEIS). Its objective is to provide all stakeholders with relevant, up to date and accurate information on South Africa's emissions profile for informed decision making.

Emission sources and data providers are classified according to groups:

- Group A: “Listed activity published in terms of section 21(1) of the Act”. Emission reports from Group A must be made in the format required for NAEIS and should be in accordance with the AEL or provisional AEL.
- Group B: “Controlled emitter declared in terms of section 23(1) of the Act”. Emission reports must include any information that is required to be reported in terms of the notice published in the Gazette in terms of section 23 of the Act.
- Group C: “Mines” where emission reports must be made in the format required in NAEIS.

After registration on NAEIS the facility or their data provider must submit the required information for the preceding calendar year to the NAEIS by 31 March of each year.

2.1.6 Atmospheric Impact Report

According to the NEM: AQA, an Air Quality Officer (AQO) may require the submission of an Atmospheric Impact Report (AIR) in terms of section 30, if:

- The AQO reasonably suspects that a person has contravened or failed to comply with the Act or any conditions of an AEL, and that detrimental effects on the environment occurred, or there was a contribution to the degradation in ambient air quality.
- A review of a provisional AEL or an AEL is undertaken in terms of Section 45 of the NEM: AQA.

The format for Atmospheric Impact Reports is stipulated in the Regulations Prescribing the Format of the Atmospheric Impact Report, as amended, Government Gazette No. 36904, Notice Number 747 of 2013 (11 October 2013).

2.1.7 Regulations Regarding Atmospheric Dispersion Modelling

Air dispersion modelling provides a cost-effective means for assessing the impact of air emission sources, the major focus of which is to determine compliance with the relevant ambient air quality standards. Regulations regarding Air Dispersion Modelling were promulgated in Government Gazette No. 37804 vol. 589; 11 July 2014 and recommend a suite of dispersion models to be applied for regulatory practices as well as guidance on modelling input requirements, protocols and procedures to be followed. The Regulations Regarding Air Dispersion Modelling are applicable:

(a) in the development of an air quality management plan, as contemplated in Chapter 3 of the NEM:AQA;
(b) in the development of a priority area air quality management plan, as contemplated in Section 19 of the NEM:AQA;
(c) in the development of an atmospheric impact report, as contemplated in Section 30 of the NEM:AQA; and,
(d) in the development of a specialist air quality impact assessment study, as contemplated in Chapter 5 of the NEM: AQA.

2.2 Air Quality Management Plan Implementation

The input from various stakeholders within the VTAPA is required to ensure the successful implementation of the VTAPA AQMP. As listed in the 2013 medium term report (DEA, 2013), these include:

1. Government departments with mandates in terms of NEMAQA
    a. National Government – Department of Environmental Affairs (DEA)
    b. Provincial Government – Gauteng and Free State Environmental Departments
    c. Local Government – Metropolitan, District and Local Municipalities
2. Government department not mandated in terms of NEMAQA
    a. Department of Mineral Resources (DMR)
    b. Department of Agriculture, Forestry and Fisheries
    c. Department of Health
    d. Department of Energy
    e. Department of Human Settlements
    f. Department of Transport
3. Industry
4. Civil Society
5. The public and non-industrial emitters.

The DEA established the Multi-Stakeholder Reference Group (MSRG) and Implementation Task Teams (ITTs) for the VTAPA, according to the requirement of Section (19) (6) (c) of the Air Quality Act on the implementation of the Priority Area AQMP. The MSRG and ITTs provide a platform for the sharing of information and the reporting on progress on the implementation of the VTAPA AQMP (i.e. air quality management, interventions and strategies, performance, etc.). It also provides the necessary platforms for understanding priorities and concerns from the various stakeholders, and to improve the utilisation of available resources. One of the initiatives from the VTAPA MSRG was the formation of an Awareness Task Team aiming to improve awareness around air pollution.

The MSRG meets bi-annually and consists of representatives from:

- Relevant national departments, affected provincial departments, district and local municipalities,
- Non-Government Organisations and Community Based Organisations,
- Industries,
- Academia, and
- Interested and affected parties within the VTAPA.

The ITTs meet quarterly per District and comprise of:

- AQOs from DEA, the relevant province (Gauteng and Free State); district and local municipalities,
- Non-Government Organisations and Community Based Organisations, and
- Industries.

In addition, the Authorities comprising of the DEA and AQOs meet quarterly whereas the Project Steering Committee (PSC) meetings are held per milestone.

In order to capacitate affected communities within the VTAPA, the DEA has conducted workshops in Soweto and Ivory Park, City of Johannesburg as well as Zamdela, Fezile Dabi District Municipality.

3 GEOGRAPHY AND DEMOGRAPHICS

The VTAPA extends from Soweto in the north-west, to Sasolburg in the southwest, to Deneysville and Oranjeville in the south-east. The towns of Vereeniging, Vanderbijlpark and Meyerton fall within this geographic area together with various low-income settlements such as Boipatong, Bophelong, Evaton, Orange Farm, Sebokeng, Sharpeville and Zamdela. The land-use across the VTAPA includes: industrial; commercial; low intensity agricultural; and residential activities, all within close proximity to one another. High density urban and suburban areas surround the VTAPA to the north and northeast, specifically the City of Johannesburg and Ekurhuleni Metropolitan Municipalities.

The terrain elevation (Figure 3-1) across the VTAPA ranges between 1 332 and 1 916 metres above mean sea level (mamsl) where the highest elevation is in the north-east corner of the VTAPA (Suikerbosrand Nature Reserve, near Heidelberg). In general, the northern and eastern areas of the VTAPA have the highest elevation while the low-lying areas in the west and southwest form the drainage areas of the Vaal river.

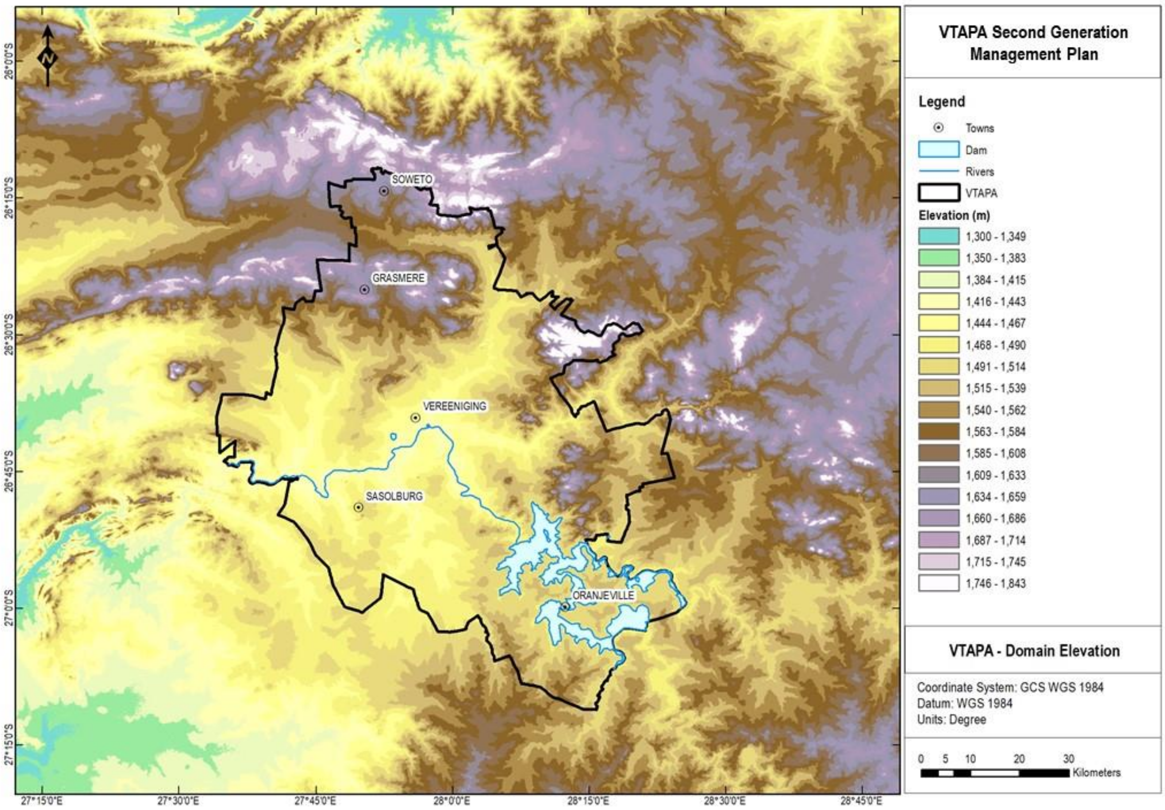


Figure 3-1: Terrain elevation across the VTAPA

The population in the VTAPA, according to the 2001 Census, was 2 532 362, with the highest population density falling within Soweto and the second-highest within the Emfuleni Local Municipality. Both these areas comprise primarily of low-income settlements. Most of these households rely partially on coal and wood for cooking, space heating and lighting purposes. According to the 2011 Census (StatsSA, 2011), the population of the area grew to 2 848 140 (Table 3-1). By 2016, the population within the VTAPA had risen to 3 127 907, a 10% growth over five years (Table 3-1). The 2011 census found that the only Local Municipalities with more than 10% of households using coal, wood or dung for cooking were Emfuleni (17.8%) and Metsimaholo (12.6%).

Table 3-1: A comparison of the population sizes of each of the District Municipalities and Local Municipalities within the VTAPA

District / Metropolitan Municipality	Local Municipalities / Administrative Areas	Population size (2011 Census) (a)	Population size (2016 Community Survey) (b)
City of Johannesburg	Southern part of CoJ	1 882 065	**2 119 286**(c)
Fezile Dabi DM(d)	Metsimaholo LM	149 109	**163 564**
Sedibeng DM	Midvaal LM	95 301	111 612
	Emfuleni LM	721 665	733 445
	Total	816 966	**845 057**
TOTAL VTAPA	**TOTAL**	**2 848 140**	**3 127 907**

Notes:

(a) 2011 Census reported statistics at small-place level.

(b) 2016 Community Survey reported statistics for metropolitan areas, district and local municipality level only.

(c) Approximately 42% of the total population of the City of Johannesburg (COJ) reside within the VTAPA. Population statistics were estimated for the areas of COJ within VTAPA; assuming changes between 2011 and 2016 were the same across small place levels.

(d) Fezile Dabi DM consists of four local municipalities, of which Metsimaholo is the only LM encompassed in the VTAPA

To highlight the changes in the demographics, population size was compared between 2001 and 2011 to provide an indication of population change over this period (Figure 3-3). It should be noted that the boundaries changed between the two census years and therefore a quantitative comparison was not possible.

Indicators for the following risk factors associated which may affect health impacts associated with air pollution exposure, include:

- Proportion of people per sub-place (SP) in vulnerable age group (less than 15 years and more than 65 years of age);
- Proportion of people older than 20 years with no schooling;
- Proportion of informal dwellings within each SP, with 'informal' combining the two categories relating to shacks; and,
- Proportion of households within a SP not using electricity for lighting, i.e. all other forms of energy but electricity.

Figure 3-4 to Figure 3-7 show various census-derived indicators as a proportion of the total population within each SP. White-filled areas within the VTAPA boundary of the figures indicate: industrial areas; nature reserves; and, other sparsely-populated areas. Note that 2016 Community Survey results were not reported at small place level and are not presented in the maps., The spatial patterns are however assumed to have remained similar between the 2011 Census and 2016 Community Survey.

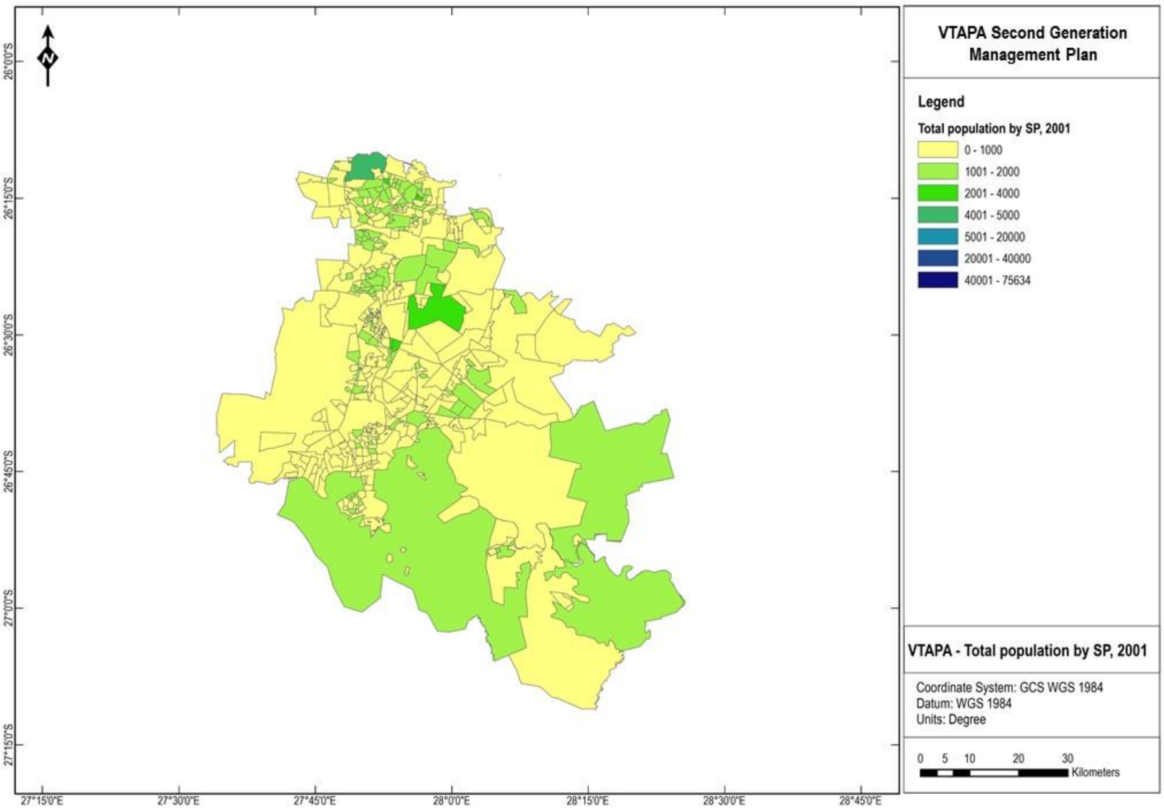


Figure 3-2: Total population by SP in the VTAPA, 2001 (StatsSA, 2011)

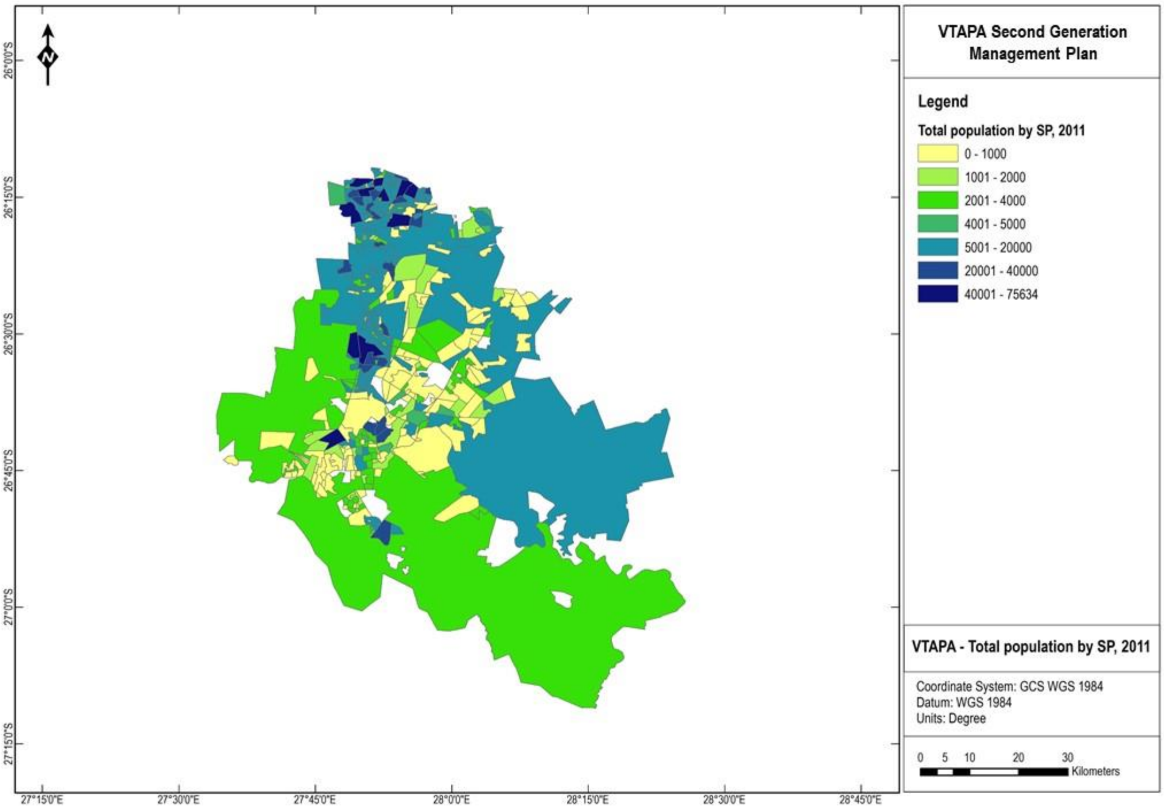


Figure 3-3: Total population by SP in the VTAPA, 2011 (StatsSA, 2011)

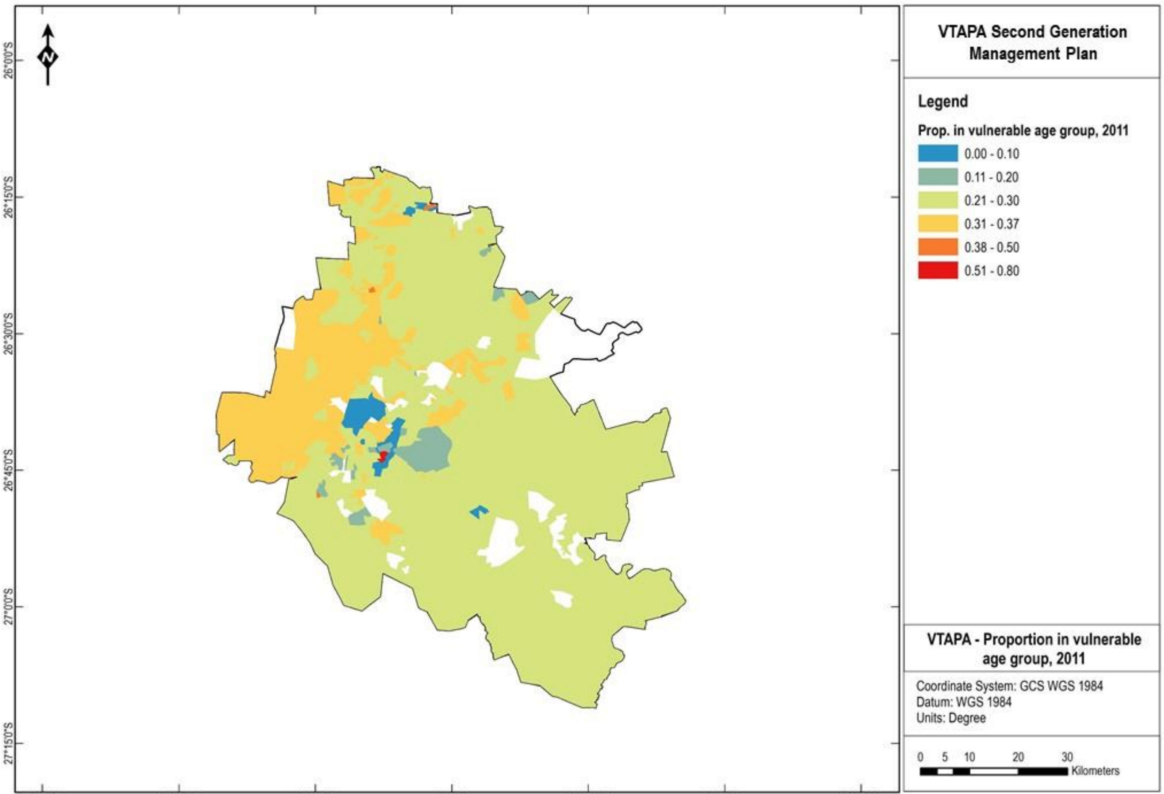


Figure 3-4: Proportion of people per SP in vulnerable age group, 2011 (StatsSA, 2011)

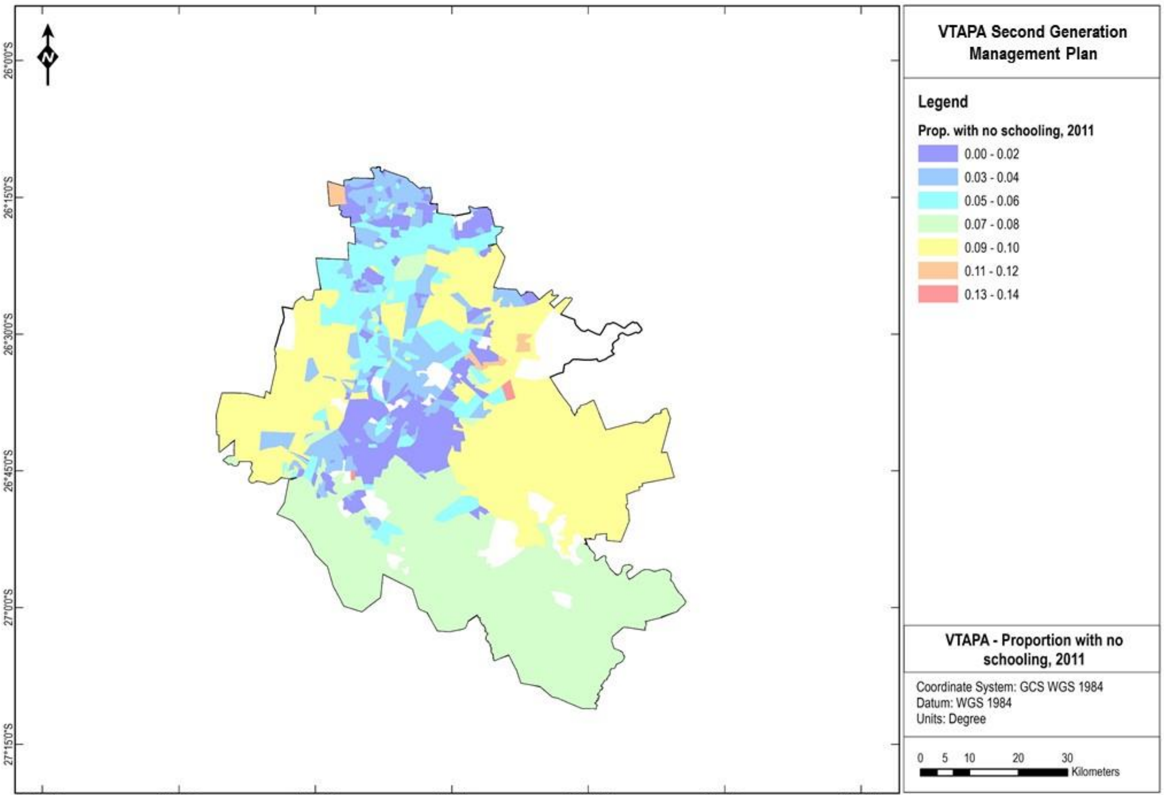


Figure 3-5: Proportion of people older than 20 years within SP with no schooling

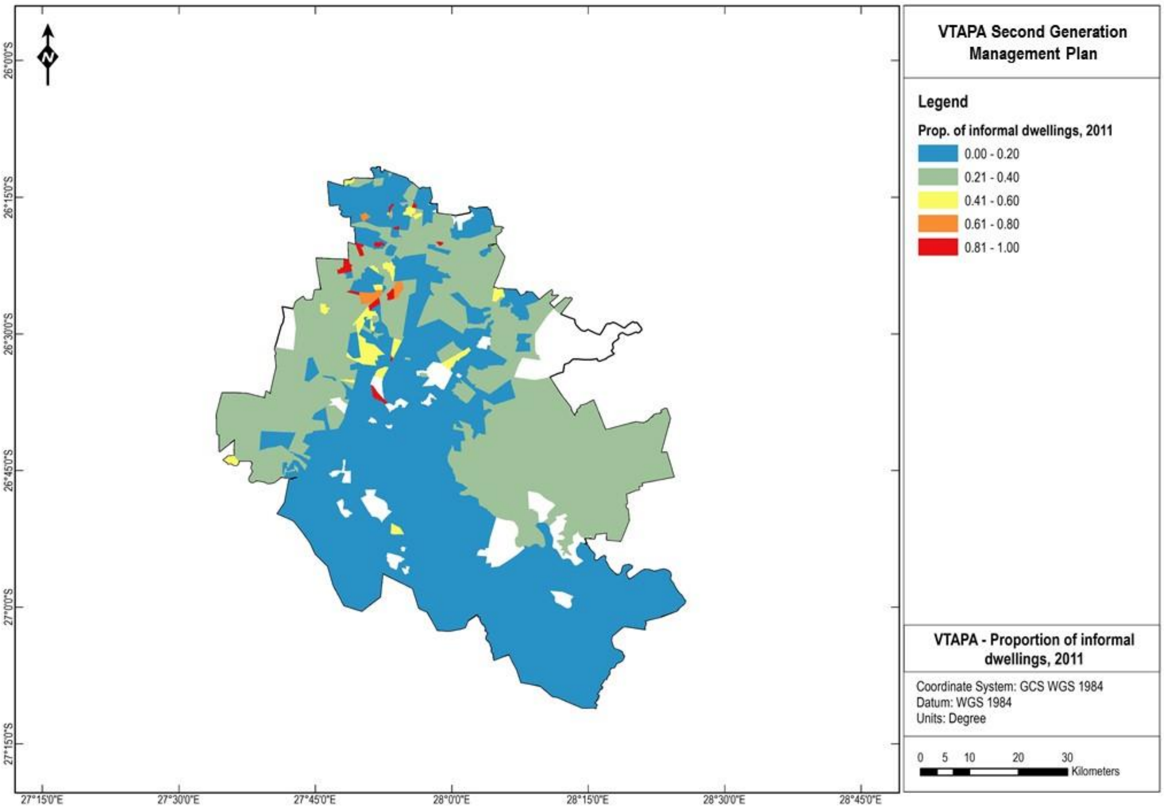


Figure 3-6: Proportion of informal dwellings within each SP

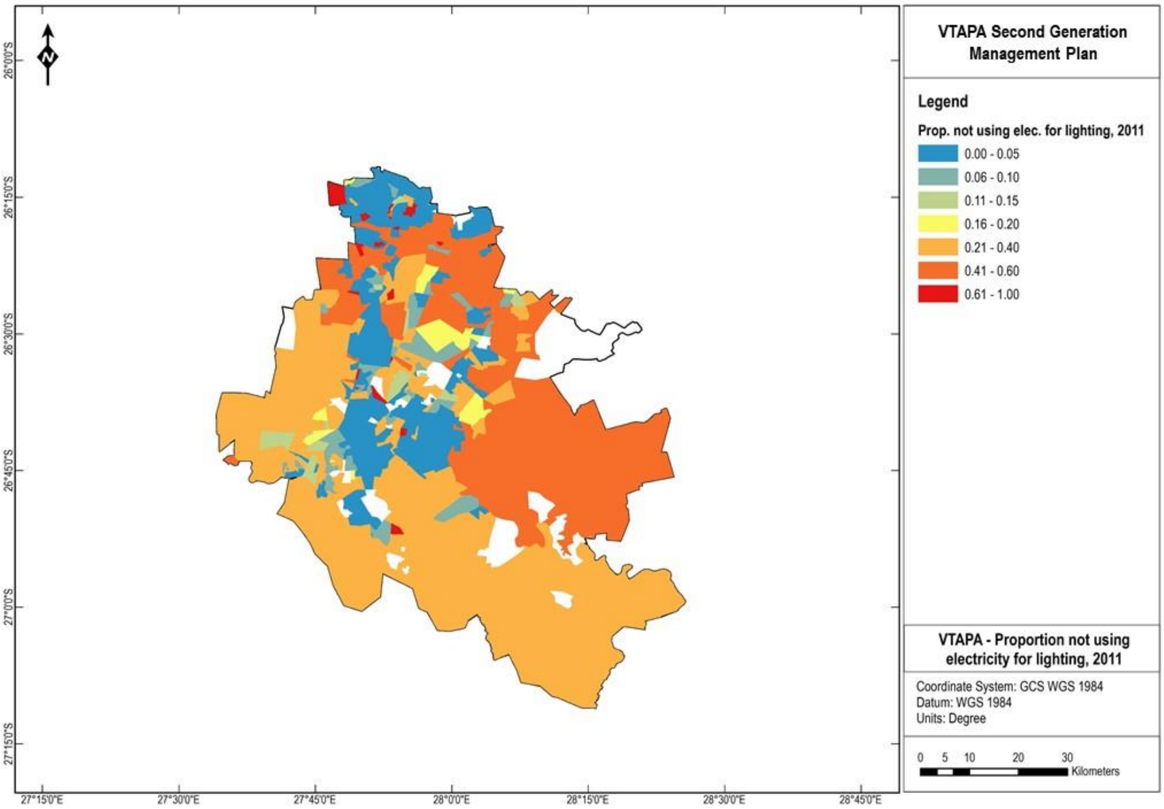


Figure 3-7: Proportion of households within a SP not using electricity for lighting

4 REGIONAL CLIMATE AND ATMOSPHERIC DISPERSION CONDITIONS

Meteorological data from air quality monitoring stations in the VTAPA was accessed as an indication of climate and dispersion conditions. Air Quality Monitoring Stations (AQMS) from which data was accessed at the time of reporting include the parameters and data periods given in Table 4-1. The spatial representation of the ambient monitoring stations across the VTAPA is shown in Figure 4-1.

Table 4-1: Meteorological data recorded at AQMS within the VTAPA

Station name (owner)	Data accessed	Data period	Average data availability
Sharpeville (DEA)	Wind Direction; Wind Speed; Temperature; Pressure; Relative Humidity; Rainfall; Solar Radiation	2013 - 2015	93%
Three Rivers (DEA)	Wind Direction; Wind Speed; Temperature; Pressure; Relative Humidity; Rainfall; Solar Radiation	2013 – 2015	90%
Zamdela (DEA)	Wind Direction; Wind Speed; Temperature; Pressure; Relative Humidity	2013 – 2015	74%
Kliprivier (DEA)	Wind Direction; Wind Speed	2014 – 2016	72%
Sebokeng (DEA)	Wind Direction; Wind Speed	2014 – 2016	85%
AJ Jacobs (Sasol)	Wind Direction; Wind Speed; Temperature	2013 – 2015	>99%
Eco Park (Sasol)	Wind Direction; Wind Speed; Temperature; Pressure; Rainfall	2013 – 2015	98%
Leitrim (Sasol)	Wind Direction; Wind Speed; Pressure	2013 – 2015	72%

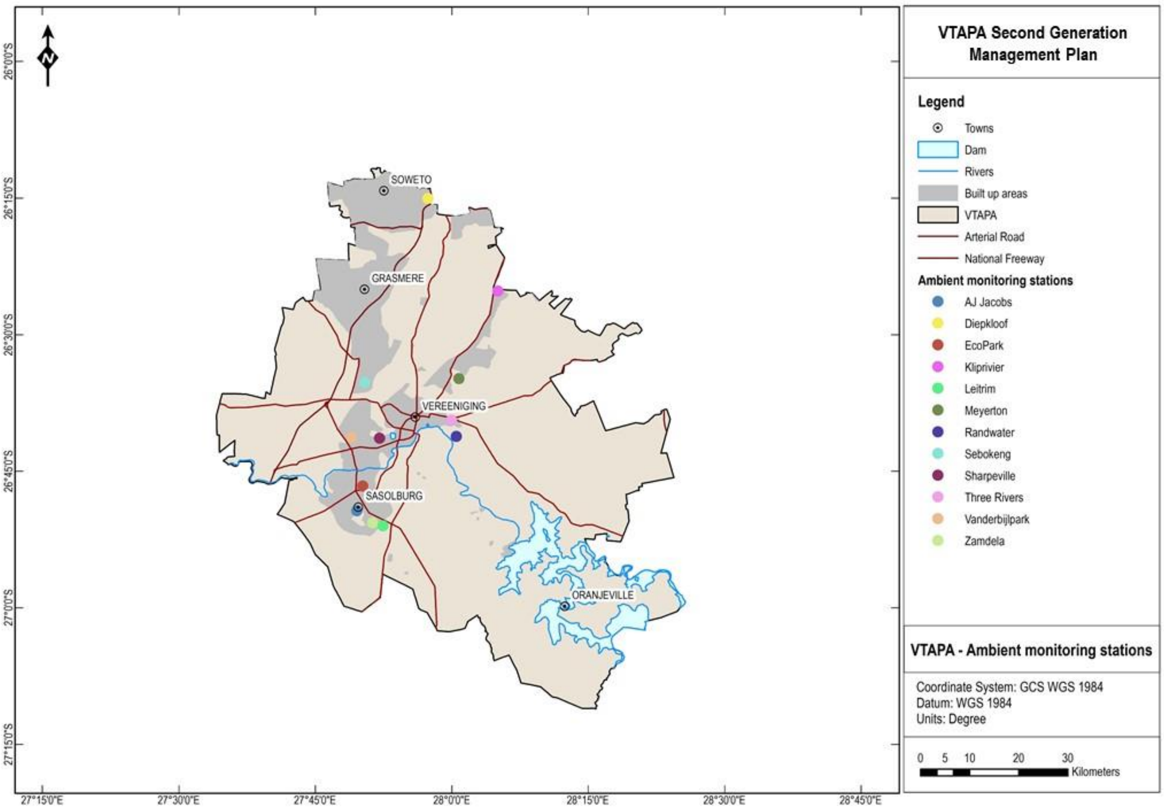


Figure 4-1: VTAPA - Ambient monitoring stations

4.1 Surface Wind Field

The vertical and horizontal dispersion of pollution is largely a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution of pollutants. The generation of mechanical turbulence is similarly a function of the wind speed, in combination with the surface roughness.

Wind roses comprise 16 spokes which represent the directions from which winds blew during the period. The wind rose colours reflect the different categories of wind speeds. For example, the dark green areas represent winds of 3 to 4 m/s. The dotted circles provide information regarding the frequency of occurrence of wind speed and direction categories. For the current wind roses, each dotted circle represents a 2% frequency of occurrence. The figure given in the centre of the circle described the frequency with which calms occurred, i.e. periods during which the wind speed was below 1 m/s.

Period average wind roses are reflected in Figure 4-2; day-time and night-time average wind roses provided in Figure 4-3 and Figure 4-4, respectively.

There is some variability in wind fields across the VTAPA monitoring stations, however a predominance of wind from the north-easterly and north-westerly sectors are evident at all stations, with possible exception of Eco Park, where a south-easterly flow is dominant (Figure 4-2). Winds exceeding 4 m/s are more frequently recorded at Sharpeville, Leitrim, and Eco Park. The Leitrim station recorded the fewest calm conditions (6%), while calm periods were most frequent at the AJ Jacobs station (30%).

Day-time airflow for the area (Figure 4-3) reflects similar patterns as the period averages. In general, the stations indicate winds more frequently from the north-westerly or westerly sectors. At AJ Jacobs winds from the north also occur during the day. At all stations, day-time airflow shows lower incidences of calm conditions.

Night-time conditions (Figure 4-4) are characterised by lower wind speeds and higher incidences of calm conditions. In general, airflow from the southwest decreases during the night with a slight increase in winds form the easterly to north-easterly sectors.

4.2 Temperature

Average temperatures across the five AQMS located across the VTAPA (Table 4-2) show that the warmest temperatures are observed between December and February, while lowest temperatures are observed in June or July. Average temperatures across the province are generally mild. The coolest temperatures were recorded at the Zamdela AQMS and the warmest at the AJ Jacobs station.

Table 4-2: Average ([maximum + minimum]/2) monthly temperatures (°C) at six AQMS across the VTAPA

Station Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sharpeville	24.1	22.8	22.1	16.4	14.3	11.5	9.7	13.7	15.7	20.5	21.1	24.0
Three Rivers	23.9	21.9	20.8	15.2	13.7	9.1	8.4	12.3	14.2	20.0	20.9	25.0
Zamdela	21.3	19.9	19.7	14.2	11.7	7.8	7.6	10.4	13.9	15.0	15.9	20.3
AJ Jacobs	28.6	28.2	27.1	27.6	25.1	22.2	21.0	21.7	23.3	23.1	18.9	28.4
Eco Park	24.0	22.4	22.0	16.8	14.4	11.5	9.6	13.6	14.9	19.3	17.8	23.9

Long-term average (1903-1984) maximum, average and minimum temperatures for Vereeniging are given in Table 4-3 (Schulze, 1986). Annual maximum, minimum and average temperatures are given as 23.9°C, 9.1°C and 16.6°C, respectively, based on the long-term record. Average daily maximum temperatures range from 27.8°C in January to 17.7°C in July, with daily minima ranging from 15.5°C in January to just above 0°C in June and July.

Table 4-3: Long-term minimum, maximum and average temperature (°C) for Vereeniging

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maximum (°C)	27.8	27.2	26.1	23.3	20.5	17.7	18.3	21.2	24.8	26.3	26.6	27.5
Average (°C)	21.7	21.3	19.8	16.4	12.5	8.9	9.2	12.2	16.4	19.0	20.2	21.2
Minimum (°C)	15.5	15.2	13.2	9.2	4.4	0.2	0.3	3.1	8.0	11.6	13.7	14.8

4.3 Rainfall

Long-term median monthly rainfall for Vereeniging (Table 4-4) shows a trend typical of South African summer rainfall areas with peak rainfall in December – February. Annual average rainfall for the area is approximately 650 mm.

Table 4-4: Long-term median monthly rainfall for Vereeniging (Schulze and Lynch, 2007)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual average
Rainfall (mm)	108	83	70	34	10	2	0	3	12	55	90	100	656

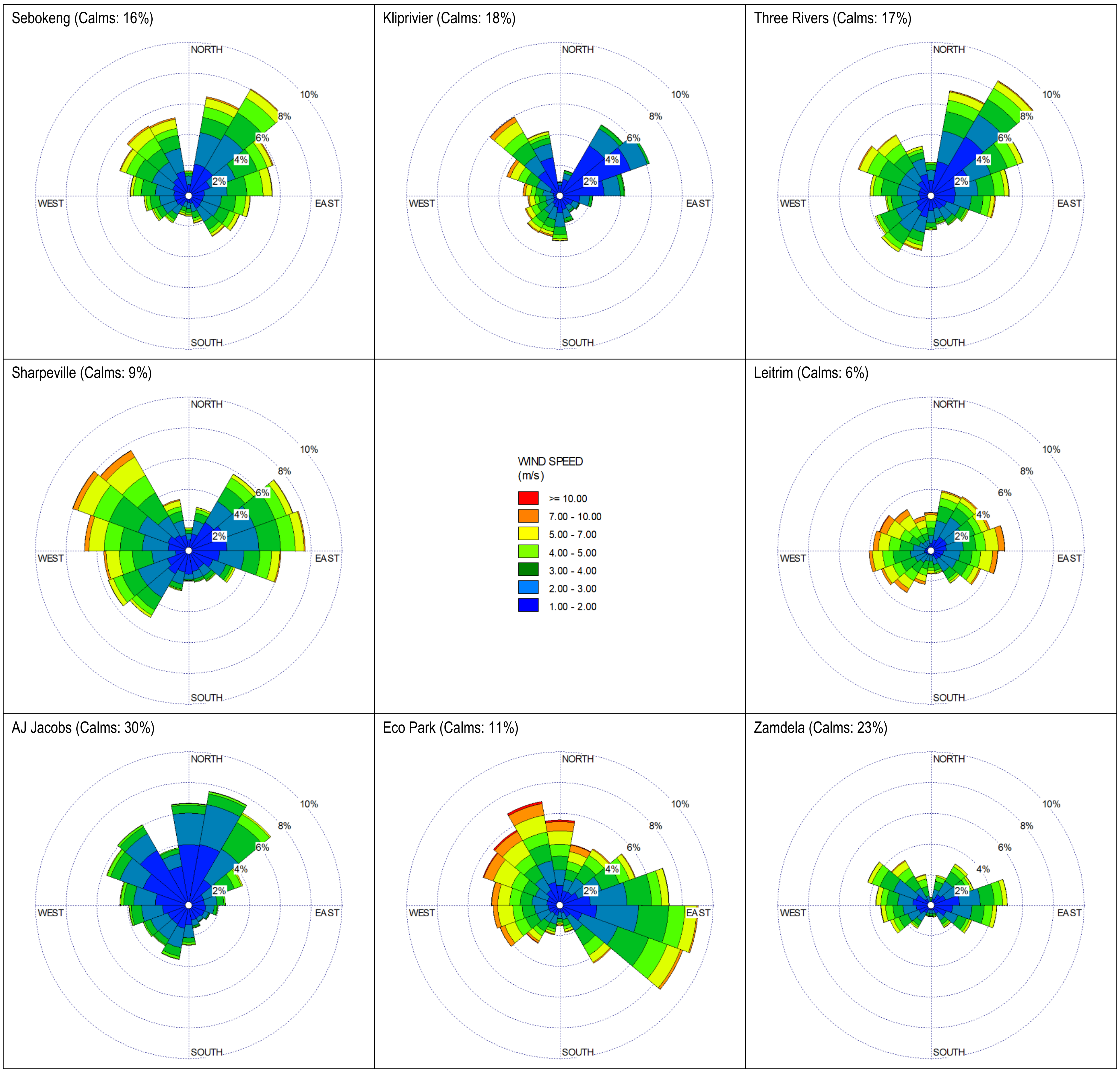


Figure 4-2: Period wind roses for eight AQMS across the VTAPA

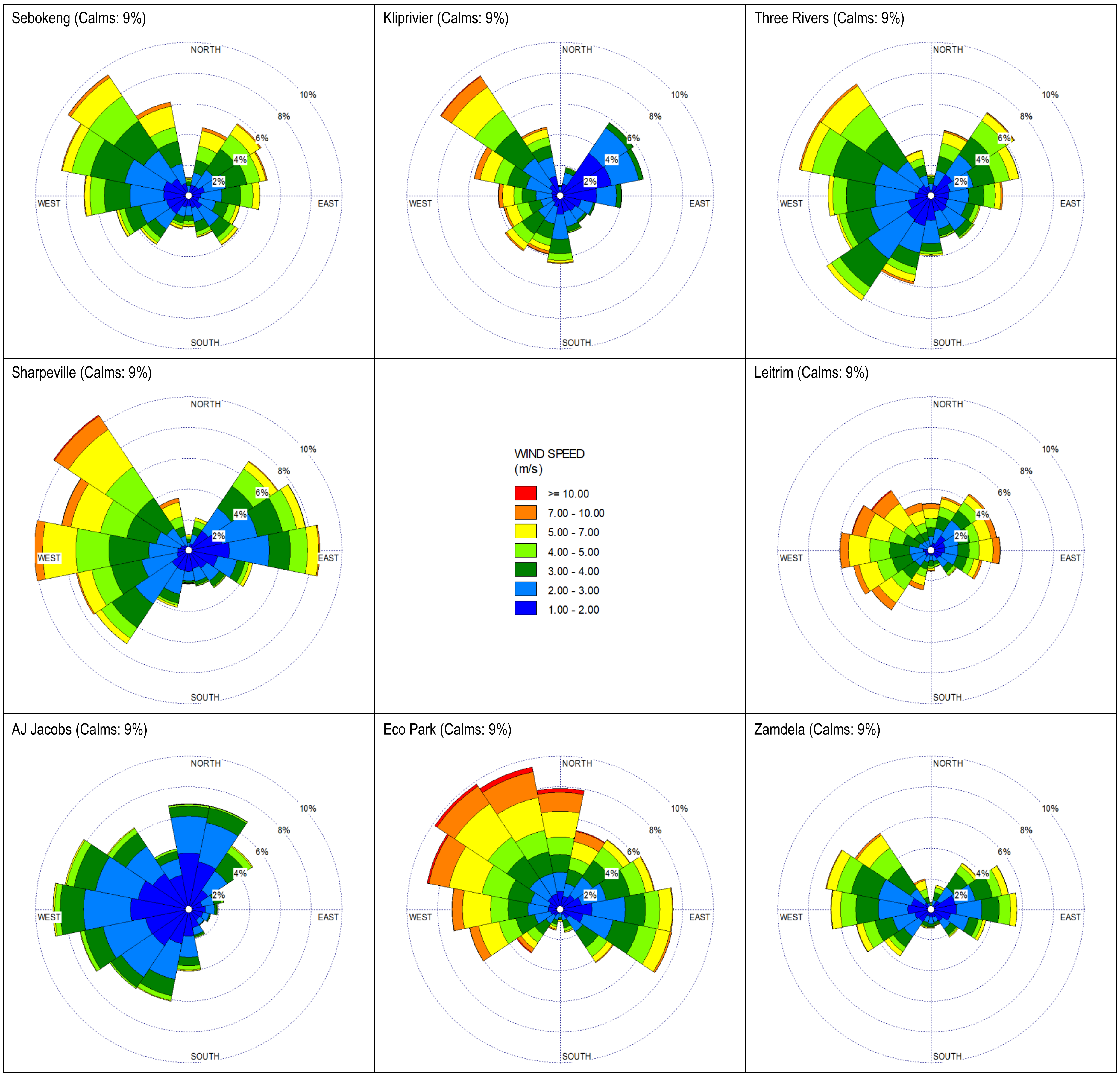


Figure 4-3: Day-time wind roses for eight AQMS across the VTAPA

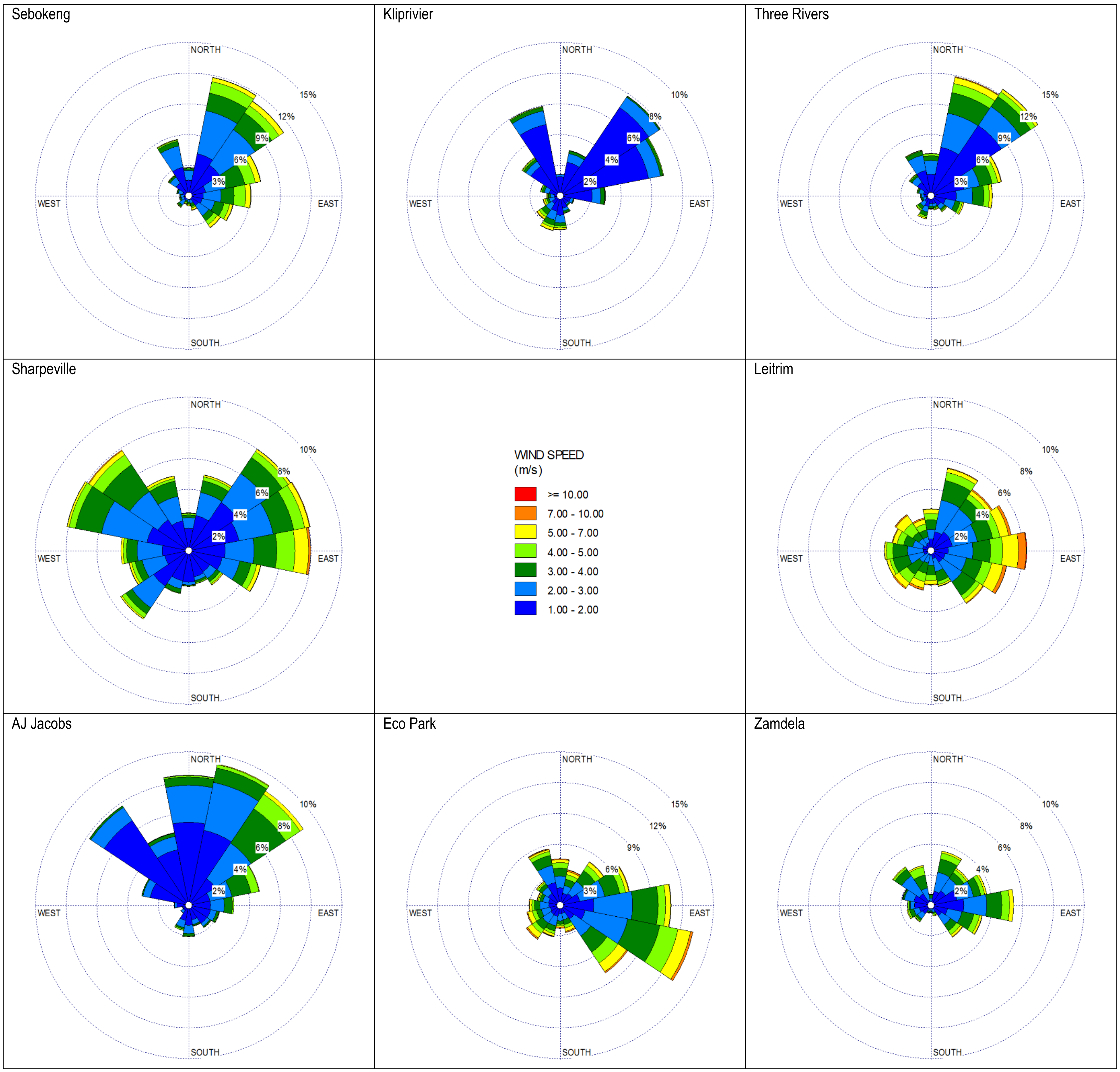


Figure 4-4: Night-time wind roses for eight AQMS across the VTAPA

5 BASELINE CHARACTERISATION

5.1 Emission Sources

An emission inventory has been created for two purposes, that is, primarily to show emissions emanating within VTAPA - thus geared for air quality management within the Priority Area, and secondly from the surrounding areas to form input into air quality modelling. The management geared inventory includes emissions only from within VTAPA boundaries while the modelling inventory takes into account all sources within the model domains. Figure 5-1 shows the extent of these domains.

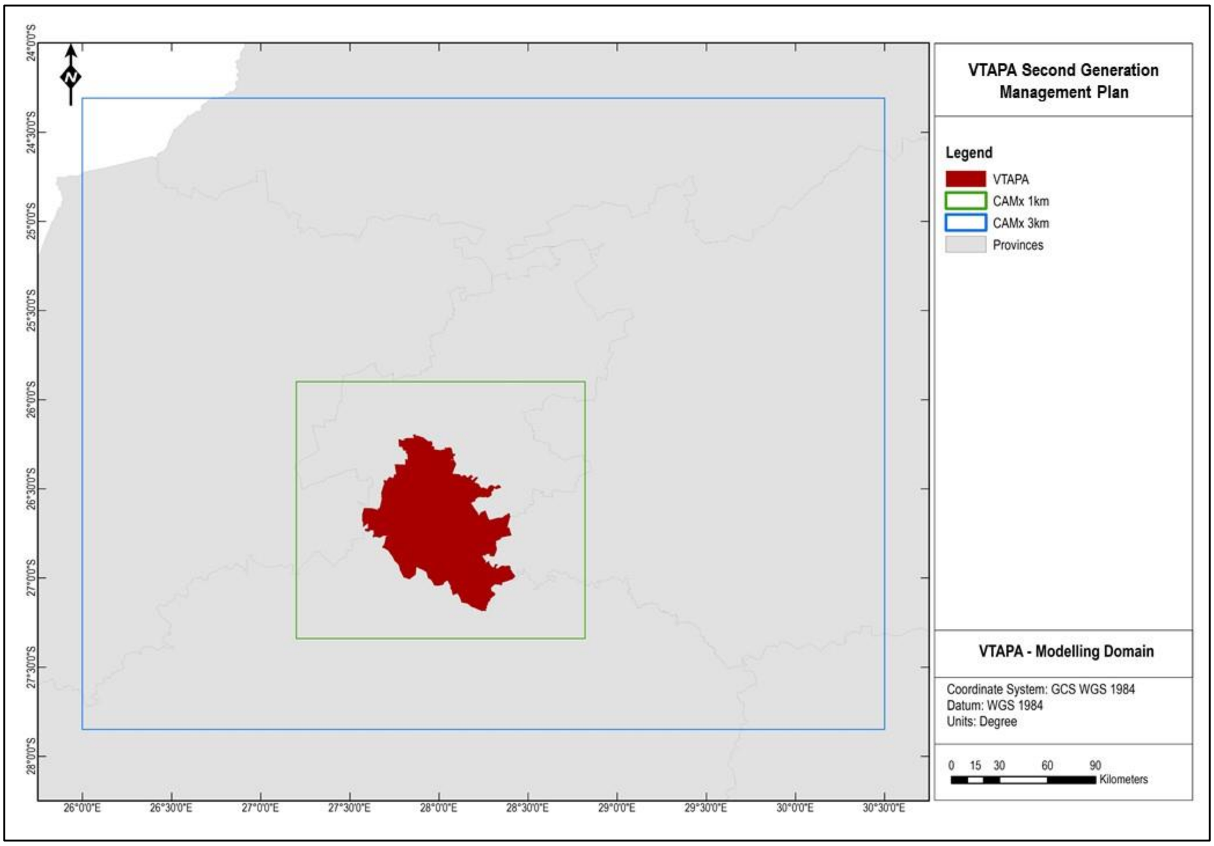


Figure 5-1: Air quality modelling (and thus emission inventory) domains

A regional 3 km resolution modelling domain aims to capture Highveld regional sources that may impact VTAPA while a finer resolution 1 km domain over VTAPA aims to simulate ambient air quality in more detail. An inventory is created for both domains, but the following emission sections only report on emissions within the 1 km VTAPA domain.

5.1.1 *Industrial Sources*

Industrial sources of air pollutants represent mostly stationary facilities operating under licenses or registration where emissions are reported to the authorities annually. Emissions from these sources are therefore, in theory, readily available, or easily calculated from available activity data. In practice, gaps in industrial emissions inventories are usually associated with smaller industries where detailed activity information may not be tracked or is not reportable. The verification and quantification processes have been initiated by identifying gaps in the industrial emission inventory. These gaps can be addressed as part of the capacity building process to run in parallel with the AQMP review.

5.1.1.1 Methodology

The quantification of air pollutant emissions from industrial activities relied on reported activity data reported through the NAEIS for the 2017 calendar year. The sources extend across the large resolution dispersion modelling domain (3 km-resolution). The data were checked against the AELs for the reporting industries. Verification of VTAPA sources and emissions was carried out using the list of industries quantified in the 2009 VTAPA management plan, and earlier NAEIS databases for the VTAPA sources.

Prior to dispersion modelling, further verification of stack exit parameters was performed on the inventory to screen inaccurate input parameters since these would result in erroneous dispersion simulations. The data screening included removing all rows with total emissions less than 1 kg emissions. Since the dataset included both reported and system calculated values (based on emission factors and production rates), reported values were used in preference to system calculated emission rates; except where reported values were zero or unrealistically high. All exit temperatures lower than 25°C were changed to 25°C. Exit velocities that were unrealistically high were changed to 10 m/s (informed by a typical engineering midpoint). The dataset included petroleum storage tank farms however tank heights were not reported on and all tanks were given a typical height based on average heights from other data sets (10 m). Tank emissions parameters, including diameters (0.01 m) and exit velocities (0.01 m/s), were set to the values recommended by the Regulations for Dispersion Modelling (Government Gazette No 37804 published 11 July 2014). Emission rates for two brick clamp kilns were deemed incorrect based on comparison with similar operations. These sources, located outside of VTAPA, were removed from the database as the incorrect emissions could not be validated prior to dispersion modelling. Emission rates from a ceramic manufacturing facility was similarly deemed incorrect based on comparison to emission rates from similar processes. The error, assumed to be a unit conversion error since it was orders of magnitude too high, was adjusted to be more in line with the similar processes.

5.1.1.2 Results

The available information recognised 104 facilities in the VTAPA, mostly in the Emfuleni Local Municipality (Figure 5-1). Of these, 40 facilities operate listed activities under Section 21 of NEM: AQA. A total of 48 sources are classified as Section 23 Controlled Emitters. The locations of these sources are shown in Figure 5-2.

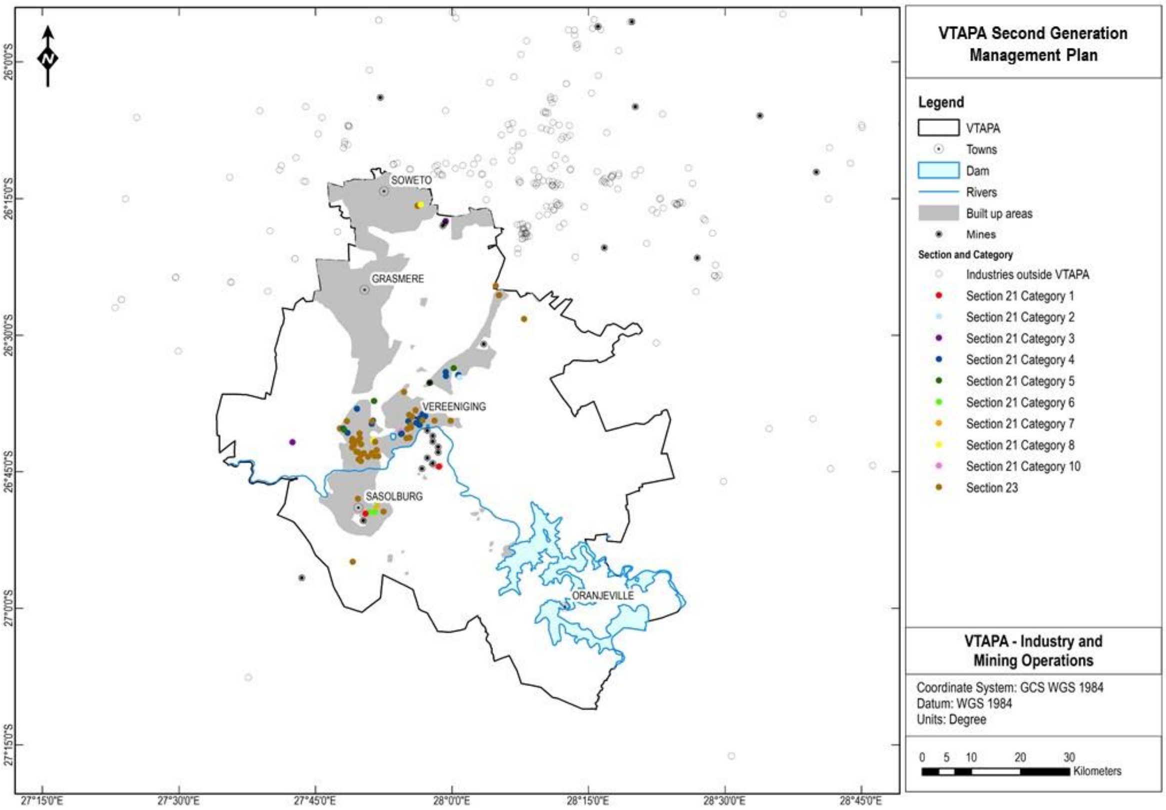


Figure 5-2: Industrial and mining sources identified in the VTAPA

Annual emissions for the pollutants of concern from industrial sources within VTAPA are summarised in Table 5-1 and graphically presented in Figure 5-3. Section 21 Category 1 sources (combustion sources for the purposes of steam raising or electricity generation) contribute the largest quantities of sulfur dioxide (SO_2) and oxides of nitrogen (NO_X) followed by Section 21 Category 4 sources - Metallurgical Industry, and then Petroleum Industry (Section 21 Category 2) sources. The largest emissions of thoracic particulate matter (PM_{10}) are the Section 21 Category 4 sources, followed closely by Section 21 Category 5 sources – Mineral Processing, Storage and Handling. $PM_{2.5}$ emissions are not reported by all facilities, with Section 21 Category 5 sources being the main reported emitter followed by Section 21 Category 1 sources.

Table 5-1: Total industrial emissions from sources in VTAPA

Priority Area and Classification	Number of individual sources	Reported emissions in 2017 (tonnes per annum)			
		SO_2	NO_X	PM_{10}	$PM_{2.5}$
VTAPA	**40**	**232 668.82**	**118 459.48**	**16 807.56**	**255.99**
Section 21 Category 1	2	208 809.20	112 075.22	7 381.14	15.60
Section 21 Category 2	2	4 779.83	3 113.46	3.14	-
Section 21 Category 3	2	-	-	40.89	-
Section 21 Category 4	16	9 712.76	1 969.01	1 153.94	0.38
Section 21 Category 5	10	2 084.38	573.16	7 602.56	240.00
Section 21 Category 6	3	498.96	-	-	-
Section 21 Category 7	2	0.00	45.82	97.81	-
Section 21 Category 8	1	1 449.87	472.70	0.24	-
Section 21 Category 10	1	694.44	-	-	-
Section 23 Controlled Emitter	48	4 639.37	210.10	527.84	0.01

Table 5-2 provides the emissions from industrial sources in the 1 km model grid spaced domain and VTAPA. Most emissions are from the neighbouring areas to VTAPA.

Table 5-2: Total industrial emissions from sources in VTAPA (tonnes per annum)

	NO_X	SO_2	CO	NMVOC	PM_{10}	$PM_{2.5}$	NH_3
Model domain	1 013 165	1 966 232	121 611	30 941	257 084	96 878	1 269
VTAPA only	118 459	232 669	6 761	830	16 808	256	70
% in VTAPA	12%	12%	6%	3%	7%	0.3%	6%

5.1.1.3 Comparison with other inventories

Comparison is done against the 2009 VTAPA inventory and the 2013 medium-term review.

The medium-term review of the 2009 Vaal Triangle Airshed Priority Area:

A comparison between the 2009 and 2018 industrial emissions for VTAPA is provided in Table 5-3. Based on the two inventories, SO_2 emissions increased by 7% and NOx emissions by 5% between 2009 and 2018. PM_{10} emissions between 2009 and 2018 decreased by 33% but are slightly higher than the 2013 medium-term review. The difference between the 2009 and 2018 SO_2 and NOx emissions are most likely due to more accurate reporting lately and not necessarily an increase in emissions. The causes of the reduction in PM_{10} emissions are not clear but could be an actual reduction in industrial PM_{10} emissions since the 2017 emission inventory is regarded more comprehensive than the one in 2009. The 2009 emission inventory for the industrial sectors was based on emissions data obtained from industries (use of questionnaires), data which was already in the public domain and emission estimates from emission factor application. Of all identified industries and mines, 51% responded with updated emissions information reflecting the then current operating conditions (as for 2006). Information for 37% of the remaining industries was obtained from the NEDLAC (National Economic Development and Labour Council) Dirty Fuels study conducted in 2004 and EIA (Environmental Impact Assessment) information with 12% of the sources unaccounted for.

Based on the 2013 medium-term review, SO_2 and NOx industrial emissions were higher than in 2009, but with significantly lower PM_{10} emissions. The 2018 emission inventory reflects slightly higher SO_2 and NOx emissions compared to the 2009 inventory, but lower than the 2013 medium-term review. For PM_{10}, 2018 is also significantly lower than the 2009 reported emissions, but slightly higher than the 2013 emissions. The power generation sector (Section 21 Category 1 sources) contributed 87% of the SO_2 and 84% of the NOx emissions in 2013, compared to the reported 95% for both SO_2 and NOx in the 2018 inventory. PM_{10} emissions were also mainly a result of the power generation sector (39%) in 2013, whereas it is now shared between the Section 21 Category 1 sources (Combustion Installations) and Section 21 Category 5 sources (Mineral Processing, Storage and Handling) at 44% and 45% respectively. The discrepancy between the 2013 medium-term industrial inventory can be attributed to the sources of information used; with an MSc in air quality assessment the main source of information (47%) although direct contact with industries is given as the main source for PM_{10}, SO_2 and NO_X emissions.

Table 5-3: Medium-term VTAPA AQMP review versus 2018 VTAPA AQMP industrial emissions (tpa)

	PM_{10}	SO_2	NOx
2009 AQMP	25 266	215 916	112 956
2013 Medium-term review	13 668	247 224	131 778
2018 VTAPA AQMP	16 808	232 669	118 459

5.1.2 Mining Sources

Pollutants typically emitted from mining activities are particulates, with smaller quantifies associated with vehicle exhaust emissions. Mining activities, especially open-cast mining methods, emit pollutants near ground-level over (potentially) large areas.

5.1.2.1 Methodology

Emissions from mines in VTAPA referred to activity data reported through the NAEIS for the 2017 calendar year.

5.1.2.2 Results

Mining activity in VTAPA is limited to two opencast mines (one dolomite and one coal). An underground coal mine was identified within 5 km of the south-western boundary of VTAPA (Table 5-4). Production rates were received from one of the opencast mines and the underground mine. Opencast mining results in 99.9% of the total particulate emissions from mining in the VTAPA whereas underground mining and quarries by comparison result in less than 1% of total mining particulate emissions.

Emissions from the opencast mine, a large colliery within VTAPA, dominate the mining emissions for the modelling domain; representing 99% of mining related emissions from facilities in VTAPA (Table 5-5). Within the 3 km modelling domain, sources in the VTAPA represent 63% of mining emissions in the modelling domain. Although VTAPA opencast mine is the largest facility based on mining material throughput, it may be over-represented in the modelling domain based on the number of large open-cast mines outside of the VTAPA in the dispersion modelling domain.

Table 5-4: Estimated emissions from mining operations sources in VTAPA

Priority Area and Classification	Number of mines	Reported emissions in 2017	
		PM_{10}	$PM_{2.5}$
Open-cast mines	1	26 579.3	2 920.1
Quarries	1	6.6	0.7
Underground mines	1	0.01	0.001
Total emissions		**26 585.9**	**2 920.8**

Table 5-5: Estimated emissions from mining operations sources in VTAPA (tonnes per annum)

	PM_{10}	$PM_{2.5}$
Model domain	42 231	4 642
VTAPA only	26 586	2 921
% in VTAPA	63%	63%

5.1.2.3 Comparison with other inventories

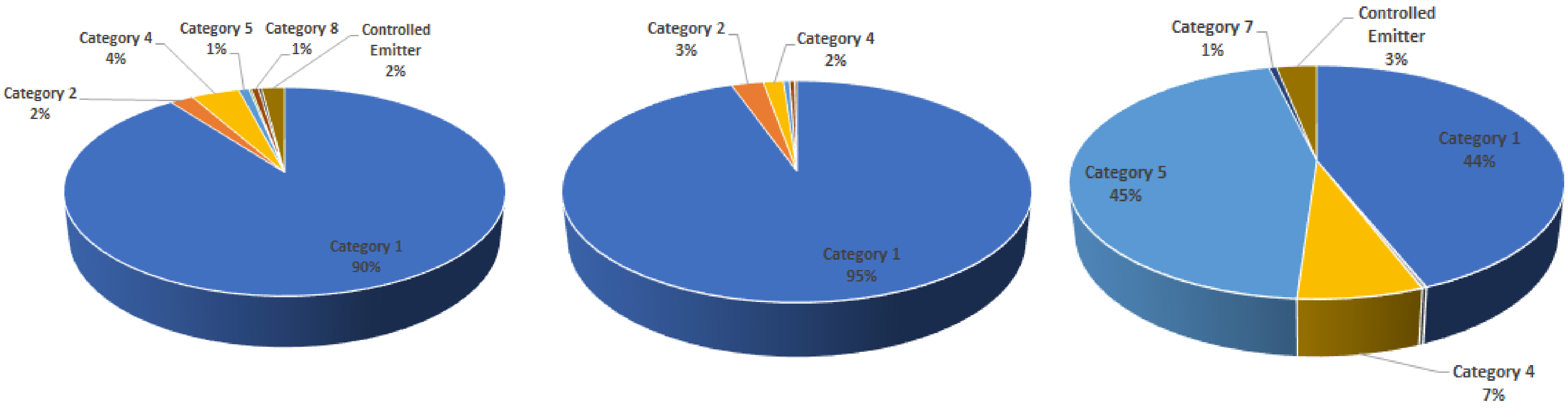
Comparison is done against the 2009 VTAPA inventory and the 2013 medium-term review.

The medium-term review of the 2009 Vaal Triangle Airshed Priority Area:

There is a significant increase in the reported PM_{10} mining emissions for the 2018 VTAPA inventory compared to the 2009 emissions from mines (Table 5-6). The same mines reported on in the 2018 inventory were operational in 2009, but emissions from the quarry were not quantified at the time due to insufficient available data. As mentioned above, current (2018) emissions from the opencast coal mine may be over-estimated.

Table 5-6: Medium-term VTAPA AQMP review versus 2018 VTAPA AQMP mining emissions (tpa)

	PM
2009 AQMP (2013 medium-term review)	4 554
2018 VTAPA AQMP	26 586



(a) SO_2 (b) NO_X (c) PM_{10}

Figure 5-3: Industrial emissions from sources in VTAPA (a) SO_2, (b) NO_2, and (c) PM_{10}

5.1.3 Mobile Sources

The modern internal combustion engine can emit various pollutants into the atmosphere, including NO$_X$, SO$_2$, carbon monoxide (CO), PM, and volatile organic compounds (VOC). The ambient concentrations of all of these pollutants are regulated in South Africa. Air pollution from traffic is known to have negative health impacts due to factors such as its emission at ground-level (e.g., levels where people can be directly exposed) and its composition. Diesel exhaust was classified as a confirmed human carcinogen in June 2012 (Silverman *et al.*, 2012; WHO, 2012).

In terms of the VTAPA modelling domain, vehicle emissions are not only important because of the inclusion of Gauteng Province, but also due to the widespread use of vehicles for personal transport and commercial purposes resulting in a regional source of both NO$_X$ and VOC. This has an impact on ozone formation and, in general, the oxidative nature of regional atmospheric chemistry (in conjunction with other emission sources like biogenic and biomass burning). Figure 5-4 shows the road network within VTAPA and the relative contribution of each road type to total network length.

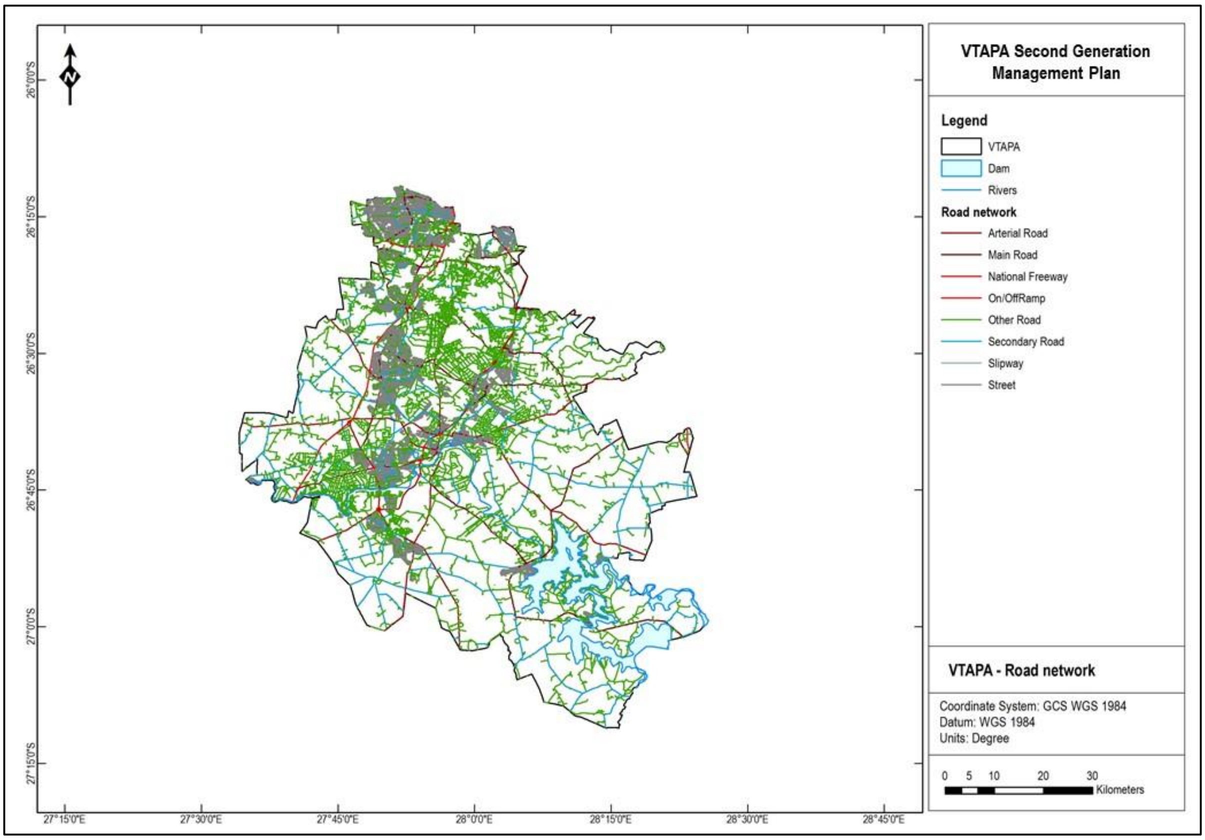


Figure 5-4: Road network within VTAPA

The network shown in Figure 5-4 is delineated by the Department of Rural Development and Land Reform's National Geo-spatial Information services (www.ngi.gov.za) transportation "TRAN_ROADS" product. This is the official national roads dataset - previously referred to as the Chief Directorate Surveys and Mapping roads dataset (CDSM). The CDSM indicator will be used in this section to refer to the official roads dataset. It is common to see the majority of road length dedicated to streets and other non-access roads. These are however much smaller, and do not have the same capacity as the larger arterial roads. Thus, two factors play a role in emission intensity when considering these two types of roads; while arterial roads may carry more volume and lead to higher emissions, congestion on smaller roads (therefore lowering speed and travel time) can also increase emissions.

In general factors that impact vehicle emissions estimates are:

- Fuel type
- Fuel specifications
- Engine technology
- Engine capacity
- Vehicle speed
- Vehicle age
- Engine/exhaust temperature
- Number of kilometres travelled.

Other, more detailed, factors requiring information that is generally not available (particularly on such a large a scale) are gearing, driving style, tyre friction and road grading.

The basis of deriving vehicle emissions is an estimate of Vehicle Kilometres Travelled (VKT). This data represents an activity to which emission factors are applied. The emission factors are dependent on all other factors noted above. Thus, any approach to generate a vehicle emission inventory includes an estimation of VKT and use of appropriate emission factors. The level of detail included in each factor varies depending on available information. One of the largest obstacles in vehicle emissions estimation for air quality modelling lies in the requirement that a realistic emission inventory will also need to be spatially representative at each grid cell, in other words the goal is to achieve the best information at every grid cell. This is not necessarily possible for all of the above-listed factors because many (for example, fuel type) are not tracked at a fine scale. Thus, assumptions are made using spatial surrogates to generate a grid-based emission inventory that is spatially representative.

There are instances when very detailed information is available (such as traffic count data); however, these are then often spatially limited. Assumptions are then used to extrapolate this data to the larger spatial scale – this is termed a bottom-up approach. When larger scale, but more generalized data exists, assumptions are made to create a finer scale variation based on surrogates – this is termed a top-down approach. Both these approaches are viable when estimating vehicle emissions, but largely depend on the data available.

5.1.3.1 Methodology

The on-road vehicle emission inventory employs both a top-down and bottom-up approach. This is possible due to road count data being available from various sources. For both methodologies the common underlying spatial units are the CDSM road links (seen in Figure 5-4). The road link spatial data is for year 2015. Emissions for the classes listed in Table 5-7 are estimated. These follow the eNATIS broad classifications as reported in the provincial statistics.

Table 5-7: Vehicle classes for which emissions are estimated

Class	Short name
Passenger motor-vehicles (petrol)	MOTOVP
Passenger motor-vehicles (diesel)	MOTOVD
Minibus taxis	TAXI
Motorcycles	BIKE
Light commercial vehicles (petrol)	LDVP
Light commercial vehicles (diesel)	LDVD
Buses	BUS
Heavy vehicles	HCV

A top-down approach utilizes fuel sales to estimate VKT and allocates this to roads by their type; however, the bottom-up approach serves as a starting point of the emission inventory.

Road count data is used to estimate VKT for each station by applying the count to the immediate road link. The extents are limited in this way because there is no other methodology to describe traffic flow in other links around the station, except using a full-scale network flow model. These links are then removed from the full road network together with estimated fuel consumption for that link by converting VKT to fuel-use using fuel efficiency data. This ensures there is no double counting of both VKT and spatial features. After all bottom-up estimations are done, the remaining road network is used for the top-down approach.

Bottom-up

For this approach, two sources of road counts data were used, namely (Figure 5-5):

- SANRAL national counts for 2016 (through the SANRAL Yearbook Traffic Summaries)
- GAUTRANS Gauteng Manual counts for 2015 (available from Gauteng Department of Roads and Transport)

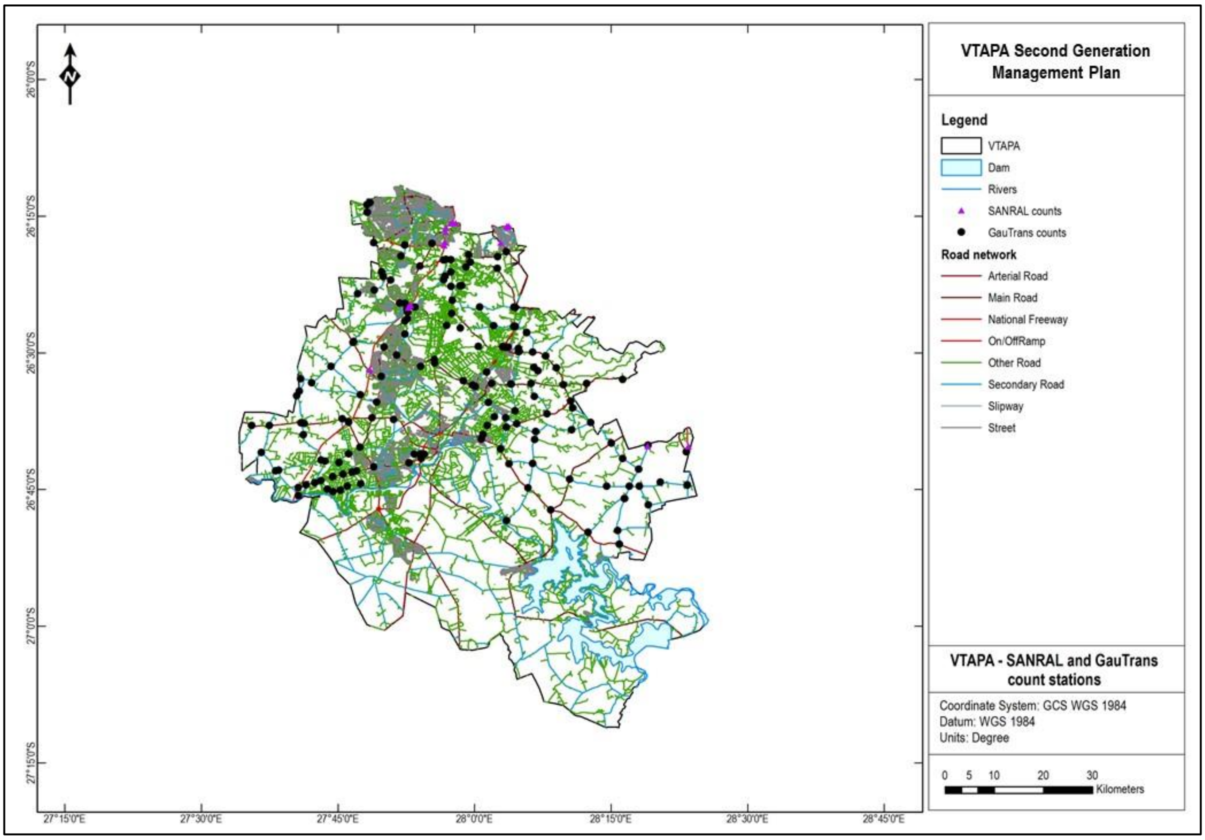


Figure 5-5: Locations of SANRAL and GAUTRANS count stations used for bottom-up approach

The SANRAL counts cover only SANRAL maintained roads, which include primarily the national routes. The GAUTRANS counts cover only the province of Gauteng and include primarily main roads. SANRAL counts offer annual total counts for each station and only stations with >50% annual data coverage were used. For stations with <100% data coverage counts had to be scaled upwards to 100%. GAUTRANS offer only 12-hour (assumed 6 am-6 pm) counts for a few days which must be scaled upward firstly for the remaining 12 hours using a typical diurnal profile and then for the remainder of a 366-day year in 2016. SANRAL counts split counts by Light Vehicle, Short Heavy, Medium Heavy and Long Heavy. GAUTRANS provides counts for Light, Heavy, Taxi and Bus classes. For all data sources their native classes are remapped to those listed in Table 5-7.

With the annual totals split by class, an annual VKT was derived by assigning a CDSM road link (and thus length) to each count station. All VKT are converted into fuel consumption using the efficiency data extracted from the COPERT model (see "Emission Factors" section below). This fuel consumption is subtracted from the provincial fuel sales, together with the road links associated with counts, going into the top-down methodology.

The SANRAL count data is also useful in that average vehicle speeds are given. Using this information, it was possible to assign typical speeds for different CDSM road types. These speeds are necessary for selecting appropriate emission factors further in the process. Figure 5-6 shows the average speeds for light, heavy and overall classes for each CDSM road class.

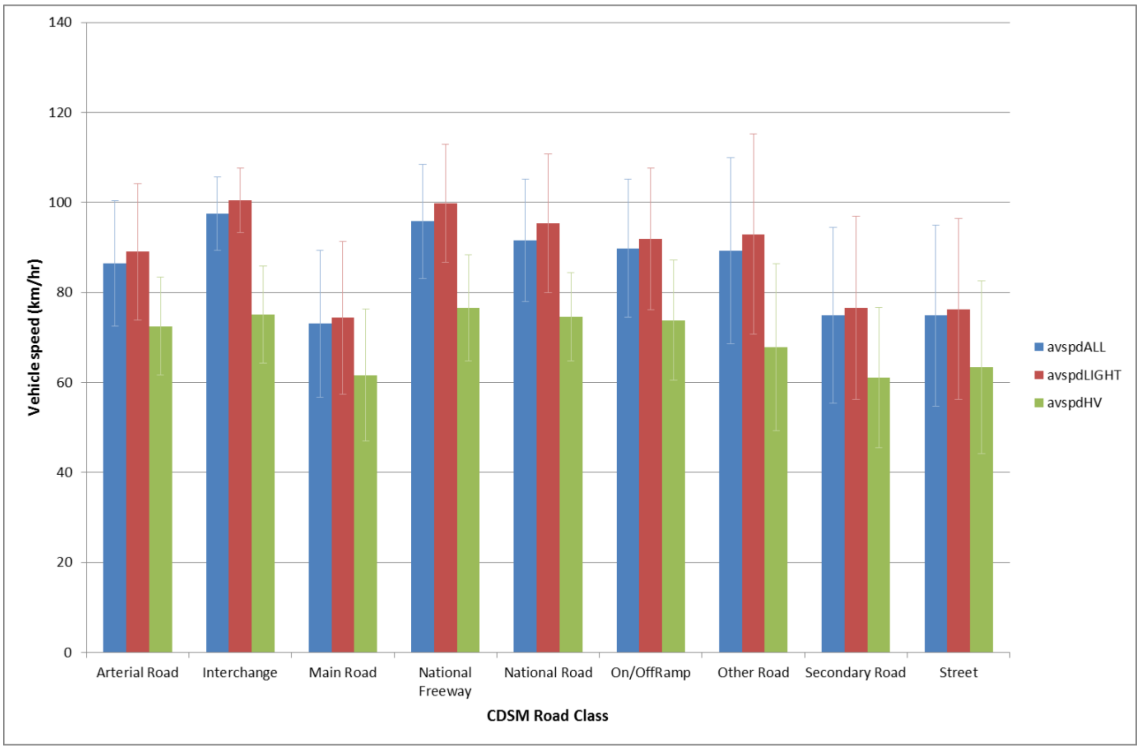


Figure 5-6: Average vehicle (all, light and heavy) speeds for each CDSM road class (derived from SANRAL count data) (variation bars indicate standard deviation)

Top-down

The top-down approach uses provincial fuel sales and fuel efficiency data (from COPERT; see "emission factors" section) to estimate VKT. A key assumption is that fuel sales equate to fuel consumption. This is true for total national volume, however if one tries to look at sales spatially, the possibility of fuel sales being consumed elsewhere is likely. Therefore, provincial sales are used rather than Magisterial District sales (also available from DoE) to minimize this effect.

There is inherent difficulty in assigning the fuel/VKT to specific road links. Similar to the domestic fuel use emissions methodology, national household survey data are used to further disaggregate provincial fuel sales based on travel activity. The National Household Travel Survey 2013 (NHTS; StatsSA, 2013) trip information per mode of transport was used to this end. Survey data are collected at the "Travel Analysis Zone" (TAZ) level, and is a unique demarcation compared to Census spatial units. A provincial proportion of trip activity was derived, and fuel sales disaggregated accordingly. Figure 5-7 (petrol) and Figure 5-8 (diesel) show the percentage of total fuel in TAZ's within VTAPA.

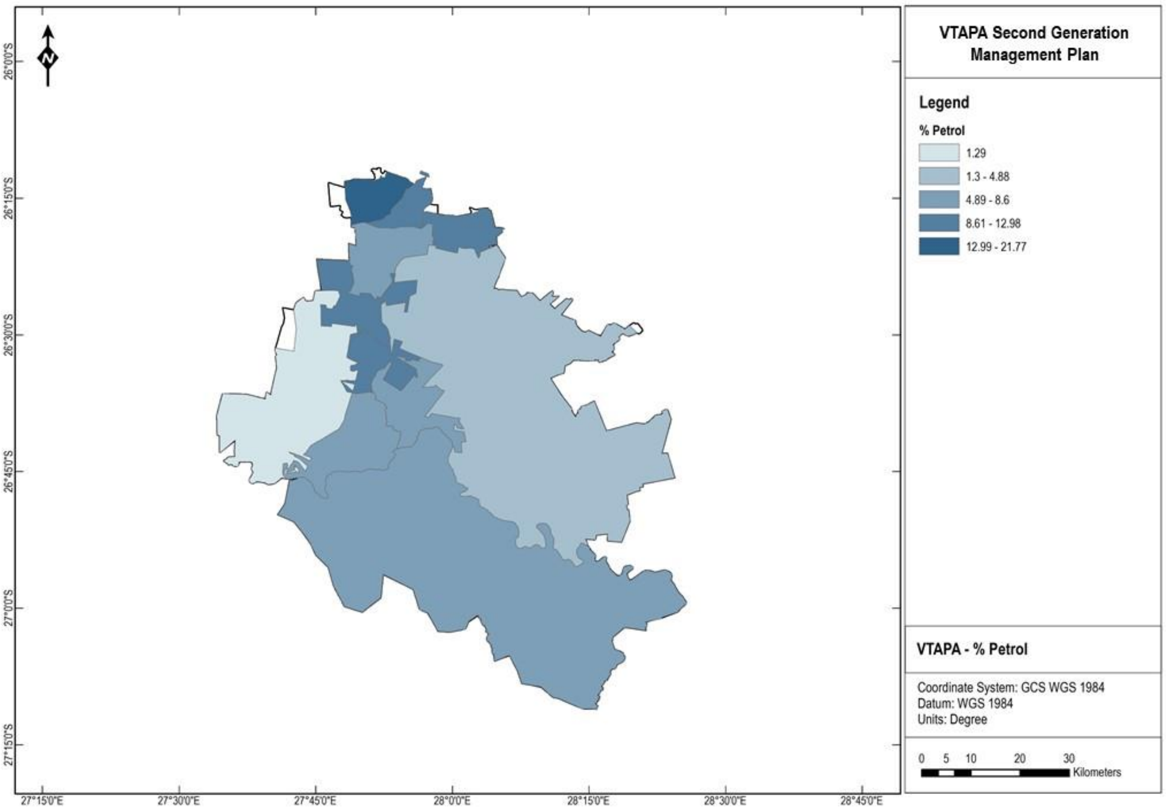


Figure 5-7: Percentage of total fuel allocated to only TAZ's within VTAPA - petrol

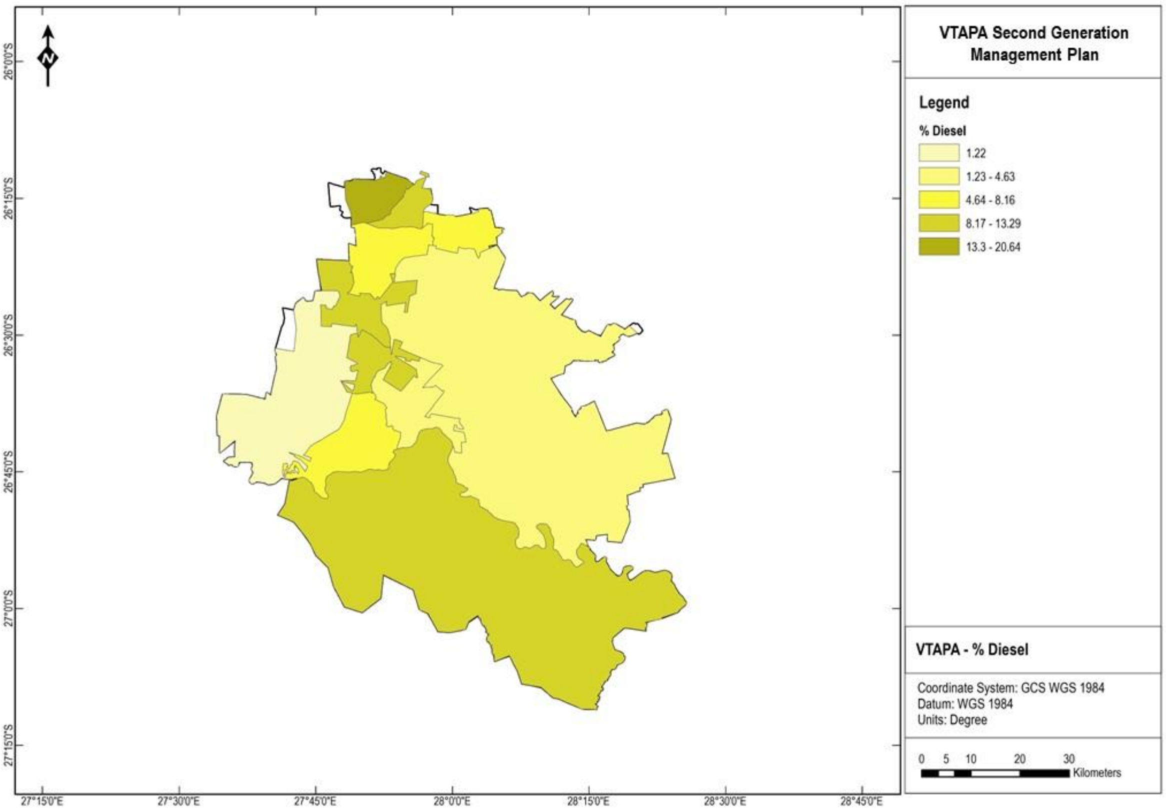


Figure 5-8: Percentage of total fuel allocated to only TAZ's within VTAPA - diesel

Once fuel sales are allocated to TAZ, it is necessary to disaggregate further down to road level. This is accomplished by using data from the South African Road Classification and Access Management Manual (SARCAMM; Committee of Transport Officials, 2012). Tables B and C of the manual provide typical average annual daily traffic (AADT) for different road classes. These typical road AADTs were used to proportionally distribute fuel to different CDSM road classes. However, further refinement to the CDSM road classes was necessary to assign both a commercial and urban/rural status. This was achieved using Census 2011 household weighted Enumerator Type and Geotype data at the sub-place level. This effectively means assigning a commercial/non-commercial and urban/rural status to the CDSM road types seen in Figure 5-4. The result is 40 unique road classes, to which typical AADT from the SARCAMM can be assigned. Fuel within each TAZ is then distributed by the typical AADT proportion amongst classes. The final level of disaggregation is achieved by then allocating fuel proportionally within classes based on link length. The result is a fuel consumption estimate on each of the remaining (after removals from the bottom-up processing) CDSM roads. This fuel consumption is converted to VKT using the COPERT-derived fuel efficiency data

Emission factors

For this study, “hot running” (thermally stabilized engine and exhaust treatment) emission factors were derived from the COPERT 5 (version 5.0.1145) model. The model is developed by EMISIA SA and supported by the European Environment Agency (EEA). The methodological approach (and thus formulae) for COPERT 5 is identical to the Tier 3 methodology laid out in the EMEP/EEA air pollutant emission inventory guidebook 2013 (European Environment Agency, 2013) for “Exhaust emissions from road transport” (Part B, Section 1.A.3.b.i-iv).

The COPERT approach was chosen since all other locally derived emissions factors (e.g. Stone, 2000; Wong, 1999; Wong and Dutkiewicz, 1998) provided an emission factor at a generalized single speed; while what is required for this emission inventory is a speed-based estimate since emissions factors are sensitive to vehicle speed. Additionally, locally derived emission factors represent a much older vehicle fleet; typically pre-EURO2.

Emission factors were modelled for EURO1-6 stage vehicles from the classes specified in Table 5-7. Table 5-8 lists the approximate manufacture years for each EURO stage.

Table 5-8: Vehicle EURO stage manufacture years

EURO stage	Vehicle model year
EURO1	1992-1995
EURO2	1996-1999
EURO3	2000-2004
EURO4	2005-2009
EURO5	2010-2014
EURO6	2015-current

Emission factors for CO, NO_X, non-methane VOC (NMVOC), $PM_{2.5}$, methane (CH_4), ammonia (NH_3) and SO_2 were estimated in COPERT for speeds from 10 to 120 km/hr (in 10 km/hr increments). COPERT also estimated fuel consumption (i.e. efficiency in l/km) for each speed. Note that in practice the closest emission factor speed is matched to the specific speeds in Figure 5-6 for vehicles travelling on that road. The full emission factor/fuel consumption dataset thus comprised 4 032 factors (6 EURO classes by12 speeds by 7 vehicle classes by 8 pollutants).

Since there is no indication of vehicle age or technology within the activity data used (both counts for the bottom-up and fuel sales for the top-down) it is necessary to aggregate the emission factors by EURO stage. To simply take an average would not be accurate since that would assume all vehicle ages exist at an equal proportion in the vehicle parc. This is not true as newer vehicles enter the parc, older ones leave; resulting in a shift towards newer vehicles. The spread of vehicle age in a parc can be determined through scrapping curves. A weighted average of emission factors between EURO stages can then be obtained to derive a single emission factor per vehicle class and pollutant (still at the different speeds). The scrapping curve used in this study is based on Merven *et al.* (2012) eNATIS calibrated (year 2010) Weibull cumulative distribution functions that show probability of vehicle survival as a function of age. These functions are then applied to the time periods relevant to this study (Table 5-8). Figure 5-9 shows the scrapping curves used for each class.

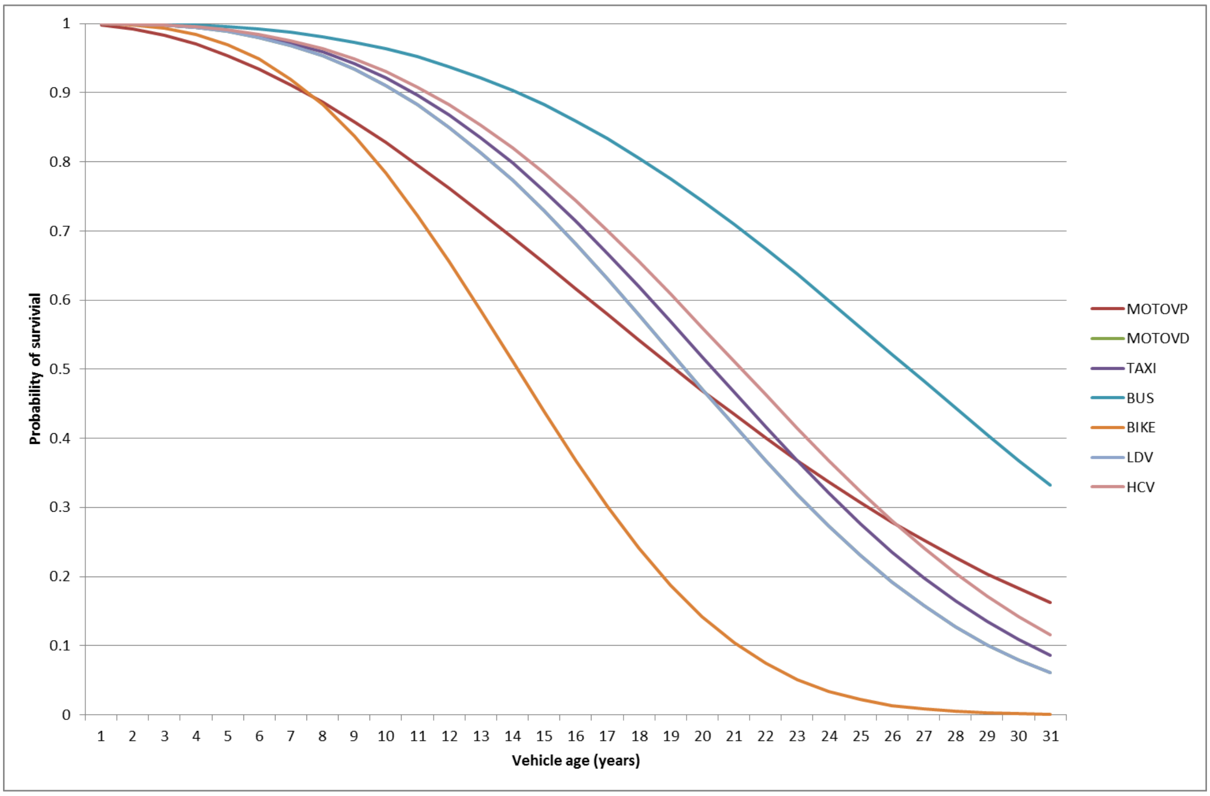


Figure 5-9: Scrapping curves used to weight EURO stage emission factors (note the MOTOVD and LDV curves are identical therefore the one is obscured)

These curves were used for deriving an age proportion weighted average emission factor for each speed (now synonymous with road type) and pollutant per vehicle class. Figure 5-10 shows diesel NOx emission factors derived from COPERT and illustrate the importance of vehicle speed. Figure 5-11 shows similar but for petrol classes.

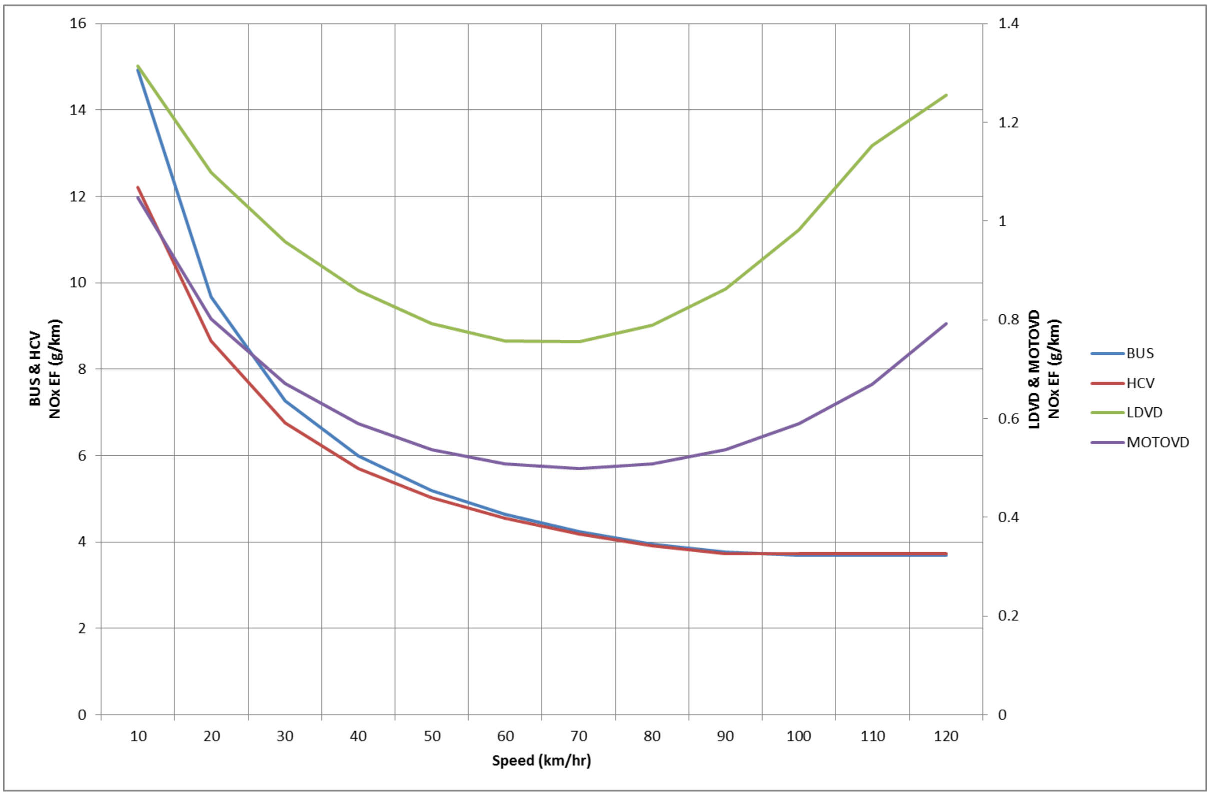


Figure 5-10: NOx emission factors for diesel classes

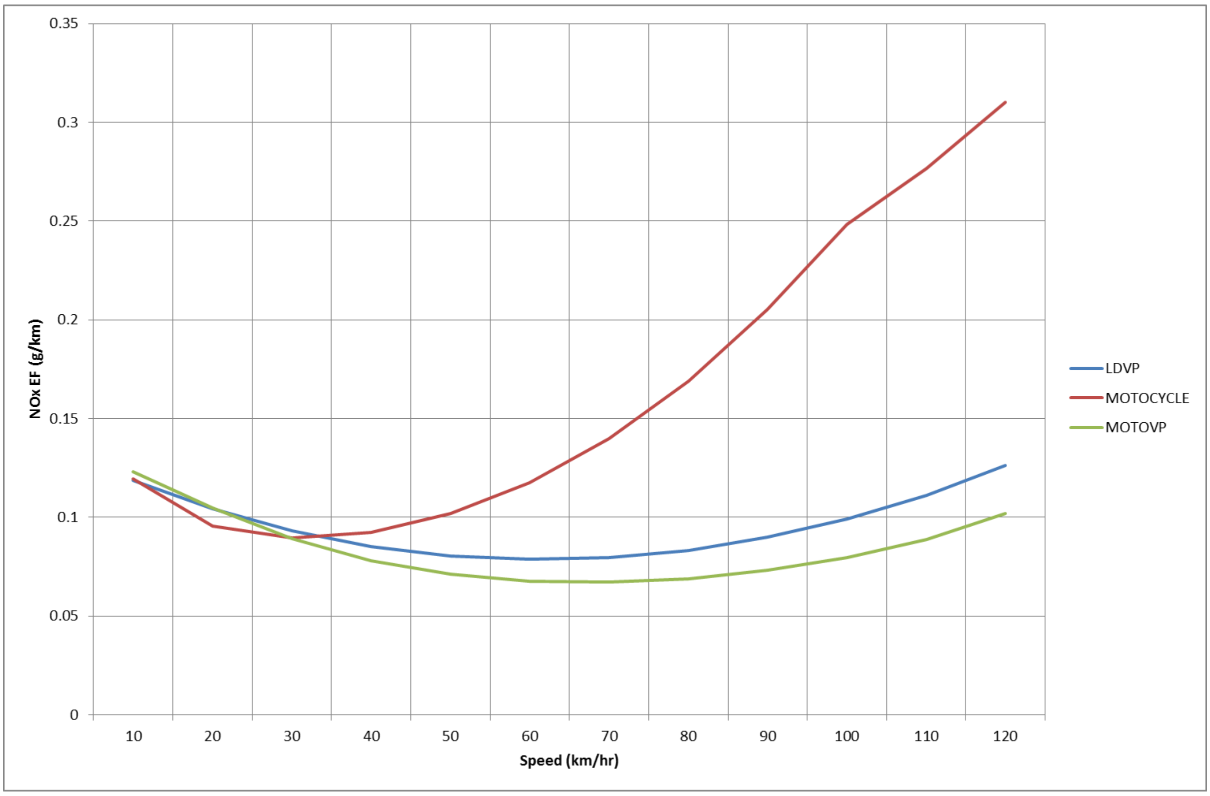


Figure 5-11: NOx emission factors for petrol classes

The emission factors were then applied to the VKT per vehicle class and road type to derive an annual emission estimate per road link for all pollutants of concern.

For verification, the NOx output from COPERT was compared with the most recent local emission factor study (i.e. Goyns, 2008). Goyns (2008) provides emission factors derived from detailed load-based measurements and then factor calculations (albeit for a small sample of vehicles). COPERT emission factors compare very well with those derived during Goyns (2008) study, particularly for petrol motor-vehicles (only EURO2 and EURO3 available in Goyns, 2008) with COPERT slightly over-estimating. For diesel motor-vehicles, COPERT slightly under-estimates NOx emission factors (note that only EURO2 could be compared).

Considering activities occurring internationally, i.e. those regarding the adoption of a new World Harmonised Light-Duty Test Procedure (WLTP), emission factors derived through COPERT are likely to change (Demuynck et al., 2012). The WLTP aims to introduce real-world driving patterns and early indications are that at least CO_2 emissions will increase (Tsiakmakis, et al., 2017).

Temporal profiles

Emissions are estimated as annual tonnage; however, temporal variation (particularly diurnal) of vehicle activity is an important factor to consider for modelling purposes. Introduction of pollutants into the morning and evening boundary layer have profound consequences for concentrations at the surface. This is true for both primary and secondary species.

Average diurnal vehicle activity recorded from 3 570 automated SANRAL counting stations were analysed. This data were made available directly from Mikros Traffic Monitoring through facilitation from DEA. The data included averaged diurnal and weekly variation, similar to those seen in the published SANRAL Mega-Yearbook. During emissions processing for modelling, annual tonnage is first scaled by monthly variation profiles. The resulting emission rate is then scaled for day of week (i.e. Sunday to Friday) since vehicle emissions are different for weekends and weekdays. These rates are then finally scaled for diurnal variation; and there are two diurnal profiles; one for weekends and one for weekdays. The result is an hourly emission rate for each grid cell.

Monthly average activity for each station was not available and therefore data was taken directly from the SANRAL Mega-Yearbook. Data from 11 representative stations were copied. These stations are all high-volume stations and had higher than 99% data coverage for the year. Figure 5-12 shows the derived monthly profile.

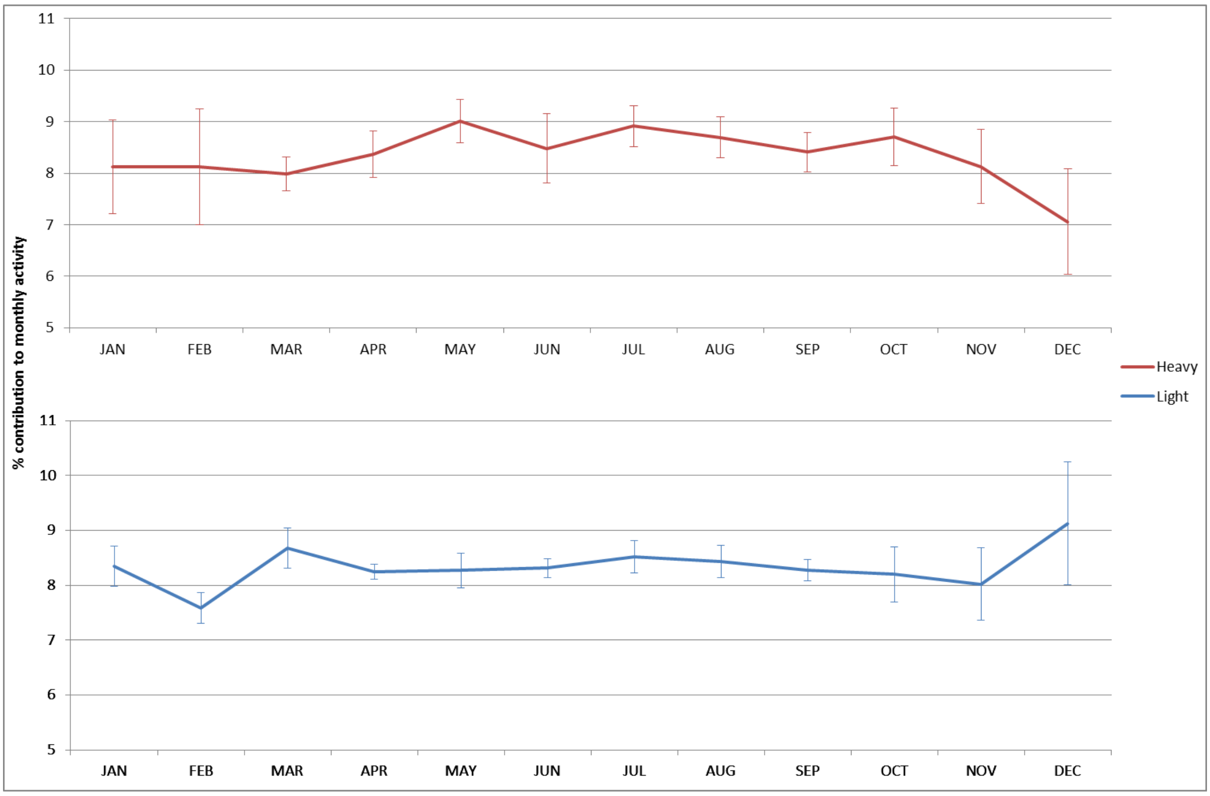


Figure 5-12: Monthly profile derived from SANRAL count data (11 stations only)

The weekly and diurnal profiles were derived from all stations. Figure 5-13 shows the weekly profile; illustrating lower volume on the weekends. Figure 5-14 shows the diurnal profile for weekends and weekdays. Note that the y-axis shows percentage activity and not magnitude. Emission rates passing through the weekly profile will be lower for weekends than weekdays; and this rate is passed to the diurnal profile.

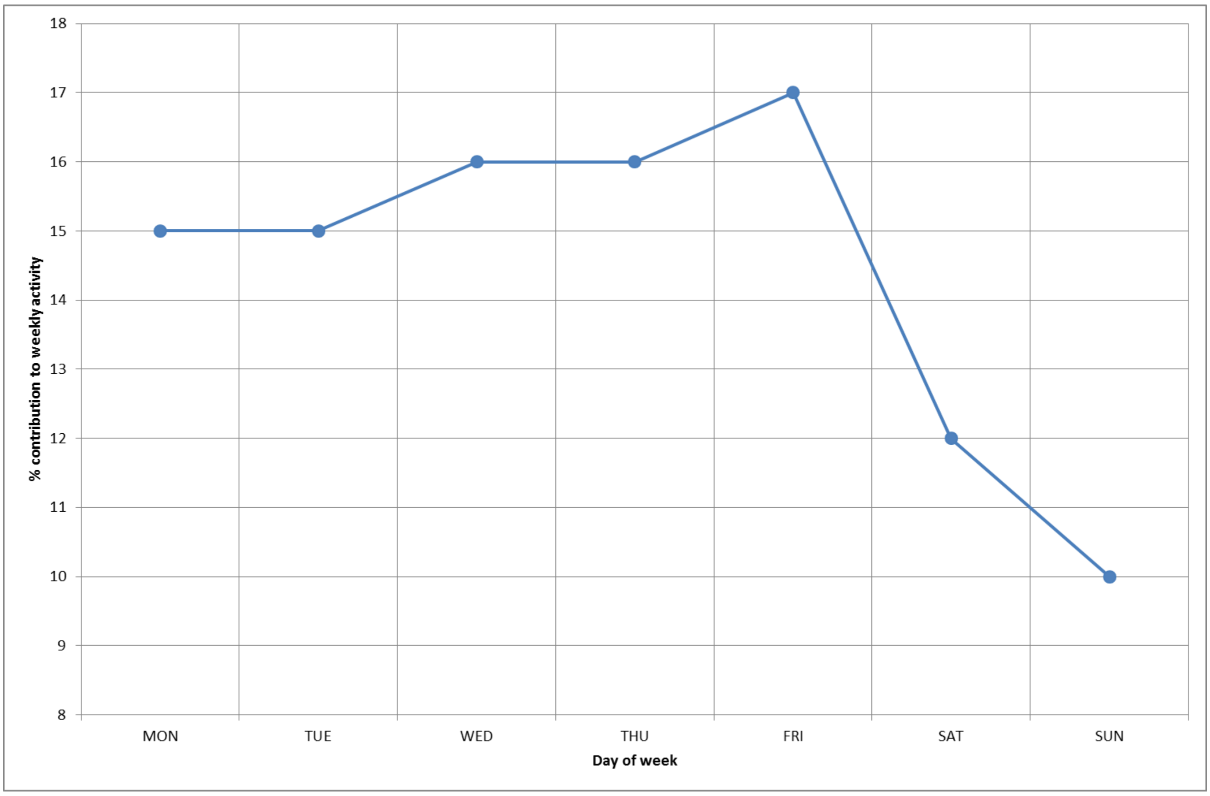


Figure 5-13: Weekly profile derived from SANRAL count data

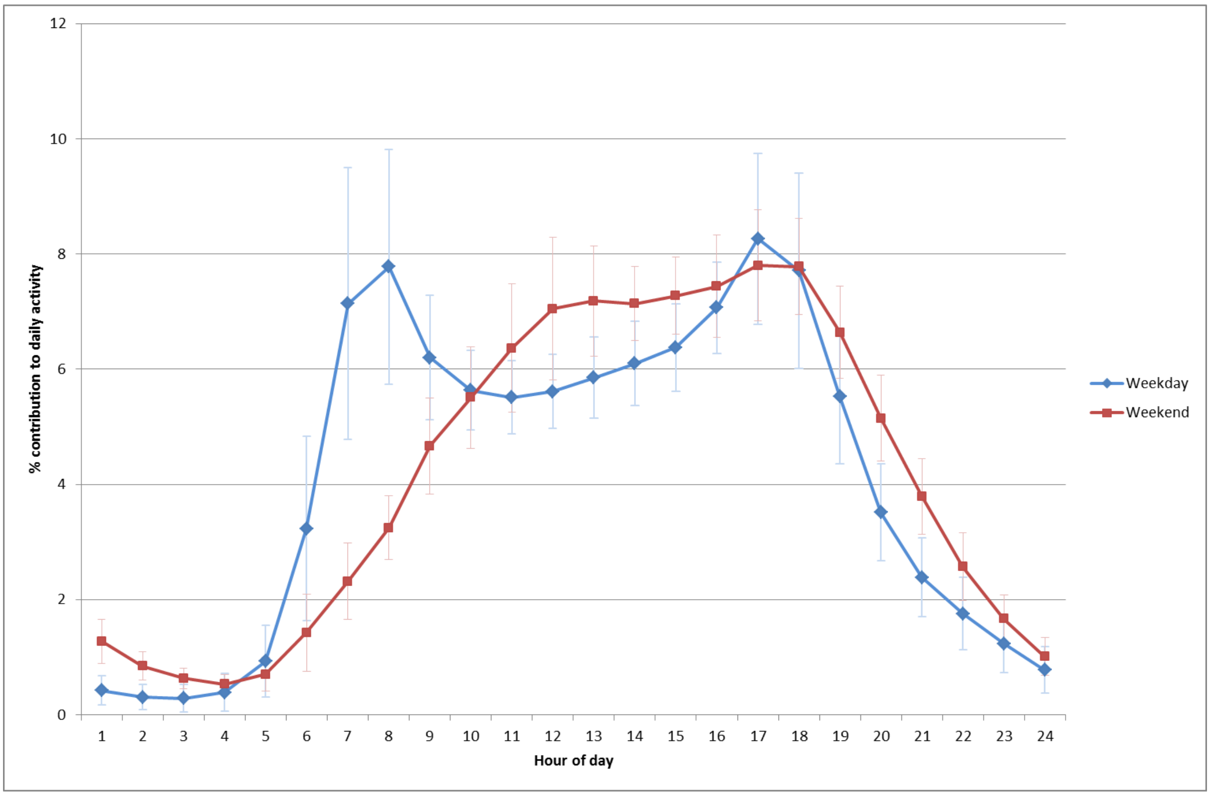


Figure 5-14: Weekend and weekday diurnal profiles derived from SANRAL count data (bars indicate standard deviation)

5.1.3.2 Results

Table 5-9 provides estimated total annual emissions from on-road vehicles based on the hybrid bottom-up/top-down approach in the model (1 km fine grid) for the VTAPA only. Most of the total domain emissions are estimated to occur outside the VTAPA since Johannesburg (and much of Gauteng) has been included in the model domain. This is more clearly seen in Figure 5-15. The VTAPA highest vehicle emissions occur in the north around Soweto and along the inhabited corridor (Figure 5-15).

Table 5-9: Estimated on-road vehicle emissions (tonnes per annum)

	CO	NOx	NMVOC	PM	CH_4	NH_3	SO_2
Model domain	39 379	31 103	3 680	925	540	2 058	964
VTAPA only	9 635	8 299	967	245	138	493	251
% in VTAPA	24	27	26	26	26	24	26

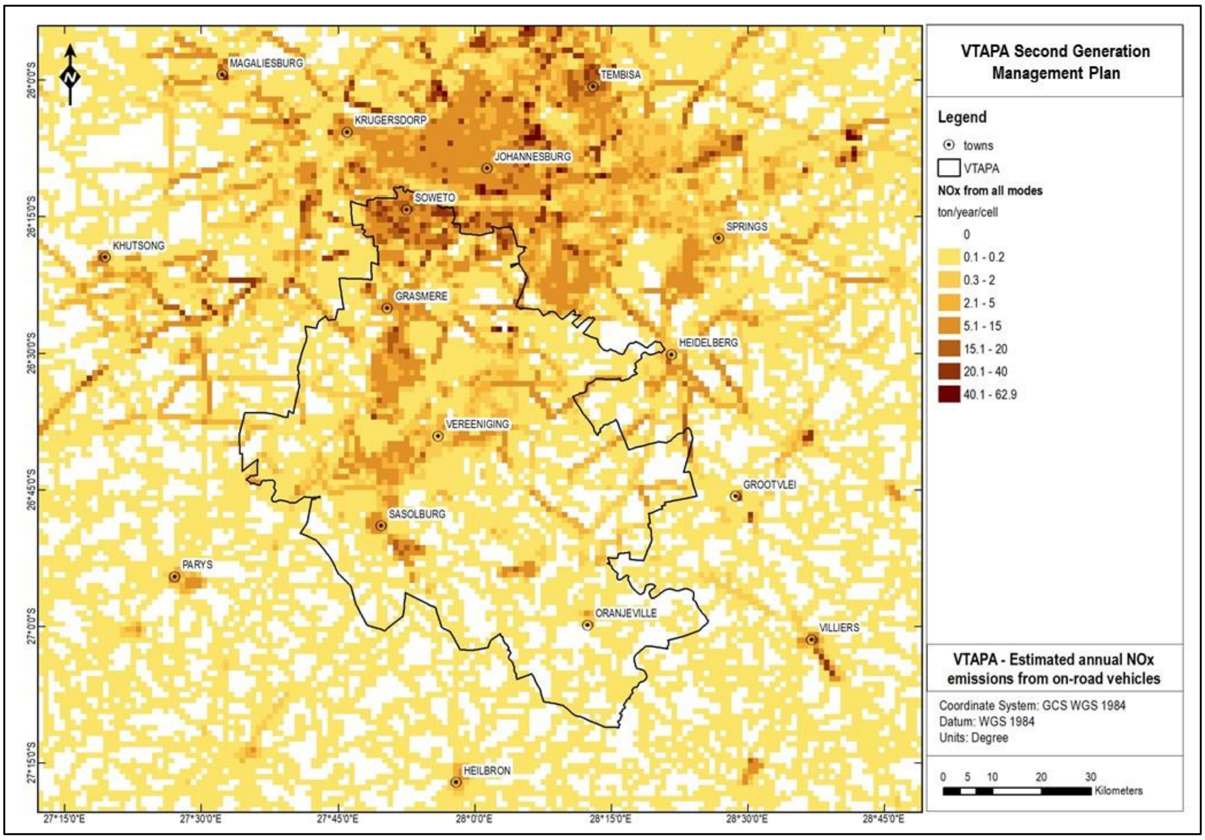


Figure 5-15: Map showing estimated annual NOx emissions from on-road vehicles (all classes) in the 1 km model domain and VTAPA (outlined in black)

5.1.3.3 Comparison with other inventories

While comparison with other inventories is difficult to accomplish, due to the differences in source data, methodology and focus of the respective inventories, it is seen as a useful exercise in illustrating the range of estimates possible. There are indeed often obvious reasons as to why two inventories would be different.

The medium-term review of the 2009 Vaal Triangle Airshed Priority Area: The medium-term review did not recalculate emissions from vehicles due to insufficient required road data, and thus estimates from the 2009 AQMP were assessed. The methodology used in the 2009 AQMP was similar to that employed within this AQMP, in that count data (where available) formed the basis of a bottom-up approach while "left-over" fuel was used in a top-down estimate. Magisterial fuel sales data for 2006 was used while count data represented the period 2004 to 2006. Class splits were derived from 2005 NATIS data. Emission factors were sourced from Stone (2000) and Wong and Dutkiewicz (1998). Table 5-10 shows the 2009 AQMP estimates with this AQMP estimates for NOx, PM_{10} and SO_2.

Table 5-10: 2009 versus 2018 AQMP vehicle emissions (tpa)

	PM	SO_2	NOx
2009 VTAPA AQMP (2013 medium term review)	1 068	448	16 593
2018 VTAPA AQMP	245	251	8 299

It is clear that 2009 AQMP estimates are higher by at least a factor of 1.8. One of the leading reasons for this is the differences in emission factors (including fuel consumption rates). The 2009 AQMP utilized emission factors representative of a very old vehicle fleet (pre-EURO2; vehicles older than 1999). Additionally, the emission factors corresponded to idle speeds rather than road speeds. These lead to the emission factors being higher than those generated by COPERT (and thus the EEA guidelines for Tier 3). While this has led to a higher estimate, it is currently unclear what the 2018 modern fleet is comprised of in terms of vehicle age (although assumed to be much newer than 1999 model years). More importantly, it is unclear what emission factors are appropriate for the current VTAPA fleet using current specification fuels in current driving cycles. These factors, once refined through wide-scale surveys and emissions testing using the WLTP, can lead towards a much more refined estimate.

Motor Vehicle Emission inventory (part of the Integrated Strategy for the Control of Motor Vehicle Emissions):
The Motor Vehicle Emission inventory (MVEI here) covered a national scale and was conducted in 2013. It used a hybrid of top-down and bottom-up approaches; albeit with a much more refined GIS handling of the bottom-up count allocation compared to the 2009 VTAPA AQMP. The emission inventory focused on the national level and was geared for strategic assessment. Fuel sales for 2009 were used and road counts covered 2011. It is stated that the emission factors used are the EEA Tier 1 dataset as found in the EMEP/EEA Emission Inventory Guidebook 2009 (Chapter 1.A.3.b.i-iv; updated in 2012). It should be noted that the tables may have changed since those documented in the MVEI do not correspond with those found within the EEA 2009 guidebook. Table 5-11 shows the Motor Vehicle Emission inventory estimates for City of Johannesburg compared with those estimated for this AQMP (CoJ is a part of the 1km resolution domain).

Table 5-11: CoJ vehicle emission estimates from the Motor Vehicle Emission inventory vs 2018 VTAPA AQMP estimates

	NOx	SO_2	CO	PM_{10}	NMVOC
Motor Vehicle Emission inventory for CoJ	40 676	751	228 830	1 677	34 319
2018 VTAPA AQMP (CoJ area)	11 899	317	16 194	365	1 596

SO_2 shows the lowest difference with the MVEI (factor of 2.4), while NMVOC shows the highest (factor of 21). CO is the second highest with a factor of 14 difference. Large differences in CO and NMVOC generally indicate a difference in vehicle age considered, as older vehicles tend to be much more inefficient.

The EEA does indicate that Tier 1 emission factors could be used for developing countries (lacking more detailed information); however, it is also states that emissions may be over-estimated if the vehicle fleet of the country is newer than EURO2.

"*However, a consequence of this approach, in the context of the legislative emission requirements for more modern vehicles, is that the Tier 1 emission factors will give somewhat higher emission values than a Tier 2 or 3 methodology for countries whose fleet comprises vehicles which comply with more recent (i.e. Euro 2 / Euro II and later) emission standards.*" EEA, 2013.

This is due to the fact that Tier 1 emission factors represent an EU vehicle fleet in 1995. More specifically, the emission factors used for the MVEI correspond to vehicles with technology at the ECE 15/04 (1985 – 1992) and Open Loop (late 1980s) legislative levels. It is therefore unsurprising to see the differences between the MVEI Tier 1 results and the 2018 VTAPA AQMP estimates here. With regards to PM_{10}, further differences are due to the fact that the MVEI included PM from brake and tyre wear.

5.1.4 Domestic Fuel Burning

There is growing evidence of a decreased reliance on fuel combustion for energy use in the domestic environment in South Africa. This is primarily due to increased access to electricity. According to Statistics South Africa (via the official Census and annual general household surveys), the percentage of households, as of 2013, with access to electricity is 85.4%. While this does not necessarily mean the total disuse of fuel combustion in those homes (particularly for heating), it does offer an indication of potentially decreased domestic fuel combustion. This could potentially be offset by population growth; particularly in areas predominantly reliant on indoor fuel combustion. Figure 3-3 (Section 3: Geography and Demographics) shows the population growth in the area based on a comparison of Census 2001 and 2011 results. There is growth primarily within the central and eastern regions of the VTAPA. Figure 5-16 also shows that the central region is particularly dense with respect to population.

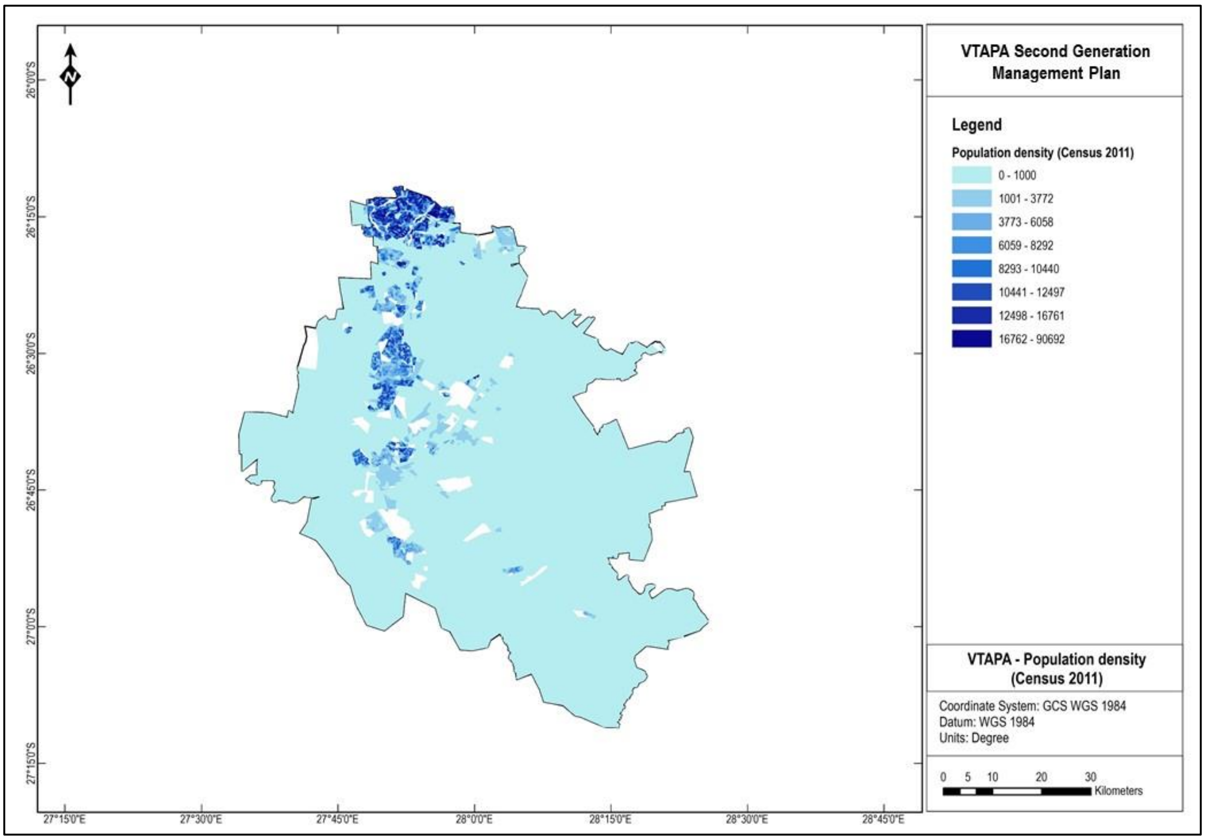


Figure 5-16: Population density within VTAPA (derived from Census 2011 results)

However, these areas are not necessarily dominated by fuel combustion; as seen in Figure 5-17 and Figure 5-18 showing an intra-small area level (SAL) percentage of fuel use. A potential reason could be that newer areas are electrified.

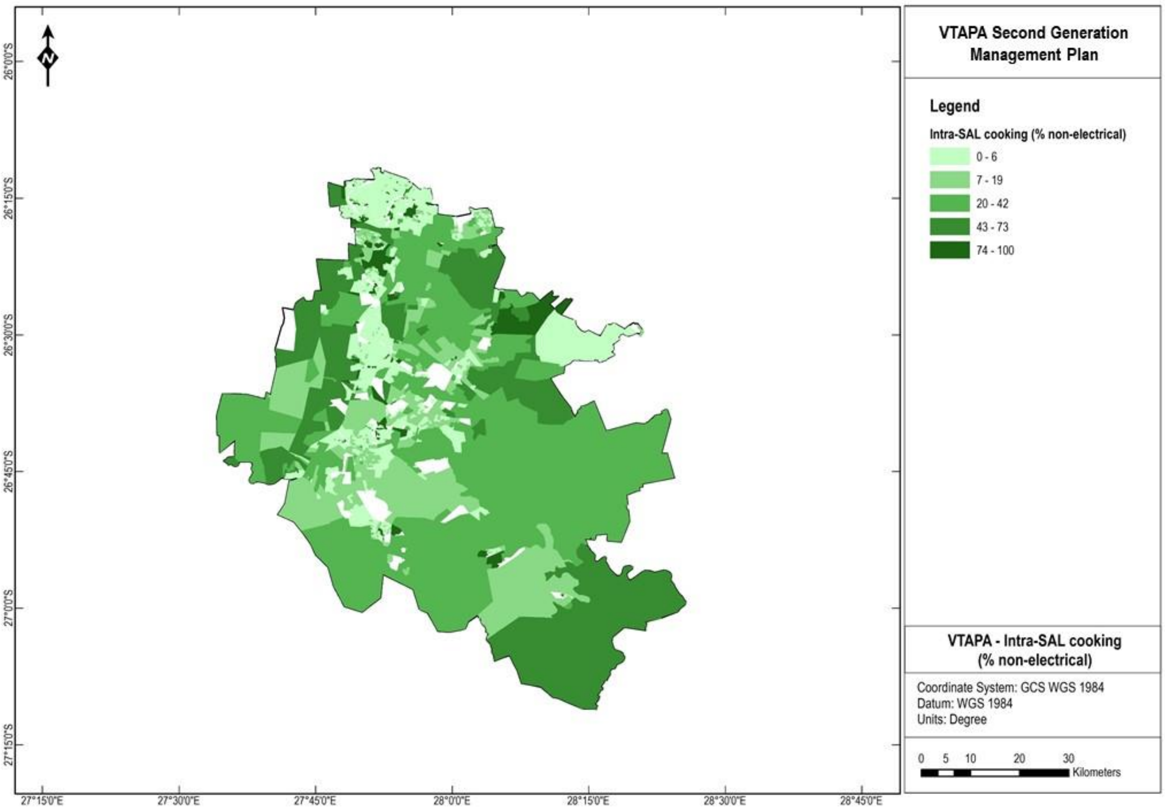


Figure 5-17: Intra-SAL percentage of non-electric energy use for cooking

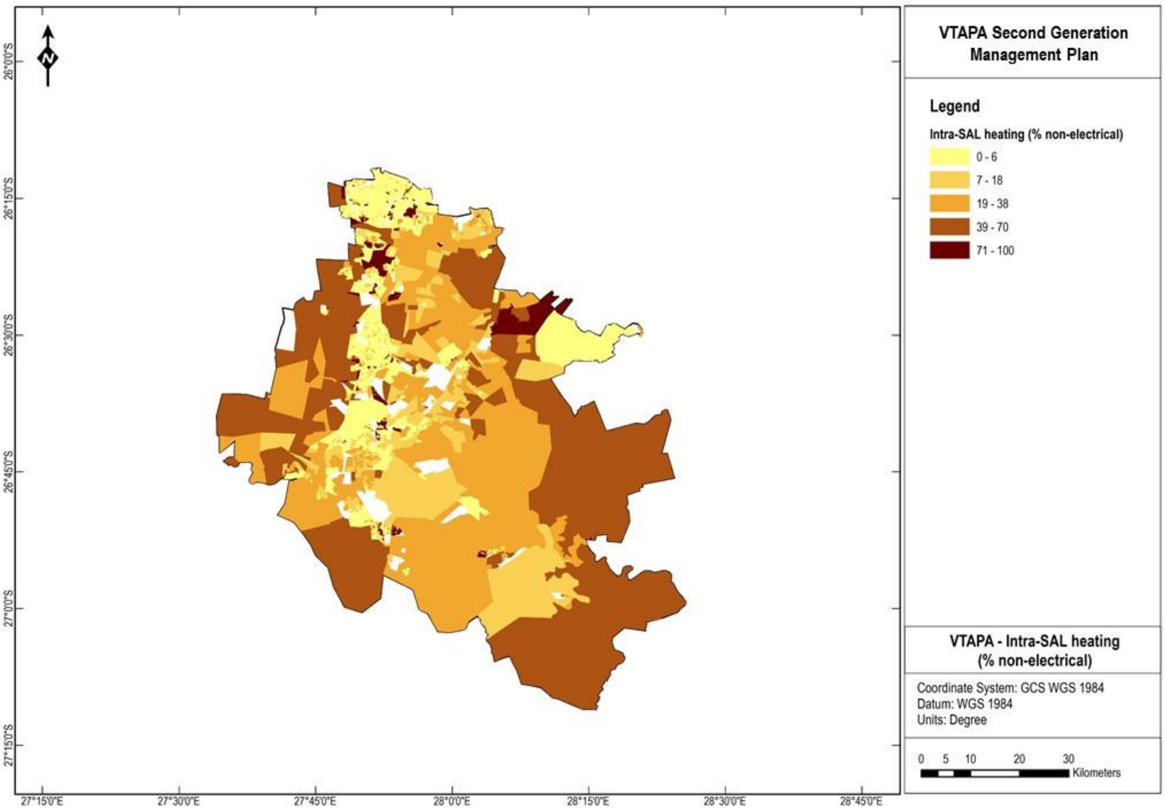


Figure 5-18: Intra-SAL percentage of non-electric energy use for heating purposes

One of the most pertinent issues around household fuel combustion is the proximity of the emission source to people. This is exacerbated by poor combustion devices and improper indoor ventilation. Important pollutants include PM, CO, SO_2, NO_X and various VOCs. The amount of each pollutant emitted depends on the type of fuel burnt, for example, SO_2 is relevant for coal combustion, while PM and VOC are concerns for wood burning.

The spatial variability and different pollutant contributions (both primarily driven by variability in fuel use by type) need to be captured in detail to estimate a gridded representation of emissions from domestic fuel burning. Approaches to derive at an emission inventory for domestic fuel use generally rely on activity data from a national Census. The data from the South African Census is based on questions around the type of fuel used for cooking, heating and lighting. This represents, at a spatial level of Census geographic units, the number of households using a specific type of fuel. Top-down approaches, that utilize a regional fuel consumption estimate, disaggregate the regional sum down to these geographic units. Bottom-up approaches, that utilize a fuel consumption estimate per household, scale up fuel use by number of households within each geographic unit. Each approach has benefits and disadvantages and depends highly on available data and its uncertainty.

5.1.4.1 Methodology

Both a top-down (for gas, paraffin and coal) and bottom-up (for wood) approach was used for the domestic fuel use emissions in this study; and the spatial aspect was refined using a dwelling inventory. Both methodologies have inherent uncertainties. Bottom-up approaches, while often based on data derived from direct surveys, are subject to small sample size and will tend to aggregate uncertainty further away from the survey community and scaling is applied purely according to number of households found in other regions. Top-down approaches rely on a national fuel consumption estimate, which is subject to uncertainty in assumptions on the aggregated national level. A bottom-up approach for wood combustion was selected as the top-down approach derived per-household proved to be 3-times higher than available survey data. This sector inventory makes use of Census information, and thus only emissions from coal, wood, LPG and paraffin use are estimated.

Top-down

The national residential fuel consumption data (Table 5-12) was acquired from the annual published DOE energy balance data (DOE, 2014; available online). The methodology used to derive energy balance statistics are based on International Energy Agency (IEA) best practice and is applied through collaboration of DOE with Statistics South Africa. Commodity flow (defined as the movement of a commodity from its point of production to where it is transformed or finally consumed) consumption estimates for the residential sector where used.

The data represented year 2014, as statistics for subsequent years were not yet available. Notably the coal consumption estimate has decreased by more than a factor 10 compared to previous years. No definite reason is given; however, mention is made that the assumption used to calculate data for bituminous coal was reduced from 66% to 5% of domestic coal merchant sales. The lower 2014 data was used. Table 5-12 provides the DOE reported consumption data.

Table 5-12: Top-down residential fuel consumption as estimated by DOE (2014)

Fuel	DOE name	Residential consumption	Native units
Bituminous coal	BITCOAL	508 057	tons
Gas	LPG	148 541	kilolitres
Paraffin	OTHKERO	288 158	kilolitres

In order to convert gas consumption to tons (appropriate for emission factors) a density of 0.54 kg/L for LPG (Afrox specifications) was used.

Community Survey 2016 and Census 2011 data was used to proportionally disaggregate national fuel consumption to provincial and then Small Area Level (SAL) geographic units (the finest level of spatial detail provided by the officially released Census 2011 dataset). This is achieved by calculating the provincial proportion of national households using coal, gas or paraffin. The Community Survey provided the number of fuel burning households; but only up to local municipality level. Further disaggregation to SAL was achieved by proportions derived from Census 2011. Thus the actual number of households is based on Community Survey 2016. The Census questions allow respondents to answer multiple fuel types within and between different applications of cooking and heating. It is assumed that most of the fuel mass is consumed by either cooking or heating and thus lighting statistics are not considered here. While it is not necessary to distinguish multiple fuel type responses within an application, it is not appropriate to, for example, add households from cooking and heating categories together as this leads to double counting. Furthermore, the choice of which type of energy application category to use (i.e. cooking or heating) is important as each may display different proportions per area, and depending on the proportion used, will lead to a different spatial distribution of fuel use. The choice needs to be made around which application to use as a representation of households using a certain type of fuel. The approach for this study is to use the application with the greatest number of households per fuel type.

The provincial consumption is then further disaggregated down to the Census SAL. Further spatial refinement is possible via the StatsSA Dwelling Frame database. This is a database of dwelling units created and updated during each national Census. This is necessary for modelling since there is a high likelihood that a single SAL may span many model grid cells; therefore, a methodology for disaggregating the fuel to a finer level of detail is needed. The dwelling frame database is likely to be more accurate than the Eskom Spot Building Count dataset; however, there are still some issues within the current database (e.g. for some enumerator areas points are randomly placed).

Bottom-up

The average per-household fuel consumption for wood derived through a top-down approach was three times higher than available survey data. Per-household estimates for the other fuel types were within reasonable range compared to available survey literature (i.e. coal, gas and paraffin). Table 5-13 shows the survey literature used to appraise a top-down wood estimate and the average per-household fuel consumption that was used for this bottom-up approach.

Table 5-13: Survey information used for bottom-up wood consumption

Study	Location	Dwelling Type	Wood source	Dwelling electrification	Mean wood consumption (kg/HH/year)	Standard deviation (kg)
Kaoma & Shackleton (2015)	Bela-Bela, Limpopo	Township	Collected	Electrified	1 300	1 700
	Bela-Bela, Limpopo	Township	Bought	Electrified	1 100	2 400
	Bela-Bela, Limpopo	Informal	Collected	Non-electrified	6 430	23 420
	Bela-Bela, Limpopo	Informal	Bought	Non-electrified	900	1 000
	Tzaneen, Limpopo	Informal	Collected	Electrified	5 100	13 700
	Tzaneen, Limpopo	Township	Collected	Electrified	2 200	3 600
	Tzaneen, Limpopo	Informal	Bought	Electrified	2 500	2 400
	Tzaneen, Limpopo	Township	Bought	Electrified	3 200	3 800
	Tzaneen, Limpopo	RDP	Collected	Non-electrified	4 100	5 200
	Tzaneen, Limpopo	RDP	Bought	Electrified	2 100	2 100
	Zeerust, North West	RDP	Collected	Electrified	3 100	4 400

Study	Location	Dwelling Type	Wood source	Dwelling electrification	Mean wood consumption (kg/HH/year)	Standard deviation (kg)
	Zeerust, North West	Township	Collected	Electrified	6 960	18 840
	Zeerust, North West	RDP	Bought	Electrified	1 500	3 500
	Zeerust, North West	Township	Bought	Electrified	1 200	2 300
	Zeerust, North West	Informal	Collected	Non-electrified	5 330	3 920
	Zeerust, North West	Informal	Bought	Non-electrified	2 200	2 700
Scheepers (2013)	Bela-Bela, Limpopo	Township	Collected	Electrified	1 833	0
				Average	**3 003**	

The average wood consumption of 3 tons per household per year was used to estimate wood usage for the SALs in the model domains. This is achieved by simply multiplying the usage by the number of households in that SAL using wood (for cooking or heating whichever is higher). The StatsSA Dwelling Frame database is then used to disaggregate the usage to a finer spatial resolution appropriate for use on the model grids.

Emission factors

A comparison of emission factors was done, considering those from the FRIDGE study (Scorgie *et al.*, 2004), the USEPA AP-42 dataset, the GAINS United States and Australia model (Amann *et al.*, 2011), Ballard-Treemer (1997), Britton (1998), Scorgie (2012) and Makonese *et al.* (2015). Many of the South African studies focused on coal. A recent study (Kornelius *et al.*, 2015) produced emission factors for wood burning; however, these were for gasification stoves and were thus not deemed representative of what people currently use in their homes. A hybrid selection from the studies mentioned is considered in this household fuel combustion emissions methodology.

Table 5-14 lists the emission factors used.

Table 5-14: Emission factors used for domestic fuel combustion

Pollutant	Gas		Paraffin		Wood		Coal	
	Factor (g/kg)	Source	Factor (g/L)	Source	Factor (g/kg)	Source	Factor (g/kg)	Source
SO_2	0.01	FRIDGE	0.851	FRIDGE	0.123	Ballard-Tremeer, 1997	11.6	Scorgie, 2012
PM_{10} c(a)	0	NA	0	NA	1.035	AP-42	0	Makonese *et al.*, 2015
$PM_{2.5}$	0.068	AP-42	0.359	AP-42	13.745	AP-42	16.146	Makonese *et al.*, 2015
NO_X	1.4	FRIDGE	1.5	FRIDGE	1.224	AP-42	3.95	Makonese *et al.*, 2015
VOC	0.018	AP-42	0.085	AP-42	19.867	AP-42	5	FRIDGE
NH_3	0	NA	0	NA	0	NA	0.0003	AP-42
CO	13.6	FRIDGE	44.9	FRIDGE	114.577	FRIDGE	94.38	Makonese *et al.*, 2015
CH_4	0.012	AP-42	0.213	AP-42	2.177	AP-42	3.6	AP-42

Note: (a) PM_{10} c represents only the coarse fraction (i.e. PM with diameter 2.5 µm to 10 µm)

Temporal Profiles

Household fuel use exhibits strong diurnal and seasonal variation which, for the most part, are consistent in different regions. Fuel use is typically higher in the morning, evening and in winter. However, measurements of actual activity are not routinely done or are not published. Examples of measurements include in-home monitoring of stove temperature, personal PM monitoring and questionnaires. These measurements are also difficult to accomplish due to cost, and therefore the sample size tends to be small; which would only be useful for modelling on a much smaller spatial and temporal scale. Alternatively, air quality monitoring data could be used, provided the station is located close to a densely populated residential area where fuel use occurs and where other significant pollution sources are not nearby. Other confounding factors are that the pollutant is subject to atmospheric chemistry and due to multiple possible sources (e.g. vehicles or wind-blown dust). Therefore, black carbon measurements from the Zamdela station were chosen to represent temporal variation of domestic fuel combustion as the data satisfied criteria of completeness, high likelihood of single source contribution, presence of domestic fuel combustion, and relatively little atmospheric chemistry impacts. Ambient black carbon data for 2016 was used to generate diurnal, weekly and seasonal profiles for household fuel combustion. Figure 5-19 shows the temporal profiles that were used to disaggregate the annual emissions estimate down to an hourly rate during air quality modelling.

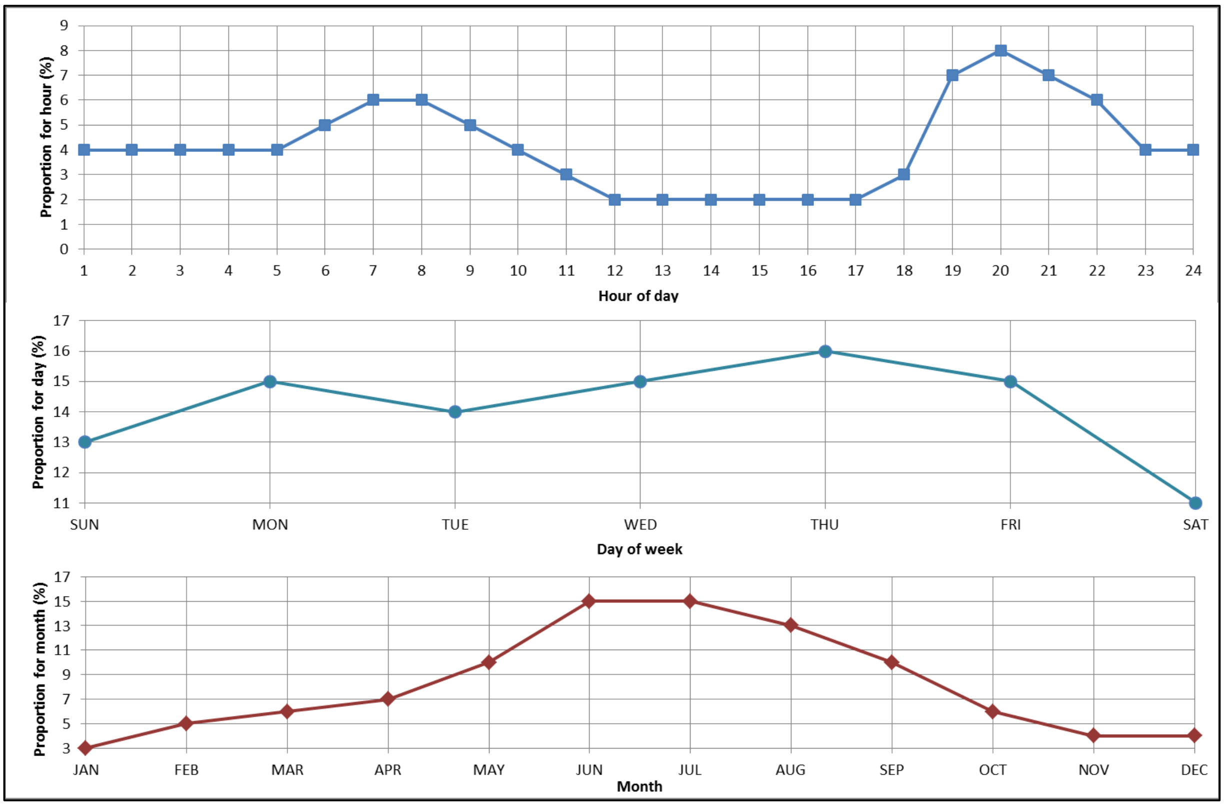


Figure 5-19: Temporal variation used to disaggregate annual domestic fuel combustion emissions

5.1.4.2 Results

Emission estimates were calculated by simply multiplying the gridded fuel use (obtained via top-down and bottom-up approaches) by emission factors. Figure 5-20 to Figure 5-23 shows the fuel usage in SALs for the fuel types included. The fuel use is presented as per household to account for the fact that some SALs will have higher consumption due purely to higher number of households.

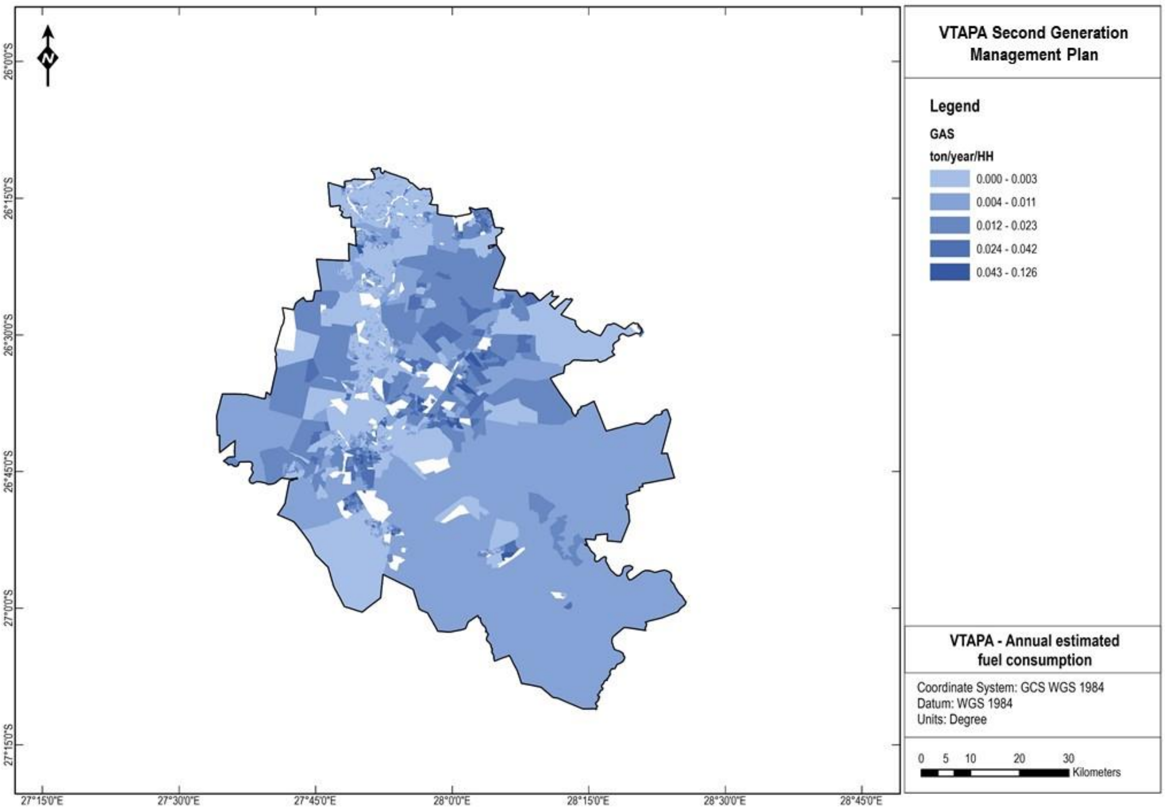


Figure 5-20: Annual estimated fuel consumption for different fuels used for domestic combustion - gas

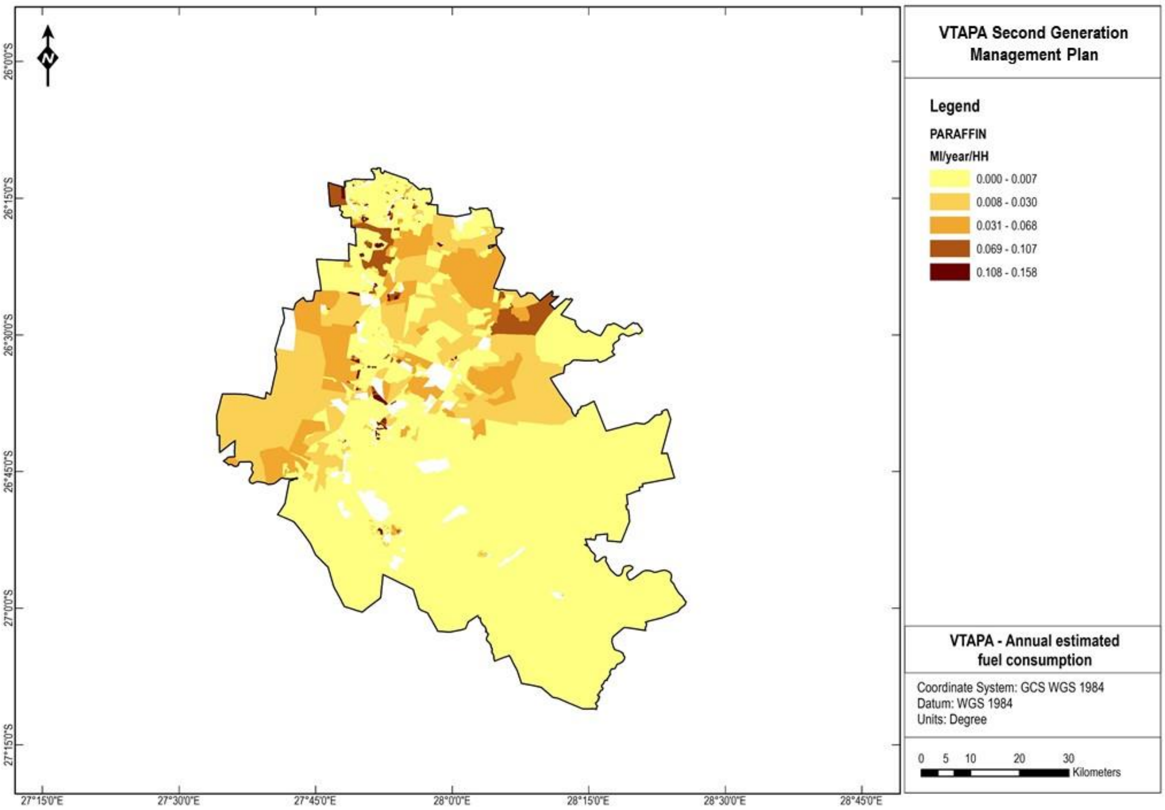


Figure 5-21: Annual estimated fuel consumption for different fuels used for domestic combustion - paraffin

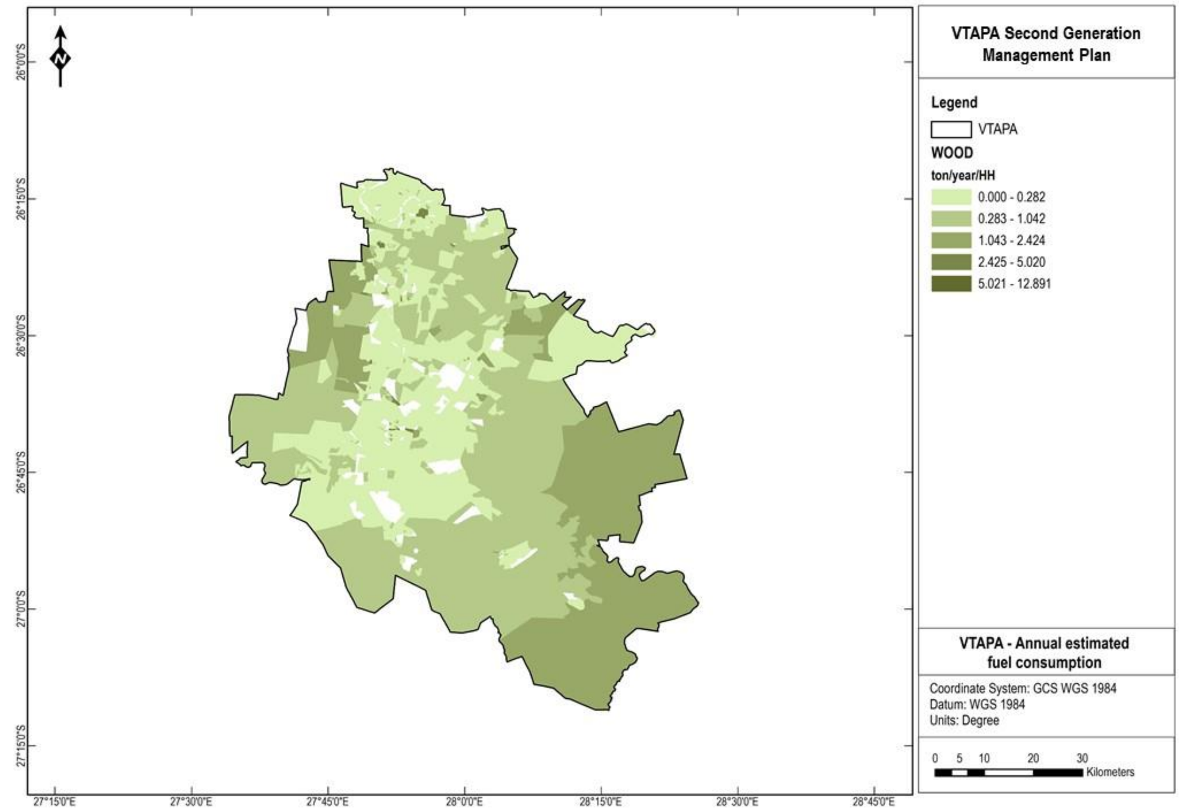


Figure 5-22: Annual estimated fuel consumption for different fuels used for domestic combustion - wood

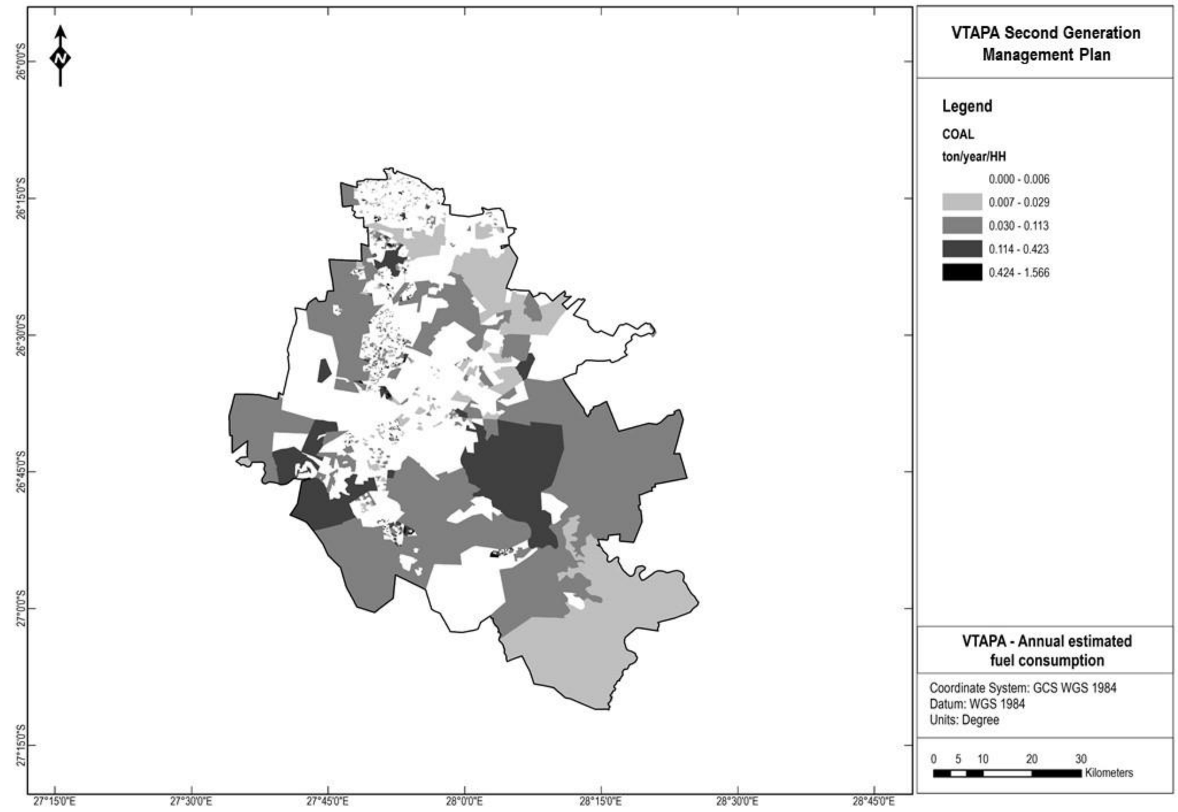


Figure 5-23: Annual estimated fuel consumption for different fuels used for domestic combustion - coal

In terms of sheer volume wood consumption is highest, followed by coal. Wood use is also more spread out towards the outer regions. Table 5-15 lists annual tonnage estimates of emissions from all fuels.

Table 5-15: Estimated emissions from domestic fuel combustion (tonnes per annum)

	SO_2	PM_{10}(a)	$PM_{2.5}$	NOx	NMVOC	NH_3	CO	CH_4
Model domain	2 115	288	6 674	1 154	6 411	0.045	51 457	1 249
VTAPA only	261	68	1 242	184	1 404	0.005	9 982	220
% in VTAPA	12%	23%	19%	16%	22%	12%	19%	18%

Note: (a) PM_{10} represents only the coarse fraction here (i.e. PM 2.5 µm to 10 µm)

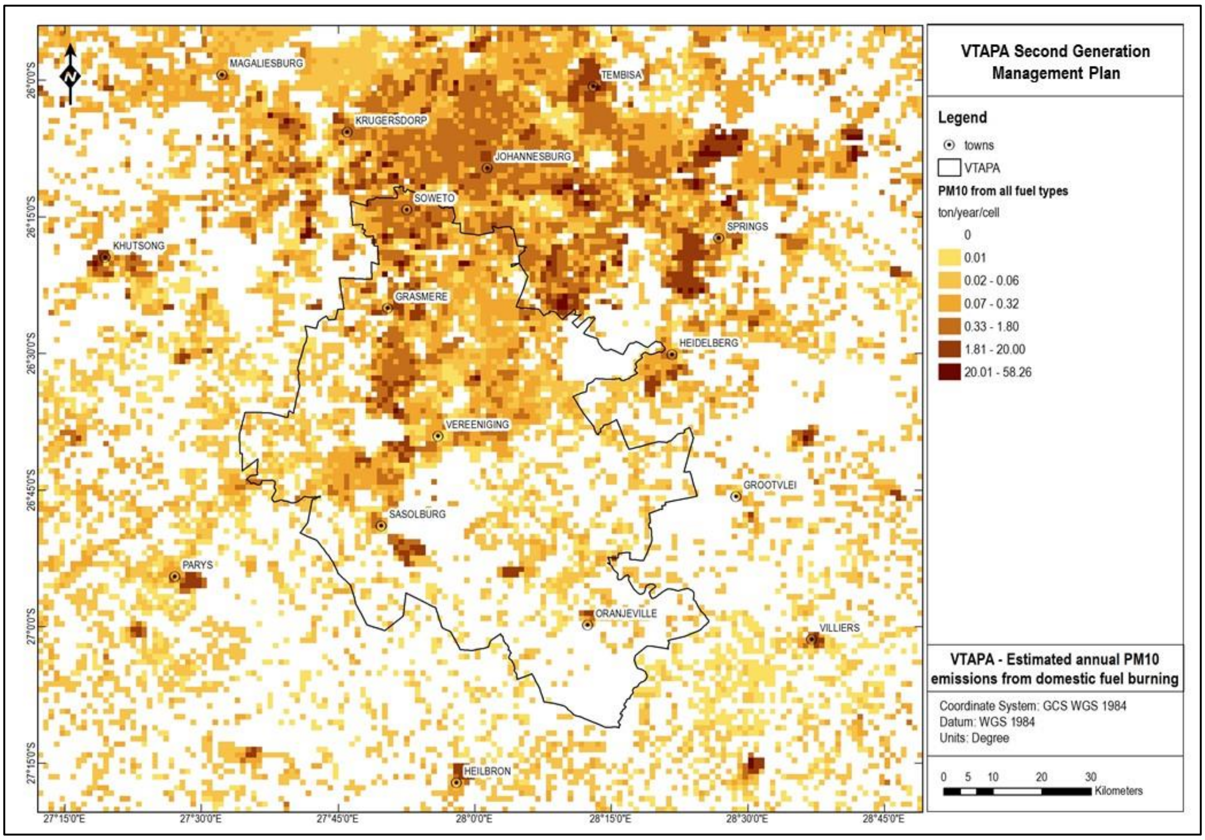


Figure 5-24: Map showing estimated annual PM_{10} emissions from domestic fuel combustion (all fuel types) in the 1 km model domain and VTAPA (outlined in black)

A large proportion of emissions occur outside the VTAPA due to the inclusion of Johannesburg and Ekurhuleni. Within VTAPA the northern region accounts for the majority with spatially limited spots in the south (e.g. south of Sasolburg) (Figure 5-24).

5.1.4.3 Comparison with other inventories

While comparison with other inventories is difficult to accomplish, due to the differences in source data, methodology and focus of the respective inventories, it is seen as a useful exercise in at least illustrating the range of estimates possible.

The medium-term review of the 2009 Vaal Triangle Airshed Priority Area:

The medium-term review used a bottom-up approach with per household fuel consumption derived “in-house”, taking into account an “Energy activity dedication factor” and a “Fuel dedication profile” at the StatsSA sub-place level. Both Census 2001 and Community Survey 2007 were used for household activity data. Emission factors are primarily from the US EPA AP-42 database. Table 5-16 shows the difference in estimates from the medium-term review and this 2018 VTAPA AQMP.

Table 5-16: Medium-term VTAPA AQMP review versus 2018 VTAPA AQMP domestic fuel combustion emissions (tpa)

	PM	SO_2	CO	NOx
2009 AQMP (2013 medium-term review)	1 836	826	16 914	464
2018 VTAPA AQMP	1 310	261	9 982	184

The medium-term review estimates are at most 3 times higher (for SO_2) than the estimate for this 2018 AQMP. This is a result of different emission factors, methodology (relating primarily to fuel consumption data) and a potential decrease in fuel combustion due to electrification.

Table 5-17 shows the qualitative differences in emission factors.

Table 5-17: Qualitative comparison of emission factors used (e.g. EF Higher corresponds to the emission factor used for the 2018 estimate being higher than that used for the medium term review)

	Consumption level	PM	SO_2	NOx
Coal	Medium	EF Higher	EF Higher	EF Lower
Wood	High	EF Lower	EF Lower	EF Lower
Paraffin	Low	EF Higher	EF Higher	Same

It is evident that difference in emission factors can lead to, for example, lower estimates for NOx (for both coal and wood the EF is lower); however a mix of higher and lower EFs leads to closer estimates (for PM). Looking at SO_2, it is possible that since a higher EF was used, and the difference between the two inventories is still large, fuel consumption differences play a larger role. Consumption may be different due to the bottom-up approach estimating higher rates as opposed to the top-down approach (which as earlier mentioned has decreased national coal consumption by a factor of 10 in recent years; see Table 5-12). It is also possible that electrification (and the acceptance thereof as a primary energy carrier) has legitimately resulted in lower consumption. It should be noted that the medium-term review estimates a bulk of the emissions to occur within the City of Johannesburg; and in terms of the VTAPA this would be the Soweto area. Rapid electrification of Soweto may have meant less reliance on fuel combustion for energy needs and would have reflected in the 2001 to 2011 Census.

5.1.5 Waste

Landfill emissions, due to decomposition, consist primarily of CO_2, methane (CH_4), and non-methane volatile organic compounds. Waste water treatment facilities are likely to result in emissions of CO_2, methane (CH_4), non-methane volatile organic compounds; and potentially odorous compounds such as hydrogen sulfide (H_2S) and ammonia (NH_3). Emissions from treatment facilities are dependent on the type of treatment units, temperature of waste water, liquid density, and concentrations of the various compounds in the liquid waste, residence and turnover of liquids in treatment units.

Six landfills were identified within VTAPA: four within the Emfuleni Local Municipality; two within the Midvaal Local Municipality. Two waste water treatment facilities were identified within the VTAPA: one within COJ and another within Emfuleni. Although activity data has been requested from these facilities, none has yet been received. Emissions can be quantified when activity data is provided.

Open burning of waste can impact on air quality through the emissions of a range of pollutants. In this emission inventory, an international database was used to estimate the emissions from waste burning in the VTAPA by following a top-down approach. The approach for the development of the inventory is briefly described below; the detailed methodology and data used are included in Wiedinmyer *et al.* (2014).

5.1.5.1 Methodology

The method used is similar to that reported in Wiedinmyer et al. (2014), which follows the IPCC methods (IPCC, 2006). The emissions of pollutant *i* (E_i) are estimated as the product of the emission factor of the waste (EF_i) and the amount of waste burned (W_B) as shown in equation 1.

$$E_i = W_B \times EF_i \qquad (1)$$

The generalized equation to estimate waste burned is shown in equation 2. In these equations, P is the population, P_{frac} is the fraction of the population assumed to burn their waste, MSW_P is the mass of annual per capita waste production, and B_{frac} is the fraction that is available to be burned that is actually burned. P_{frac} accounts for those whose waste is not collected.

$$W_B = P \times P_{frac} \times MSW_P \times B_{frac} \qquad (2)$$

For this methodology local data on waste per person and composition are used. Waste information is taken from Jeffares & Green (Pty) Ltd (2016); in which waste composition and amount for 2015 was calculated and assessed for 6 municipalities in South Africa. One of the municipalities was Emfuleni LM, which is in the VTAPA. No other sites from the VTAPA were included in the Jeffares & Green (Pty) Ltd (2016) study. The waste data from Emfuleni LM is used to calculate a waste per person per year estimate. This is accomplished by using the StatsSA Community Survey 2016 data on the number of people who use landfills. Waste per capita is simply the tonnage of household waste reaching the landfills (provided by the Jeffares & Green (Pty) Ltd, 2016 study) divided by the number of people whose waste is sent to landfills (from the Community Survey 2016 data for Emfuleni LM). The value estimate is 0.217 tons/person/annum. This waste generated per capita is then assumed to be representative of the whole VTAPA.

The StatsSA Census 2011 also contains a question regarding waste removal services; providing number of people who do not receive removal services. The Census 2011 was used as it provides data at the Small Area Level, as opposed to the Community Survey 2016 which provides data only at the Local Municipality level. The improved spatial disaggregation is required for modelling purposes; and differences in Census 2011 and Community Survey 2016 are relatively small. By multiplying the waste generated per capita with the number of people not receiving waste services, an estimate of amount of waste generated (that may likely be burned) is calculated.

However according to equation 2, not all waste is combustible. For example, glass and metals will not readily burn thus a burn fraction is required. The IPCC recommended fraction of 0.6 is used; i.e. 60% of the waste generated by people that do not receive removal services is burned.

Equation 1 also requires the use of emission factors. The most recent compilation of waste emission factors are in Wiedinmyer et al. (2014); figure below.

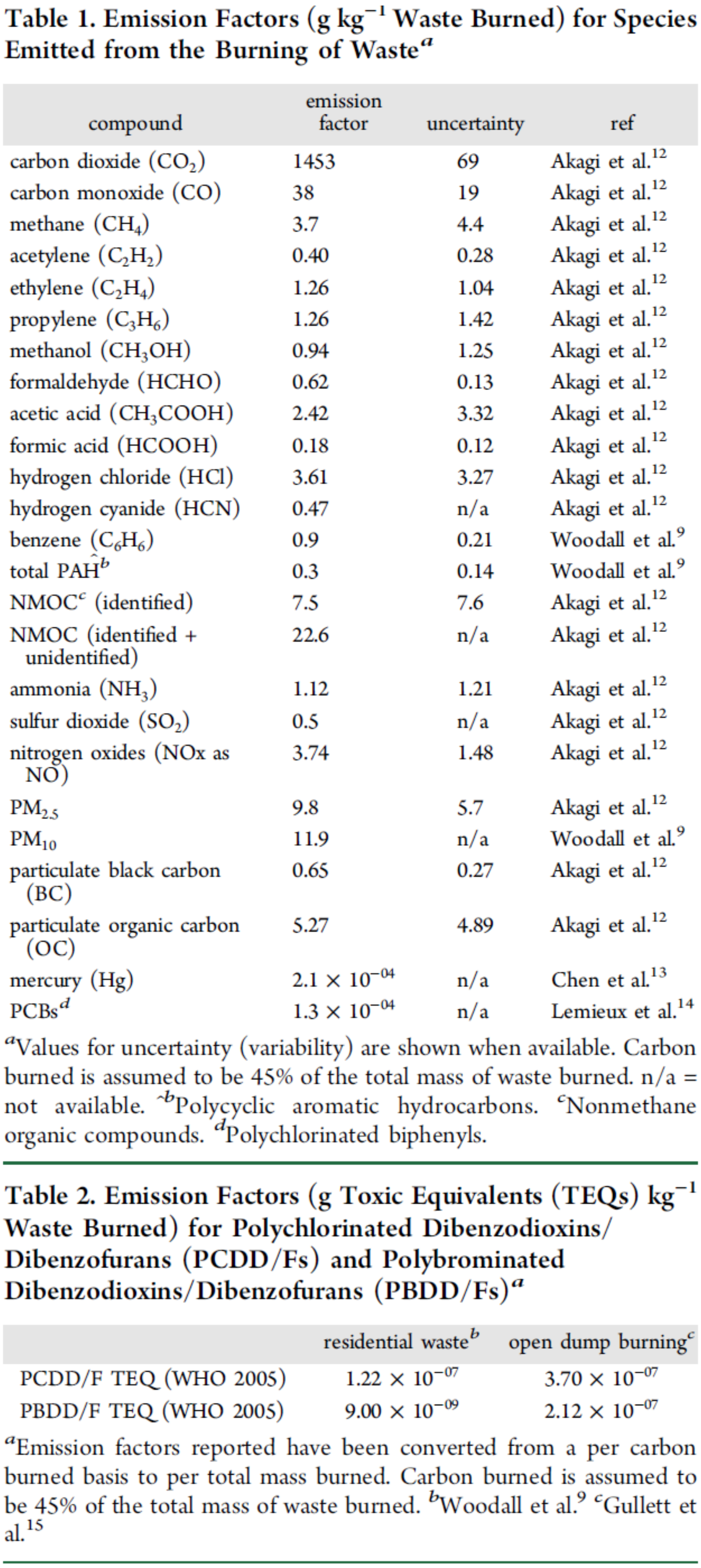


Table 1. Emission Factors (g kg^{-1} Waste Burned) for Species Emitted from the Burning of Waste[a]

compound	emission factor	uncertainty	ref
carbon dioxide (CO_2)	1453	69	Akagi et al.[12]
carbon monoxide (CO)	38	19	Akagi et al.[12]
methane (CH_4)	3.7	4.4	Akagi et al.[12]
acetylene (C_2H_2)	0.40	0.28	Akagi et al.[12]
ethylene (C_2H_4)	1.26	1.04	Akagi et al.[12]
propylene (C_3H_6)	1.26	1.42	Akagi et al.[12]
methanol (CH_3OH)	0.94	1.25	Akagi et al.[12]
formaldehyde (HCHO)	0.62	0.13	Akagi et al.[12]
acetic acid (CH_3COOH)	2.42	3.32	Akagi et al.[12]
formic acid (HCOOH)	0.18	0.12	Akagi et al.[12]
hydrogen chloride (HCl)	3.61	3.27	Akagi et al.[12]
hydrogen cyanide (HCN)	0.47	n/a	Akagi et al.[12]
benzene (C_6H_6)	0.9	0.21	Woodall et al.[9]
total PAH[b]	0.3	0.14	Woodall et al.[9]
NMOC[c] (identified)	7.5	7.6	Akagi et al.[12]
NMOC (identified + unidentified)	22.6	n/a	Akagi et al.[12]
ammonia (NH_3)	1.12	1.21	Akagi et al.[12]
sulfur dioxide (SO_2)	0.5	n/a	Akagi et al.[12]
nitrogen oxides (NOx as NO)	3.74	1.48	Akagi et al.[12]
$PM_{2.5}$	9.8	5.7	Akagi et al.[12]
PM_{10}	11.9	n/a	Woodall et al.[9]
particulate black carbon (BC)	0.65	0.27	Akagi et al.[12]
particulate organic carbon (OC)	5.27	4.89	Akagi et al.[12]
mercury (Hg)	2.1×10^{-04}	n/a	Chen et al.[13]
PCBs[d]	1.3×10^{-04}	n/a	Lemieux et al.[14]

[a] Values for uncertainty (variability) are shown when available. Carbon burned is assumed to be 45% of the total mass of waste burned. n/a = not available. [b] Polycyclic aromatic hydrocarbons. [c] Nonmethane organic compounds. [d] Polychlorinated biphenyls.

Table 2. Emission Factors (g Toxic Equivalents (TEQs) kg^{-1} Waste Burned) for Polychlorinated Dibenzodioxins/Dibenzofurans (PCDD/Fs) and Polybrominated Dibenzodioxins/Dibenzofurans (PBDD/Fs)[a]

	residential waste[b]	open dump burning[c]
PCDD/F TEQ (WHO 2005)	1.22×10^{-07}	3.70×10^{-07}
PBDD/F TEQ (WHO 2005)	9.00×10^{-09}	2.12×10^{-07}

[a] Emission factors reported have been converted from a per carbon burned basis to per total mass burned. Carbon burned is assumed to be 45% of the total mass of waste burned. [b] Woodall et al.[9] [c] Gullett et al.[15]

Figure 5-25: Emission factors used for waste burning (taken from Wiedinmyer et al., 2014)

These are calculated as gram species emitted per kilogram waste burned. There is currently very little literature on emission factors for waste burning and further research regarding this is required, particularly since waste composition is a function of broad factors such as specific country down to detailed factors like individuals' socio-economic situations.

5.1.5.2 Results

Table 5-18 provides the estimated emissions from domestic waste burning in the 1 km model domain and VTAPA. Figure 5-26 shows the estimated distribution of the PM_{10} emissions. Grid lines are shown to emphasize the actual grid resolution.

Table 5-18: Estimated emissions from domestic waste burning (units: tonnes per annum)

Area	PM_{10}	SO_2	NMVOC	NOx	NH_3
Model domain	1 203	51	2 284	378	113
VTAPA only	287	12	544	90	27
% in VTAPA	24%	24%	24%	24%	24%

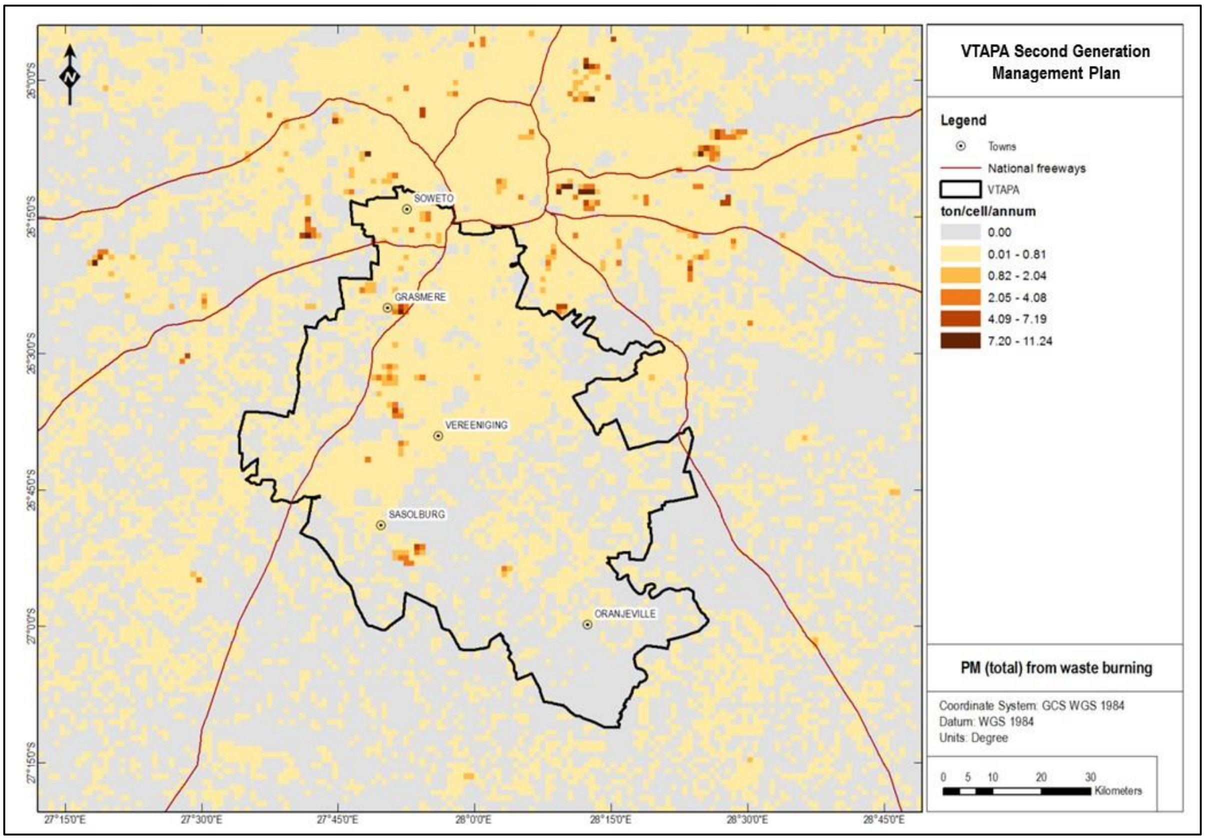


Figure 5-26: Map showing estimated annual PM_{10} emissions from waste burning in the 1 km model domain and VTAPA (outlined in black)

The spatial distribution is similar to that seen in Figure 5-16 VTAPA population density, which is expected as population is an input into the estimation model.

5.1.6 Windblown Particulate Emissions

Windblown particulates from mine waste facilities, product stockpiles, as well as ash storage facilities for large combustion sources, can result in significant dust emissions with high particulate concentrations near the source locations, affecting both the environment and human health.

5.1.6.1 Methodology

Emission quantification from these types of facilities used the in-house ADDAS model (Burger *et al.*, 1997; Burger, 2010, Liebenberg-Enslin, 2014). This model is based on the dust emission scheme of Marticorena and Bergametti (1995) referred to as MB95 (from this point forward) and Shao *et al.* (2011) (referred to as SH11). A study conducted by Liebenberg-Enslin (2014) set out to establish a best practice prescription for modelling aeolian dust emissions from mine tailings storage facilities. Site specific particle size distribution data, bulk density and moisture content were used in the dust flux schemes of MB95, and SH11 to test the effects on a local scale. This was done by coupling these schemes with the USEPA regulatory Gaussian plume AERMOD dispersion model for the simulation of ground level concentrations resulting from aeolian dust from mine tailings facilities. Simulated ambient near surface concentrations were validated with ambient monitoring data for the same period as used in the model. Coupling the dust flux schemes with a regulatory Gaussian plume model provided simulated ground level PM_{10} concentrations in good agreement with measured data. For this study, the MB95 dust flux model, as schematically represented in Figure 5-27, was used.

The model inputs include material particle density, moisture content, particle size distribution and site-specific surface characteristics such as whether the source is active or undisturbed. All input parameters that were not measured as part of this work, have been drawn from or calculated using referenced methodologies (Liebenberg-Enslin, 2014).

Meteorological data from the WRF model, run for the year 2016, were extracted for locations close to each of the identified sources and used to determine the friction velocity and threshold friction velocity. Parameters of importance include wind speed, wind direction and temperature.

5.1.6.2 Results

A total of 30 sources of windblown particulates were identified and assessed within the greater study area. Of these, 14 gold mining tailing storage facilities (TSFs) and reclaimed TSF areas fall within the VTAPA, along with three ash disposal facilities, and three areas where coal is mined, stockpiled, or discarded. A further 10 gold mining TSFs are located within the City of Johannesburg, close to the VTAPA boundary.

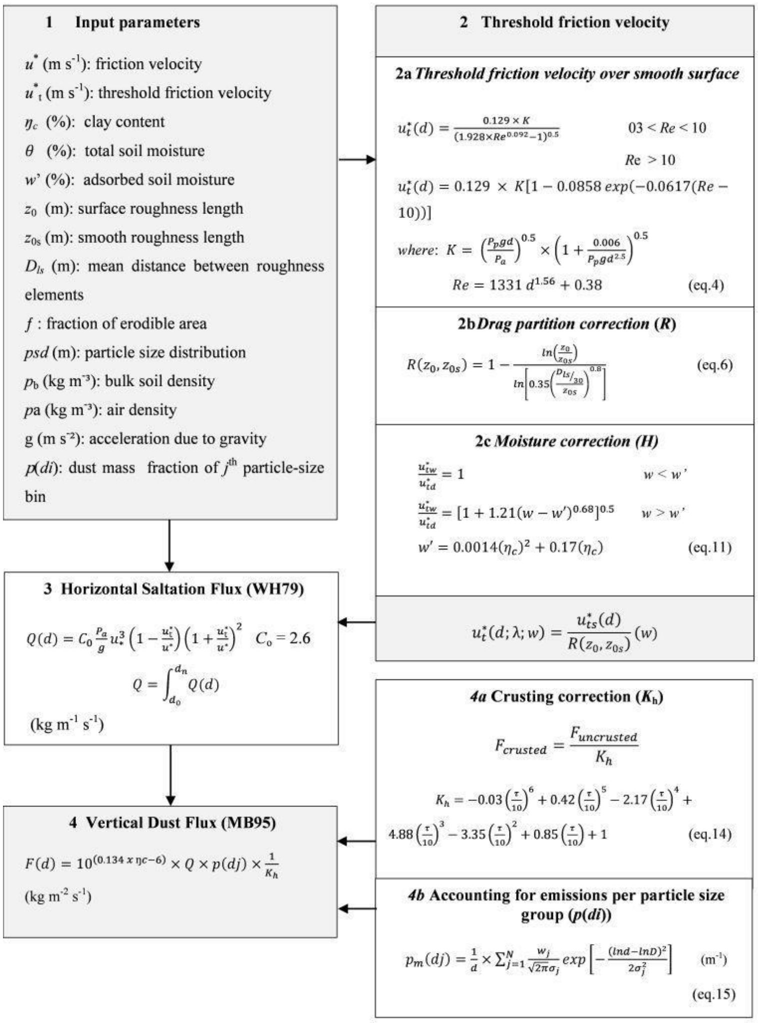


Figure 5-27: Schematic diagram of parameterisation options and input parameters for the Marticorena and Bergametti (1995) dust flux scheme (Liebenberg-Enslin, 2014)

Quantified emissions from the identified windblown dust sources (Table 5-19 and Figure 5-28) show that the largest contributing source type are the gold tailings facilities, followed by the active areas of the large ash disposal facilities. The total contribution from windblown dust to PM_{10} and $PM_{2.5}$ within VTAPA is 8 444.4 tpa and 2 448.6 tpa, respectively. The gold tailings located outside of VTAPA, within COJ, may contribute as much as 3 546.8 tpa and 1 031.0 tpa PM_{10} and $PM_{2.5}$, respectively.

Table 5-19: Emission contribution from windblown dust sources within and near VTAPA

Description	Area (m²)	Emission Rates (tonnes per annum)		
		$PM_{2.5}$	PM_{10}	TSP
Coal mining, product or discard stockpiles	9 596 773	65.7	270.6	635.6
Gold tailings (within VTAPA)	3 442 641	1 112.6	3 796.4	13 245.9
Gold tailings (within COJ)	3 039 603	1 031.0	3 546.8	9 943.6
Ash disposal	1 864 885	239.3	830.6	2 100.3
TOTAL	**17 943 902**	**2 448.6**	**8 444.4**	**25 925.4**

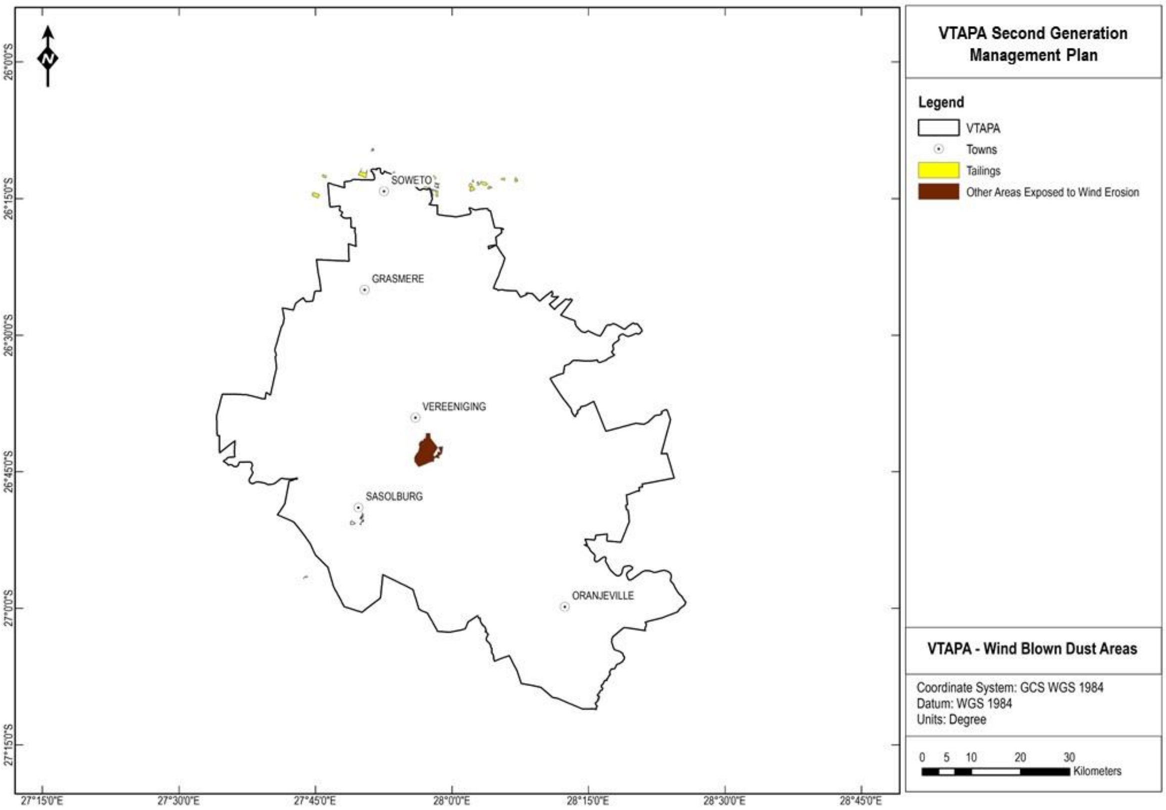


Figure 5-28: Sources of wind-blown particulate emissions

5.1.6.3 Comparison with other inventories

The 2009 VTAPA inventory and the 2013 medium-term review for windblown dust sources reported these together with the mining emissions.

5.1.7 Biogenic VOC emissions

Due to stress responses, plants emit numerous VOC compounds, primarily isoprene. These are termed biogenic VOCs (BVOCs) and play an important, and often overlooked, role in atmospheric chemistry as their VOC contribution is ubiquitous both spatially and temporally. The quantity and timing of BVOC emissions are dependent on plant type (and age), vegetation biomass, ambient temperature and light intensity. These lead to particular temporal variations with the bulk of biogenic emissions occurring in summer. Figure 5-29 shows land-cover as estimated by the MODIS PFT Land Cover product (MCD12Q1).

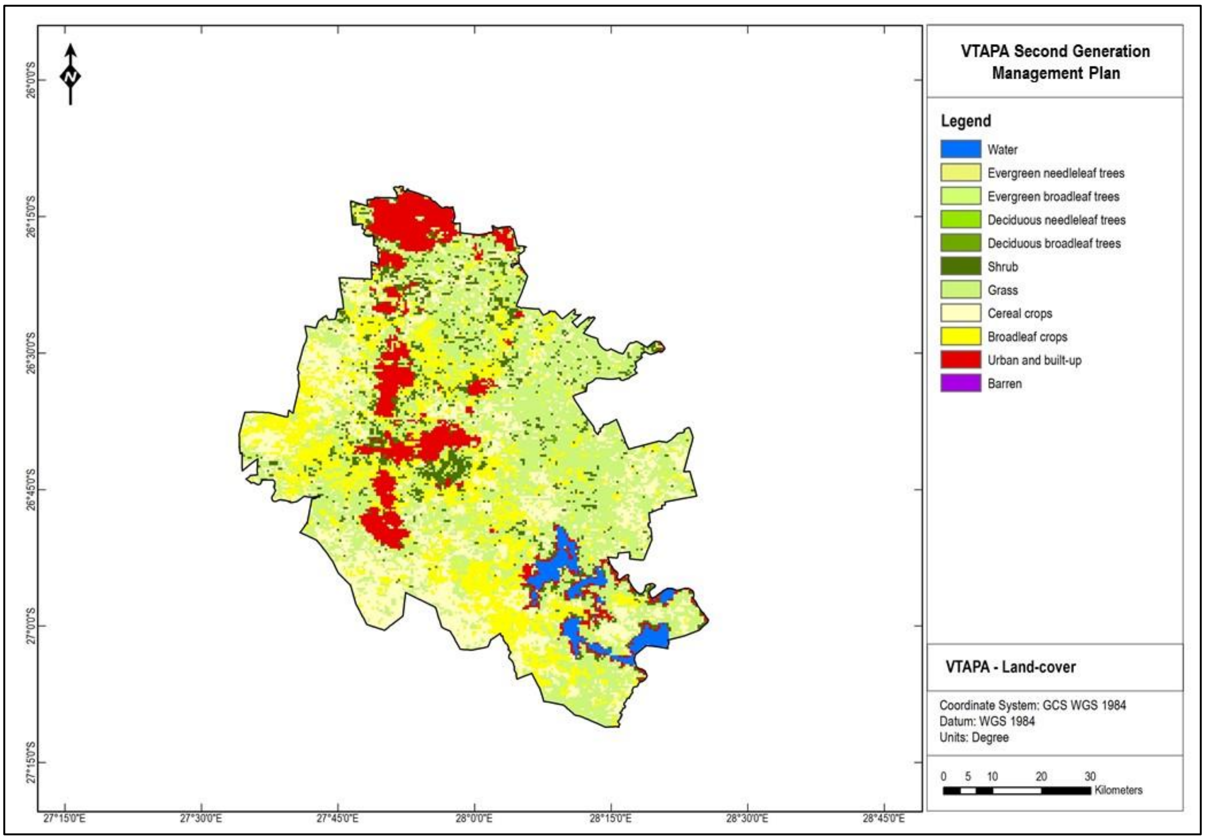


Figure 5-29: Land-cover within the VTAPA (MODIS MCD12Q1)

The majority of VTAPA is vegetated; however, it is mainly grassland and crops (low BVOC emitters). Regions of higher emissions are likely to occur around deciduous broadleaf and shrubs.

5.1.7.1 Methodology

Much of the response of biogenic emissions is dynamic; in that fine scale temporal changes will impact the magnitude of emissions. It is therefore appropriate to model such emissions so that these dynamic impacts are captured correctly. To account for this, biogenic emissions were simulated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN; Guenther *et al.*, 2006). Table 5-20 lists the data requirements for MEGAN, as well as the source of data used in this study.

The MEGAN model incorporates features such as production and loss of BVOCs in plant canopies and impacts of soil moisture as well as stress responses to drought. Model internal base emission factors are at canopy scale, which are either based on direct measurements or extrapolated from leaf and branch measurements (Guenther *et al.*, 2006). They are specific to plant functional types (PFT) and any further additions or modifications must be done accordingly.

Various plant species base emission factor databases exist or have been derived; for specific study areas or to cover global domain, by accumulating researched emission factors from around the world. An example, which is relatively comprehensive, may be found through the NCAR Biosphere-Atmosphere Interactions group's enclosure measurements database (http://acd.ucar.edu/~christin/BVOC/Enclosure_DATABASE.xls). It is often up to the user to decide how to aggregate the plant specific emission factors to the land-cover classification system being used to spatially represent vegetation distribution in the model domain. This aggregation has been applied within MEGAN for the internal emission factors for 16 classes of PFT.

Table 5-20: Input and source of data used by MEGAN

Input variable	Data source	Unit
Plant functional type	MODIS[(a)]	Class
Leaf area index	MODIS[(b)]	None
Soil moisture	WRF[(c)]	m^3/m^3
Soil temperature	WRF[(c)]	K
Soil type	WRF[(c)]	Class
Temperature	WRF[(c)]	K
Pressure	WRF[(c)]	Pa
Water vapour	WRF[(c)]	kg/kg
Wind speed	WRF[(c)]	m/s
Rainfall	WRF[(c)]	cm
PAR	WRF[(c)]	$watts/m^2$

Note:

(a) The MODIS MCD12Q1 data product is courtesy of the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access).
(b) The MODIS MCD15A2H data product is courtesy of the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access).
(c) The Weather Research and Forecasting model as run as part of this study

For this study the MODIS derived IGBP PFT land-cover data (Figure 5-29) was reassigned to the required 16 classes used by MEGAN. The MEGAN classes simply expand certain PFTs into tropical or temperate; and are otherwise the same as the MODIS IGBP classes.

The MEGAN provides output of BVOC species within the domain specified by the user's other data input. These species may be subsequently (through a post-processor) lumped into species required by chemical mechanisms used by air quality models. Currently MEGAN provides speciation post-processors for Carbon Bond 2005 (CB05; Yarwood *et al.*, 2005), Carbon Bond 6 (CB6; Yarwood *et al.*, 2010) and Statewide Air Pollution Research Center 1999 (SAPRC-99; Carter, 1999 and Carter, 2000). The Carbon Bond 2005 speciation profiles were used for MEGAN in this inventory, as this is the speciation used for the air quality model.

5.1.7.2 Results

MEGAN was run for year 2016 using inputs specified in Table 5-20. The model was run for both model domains (the coarse parent 3 km domain and the finer resolution 1 km nest). Table 5-21 provides the estimated NMVOC emissions for the 1 km domain and VTAPA itself. Figure 5-30 shows the MEGAN derived biogenic VOC emissions within the 1 km resolution model domain.

Table 5-21: Estimated biogenic VOC emissions (units: tonnes per annum)

Area	NMVOC
Model domain	45 907
VTAPA only	9 727
% in VTAPA	21%

Regions of higher emissions are generally described as "shrub" by the MODIS land-cover dataset. Areas with no emissions are classified as urban; and also do not report leaf area index in the MODIS *MCD15A2H* data. While most biogenic VOC emissions occur outside the VTAPA, biogenic VOC are important for regional air quality because ozone may be formed from NOx (anthropogenic sources tend to be high emitters) reacting with biogenic VOC.

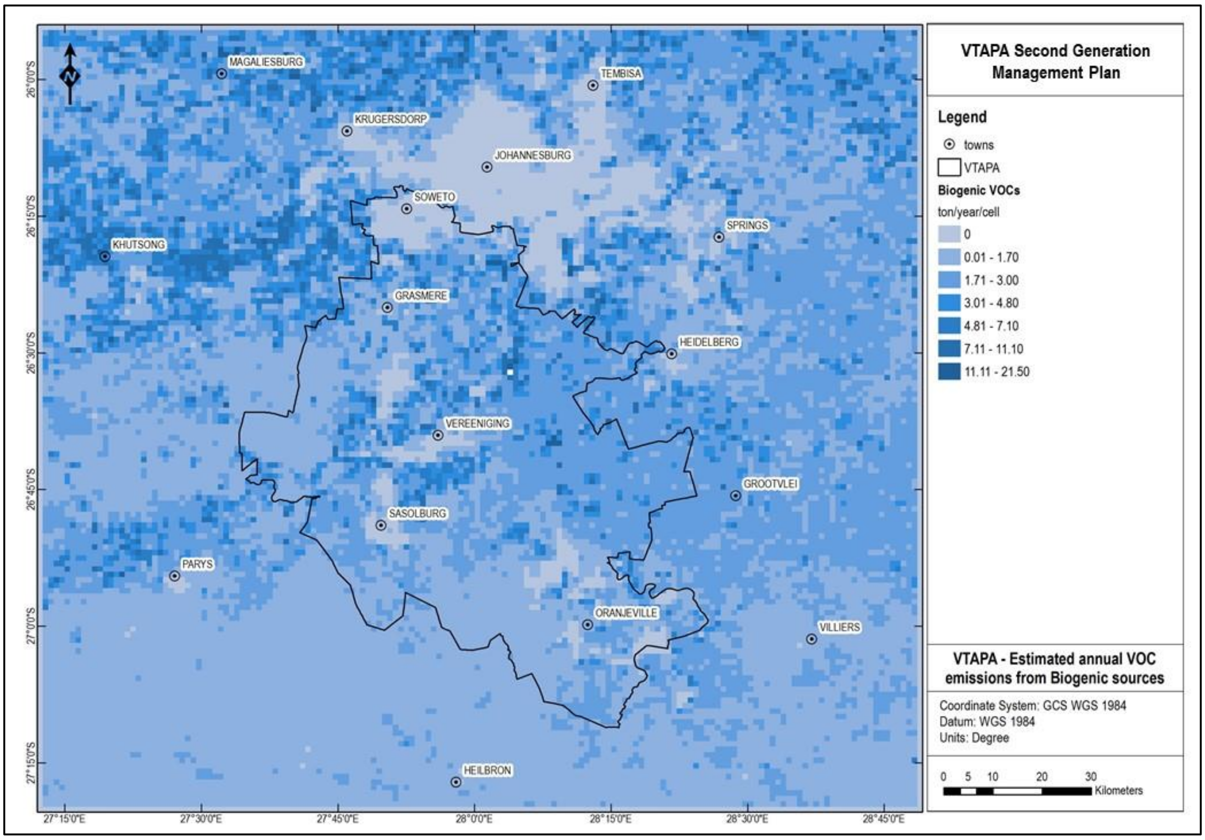


Figure 5-30: Map showing estimated annual VOC emissions from biogenic sources in the 1 km model domain and VTAPA (outlined in black)

5.1.8 Biomass Burning

Biomass burning plays a key role in southern Africa's environmental concerns (e.g. Anyamba *et al.*, 2003; Formenti *et al.*, 2003; Hely *et al.*, 2003). It alters land-cover and releases large amounts of pollutants into the atmosphere in a short period of time. Large scale agricultural burning as well as natural fires are a prominent feature of southern Africa's landscape and play a major role in the ambient air quality.

In general, biomass burning emissions are derived from remotely sensed data of active fires, burned area, land-cover, emission factors for each land-cover, and fuel loading. This provides emissions per fire detected from the period of detection, which is generally one day due to satellite overpass. Further work is generally needed to determine total fire duration within a day and assign a temporal profile to generate hourly emissions. Additionally, fire temperature or type, such as smouldering or flaming, is important since it determines plume rise.

5.1.8.1 Methodology

The MODIS instrument on NASA's AQUA and TERRA platforms provides data used to create fire, land-cover, and fuel loading data products. Detailed emission factors are available for various species from Akagi *et al.* (2013) and Yokelson *et al.* (2013). These factors are provided for individual VOC and aerosol particle species, thus enabling better characterization for input into photochemical models.

The processing of detected fires (via MODIS fire products) with emission factors and fuel loadings have been achieved on a global scale at 1 km resolution by NCAR Atmospheric Chemistry Division resulting in the Fire INventory from NCAR, or FINN, dataset (Wiedinmyer *et al.*, 2011). The FINN dataset is currently used for operational real-time forecasts (http://www.acd.ucar.edu/acresp/forecast/) as well as recent retrospective air quality studies (Jiang *et al.*, 2012, Val Martin *et al.*, 2013). Emissions of criteria pollutants, as well as VOC emissions speciated for commonly used air quality modelling chemical mechanisms, are included in the datasets. The data period covers 2002 onwards, and fire emissions are given as daily totals. While there are many biomass burning emission products available (e.g. GFED and GFAS) none are provided to the public at high enough resolution appropriate for regional/urban scale air quality modelling.

The dataset contains fields denoting fire data, location, area burnt, and individual pollutant species mass (or moles for gases, except NMVOC) per day. The NMVOC and PM species provided depend on the chemical mechanism type chosen. While no CB05 FINN dataset is provided yet, it is possible to map those in the FINN data to what is required. For this study, data with species generated for the MOZART (Model of Ozone and Reactive Tracers) was accessed. The mapping (and windowing of fires to a domain of choice) is achieved through a processor developed by Rambol-Environ (the CAMx developers). However, before this is done, some quality control is required.

Fire Commission Errors

It was found that fires are allocated erroneously to surface coal mines and large hot/reflective rooftops (e.g. warehouses and malls). This is a known issue and Schroeder *et al.* (2016) suggest solutions based on multi-temporal analysis of OLI data from the relatively recently launched (2013) Landsat-8. It should be noted that the OLI standard algorithm also exhibits these commission errors (false alarms). Unfortunately, multi-temporal analysis can only be done after the fact; and also has the potential to flag legitimately persistent sources. Nevertheless, it is likely that new biomass burning emissions products that take into account these impacts will be available soon. Regarding the FINN dataset, it was decided that these erroneous fires will be removed manually by creating a mask polygon shapefile to flag areas to remove. Figure 5-31 shows an example of fires detected over an industrial site and the outline of the mask polygon; while Figure 5-32 shows the extent of the polygons in the 1 km model domain.

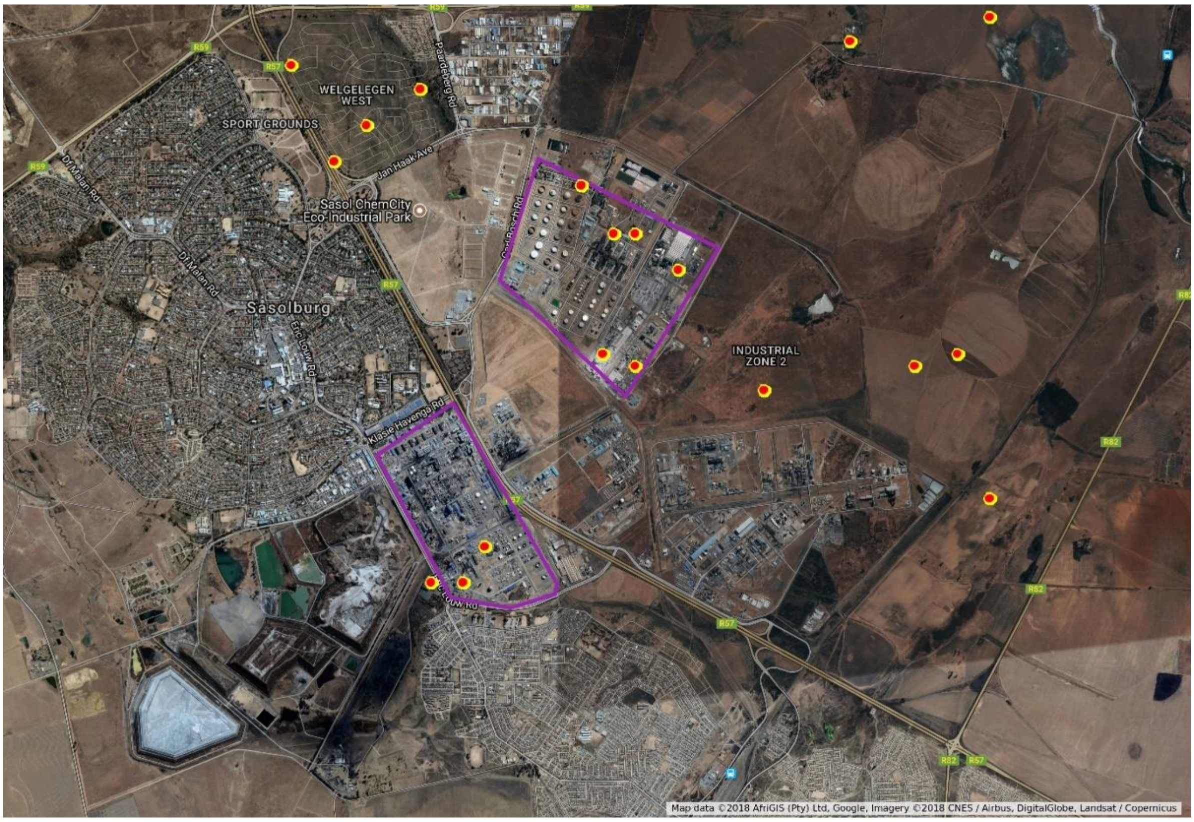


Figure 5-31: Example of commission errors in FINN dataset (dots) and polygon outline used to mask (purple boxes)

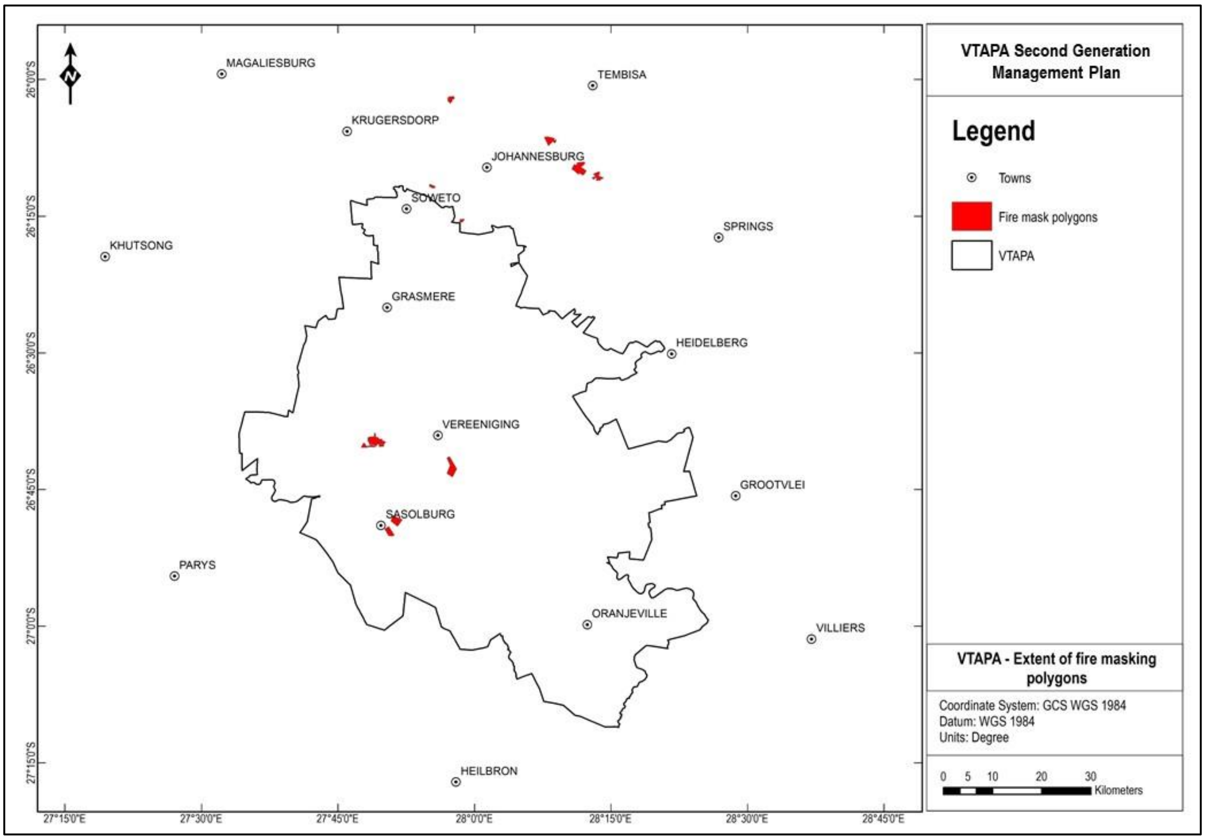


Figure 5-32: Map showing extent of fire masking polygons

After erroneous fires were removed, the emissions were speciated for the CB05 mechanism used by the air quality model.

Temporal profiles

The FINN dataset provides daily emissions estimates for fires globally. However, photochemical modelling requires hourly emissions input, such that diurnal cycles of pollutants such as ozone and NOx are simulated correctly. A normalized diurnal fire cycle, based on fire temperature cycles (Giglio, 2007; Wooster *et al.*, 2003), was used for this study. This profile is very similar to that formulated during an early study in the US (Western Regional Air Partnership, 2005). Figure 5-33 shows both these profiles.

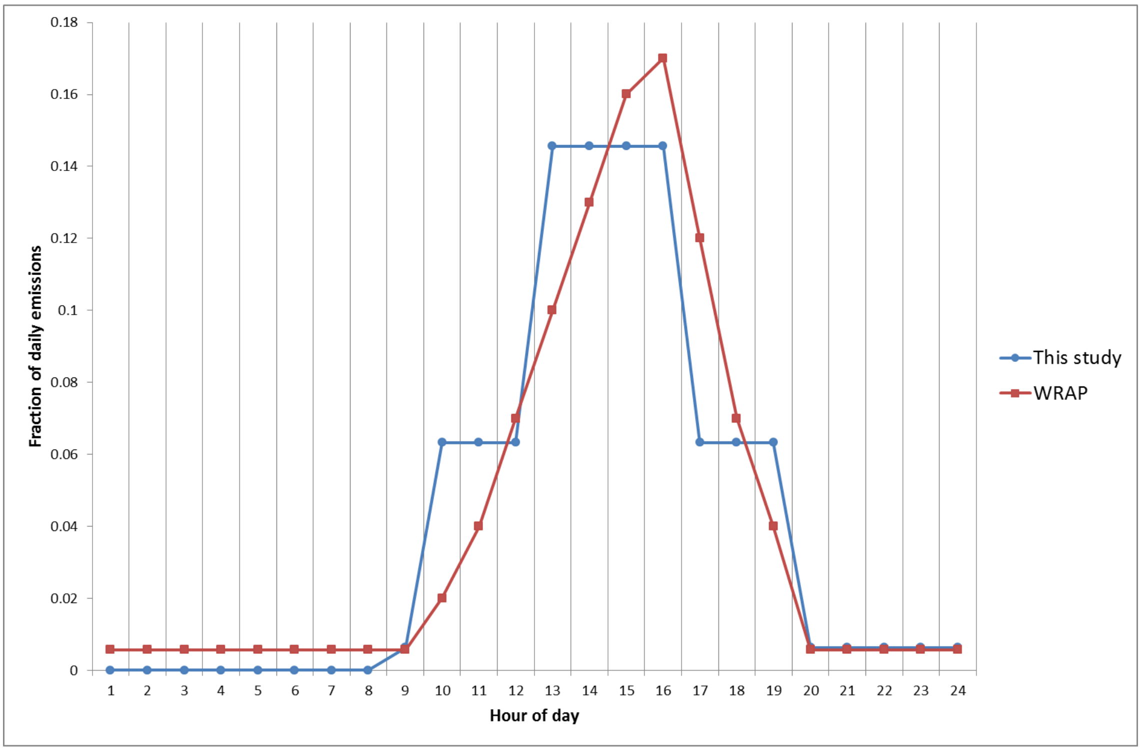


Figure 5-33: Diurnal temporal profile used for biomass burning compared to that formulated during the WRAP (2005) study

Plume rise

Further considerations are required to establish a plume rise height. Biomass burning fires can reach temperatures of over 1 200 K, resulting in significant buoyant transport into the mid-troposphere, above the boundary layer. This then needs to be represented within the model as an emission source characteristic. It is for this reason that emissions from biomass burning fires are represented as point sources in air quality models; which enables the use of stack parameters. Plume rise within CAMx is determined internally by the multi-layer stability-dependent algorithm of Turner et al. (1986). This takes into account stack parameters (height, diameter, exit velocity and exit temperature) and meteorological conditions (temperature and humidity).

FINN emissions are provided with a generalized vegetation type for each fire. For the total modelling domain (the extent of the 3 km resolution domain) the fires corresponded to the following vegetation types:

- savanna
- shrubs
- tropical forest
- temperate forest
- agriculture.

During the WRAP (Western Regional Air Partnership, 2005) study a relationship between estimated NOx emissions from fires and a "virtual acreage" was formulated. In this way the size of fire may be determined by the NOx emissions. Also, Schroeder *et al.* (2010) provide general fire temperatures for different vegetation biome classes. The virtual acreage and fire temperature were enough to derive pseudo-stack parameters. When used in a simplified plume rise equation, plume heights (top of plume) range from 300 m to 7 000 m. This, however, is only a crude estimate and actual plume height is dynamically adjusted in CAMx due to changing meteorological conditions.

5.1.8.2 Results

FINN data was extracted for the year 2016 and processed according to the methodology described. Table 5-22 shows the annual tonnage emissions from biomass burning within the 1 km model domain and VTAPA. Figure 5-34 shows the annual FINN PM_{10} estimates gridded into the 1 km model grid (gridded for display purposes

Table 5-22: FINN estimated annual emissions from biomass burning (units: tonnes per annum)

Area	CO	NOx	SO_2	NH_3	CH_4	NMOC	$PM_{2.5}$	PM_{10}[(a)]
Model domain	40 172	2 543	185	739	1 943	17 538	2486	597
VTAPA only	9 359	589	44	173	454	4 057	589	140
% in VTAPA	23%	23%	24%	23%	23%	23%	24%	23%

Note: (a) PM_{10} represents only the coarse fraction here (i.e. PM 2.5 µm to 10 µm)

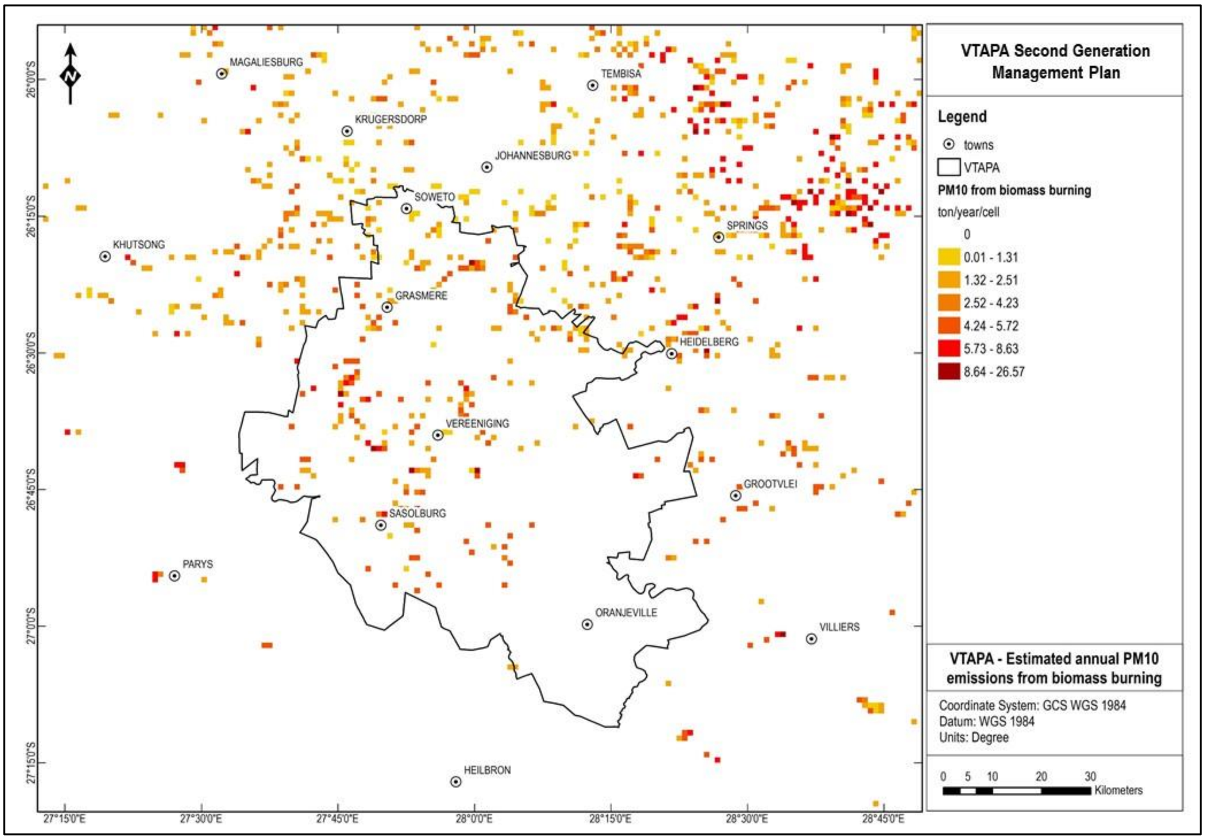


Figure 5-34: Map showing estimated annual PM_{10} emissions from biomass burning in the 1 km model domain and VTAPA (outlined in black)

While, in total, majority of emissions occur outside the VTAPA (when looking at the 1 km model domain) there are fires emitting large pollutant quantities to the west of Vereeniging. Considering that some of these fires release all pollutants within a short period, this type of emission source could have significant acute impact.

5.1.9 Airfields

Emissions from aviation occur due to the combustion of fuel in aircraft engines resulting in level emissions of NO_X, VOC, CO, PM and SO_X. The aviation emissions have localised direct impacts and the secondary impacts may be felt at large distances away from where they are released.

There are no major commercial airports within the VTAPA; however, there are 15 airstrips used for agricultural, recreational and charter flight activities. The calculation of the emissions from aircraft are dependent on: the fuel-type combusted; the number of landings and take-offs (LTO's); and the specific aircraft. The activity data required in calculating emission may include type of aircraft (fleet and engine types), aircraft movements (landing and take-off, taxing, idling, climb-out and approach), fuel consumption and aircraft handling. Due to the occasional use of the airfields in the area they are not likely to be a significant source of emissions over the study area.

5.1.10 Other Pollutants Included for Dispersion Modelling Chemistry Effects – Ammonia Emissions

Ammonia (NH_3) emissions are important as a neutralizing agent to atmospheric sulfuric acid where ammonium sulfate particles are formed. In fact, NH_3 to a large extent regulates the alkalinity of the atmosphere, making it an important consideration when dealing with secondary sulfate and nitrate aerosol formation. This emission sector is thus vitally important as input into the air quality model since large SO_2 sources are to be included presenting the potential for sulfate chemistry.

Ammonia sources are mainly (soil) biogenic, with contributions from agriculture and industry. The relative contributions of each source depend on the area of concern. For example, in areas with livestock, agricultural emissions will outweigh biogenic, and further, if an area contains an ammonia production industry, fugitive emissions could outweigh biogenic or agriculture. Figure 5-35 shows the relative coverage of agricultural areas within VTAPA according to the National Land-cover dataset for 2014.

With only coverage of 30%, emissions of NH_3 from agriculture are not expected to be large; however, the impact on sulfate formation will need to be accounted for in the modelling.

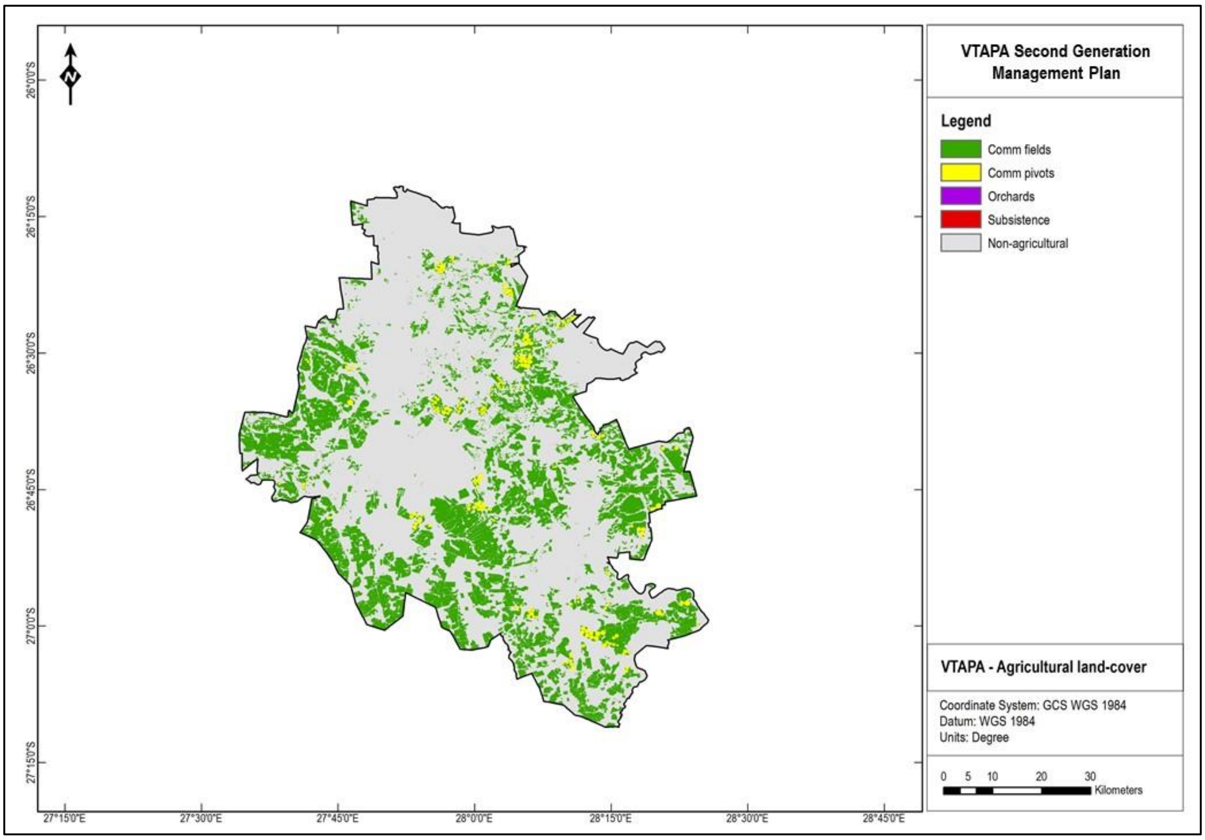


Figure 5-35: Agricultural land-cover in VTAPA (derived from NLC 2014)

5.1.10.1 Methodology

Regional estimates of NH_3 emissions are available through global emissions inventories and the most recent and high-resolution dataset available is used in this study. The impact of NH_3 emissions on the atmospheric chemistry considered in the air quality modelling is a regional one, in which secondary pollutant formation is influenced by atmospheric alkalinity. It is therefore seen as adequate that a regional estimate of NH_3 be used.

The NH_3 emissions due to agricultural activity are based on the ECLIPSE version 5 (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants; Klimont *et al.*, 2013) global emissions dataset developed with the GAINS model (Amann *et al.*, 2011). The dataset is categorized by IPCC Representative Concentration Pathways (RCP) sectors with the agricultural sector emissions referring to emissions from livestock manure (housing, storage, application on land, grazing) and mineral nitrogen fertilizer application. Data from ECLIPSE are provided as annual emission totals per grid cell together with monthly allocation factors per grid cell (i.e. multiplying the two results in monthly emissions totals per grid cell). Year 2016 ECLIPSE agricultural NH_3 emissions were used to be consistent with other sources in the inventory. The ECLIPSE dataset is provided on a global coverage at a grid resolution of 0.5˚ x 0.5˚ (approximately 50 km x 50 km). Emission estimates from agriculture are based on data from the UN Food and Agriculture Organisation (FAO), with spatial allocation driven through proxies developed through the Global Energy Assessment (GEA, 2012), which are also consistent with proxies used within the RCP projections (Lamarque *et al.*, 2010).

ECLIPSE emissions were re-gridded onto the model domains by converting to a flux (t/km^2/month) and then assigning a fractional value (based on fraction of area) within each domain's grid cell. Flux values are then converted back to emission rates (t/month) by multiplying by each domain's grid cells' area. This form of re-gridding does not use interpolation and is thus mass-consistent between the original ECLIPSE dataset and the resulting domain emissions estimated here. An area-based fraction is appropriate for such a land-cover/land-use dependent emissions source.

Temporal Profiles

The ECLIPSE data are provided as monthly estimates and as such contains a seasonal profile. This profile is shown in Figure 5-36 as an average over the air quality model 1 km domain grid cells. It should be noted that this is an average profile and each ECLIPSE 0.5˚ grid cell has a slightly different profile; thus, the standard deviation in variation bars in the plot. There is no distinction between weekdays; however, a diurnal profile is necessary as well since NH_3 emissions have a strong temperature response.

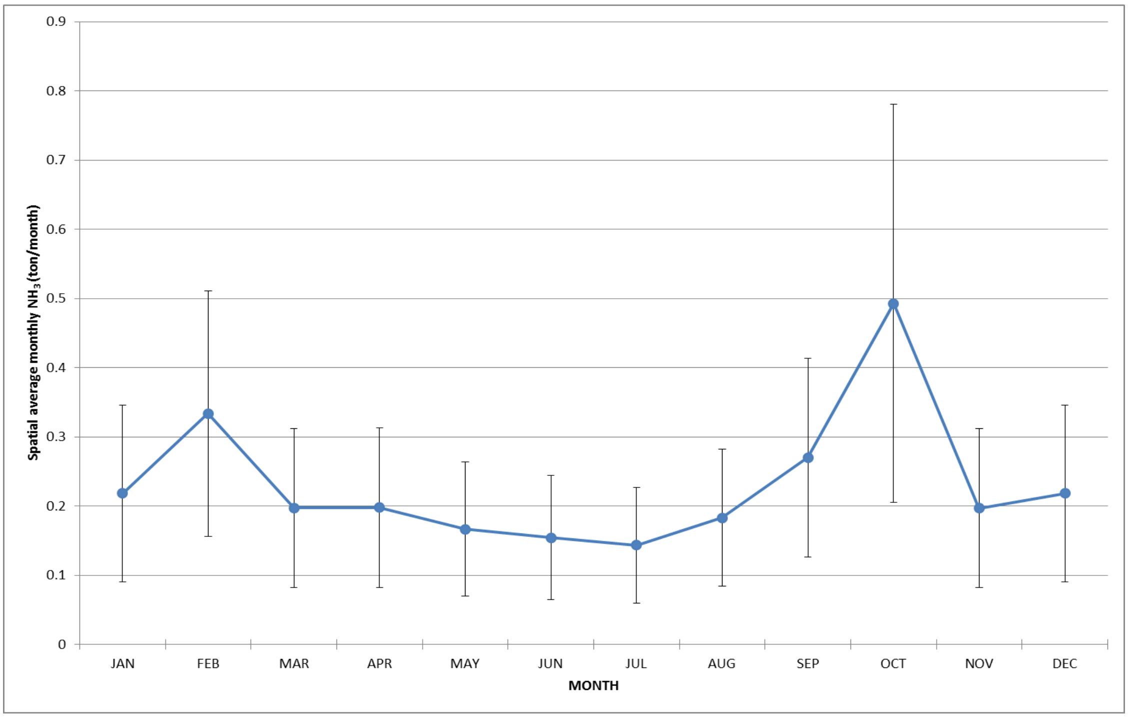


Figure 5-36: Spatial average of monthly ECLIPSE estimated NH_3 emissions from agriculture (bars show standard deviation)

Recommended diurnal profiles are provided by the United States Environmental Protection Agency (US EPA, 2004), and are representative of a simulated United States national average which is driven by specific measurement campaigns. The two diurnal profiles used here are for “fertilizer and fallow soils” and “crops”. A mix of “fertilizer and fallow soils” and “crops” was used for the growing season in South Africa, while just “fertilizer and fallow soils” was used for non-growing seasons. Maize was used as a determinant for the growing season; that being October to December. Figure 5-37 illustrates the three diurnal profiles used.

5.1.10.2 Results

Figure 5-38 shows the ECLIPSE estimated total annual NH_3 emissions from agriculture.

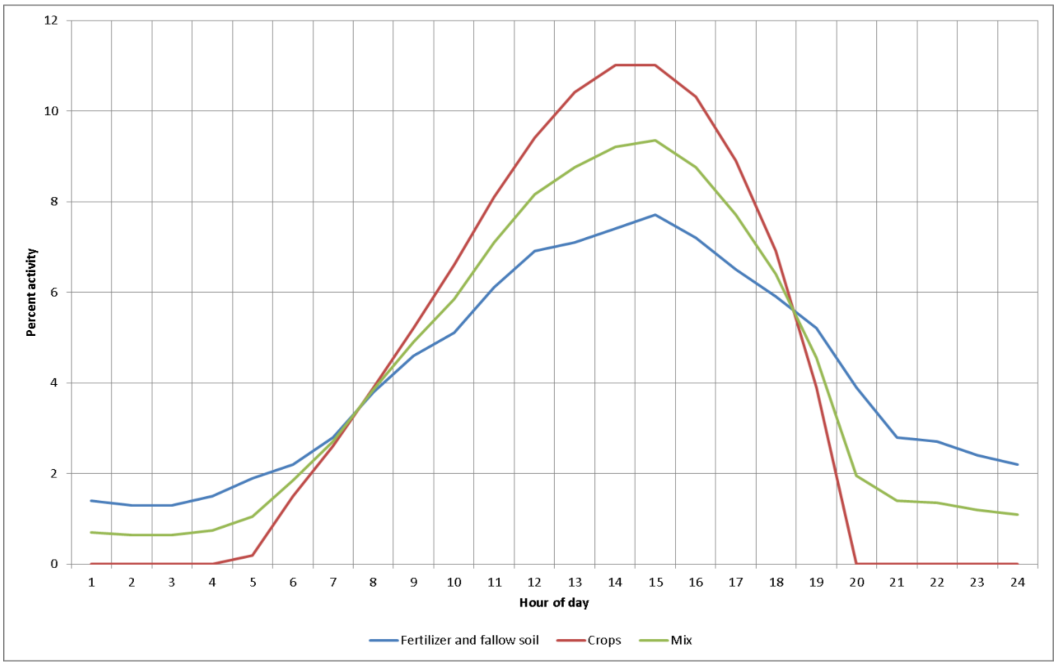


Figure 5-37: US EPA recommended diurnal emissions profiles of NH_3 from crops and fertilized soils

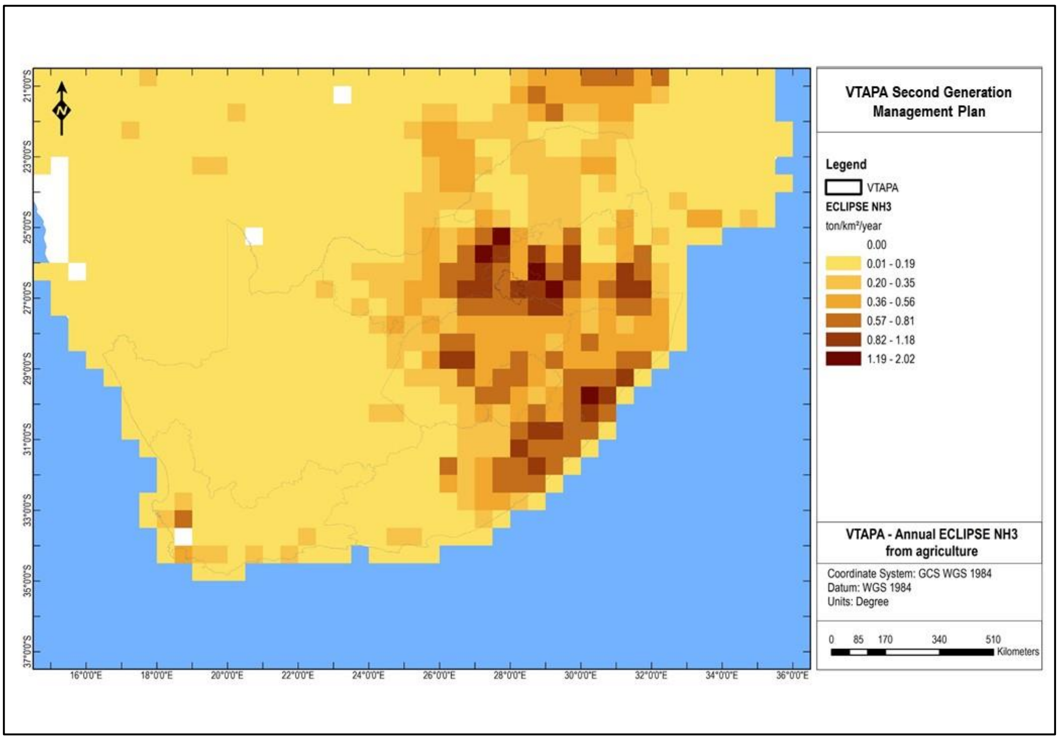


Figure 5-38: Total annual ECLIPSE NH_3 from agriculture over South Africa

Highest emissions occur along the eastern half of the country and into the interior. This corresponds to the agricultural regions, which is also relevant as all coal-fired power stations are also located in the eastern interior, which has bearing on the transformation of SO_2 into sulfate aerosols.

Table 5-23 shows the total tonnage in both the CAMx 1 km domain and VTAPA. Only 19% of NH_3 emissions from agriculture occur in the VTAPA. The total magnitude is likely higher than NH_3 from any industry; however, it should be noted that this is a large area source dispersed around the domain (similar to biogenic VOC). On average (i.e. average over all grid cells in the 1 km model domain) the total annual tonnage is 0.88 tons per grid cell.

Table 5-23: Estimated NH_3 emissions from agriculture (units: tonnes per annum)

Area	NH_3
Model domain	20 535
VTAPA only	3 890
% in VTAPA	19%

5.2 Existing Air Quality Monitoring

5.2.1 Ambient Air Quality Monitoring in VTAPA

Several ambient air quality monitoring stations (AQMS) are located across the VTAPA (Table 5-24 and Figure 4-1) and are owned and managed by both National and District government departments, as well as industry partners. Long-term ambient air quality trends are summarised in the sections below.

Table 5-24: Air quality monitoring stations in VTAPA

Provider	Network	Station	Data Available	Data Processed
DEA	VTAPA	Diepkloof	2007 to 2017	2007 to 2016
		Kliprivier	2007 to 2017	2007 to 2016
		Sebokeng	2007 to 2017	2007 to 2016
		Sharpeville	2007 to 2017	2007 to 2016
		Three Rivers	2007 to 2017	2007 to 2016
		Zamdela	2007 to 2017	2007 to 2016
Sedibeng DM		Meyerton	2017	(a)
		Vanderbijlpark	2017	(a)
Industry	Sasol	AJ Jacobs	2008 to 2017	2008 to 2016
		Eco Park	2011 to 2017	2011 to 2016
		Leitrim	2008 to 2017	2008 to 2016
	Eskom	Randwater	2012 to 2017	2012 to 2017
	ArcelorMittal	4 stations (PM_{10} only)	(b)	(b)

Notes:

(a) – data not processed since timeframes do not overlap with other stations

(b) – data requested, not yet received

5.2.2 Long-term Air Quality Data Trends

A compliance 'snap-shot' for long-term ambient data with the NAAQS is provided for 10 ambient stations across the VTAPA in Table 5-25. NAAQS compliance for SO_2 and NO_2 pollutants was more common with the following exceptions: annual NO_2 at Diepkloof, Kliprivier, Sebokeng, and Sharpeville. Hourly NO_2 concentrations were also non-compliant with NAAQS at Sebokeng in 2015. Non-compliance with the PM_{10} standards (daily and annual) is common to all stations, with few exceptions. Similarly, non-compliance with the $PM_{2.5}$ standards (daily and/or annual) was observed at all stations except: except at Diepkloof (2013 to 2015) and Three Rivers (2009, 2011, and 2013). The long-term data trends are discussed further in the pollutant-specific sections that follow. More detailed summary tables are provided in Appendix A.

Table 5-25: Summary of NAAQS compliance at 10 stations across VTAPA between 2007 and 2016

Year	D	K	Se	T	Sh	Z	R	E	AJ	L
					SO$_2$					
2007				▨		▨	-	-	-	-
2008			▨	▨		▨	-	-	🟧	
2009				▨			-	-	🟧	
2010	▨	▨			▨		-	-		
2011	▨	▨	▨	▨	▨		-	🟧 🟥	🟧	▨
2012			▨				▨	🟧 🟥	🟧	
2013									🟧	▨
2014	▨							🟨 🟧 🟥	🟧	▨ 🟥
2015		▨						🟥	🟧 🟥	
2016		▨	▨					🟧	🟧 🟥	
					NO$_2$					
2007	▨ 🟥			▨	▨	▨	-	-	-	-
2008	🟥		▨	▨			-	-		
2009	🟥	🟥		▨		▨	-	-	-	
2010	▨ 🟥	🟥		▨	▨	▨	-	-		
2011	▨	▨	▨	▨	▨	▨	-			
2012		🟥	▨				▨			
2013	🟥					▨				
2014	🟥									
2015	🟥	▨	🟥 🟨		🟥					
2016	🟥	▨								
					PM$_{10}$					
2007		🟥 🟧	🟥 🟧	🟥	🟥 🟧	🟥 🟧	-	-	-	-
2008		🟥 🟧	🟥 🟧		🟥 🟧	🟥 🟧	-	-	🟧	🟧 🟥
2009		🟥 🟧		▨	🟥 🟧	🟥 🟧	-	-		🟧
2010	🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧	▨	-	-		🟧 🟥
2011	▨	▨	▨ 🟥	▨	▨ 🟥 🟧	🟥 🟧	-	▨ 🟥		🟧
2012	🟧	🟥 🟧		🟥 🟧	🟥 🟧	🟥 🟧	▨			🟧 🟥
2013		🟥 🟧		🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧		🟧 🟥	🟧 🟥
2014	🟧	🟥		🟥	🟥 🟧	🟥 🟧	🟥		🟥	🟧 🟥
2015	🟧	▨ 🟥 🟧	🟧	🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧		🟧 🟥	🟧 🟥
2016	🟧	▨ 🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧	🟥 🟧	🟧	🟧 🟥	▨ 🟧
					PM$_{2.5}$					
2007	▨ 🟥	🟥 🟧	🟥 🟧	🟥	🟥 🟧	🟥 🟧	-	-	-	-
2008	▨	🟥 🟧	▨	🟥 🟧	🟥 🟧	🟥 🟧	-	-	-	-
2009	🟥 🟧	🟥 🟧	▨ 🟥 🟧		🟥 🟧	🟥 🟧	-	-	-	-
2010	▨ 🟥 🟧	▨ 🟥 🟧	🟥 🟧	🟥 🟧	▨ 🟥 🟧	▨	-	-	-	-
2011	▨ 🟥 🟧	▨	▨ 🟥 🟧		▨ 🟧	🟥 🟧	-	▨	-	-
2012	🟥 🟧	🟥 🟧	🟥 🟧	🟥	🟥 🟧	🟥 🟧	▨	▨	-	-
2013		🟥 🟧	🟥 🟧		🟥 🟧	🟥 🟧	▨	▨ 🟥	-	-
2014		🟥 🟧	🟥 🟧	🟥	🟥 🟧	🟥 🟧	▨			-
2015		▨ 🟥 🟧	🟥	🟥 🟧	🟥 🟧	🟥 🟧	▨			▨ 🟧
2016	🟥 🟧	▨ 🟥 🟧	🟥 🟧	🟥 🟧	▨ 🟥 🟧	🟥 🟧	🟧	🟧	🟧	▨ 🟧

Notes:
D = Diepkloof; K = Kliprivier; Se = Sebokeng; T = Three Rivers; Sh = Sharpeville; Z = Zamdela; R = Randwater; E = Eco Park; AJ = AJ Jacobs; and, L = Leitrim

🟨	Hourly non-compliance	🟧	Daily non-compliance	🟥	Annual non-compliance	▨	Data availability <75%

5.2.2.1 Sulfur Dioxide

Annual average SO_2 concentrations were compliant with NAAQS at most stations over the period 2007 to 2016 (Figure 5-39), with the exception of Eco Park (2011, 2014, 2015); Leitrim (2014), and AJ Jacobs (2015, 2016). None of the stations show a distinct reduction in annual average concentrations over the 10-year period.

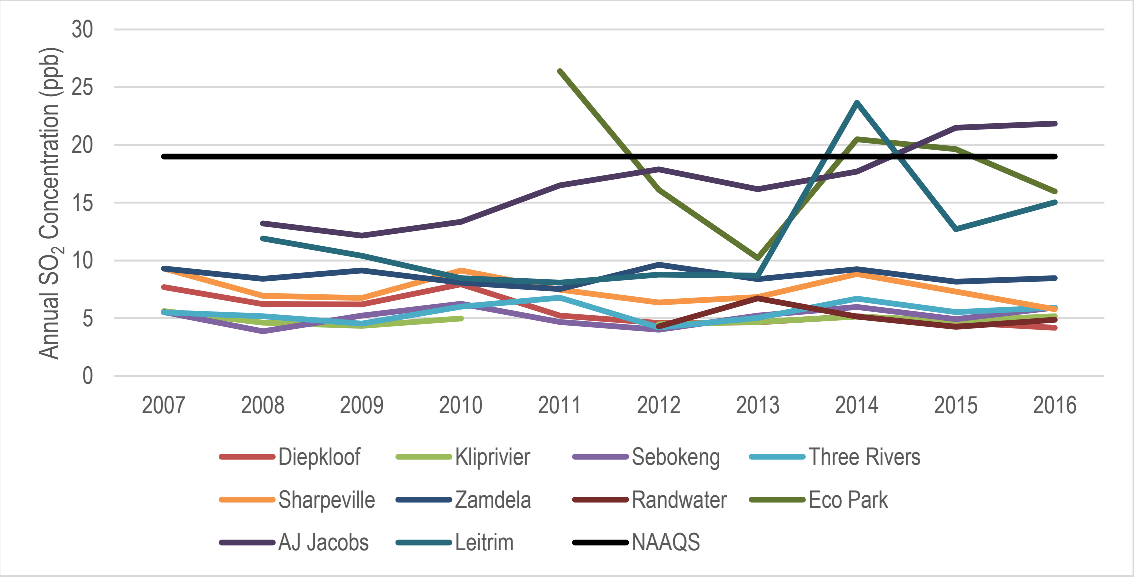
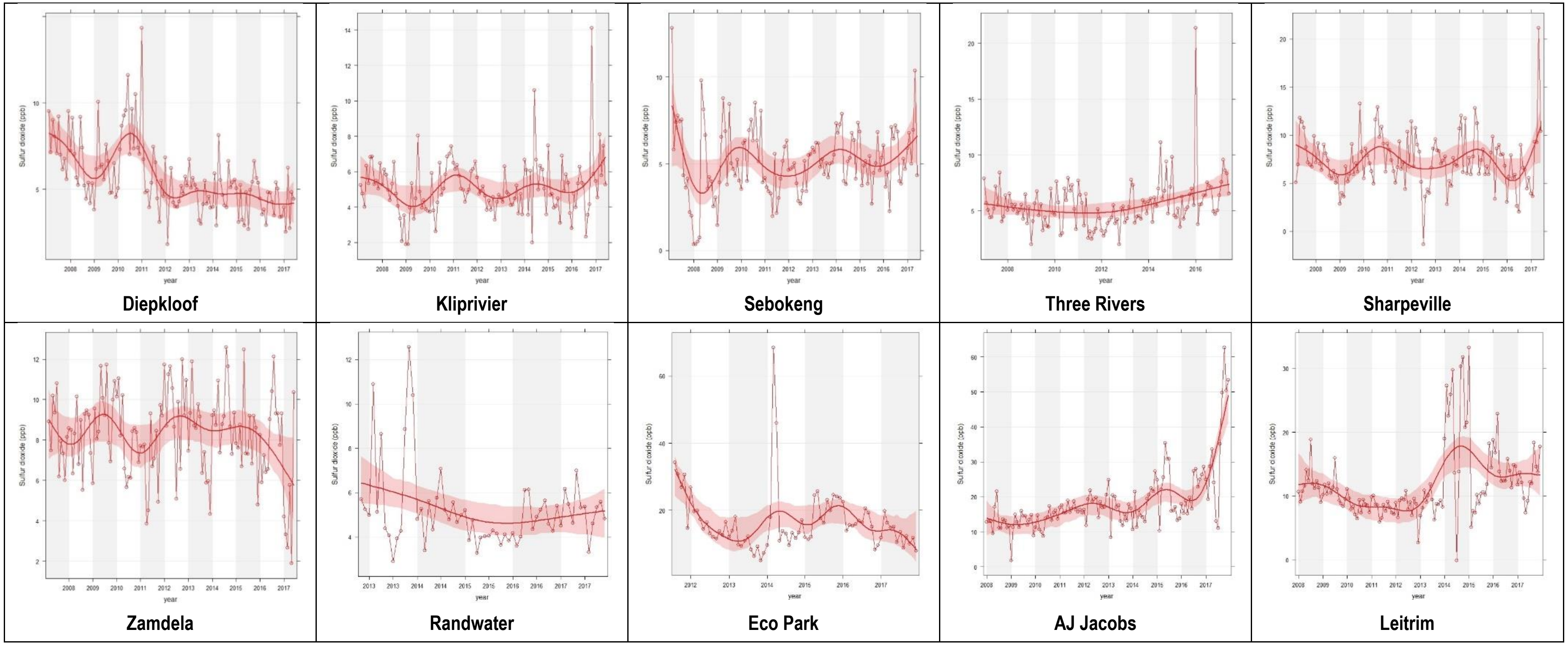


Figure 5-39: Annual average SO_2 concentrations at 10 stations between 2007 and 2016

Long-term trends were generated to understand the changes on the basis of monthly average concentrations (using the "openair" 'smoothTrend' function with the option to de-seasonalise the data and bootstrap simulations to estimate a 95% confidence interval - Carslaw, 2015). One advantage of using monthly average concentrations is that the smoothness in the trend is optimised such that it is neither too smooth (therefore missing important features) nor too variable (perhaps fitting 'noise' rather than real effects). The trends in SO_2 concentrations for 10 of the monitoring stations are provided in Figure 5-40, where small decreases are seen at Diepkloof, Zamdela, Randwater and Eco Park. Small increases in SO_2 concentrations over time are evident at Kliprivier, Three Rivers and AJ Jacobs. Concentrations at Sebokeng, Sharpeville and Leitrim show more annual variability and no distinct long-term trend.



Diepkloof

Kliprivier

Sebokeng

Three Rivers

Sharpeville

Zamdela

Randwater

Eco Park

AJ Jacobs

Leitrim

Figure 5-40: Trends in SO_2 concentrations at 10 stations (de-seasonalised monthly average concentrations)

Polar plots (Carslaw and Ropkins, 2012; Carslaw, 2013) provide an indication of the directional contribution as well as the dependence of concentrations on wind speed. Whereas the directional display is obvious, i.e. when higher concentrations are shown to occur in a certain sector, e.g. from the east at Diepkloof (Figure 5-41), it is understood that most of the high concentrations occur when winds blow from that sector (i.e. east). When the high concentration pattern is more symmetrical around the centre of the plot, it is an indication that the contributions are near-equally distributed.

At all stations hourly SO_2 concentrations were usually lower than 40 ppb. At the Diepkloof station (Figure 5-41), SO_2 concentrations above 40 ppb originate from the north-east and east at wind speeds above 2 m/s; most evident in 2007 and 2012. The Kliprivier station records higher SO_2 concentrations with southerly winds, especially at wind speeds between 4 and 8 m/s (Figure 5-42). Winds from the south-east of the Sebokeng (Figure 5-43) and Sharpeville (Figure 5-45) stations show contributions of SO_2 concentrations at all wind speeds. The Three Rivers station (Figure 5-44) records elevated SO_2 concentrations with two wind directions: winds from the north-east (lower concentrations and all wind speeds) and winds from the south (at wind speeds between 4 and 6 m/s). The Zamdela station recorded elevated SO_2 concentrations at wind speeds above 6 m/s from the north-east and other sources to the north and north-west contributing at all wind speeds (Figure 5-46). The dominant contribution of hourly SO_2 concentrations above 60 µg/m³ originate to the south-east of the Randwater station at wind speeds between 4 m/s and 6 m/s, where 2014 recorded the highest concentrations (Figure 5-47). At Eco Park, contributions originate from all sectors, but two sources located east and south of the station consistently contribute at all wind speeds (Figure 5-48). A distinct pattern of contribution from the north-east is noted at AJ Jacobs, where the highest SO_2 concentrations are associated with winds above 5 m/s (Figure 5-49). The Leitrim station records suggest two sources contributing at all wind speeds, one to the north-west and one to the north-east of the station (Figure 5-50).

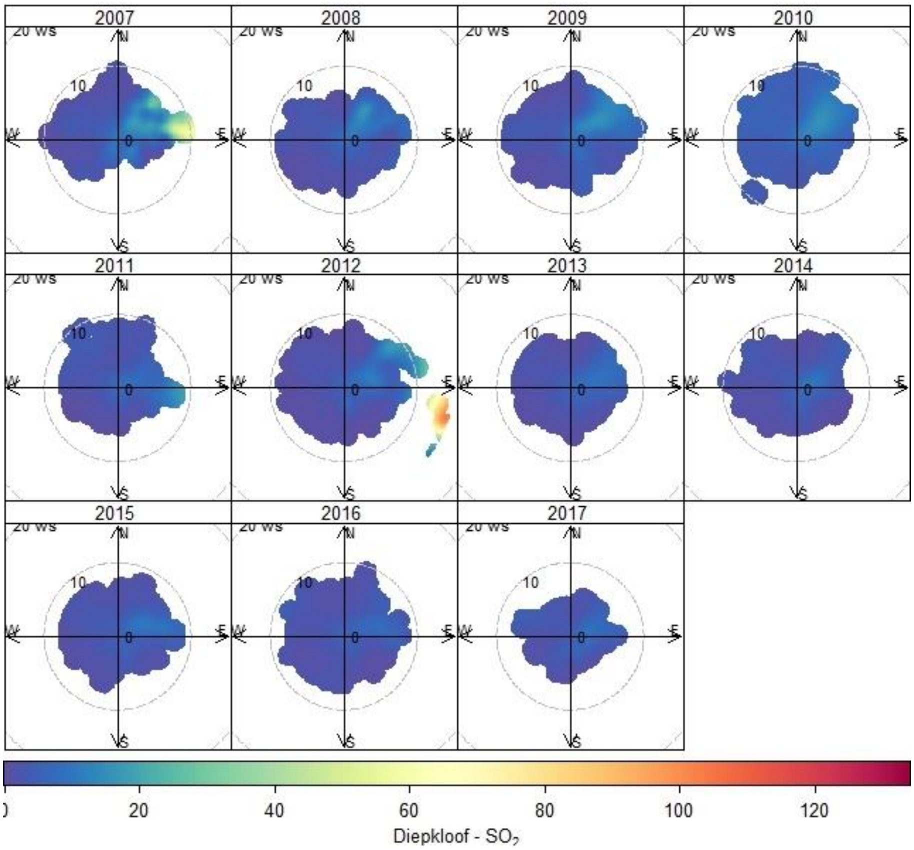


Figure 5-41: Polar plots for hourly SO_2 concentrations at Diepkloof station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

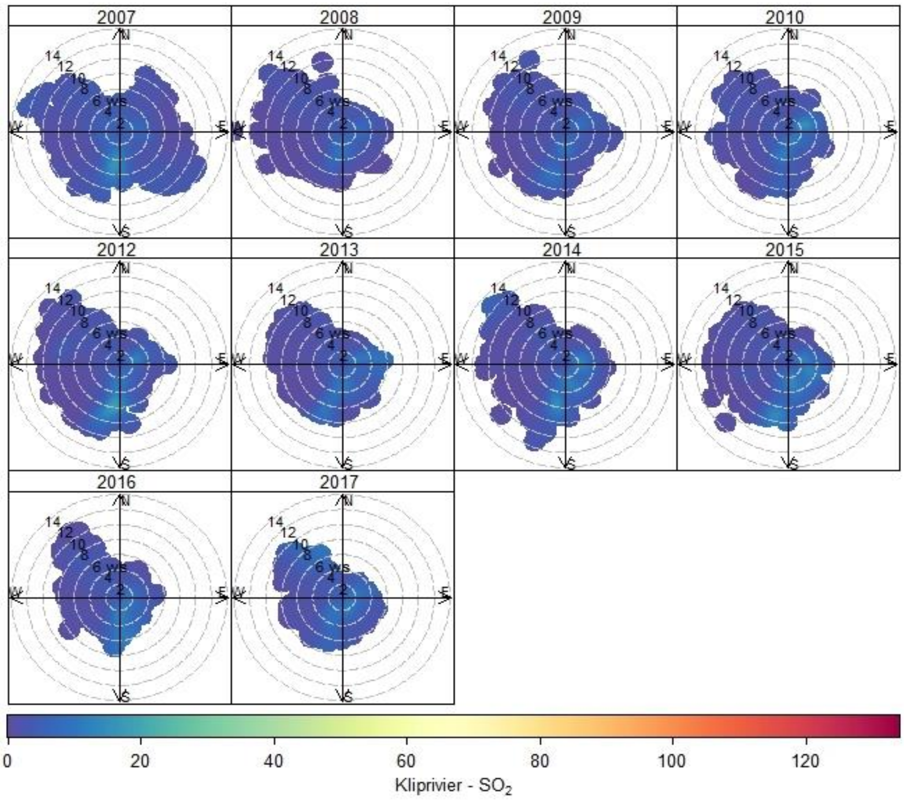


Figure 5-42: Polar plots for hourly SO_2 concentrations at Kliprivier station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

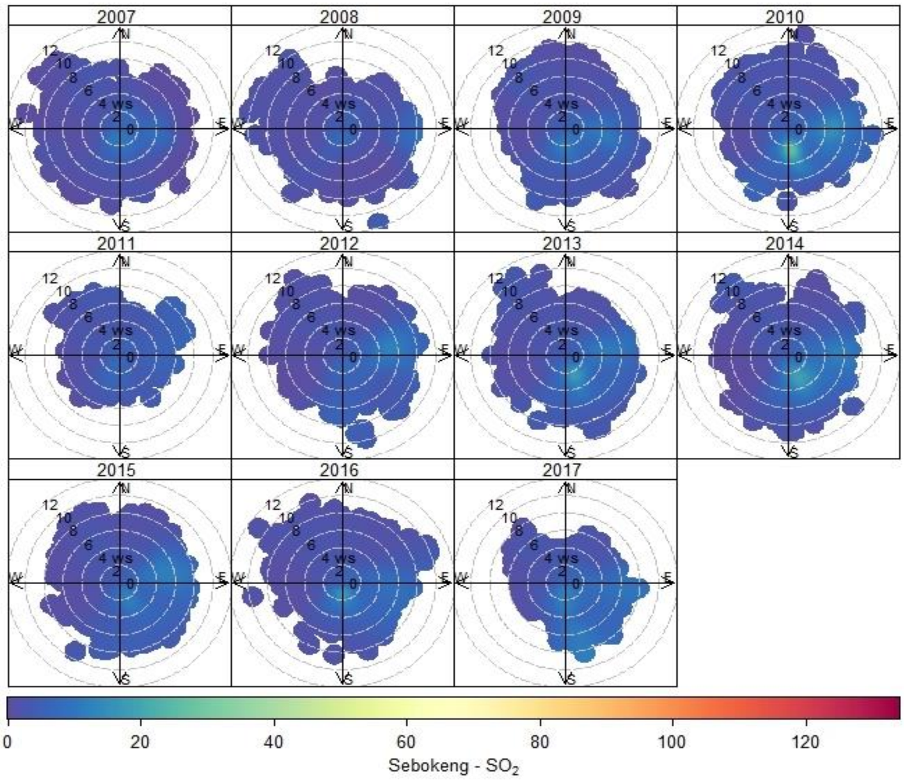


Figure 5-43: Polar plots for hourly SO_2 concentrations at Sebokeng station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

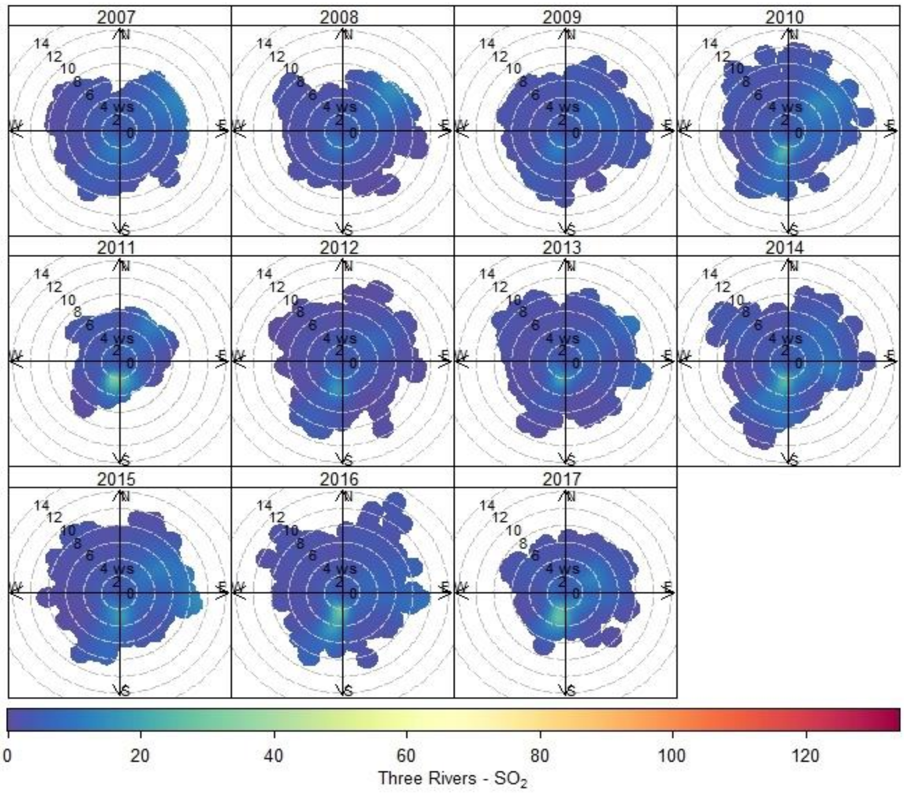


Figure 5-44: Polar plots for hourly SO_2 concentrations at Three Rivers station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

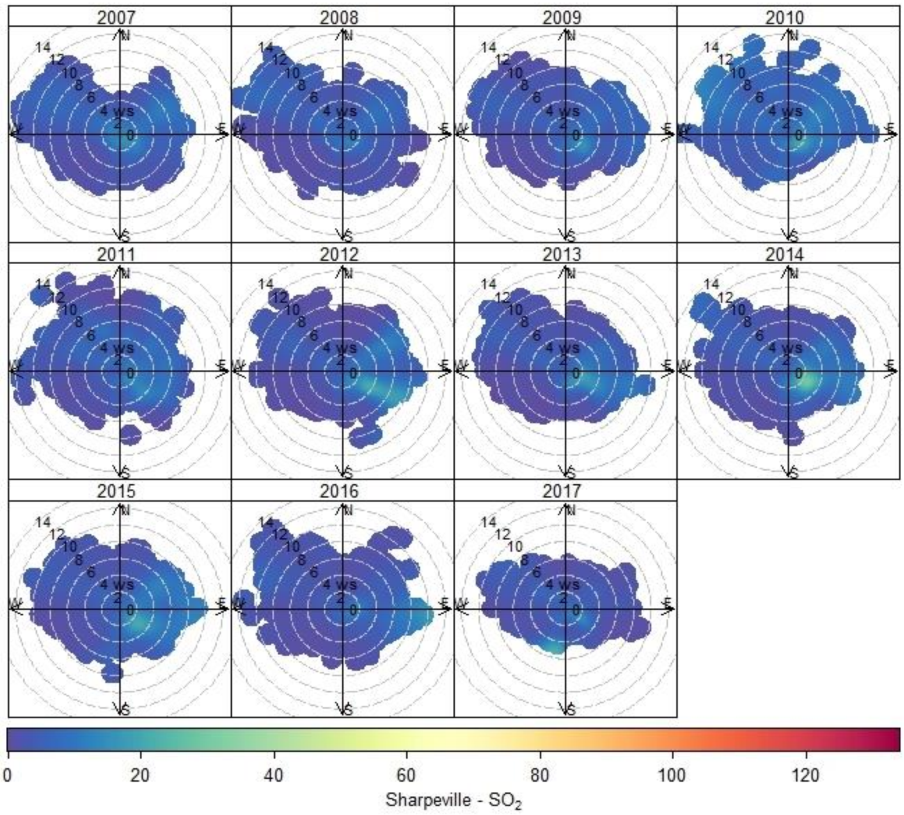


Figure 5-45: Polar plots for hourly SO_2 concentrations at Sharpeville station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

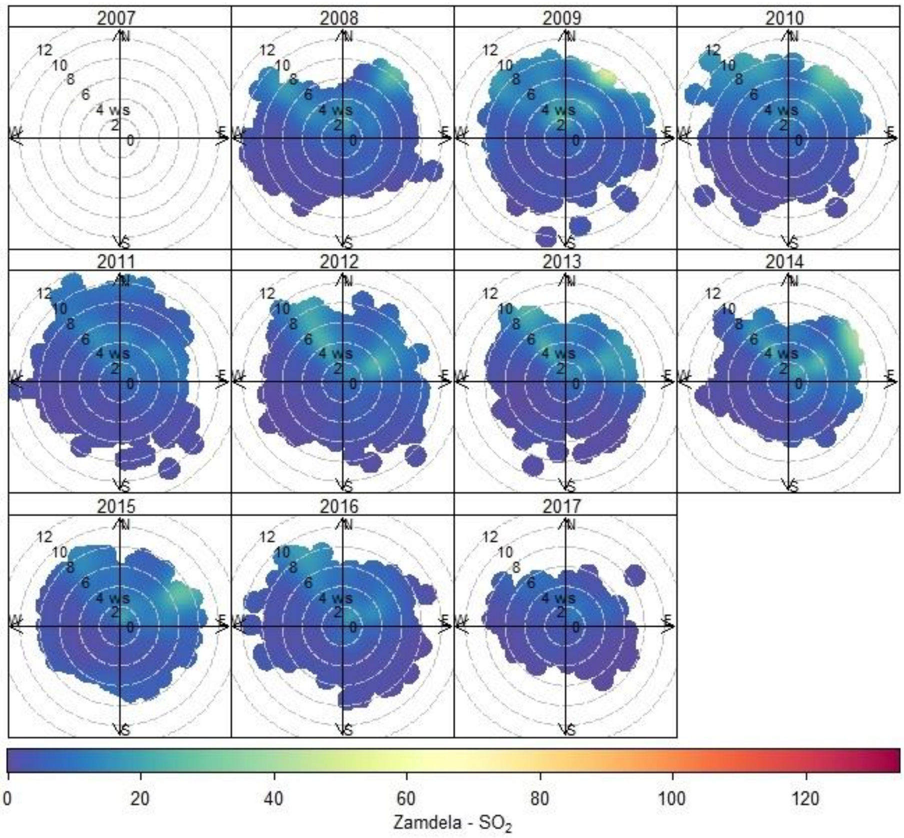


Figure 5-46: Polar plots for hourly SO_2 concentrations at Zamdela station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

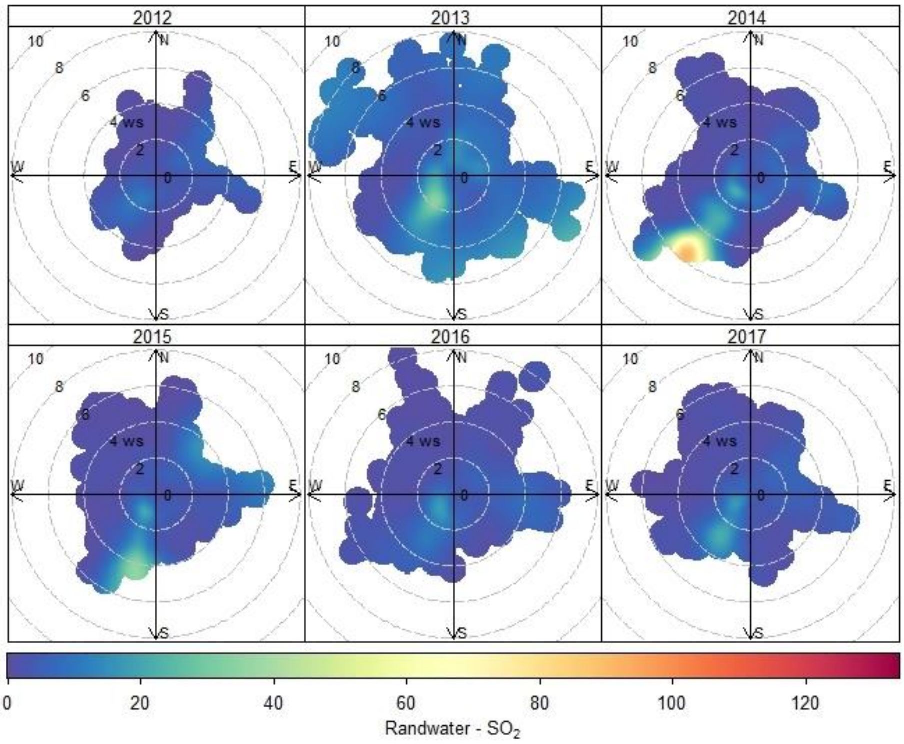


Figure 5-47: Polar plots for hourly SO_2 concentrations at Randwater station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

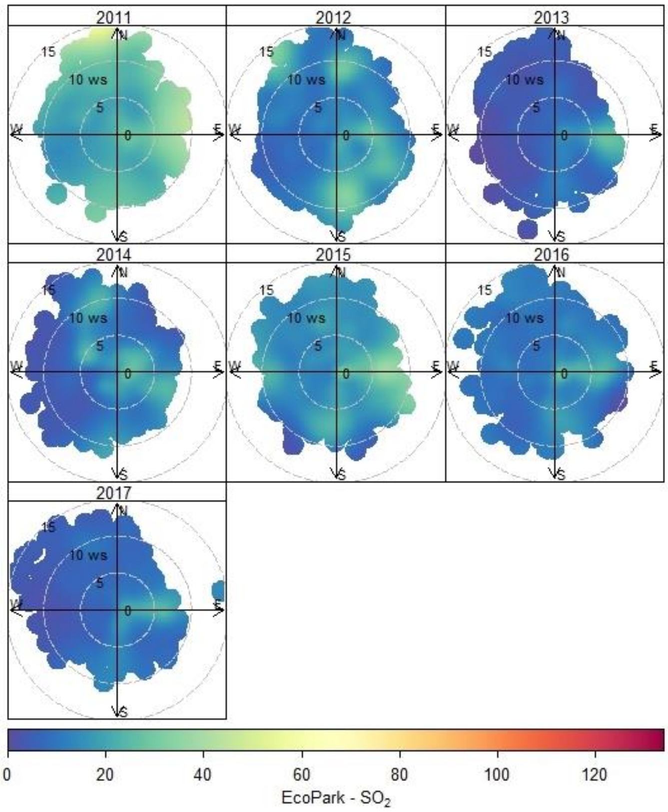


Figure 5-48: Polar plots for hourly SO_2 concentrations at Eco Park station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

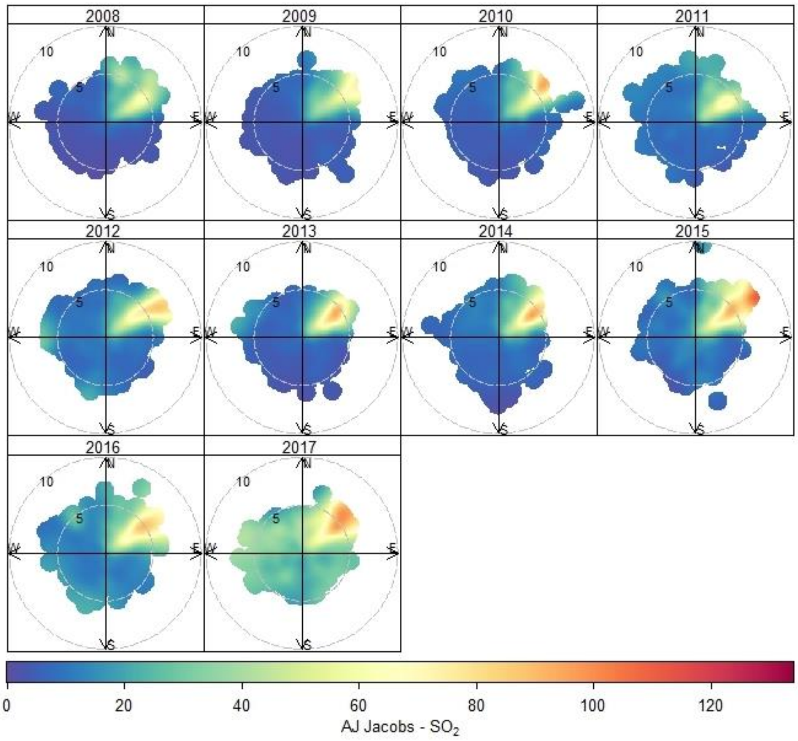


Figure 5-49: Polar plots for hourly SO_2 concentrations at AJ Jacobs station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

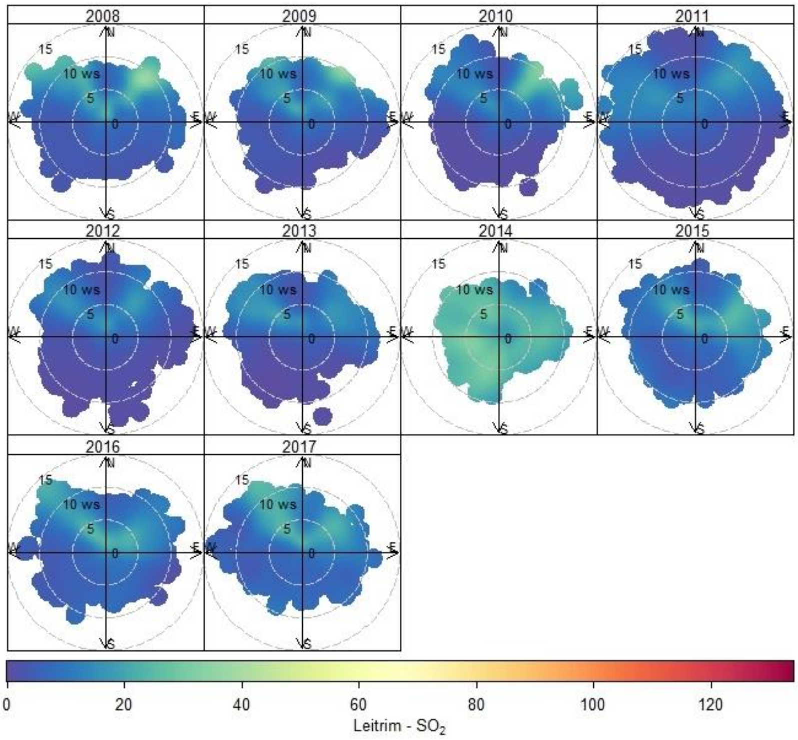


Figure 5-50: Polar plots for hourly SO_2 concentrations at Leitrim station (units: ppb; limit 134 ppb hourly NAAQ limit concentration)

5.2.2.2 Nitrogen Dioxide

Annual average NO_2 concentrations were non-compliant with NAAQS at the Diepkloof station in all years except 2011 and 2012; at Kliprivier in 2009 and 2010; and at both the Sebokeng and Sharpeville stations in 2015 (Figure 5-51). The Randwater station records the lowest annual NO_2 concentrations (Figure 5-51).

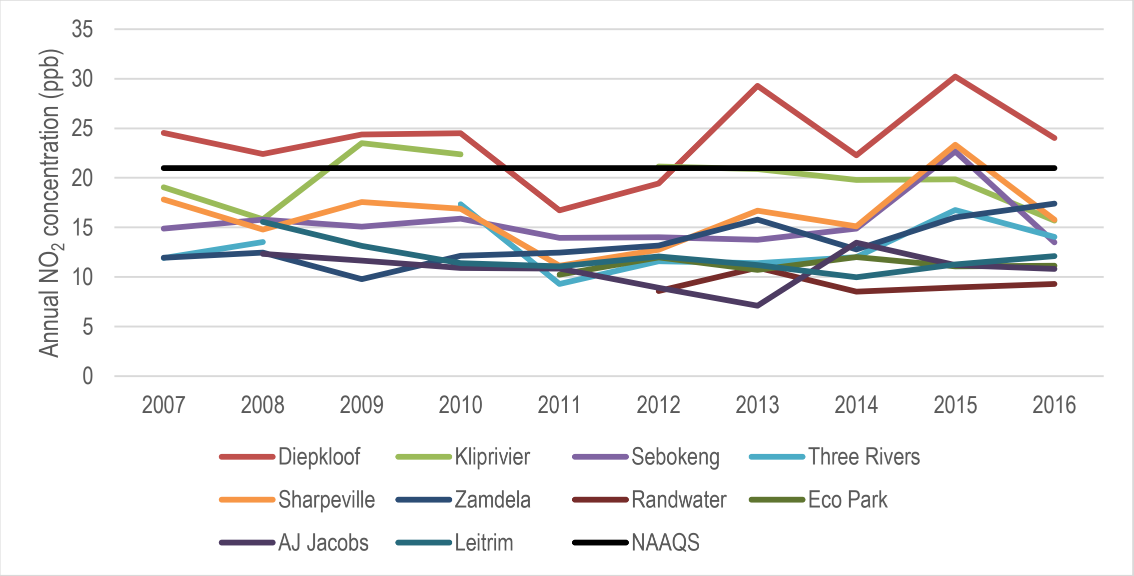
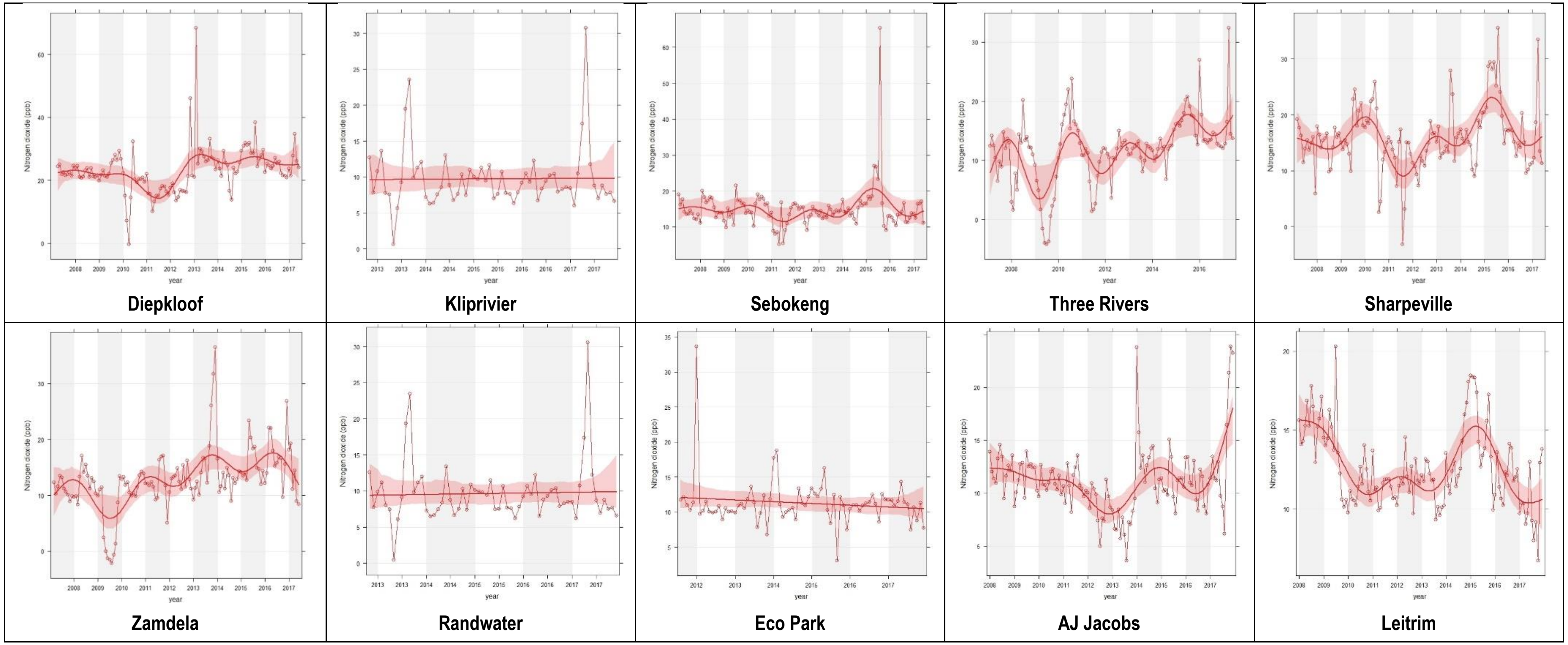


Figure 5-51: Annual average NO_2 concentrations at 10 stations between 2007 and 2016

Trend analysis (Figure 5-52) shows that the monthly NO_2 concentrations have decreased slightly at the Leitrim station, while concentrations have stayed quite similar at the Kliprivier; Sebokeng; Sharpeville; and Eco Park stations. Increased monthly average concentrations are evident at the Diepkloof; Three Rivers; Zamdela; and AJ Jacobs stations.

Polar plots were prepared for each year for all sites. At low wind speeds NO_2 contributions are equally distributed around the station during all years at Diepkloof (Figure 5-53), while higher concentrations are associated with winds from the north-east, south-west, and west during periods of higher wind speeds. Equal distribution of NO_2 contributes to records at the Kliprivier station at low wind speeds (Figure 5-54), while winds from the west and north-west have elevated contributions at wind speeds above 8 m/s. During 2014, wind from the south of Kliprivier contributed elevated NO_2 concentrations at wind speeds over 10 m/s. NO_2 concentrations at the Sebokeng station (Figure 5-55) persist mainly during low wind speeds. In 2014 winds from the north-west, north-east, and south-east of the Sebokeng station contributed NO_2 concentrations at wind speeds above 8 m/s. The Three Rivers station also has persistent NO_2 contributions at low wind speeds; however, during high wind speed events in 2010 and 2015 elevated concentrations were recorded when northerly and north-easterly winds were dominant (Figure 5-56). In addition to NO_2 concentrations associated with low wind speeds, the Sharpeville station was influenced by winds from the north-west and west (during 2007, 2011, 2014, and 2015) and to the north-east (2011) during high wind speed events (Figure 5-57). NO_2 concentrations measured at the Zamdela station are associated with winds from the north-west and north east at all wind speeds, while wind from the north-east made contributions during 2008 and 2011 (Figure 5-58). The NO_2 concentrations at the Randwater station (Figure 5-59) shows contribution from the north-west (2013 and 2016), north-west (2013 and 2016), and south-west (2016) at higher wind speeds, while low winds speeds are associated with lower NO_2 concentrations from all directions. Since vehicular exhaust emissions are significant NO_2 contributors, the observations from the stations located in high traffic areas with a strongly contributions at low wind speeds are most likely from this source. The Eco Park (Figure 5-60), AJ Jacobs (Figure 5-61), and Leitrim (Figure 5-62) stations show NO_2 concentrations following spatial and wind-field patterns very similar to SO_2 concentrations.



Diepkloof

Kliprivier

Sebokeng

Three Rivers

Sharpeville

Zamdela

Randwater

Eco Park

AJ Jacobs

Leitrim

Figure 5-52: Trends in NO_2 concentrations at 10 stations (de-seasonalised monthly average concentrations)

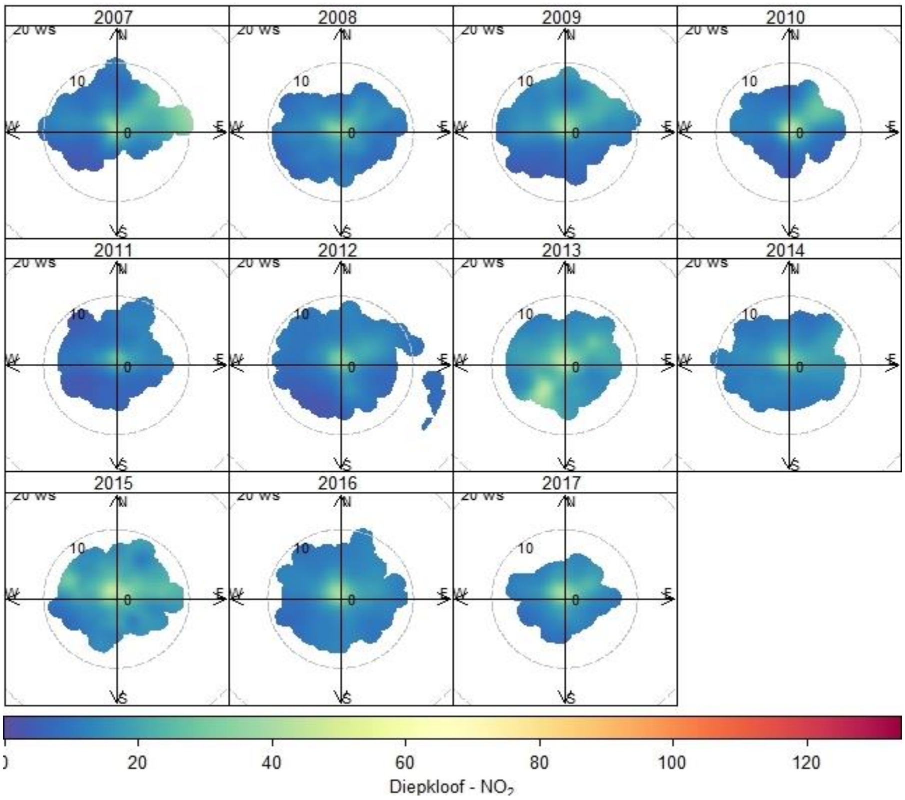


Figure 5-53: Polar plots for hourly NO_2 concentrations at Diepkloof station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

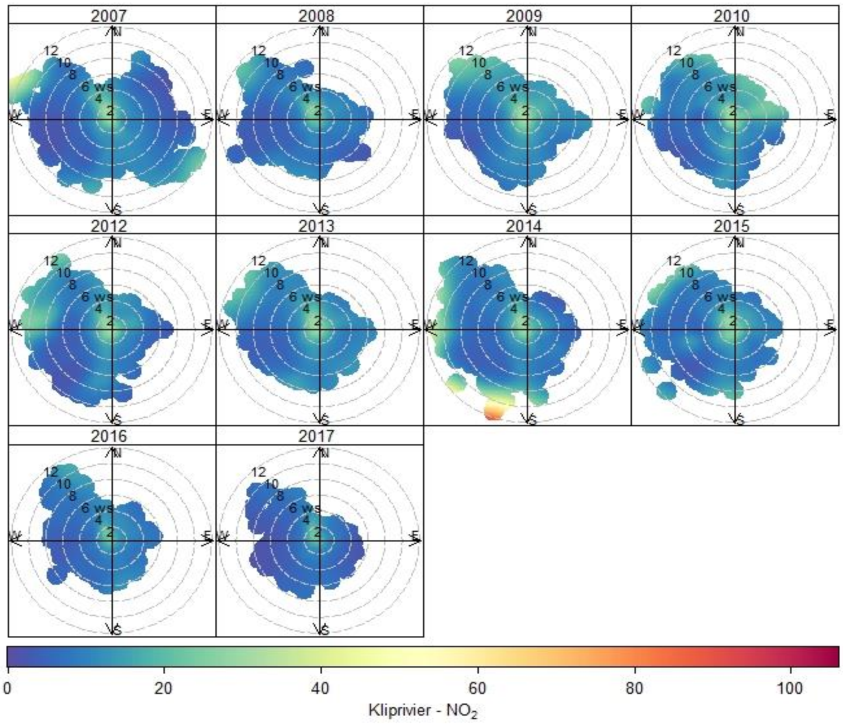


Figure 5-54: Polar plots for hourly NO_2 concentrations at Kliprivier station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

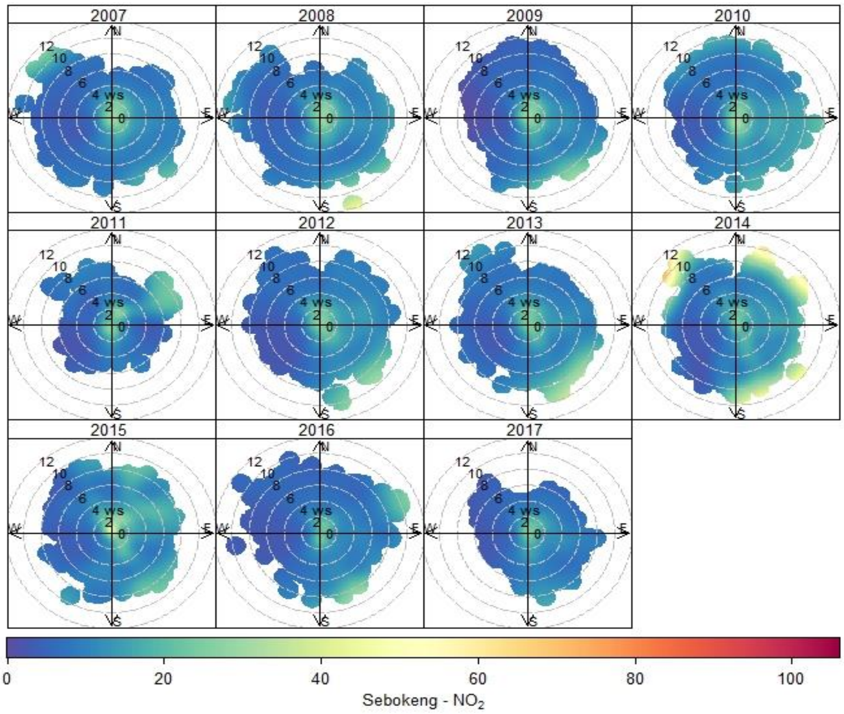


Figure 5-55: Polar plots for hourly NO_2 concentrations at Sebokeng station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

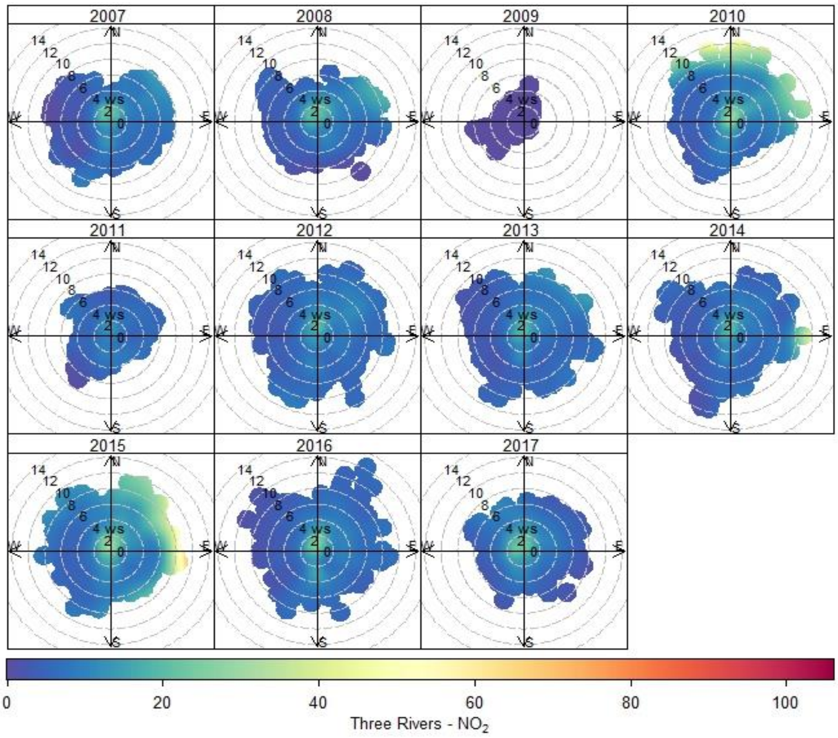


Figure 5-56: Polar plots for hourly NO_2 concentrations at Three Rivers station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

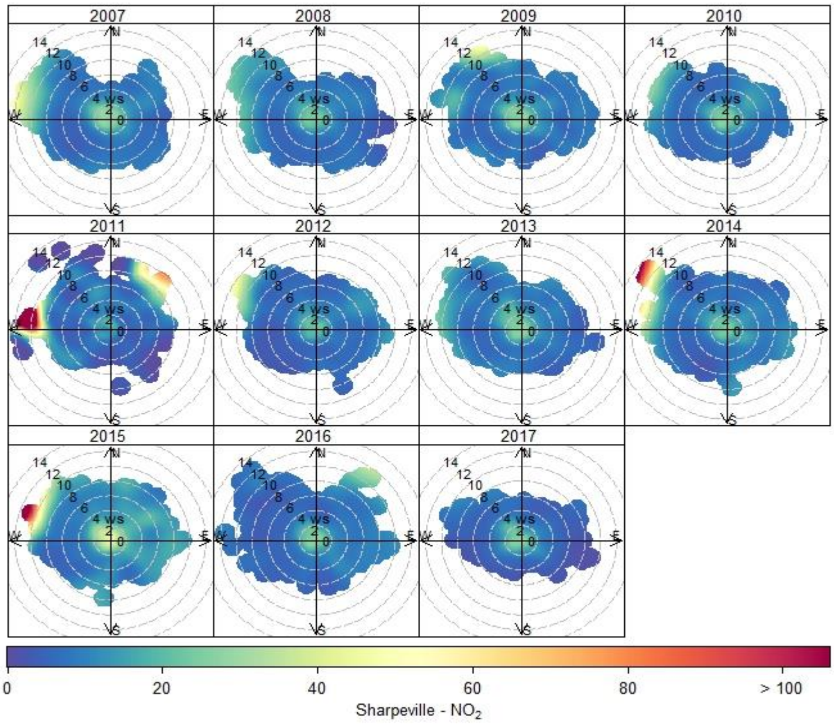


Figure 5-57: Polar plots for hourly NO_2 concentrations at Sharpeville station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

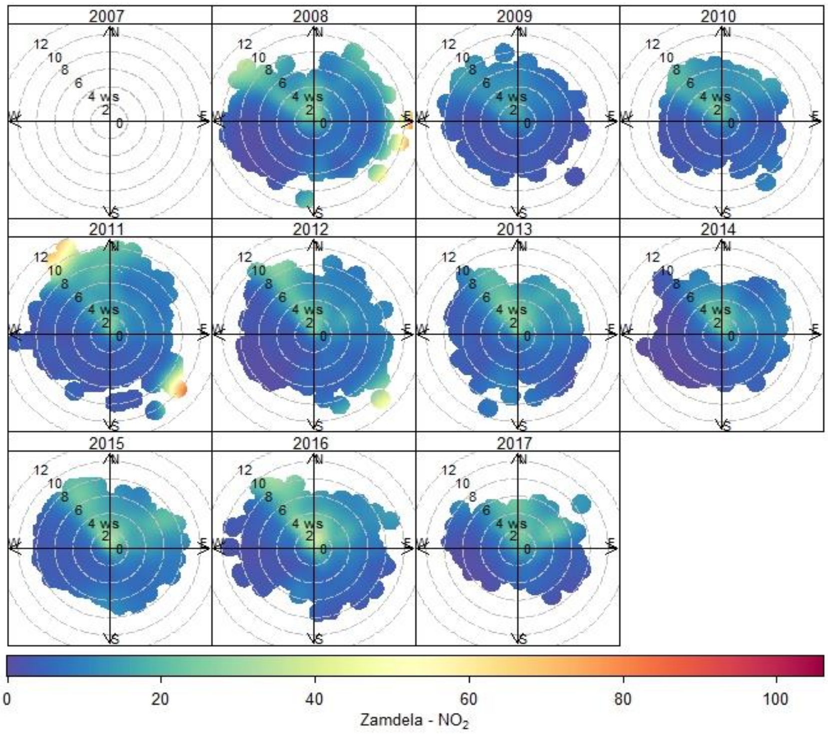


Figure 5-58: Polar plots for hourly NO_2 concentrations at Zamdela station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

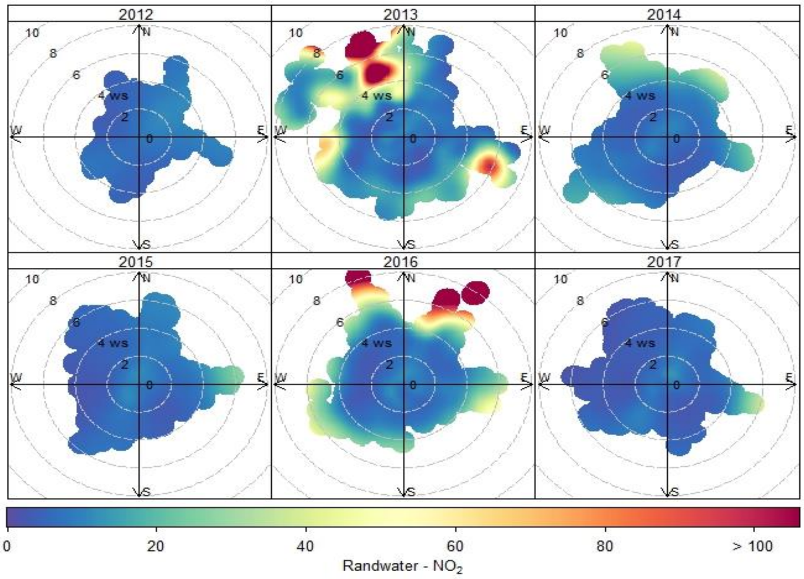


Figure 5-59: Polar plots for hourly NO$_2$ concentrations at Randwater station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

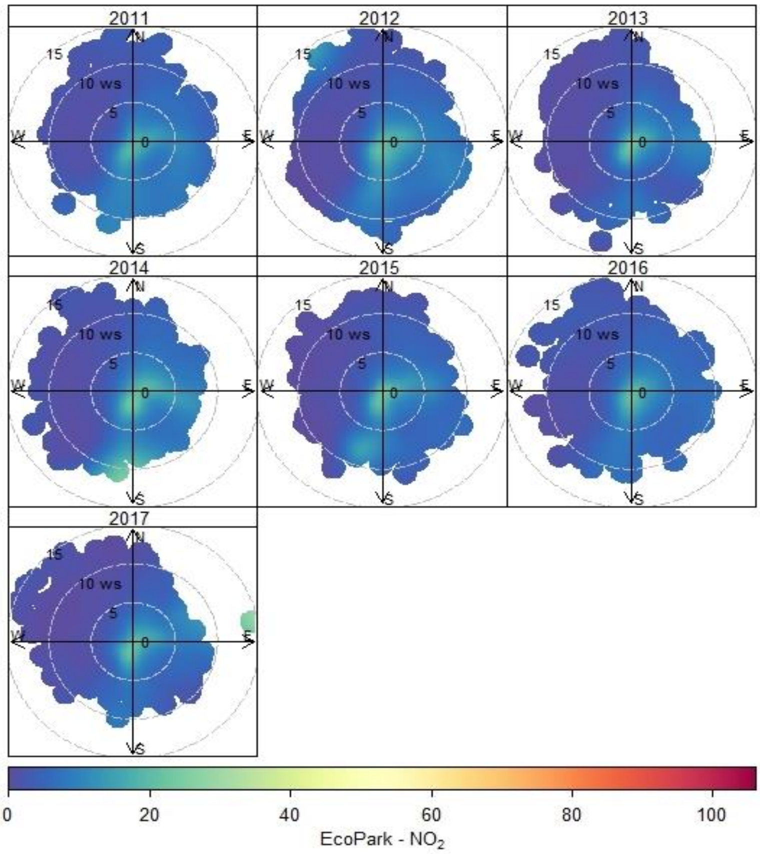


Figure 5-60: Polar plots for hourly NO$_2$ concentrations at Eco Park station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

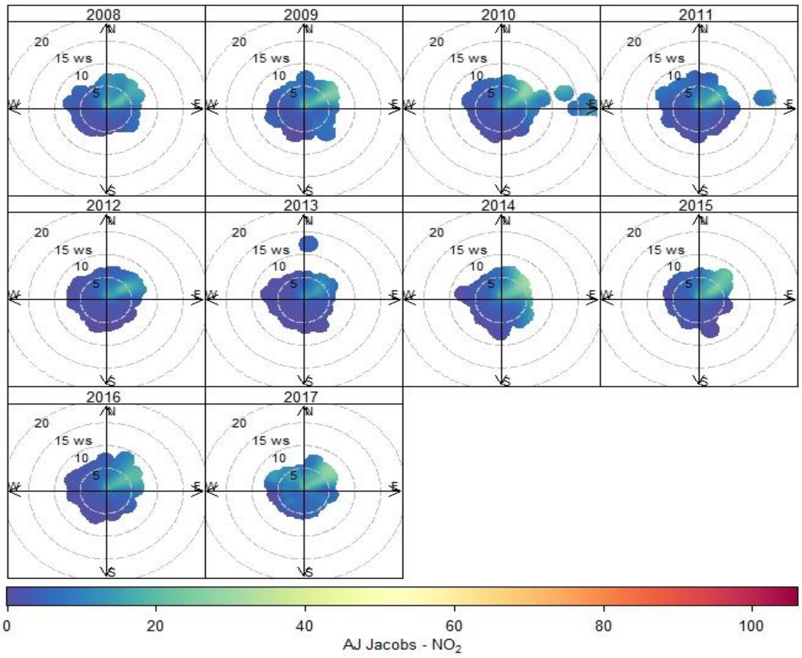


Figure 5-61: Polar plots for hourly NO_2 concentrations at AJ Jacobs station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

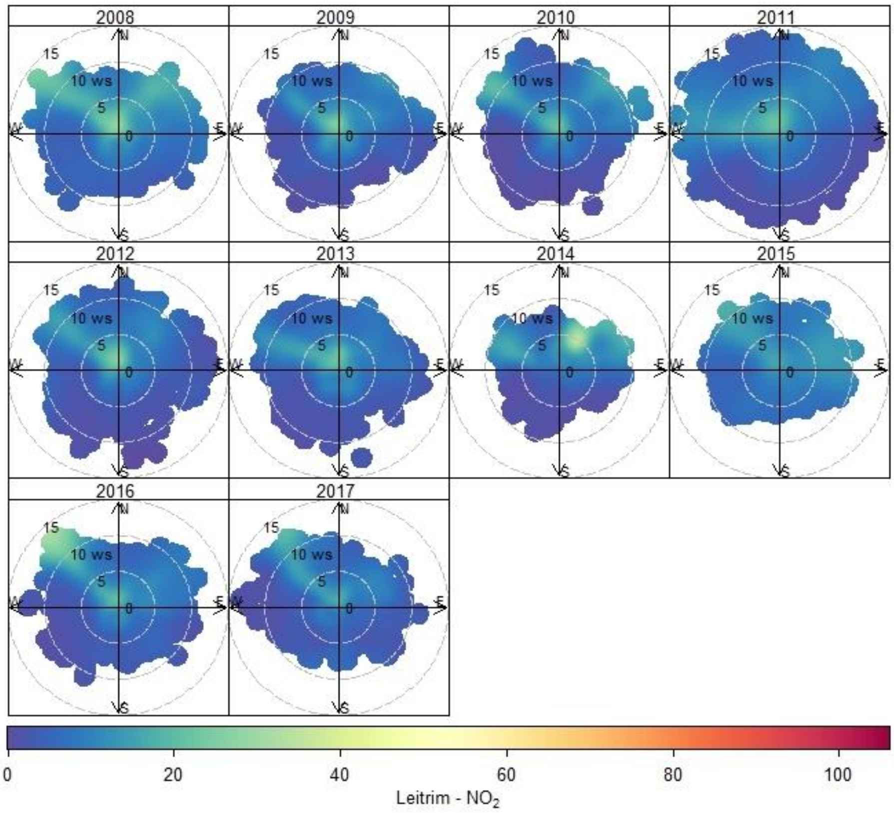


Figure 5-62: Polar plots for hourly NO_2 concentrations at Leitrim station (units: ppb; limit 106 ppb hourly NAAQ limit concentration)

5.2.2.3 Particulate Matter – PM_{10}

Annual average PM_{10} concentrations exceeded the NAAQS at all nine stations at least once during the period 2007 to 2016; the exception being Eco Park where annual PM_{10} has been compliant with NAAQS since establishment of the station (Figure 5-63). The station with the lowest annual PM_{10} concentrations was Eco Park, while the station with the highest PM_{10} concentrations – over most of the period – was Zamdela.

Trend analysis of the monthly average PM_{10} concentrations at 10 stations (Figure 5-64) shows increases at the Kliprivier and Sharpeville over the period; with no substantive change at Three Rivers and Eco Park. Decreased concentrations are evident at Diepkloof, Sebokeng, Zamdela, Randwater; AJ Jacobs and Leitrim.

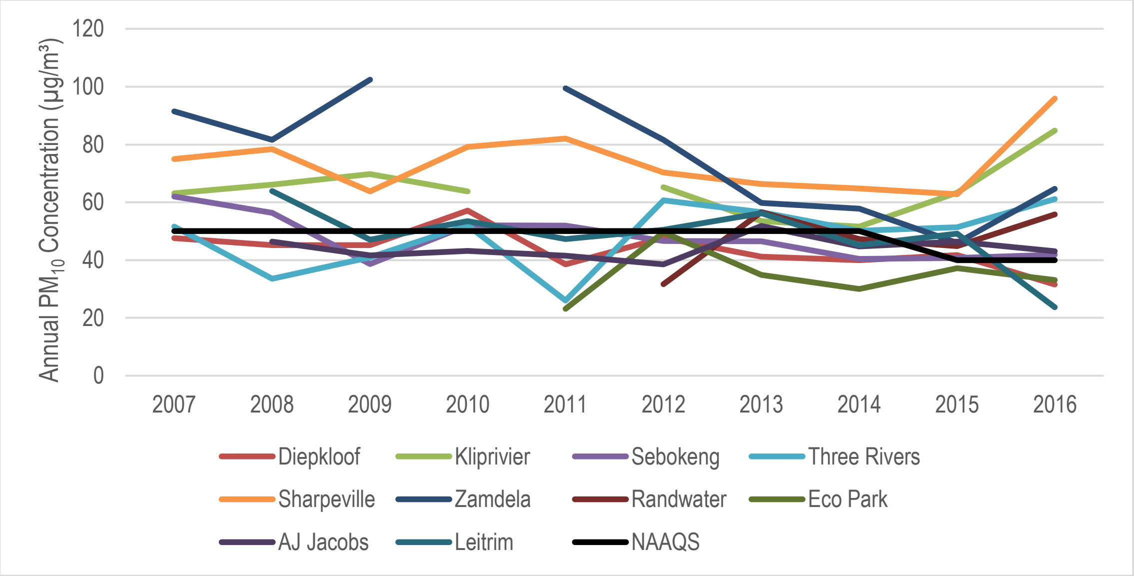
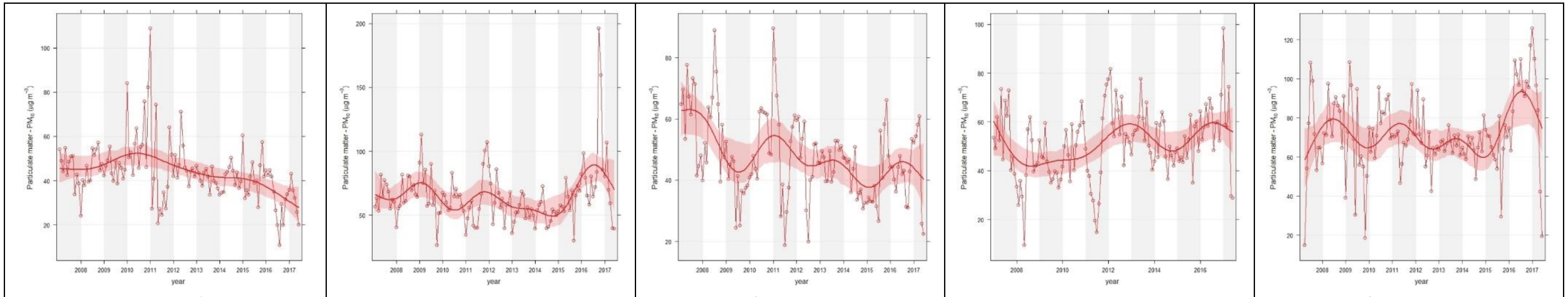
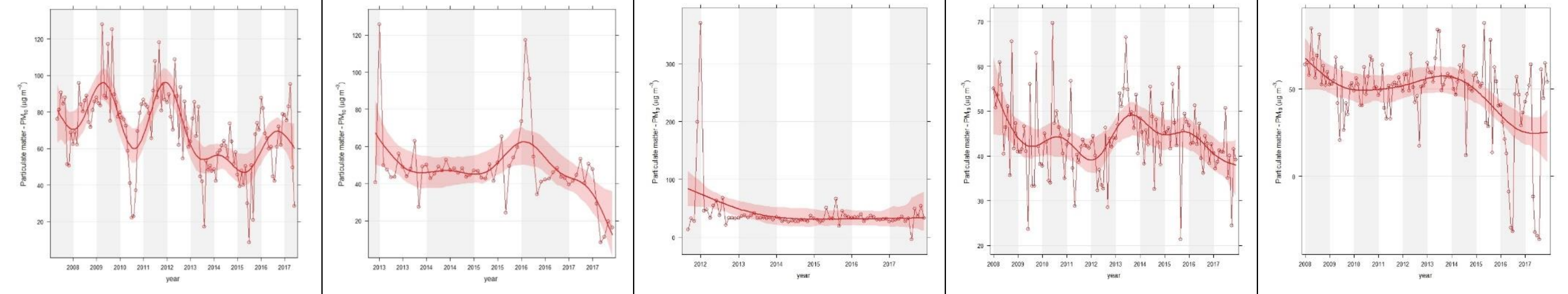


Figure 5-63: Annual average PM_{10} concentrations at 10 stations between 2007 and 2016

Polar plots for PM_{10} concentrations were generated based on daily average concentrations (Figure 5-65 to Figure 5-71). At least six of the stations show a substantial contribution at low wind speeds, including: Kliprivier, Sebokeng, Three Rivers, Sharpeville, Zamdela, and to a lesser extent, Randwater and Diepkloof. At low wind speeds (2 m/s or less) the almost symmetrical plot suggests local contributions, most likely a result of community activities. Substantial contributions from the northern sector contributed during 2010, 2011, 2014, and 2015 at the Diepkloof station, while winds from the southerly sector continually showed the lowest particulate concentrations (Figure 5-65). An improvement in PM_{10} concentrations at Diepkloof is also evident in the polar plots. During 2009, winds from the south-west of the Kliprivier station were associated with elevated PM_{10} concentrations at wind speeds higher than 4 m/s (Figure 5-66). The Sebokeng (Figure 5-67), Three Rivers (Figure 5-68) and Sharpeville (Figure 5-69) stations recorded elevated particulate concentrations from the northerly sector at wind speeds greater than 6 m/s, while winds from the south recorded the lowest PM_{10} concentrations. Particulate concentrations recorded at the Zamdela (Figure 5-70) show high concentrations from the west, north-west, north-east, east, and south, at high wind speeds (above 6 m/s), however, the concentrations from these directions are shown to decrease over the period. During 2014 the Randwater station (Figure 5-71) recorded elevated concentrations from the westerly sector at high wind speeds, while other years show persistent local sources at lower wind speeds. At the Eco Park station elevated particulate concentrations are associated with northerly winds during high wind speed events, but contributions from all directions at mid-range wind speeds can also result in elevated concentrations (Figure 5-72). At AJ Jacobs station winds from north and west result in elevated PM_{10} concentrations (Figure 5-73). Elevated particulate concentrations contribute from all directions at low wind speeds at the Leitrim station (Figure 5-74).



Diepkloof **Kliprivier** **Sebokeng** **Three Rivers** **Sharpeville**



Zamdela **Randwater** **Eco Park** **AJ Jacobs** **Leitrim**

Figure 5-64: Trends in PM10 concentrations at 10 stations (de-seasonalised monthly average concentrations)

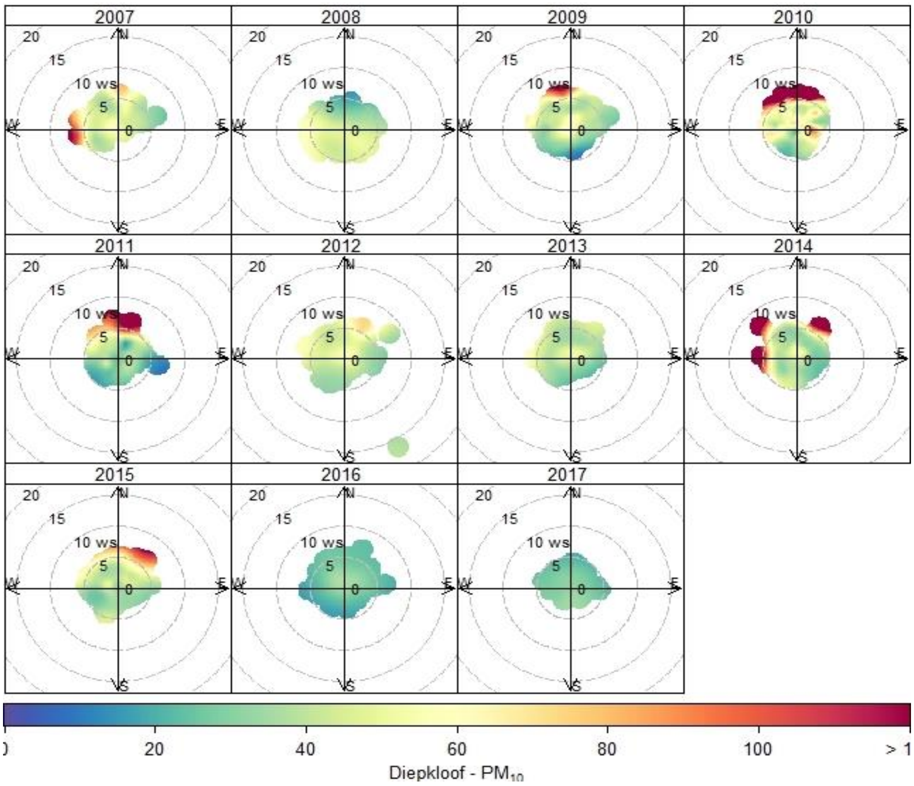


Figure 5-65: Polar plots for daily PM$_{10}$ concentrations at Diepkloof station (units: µg/m^3; limit 120 µg/m^3 daily NAAQ limit concentration enforceable up to 2015)

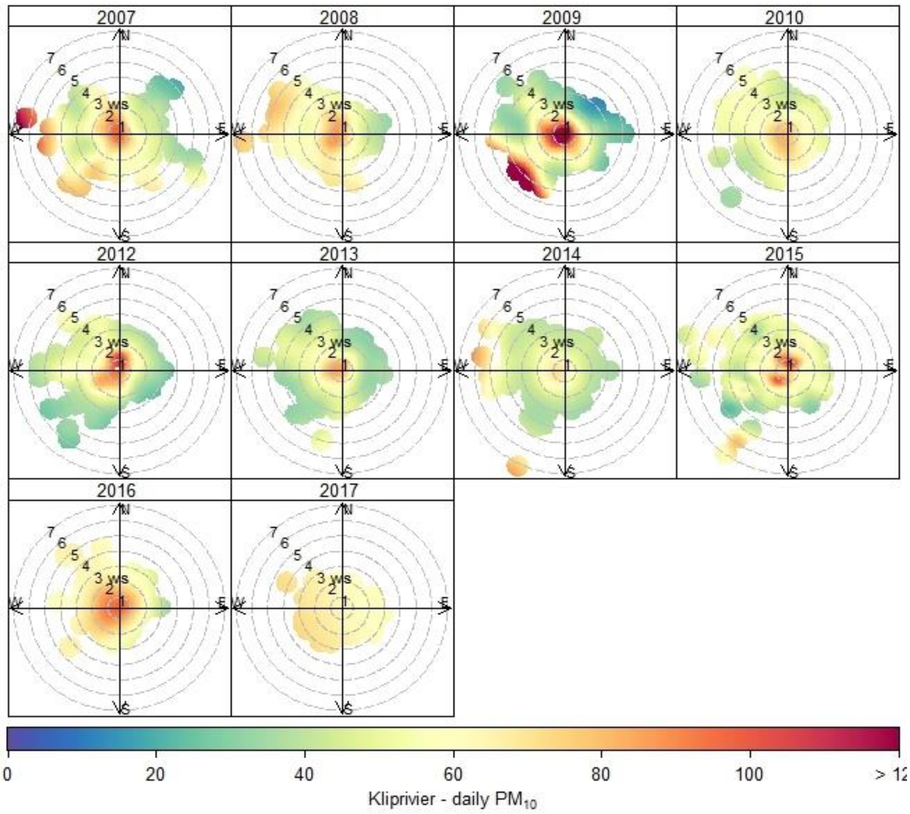


Figure 5-66: Polar plots for daily PM$_{10}$ concentrations at Kliprivier station (units: µg/m^3; limit 120 µg/m^3 daily NAAQ limit concentration enforceable up to 2015)

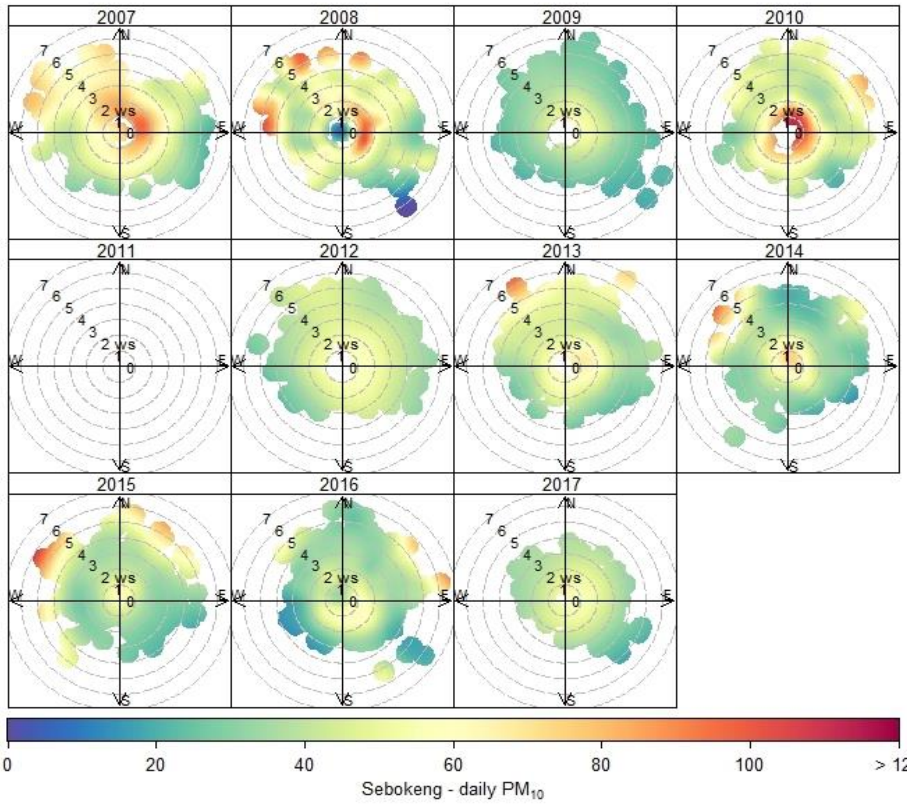


Figure 5-67: Polar plots for daily PM_{10} concentrations at Sebokeng station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

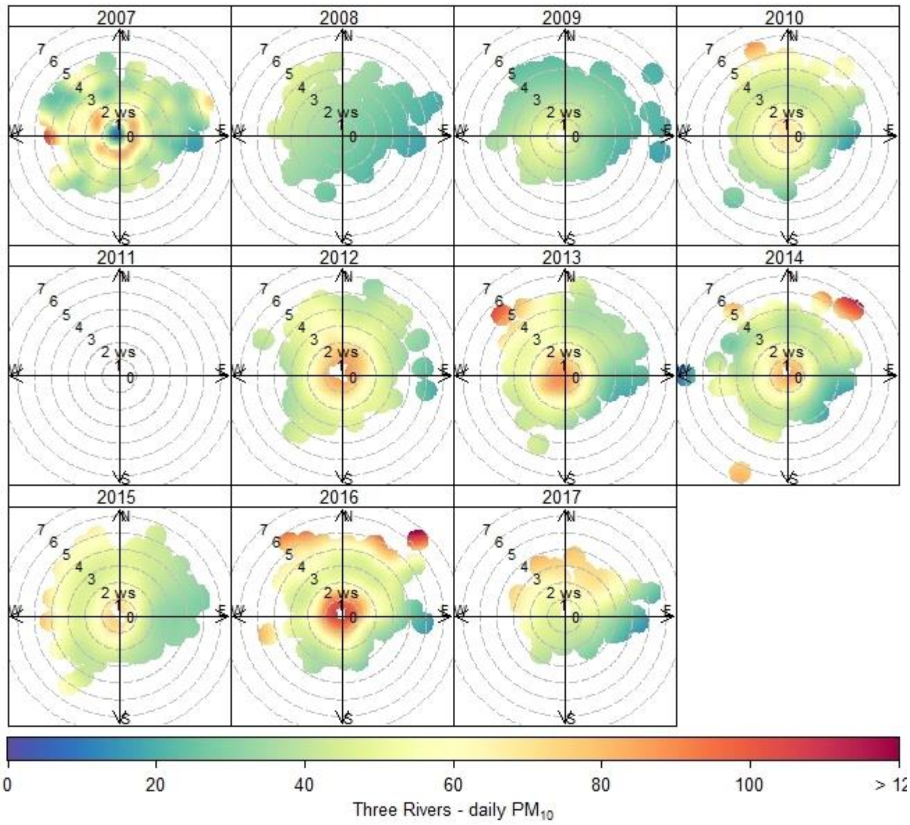


Figure 5-68: Polar plots for daily PM_{10} concentrations at Three Rivers station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

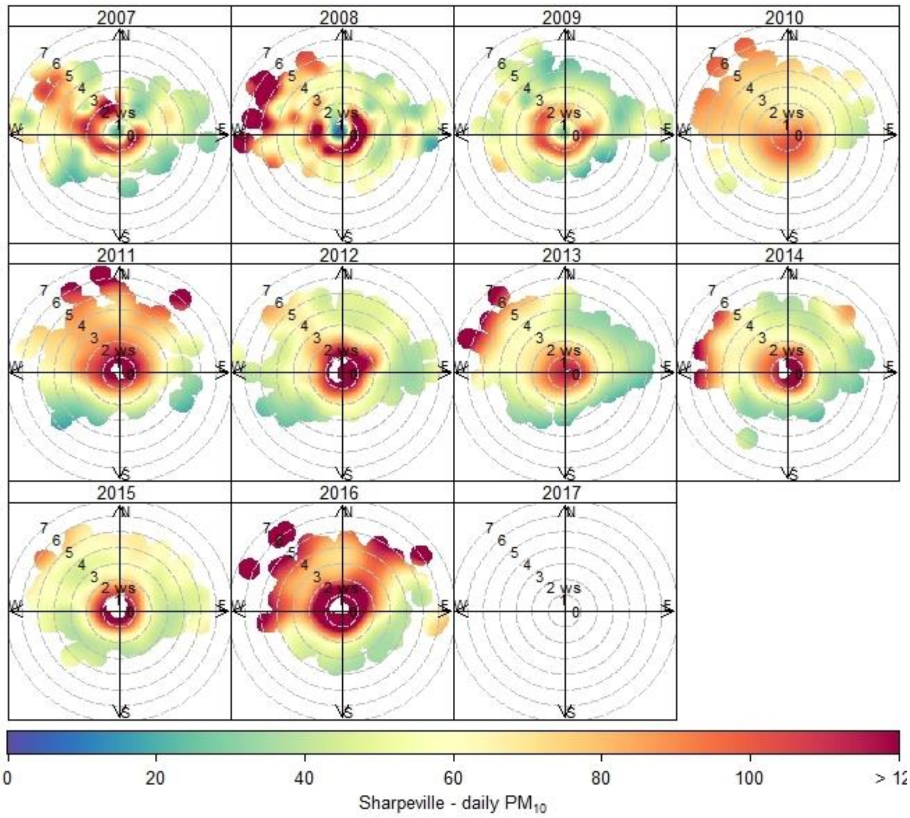


Figure 5-69: Polar plots for daily PM$_{10}$ concentrations at Sharpeville station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

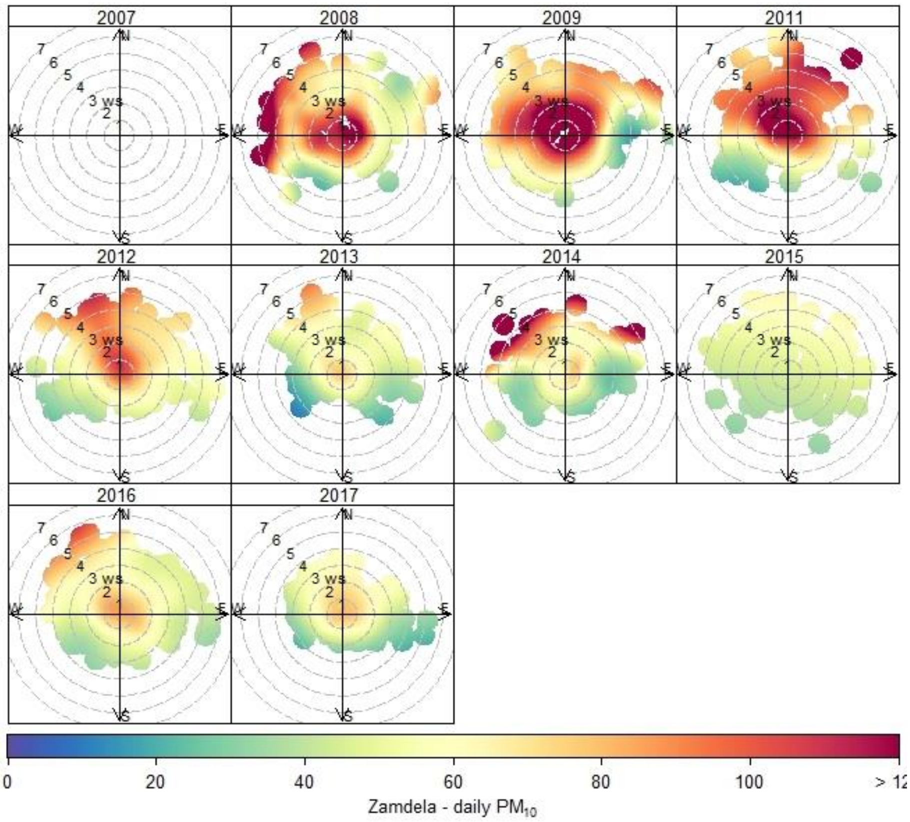


Figure 5-70: Polar plots for daily PM$_{10}$ concentrations at Zamdela station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

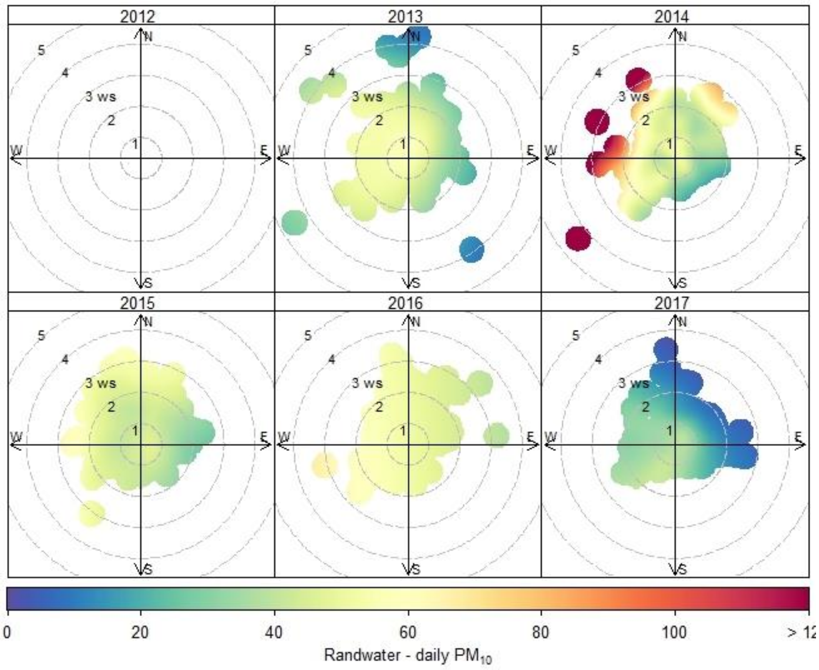


Figure 5-71: Polar plots for daily PM_{10} concentrations at Randwater station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

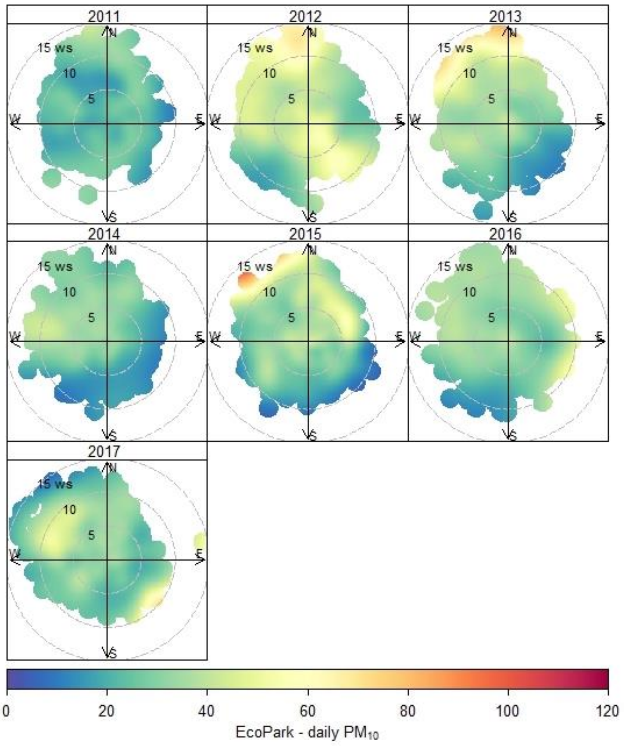


Figure 5-72: Polar plots for daily PM_{10} concentrations at Eco Park station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

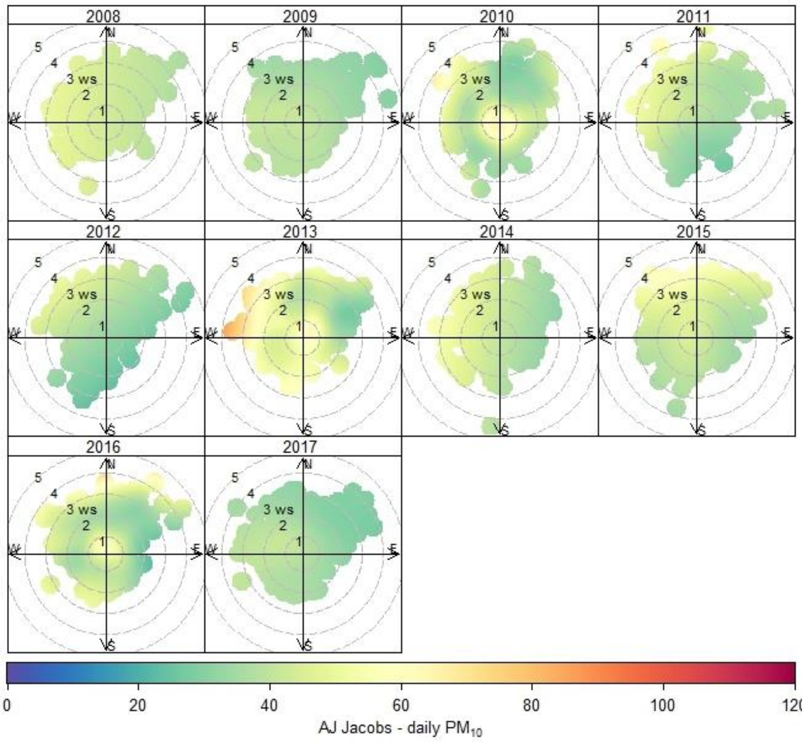


Figure 5-73: Polar plots for daily PM_{10} concentrations at AJ Jacobs station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

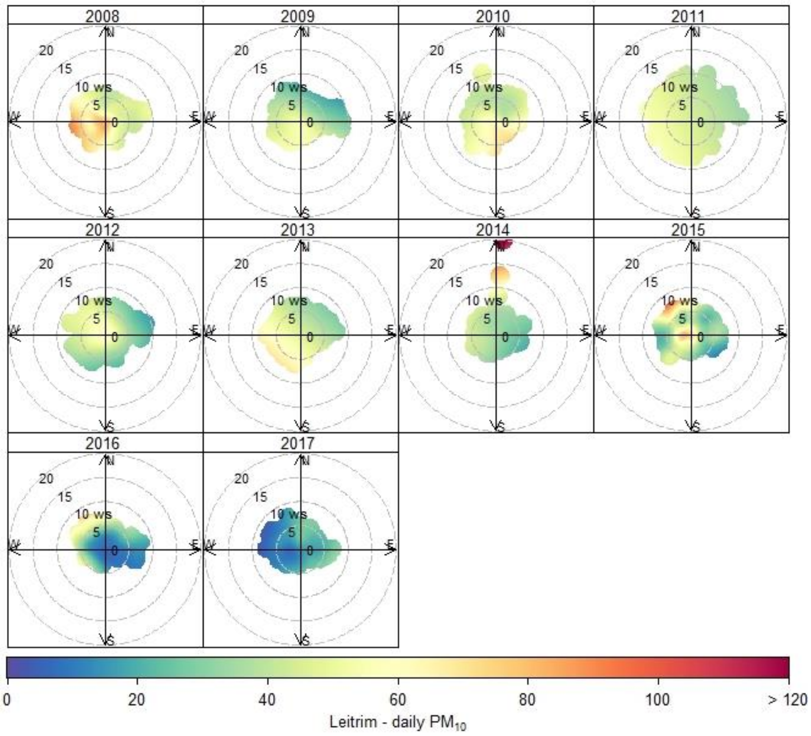


Figure 5-74: Polar plots for daily PM_{10} concentrations at Leitrim station (units: µg/m³; limit 120 µg/m³ daily NAAQ limit concentration enforceable up to 2015)

5.2.2.4 Particulate Matter – $PM_{2.5}$

At all stations, annual average $PM_{2.5}$ was in non-compliance with NAAQS, for most of the period assessed, except for AJ Jacobs where no annual exceedances are noted between 2014 and 2016 (Figure 5-75). The stations with the consistently lowest annual average concentration were AJ Jacobs and Three Rivers, while the stations with the highest concentration were Leitrim, Sharpeville, Kliprivier, and Sebokeng.

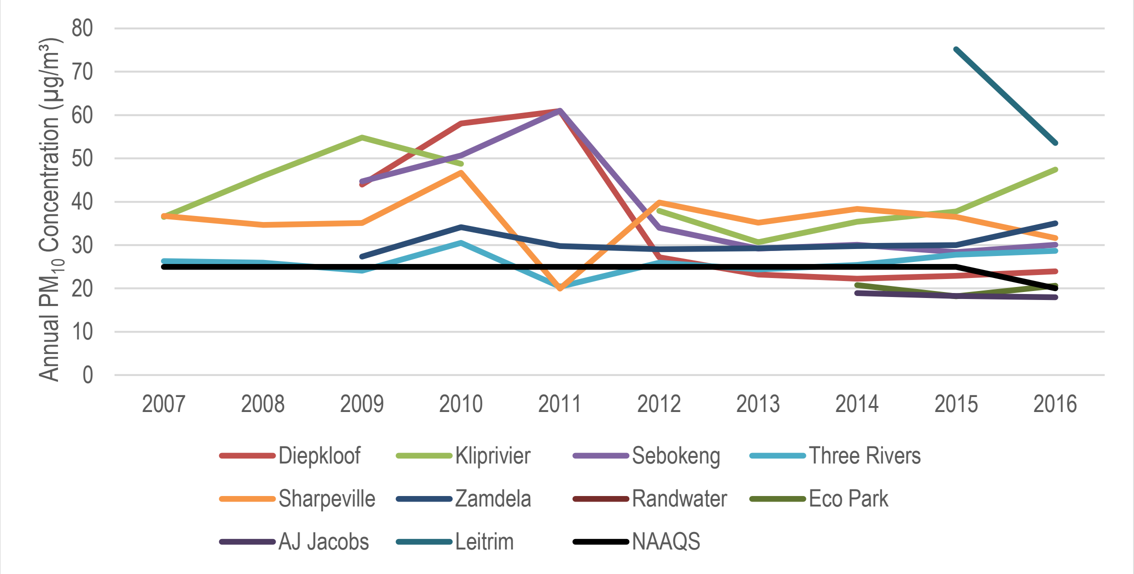
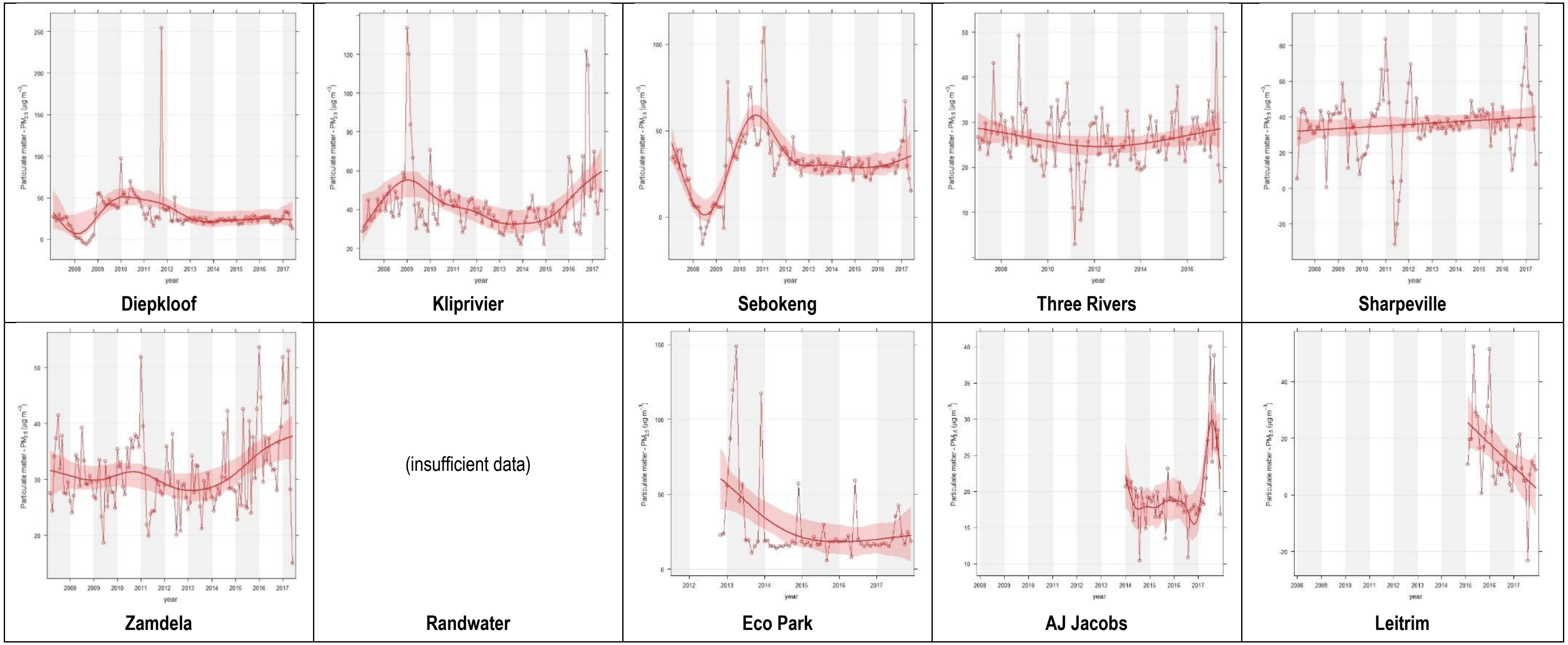


Figure 5-75: Annual average $PM_{2.5}$ concentrations at 10 stations between 2007 and 2016

Although annual average concentrations appear to have decreased at Diepkloof and Sebokeng (Figure 5-75), a trend analysis of the monthly average $PM_{2.5}$ concentrations at these two stations, together with the Three Rivers station, does not show substantive improvements (Figure 5-76). Only two years of data is available for $PM_{2.5}$ at the Leitrim station showing a decrease in concentration (Figure 5-70). The trend analysis also shows slight increases in monthly average concentrations at the Kliprivier, Sharpeville, Zamdela and AJ Jacobs stations (Figure 5-76).

From the polar plots, at least six stations have persistent $PM_{2.5}$ contributions at low wind speeds equally distributed in direction, namely: Diepkloof (Figure 5-77), Kliprivier (Figure 5-78), Sebokeng (Figure 5-79), Three Rivers (Figure 5-80), Sharpeville (Figure 5-81), Zamdela (Figure 5-82), and to a less extent Randwater (Figure 5-83). At most stations higher wind speeds from the southerly sector are associated with the lowest $PM_{2.5}$ concentrations. Changes in daily $PM_{2.5}$ contributions between years are most evident at Diepkloof; Kliprivier, Sebokeng, and Sharpeville, where elevated $PM_{2.5}$ concentrations (mainly from the northerly sector) were highest in 2010 (and 2017 at Sharpeville). The data availability for $PM_{2.5}$ at the Eco Park station in 2014 was very low with very high $PM_{2.5}$ concentrations indicating originating the north and north-west (Figure 5-84). At AJ Jacobs $PM_{2.5}$ contributions originate from many directions at all wind speeds (Figure 5-85). Elevated $PM_{2.5}$ concentrations originate from all directions at low wind speeds at the Leitrim station in 2015; while low concentrations are evident in 2016 and 2017 (Figure 5-86).



Diepkloof

Kliprivier

Sebokeng

Three Rivers

Sharpeville

Zamdela

(insufficient data)

Randwater

Eco Park

AJ Jacobs

Leitrim

Figure 5-76: Trends in PM$_{2.5}$ concentrations at 9 stations (de-seasonalised monthly average concentrations)

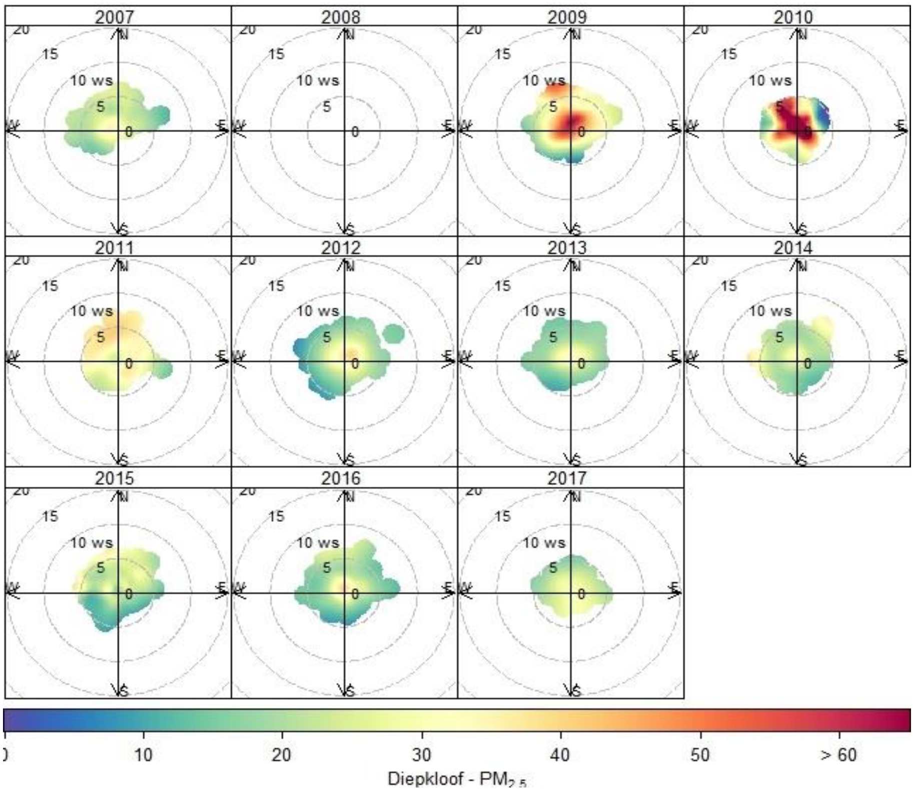


Figure 5-77: Polar plots for daily $PM_{2.5}$ concentrations at Diepkloof station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

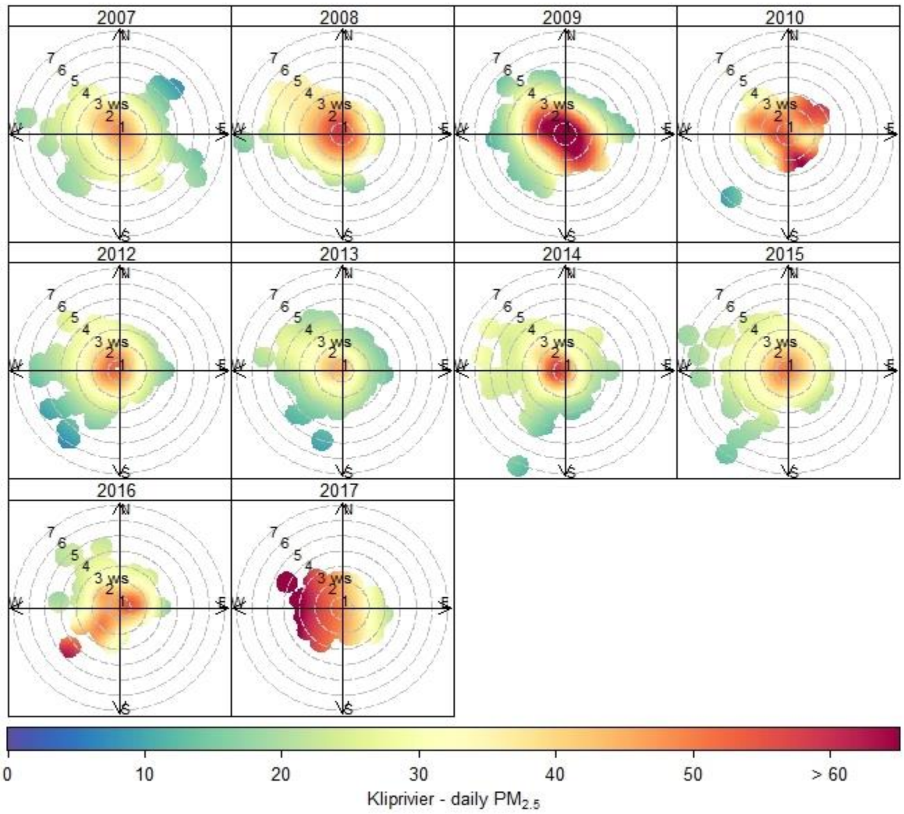


Figure 5-78: Polar plots for daily $PM_{2.5}$ concentrations at Kliprivier station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

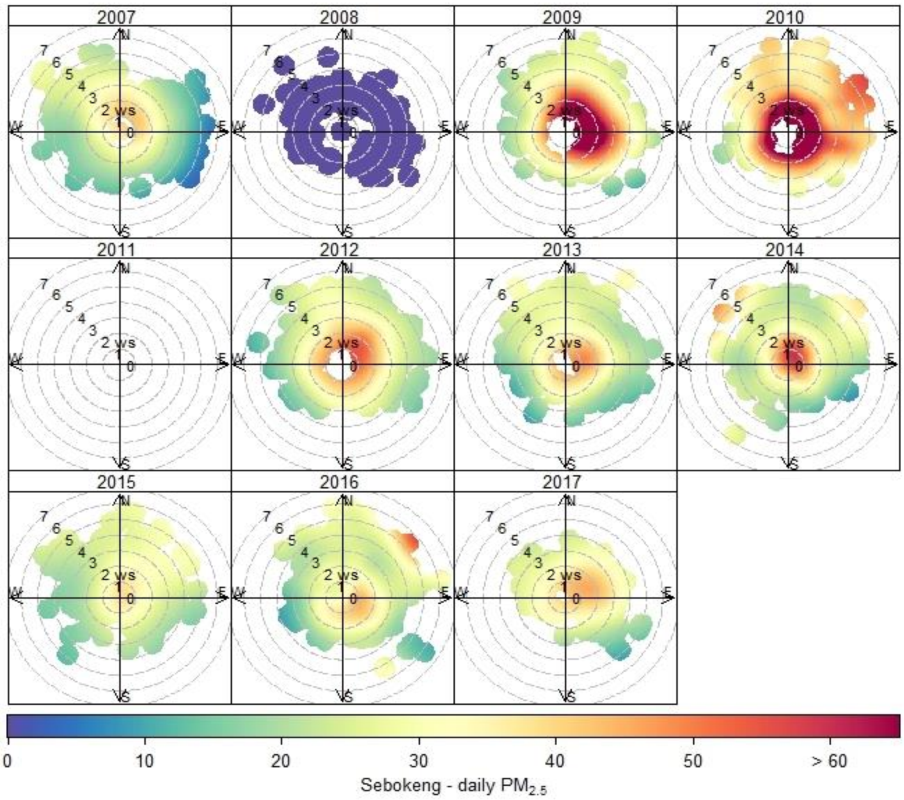


Figure 5-79: Polar plots for daily $PM_{2.5}$ concentrations at Sebokeng station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

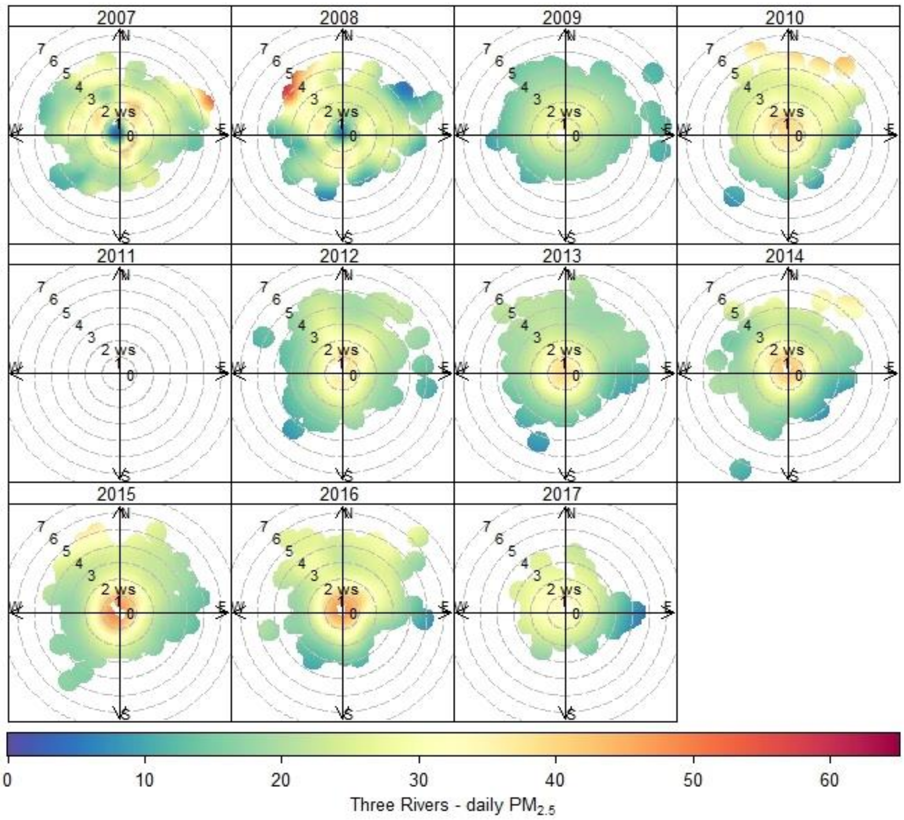


Figure 5-80: Polar plots for daily $PM_{2.5}$ concentrations at Three Rivers station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

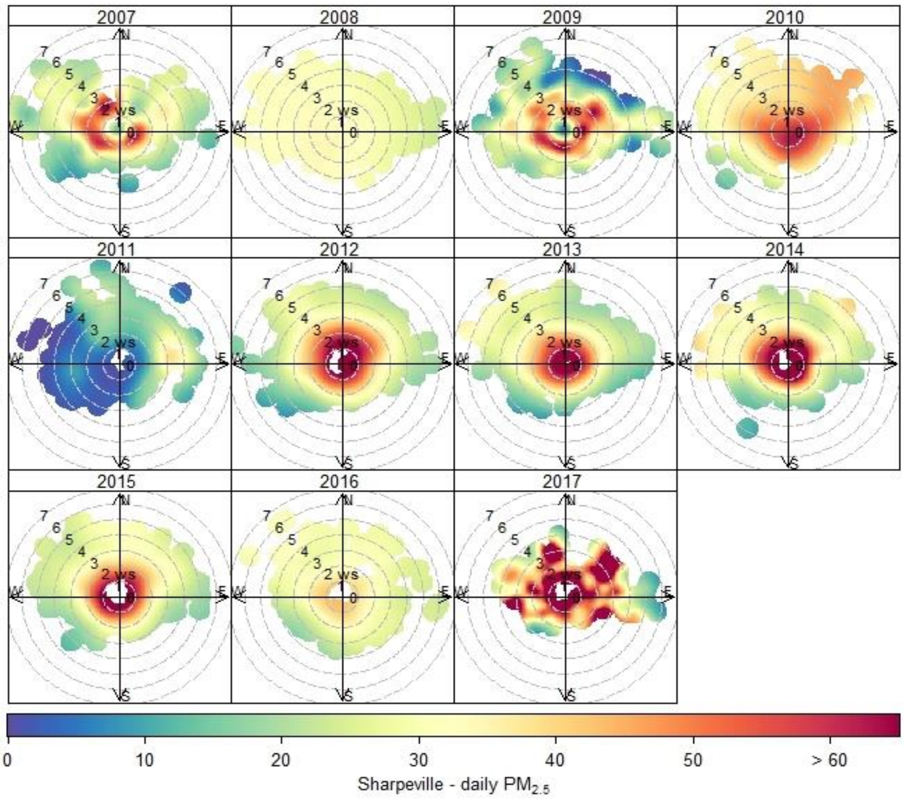


Figure 5-81: Polar plots for daily $PM_{2.5}$ concentrations at Sharpeville station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

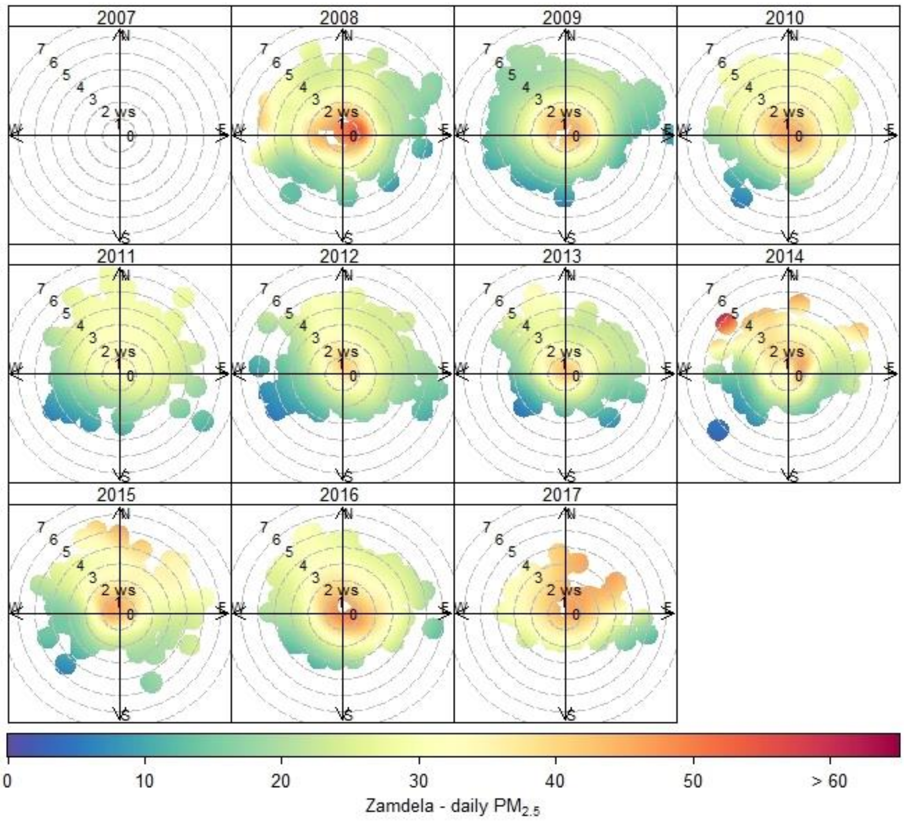


Figure 5-82: Polar plots for daily $PM_{2.5}$ concentrations at Zamdela station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

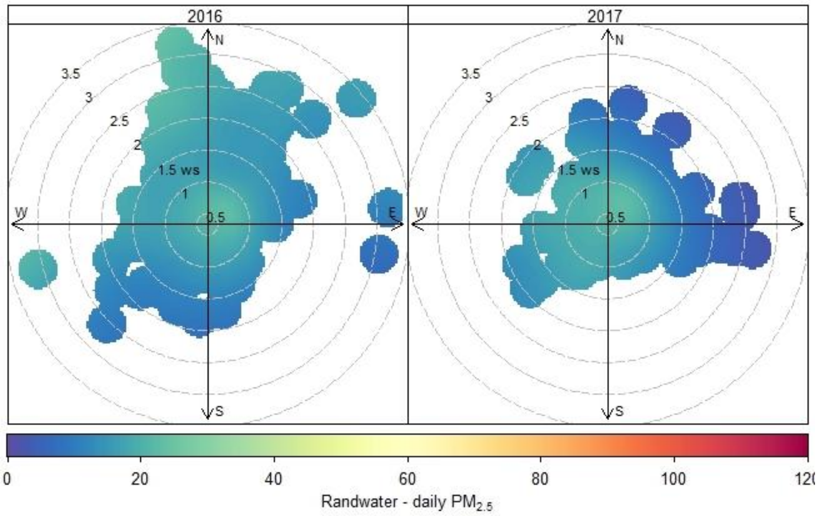


Figure 5-83: Polar plots for daily $PM_{2.5}$ concentrations at Randwater station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

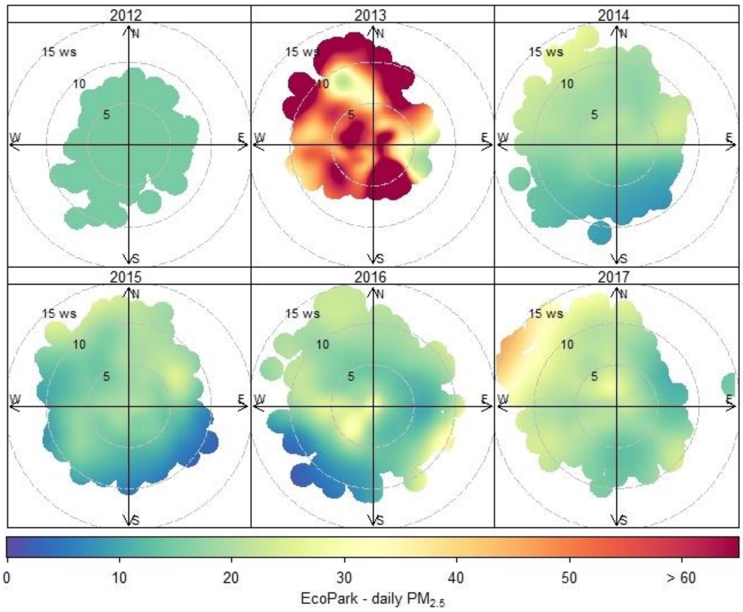


Figure 5-84: Polar plots for daily $PM_{2.5}$ concentrations at Eco Park station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

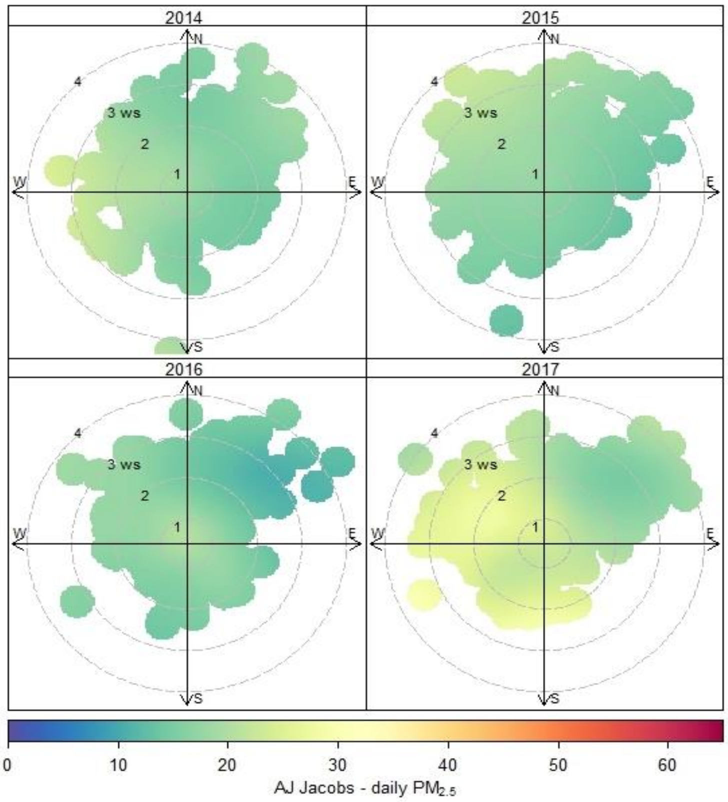


Figure 5-85: Polar plots for daily PM$_{2.5}$ concentrations at AJ Jacobs station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

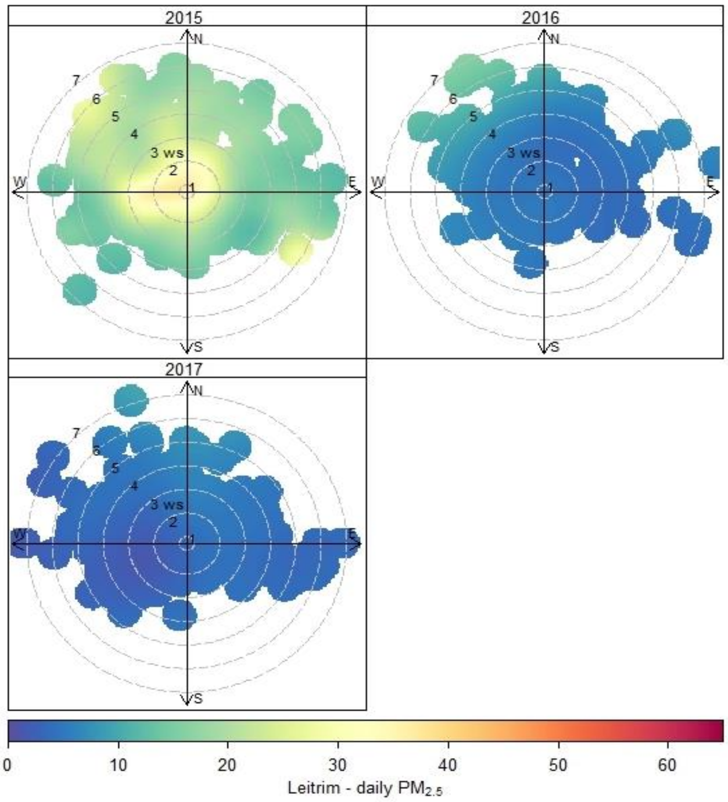


Figure 5-86: Polar plots for daily PM$_{2.5}$ concentrations at Leitrim station (units: µg/m³; limit 65 µg/m³ daily NAAQ limit concentration enforceable up to 2016)

5.3 Air quality model simulations

The primary aim of air quality modelling in this AQMP is to assess ambient air quality in the VTAPA on a more comprehensive spatial scale than what can be provided with monitoring stations. This is achieved by simulating transport and transformation of pollutant emissions on an hourly basis within the model domains and applying various analyses to the output. The air quality model used to achieve this is the Comprehensive Air Quality Model with Extensions (CAMx version 6.50) developed by Ramboll-ENVIRON (see www.camx.com).

Since 1996, CAMx has been employed extensively throughout the US by local, state, regional, and federal government agencies, academic and research institutions, as well as private consultants for regulatory assessments and general research internationally. It is one of only four chemical air quality models recommended by the US Environmental Protection Agency (US EPA). The US EPA has approved the use of CAMx for numerous ozone and particulate matter assessments for State Implementation Plans throughout the US and has used this model to evaluate regional mitigation strategies.

CAMx is a chemical air quality model that is suitable for the integrated assessment of gaseous and particulate air pollution. The model allows for integrated "one-atmosphere" (signifying that all sources and pollutants are to be modelled simultaneously) assessments of gaseous and particulate air pollution over many spatial scales, ranging from sub-urban to continental. This is achieved by solving Eurlerian pollutant mass continuity equations in time on three-dimensional grids. It is designed to unify all of the technical features required of "state-of-the-science" air quality models into a single system.

CAMx, like any air quality model, requires input of emissions data (as a representation of pollutant mass entering the model domain) and meteorological data (as a driver of pollutant advection). These inputs must be time and space varying. Other inputs required by CAMx include photolysis rates and boundary conditions. Figure 5-87 shows the basic system of processing required to run the CAMx.

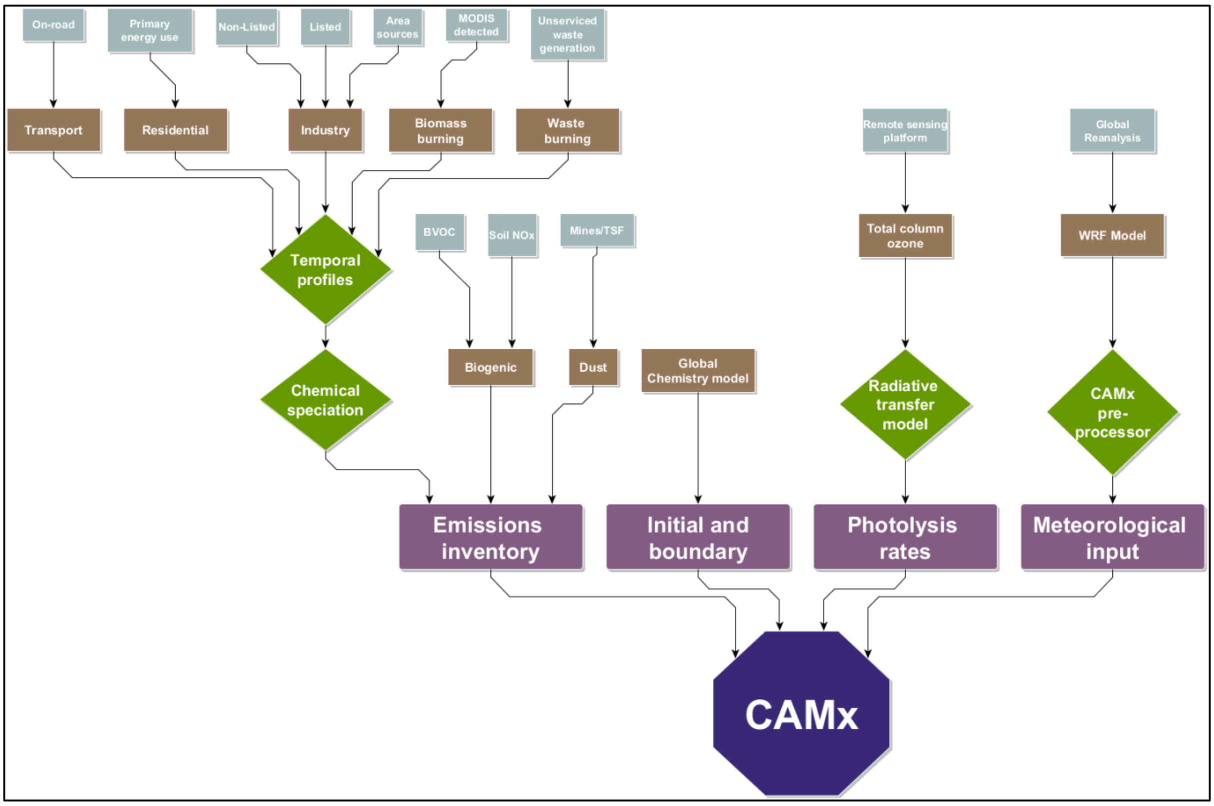


Figure 5-87: Data/processing flow for CAMx in the VTAPA AQMP

The CAMx model also features source tracking capabilities. This is made possible through the use of chemically active tracers that run parallel to the main model simulation. Thus, both primary and secondary pollutants may be tracked within one model run.

5.3.1 Emissions input

The emission inventory for use within CAMx is described in Section 5.1. Sources that make up the inventory include:

- Biogenic VOC
- Biomass burning
- Household fuel combustion
- Wind-blown dust from mines and tailings facilities
- Industrial sources, including mines (processes and handling)
- On-road vehicles
- Household waste burning
- Ammonia from agriculture

CAMx was run with Carbon Bond 6 (Yarwood et al., 2010) with CF aerosol chemistry and as such CB6 VOC emission speciation profiles are applied to sources that emit VOC. Speciation for biogenic VOC and biomass burning is not necessary as the respective emissions models (MEGAN and FINN) create output of VOC that is already speciated. CB6 considers 230 reactions and up to 112 species (gas and aerosol). The CF option treats aerosols as fine ($PM_{2.5}$) or coarse (PM_{10}); with $PM_{2.5}$ requiring further speciation to sulfates, nitrates, organic aerosol, elemental carbon and other primary aerosols. Secondary particulate chemistry includes organic and inorganic formation/partitioning from condensable gases formed during gas phase chemistry; and from aqueous inorganic chemistry.

The methodology for VOC and PM emission speciation is based on the US EPA SPECIATE tool (Simon et al., 2010). The profile database contains approximately 2171 unique process profiles for VOC and 125 profiles for PM. It should be noted that this database is made up of speciation profiles derived from measurements that may or may not be representative of local sources. This is particularly so if a local emission source is unique and a similar source has not been measured for the purpose of VOC speciation before.

Emissions data are processed via the US EPA Emissions Pre-processing System for formatting and error checking purposes. The output is useable by the CAMx model.

5.3.2 Meteorological modelling

The meteorological (and land surface) data required by CAMx is as follows:

- Land-cover
- Topography
- Leaf area index
- Surface temperature
- Snow cover
- Layer heights
- Pressure
- Temperature
- Humidity
- U wind
- V wind
- Vertical diffusivity
- Cloud water
- Rain water
- Snow water

- Graupel water
- Cloud optical depth

Many if not all meteorological models can provide surface fields such as topography, land-use and leaf area index since they utilize these parameters as input.

The Weather Research and Forecasting model (ARW core), version 3.8.1, was used to generate meteorological data for input into CAMx, the biogenic VOC model MEGAN (Section 5.1.7) and the wind-blown dust model (Section 5.1.6). Figure 5-88 shows the WRF model domains.

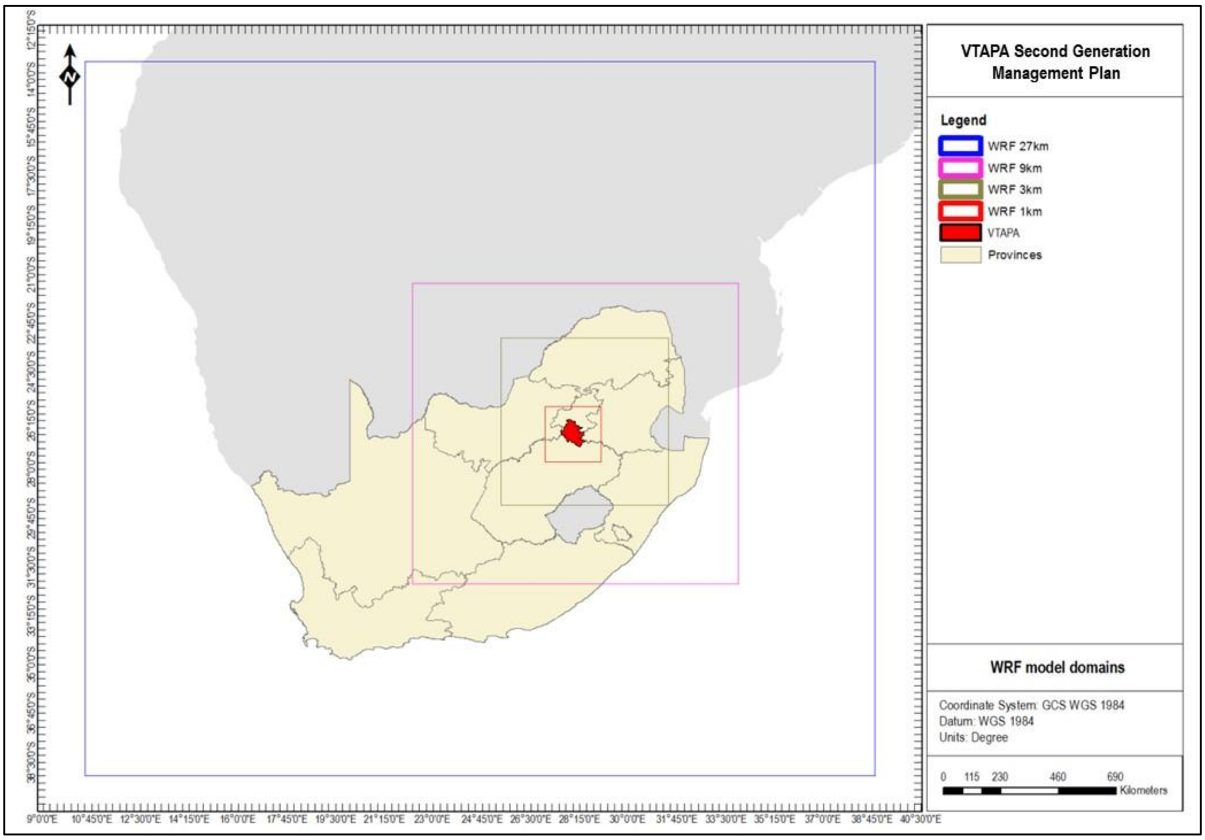


Figure 5-88: WRF horizontal grid domains

Domain horizontal grid resolution was 27km, 9km, 3km and 1km (all centred over VTAPA). Note that only the 3 km and 1 km WRF domains were used as input for CAMx; and they cover a region larger than the CAMx domains (Figure 5-1).

WRF initialization and boundary conditions are specified by the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) version 2 (Saha et al., 2011). Data assimilation was not used for this WRF run. WRF was run for three years (2017, 2016 and 2015) in line with the DEA air quality modelling guidelines (DEA, 2012). Simulations were performed on the Centre for High Performance Computing (CHPC) high performance cluster.

5.3.2.1 Comparisons to measurements

A comparison with WRF model output and measurements is necessary to ascertain model performance and usability of output. It is often desirable to evaluate meteorological model simulations with as many parameters as possible. Meteorological measurements originating from the DEA air quality monitoring stations were used. Parameters verified include temperature and winds. Rainfall data from the stations were insufficient for use in verification in that instead of representing hourly integrated rainfall they erroneously provide hourly average; i.e. for readings within an hour rainfall was averaged instead of summed. Rainfall data from the CRU TS (University of East Anglia Climatic Research Unit, 2017) dataset was used. The CRU TS (TS denoting time-series) dataset provides the individual station data that went into creating the global CRU gridded dataset. The data is comprised of monthly accumulated rainfall and cover the period 1901 – 2016. Figure 5-89 shows the locations of the stations.

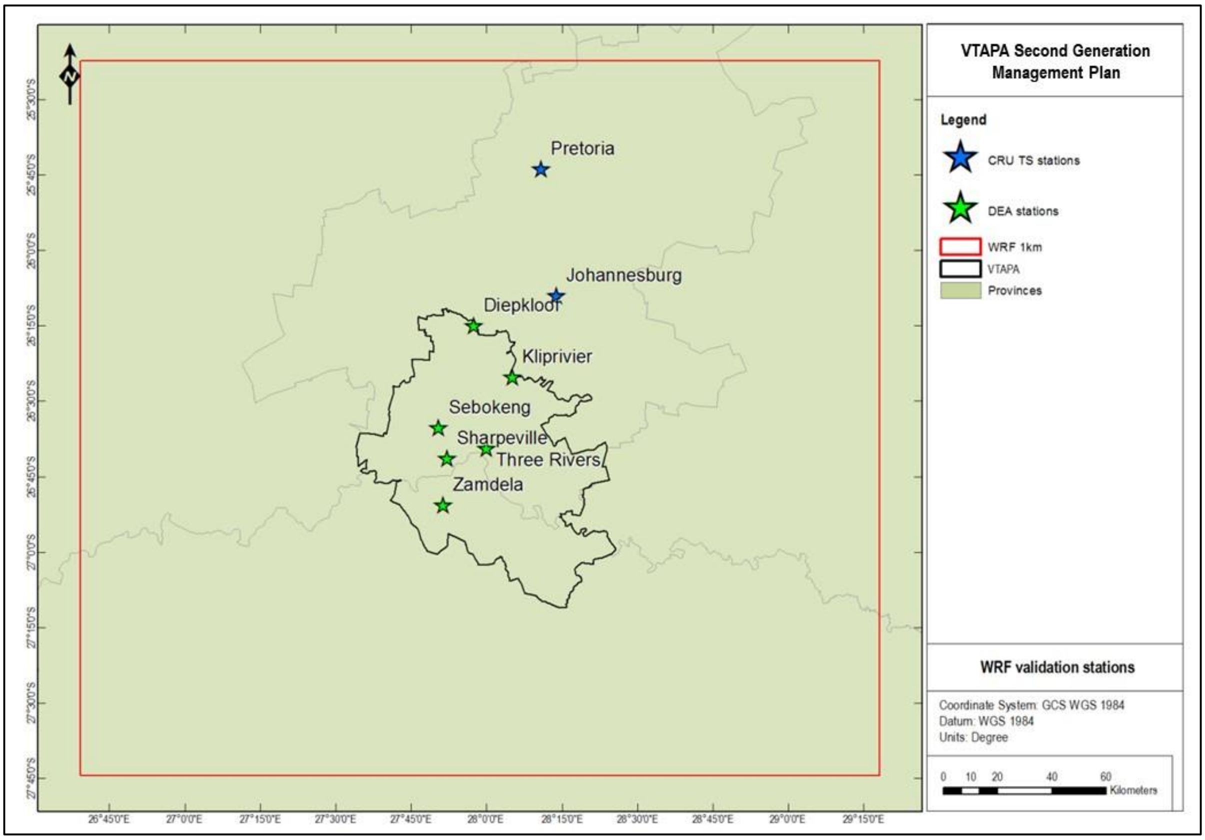


Figure 5-89: Location of stations used for comparison with WRF simulations

Data from the DEA stations were processed for quality control; with the resulting data completeness being relatively good (except for Kliprivier). Table 5-26 shows model vs measurement statistics derived from hourly comparisons for the 2016 model run. The definition of the statistical parameters is as follows:

MB: Mean Bias (model minus observation) is the mean over or under-estimate;

$$MB = \frac{1}{n}\sum_{i=1}^{N} M_i - O_i$$

MGE: Mean Gross Error ignores whether it is an over or under-estimate and gives the gross error;

$$MGE = \frac{1}{n}\sum_{i=1}^{N} |M_i - O_i|$$

NMB: Normalized Mean Bias is the MB normalized by the observed value such that over or under-estimates can be compared across sites and parameters;

$$NMB = \frac{\sum_{i=1}^{n} M_i - O_i}{\sum_{i=1}^{n} O_i}$$

NMGE: Normalized Mean Gross Error is similar to the NMB but ignores whether there is an over or under-estimate;

$$NMGE = \frac{\sum_{i=1}^{n} |M_i - O_i|}{\sum_{i=1}^{n} O_i}$$

r: This is the Pearson correlation coefficient and is a measure of the strength of the linear relationship between two variables;

$$r = \frac{1}{(n-1)} \sum_{i=1}^{n} \left(\frac{M_i - \overline{M}}{\sigma_M} \right) \left(\frac{O_i - \overline{O}}{\sigma_O} \right)$$

Table 5-26: Statistics from comparison of WRF temperature and winds with DEA station measurements

Station	Parameter	% completeness	MB	MGE	NMB	NMGE	r
DIEP	Temp	95.276	-0.789	2.468	-0.044	0.139	0.900
ZAMD	Temp	90.813	4.786	4.844	0.349	0.353	0.932
SHAR	Temp	90.221	0.636	2.421	0.036	0.136	0.920
SEBO	Temp	79.212	0.927	2.698	0.055	0.160	0.884
THRE	Temp	91.701	-0.031	2.035	-0.002	0.119	0.951
KLIP	Temp	51.719	0.742	2.494	0.046	0.155	0.929
DIEP	U Wind	95.276	-0.050	1.357	0.498	-13.592	0.619
ZAMD	U Wind	90.813	0.069	1.498	-0.699	-15.098	0.721
SHAR	U Wind	90.221	0.031	1.418	0.111	5.171	0.696
SEBO	U Wind	79.212	0.584	1.572	-1.061	-2.855	0.624
THRE	U Wind	91.701	0.127	1.344	-0.854	-9.071	0.663
KLIP	U Wind	51.867	-0.202	1.451	-1.473	10.593	0.511
DIEP	V Wind	95.276	-0.819	1.581	0.994	-1.918	0.568
ZAMD	V Wind	90.813	-0.725	1.720	2.201	-5.217	0.488
SHAR	V Wind	90.221	-0.872	1.684	3.804	-7.344	0.423
SEBO	V Wind	79.212	-0.833	1.748	1.444	-3.031	0.493
THRE	V Wind	91.701	-0.901	1.757	1.733	-3.380	0.495
KLIP	V Wind	51.867	-0.852	1.585	2.434	-4.526	0.500
DIEP	Wind Speed	95.276	0.241	0.941	0.086	0.334	0.661
ZAMD	Wind Speed	90.813	1.043	1.405	0.431	0.581	0.603
SHAR	Wind Speed	90.221	0.515	1.176	0.202	0.460	0.627
SEBO	Wind Speed	79.212	0.736	1.238	0.293	0.492	0.617
THRE	Wind Speed	91.701	0.843	1.307	0.361	0.559	0.577
KLIP	Wind Speed	51.867	1.003	1.402	0.537	0.751	0.466

Temperature is simulated well with an average over-estimate, particularly at Zamdela. Wind speed is also over-estimated, and at all stations. Figure 5-90 to Figure 5-93 show R Statistics/OpenAir timeVariation plots for the average over all stations.

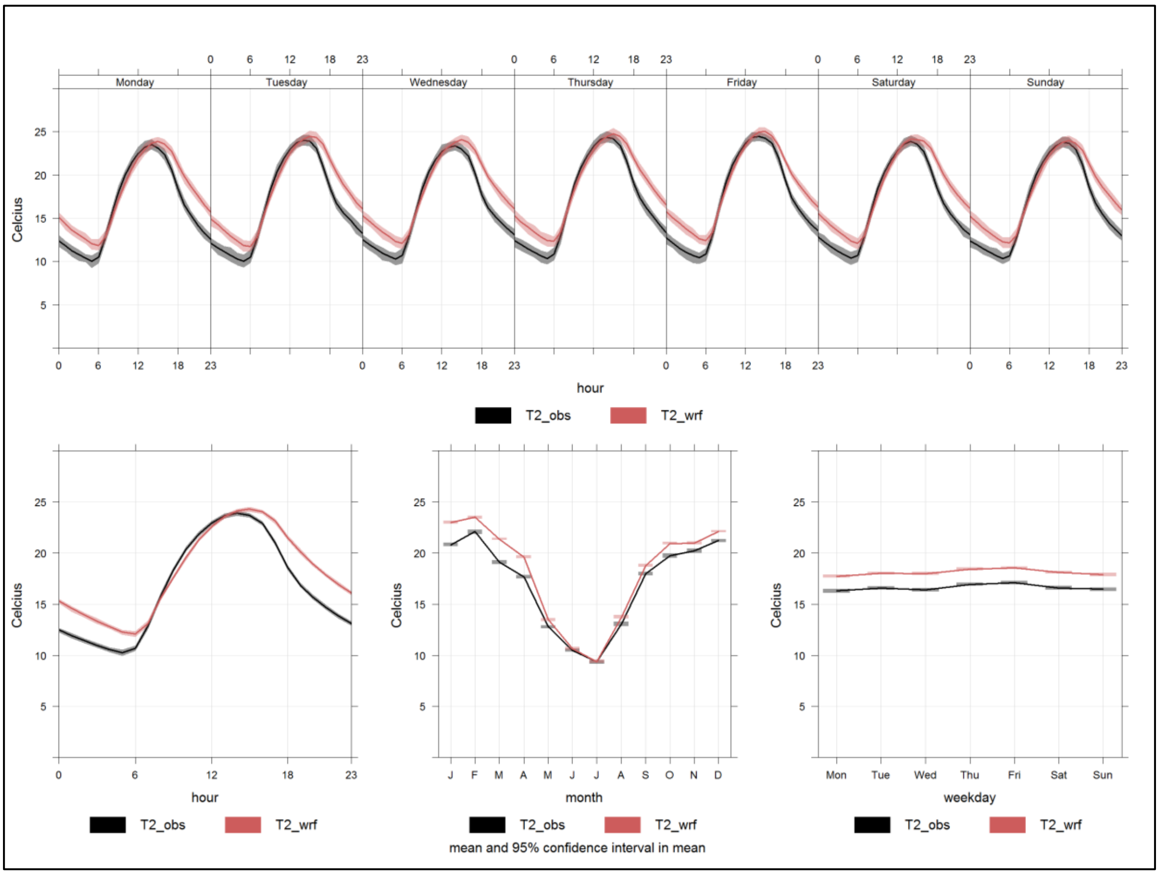


Figure 5-90: timeVariation plot of WRF and DEA station temperature (all stations averaged)

Temperature is over-estimated in the evenings, primarily in summer. There is also an hour lag between WRF peak temperature and what is measured.

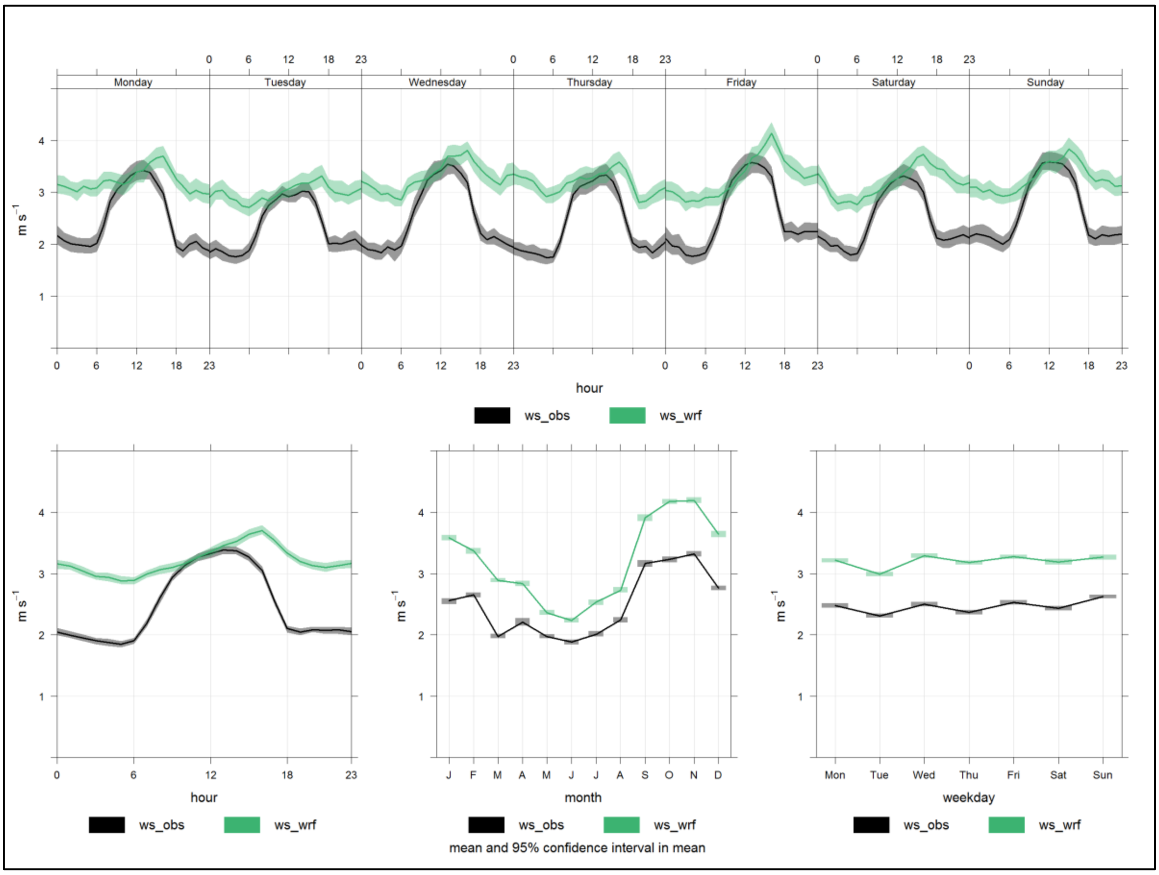


Figure 5-91: timeVariation plot of WRF and DEA station wind speed (all stations averaged)

Wind speed is also over-estimated during the evening; however, it is consistently over-estimated between seasons. The hourly over-estimate is ~1m/s.

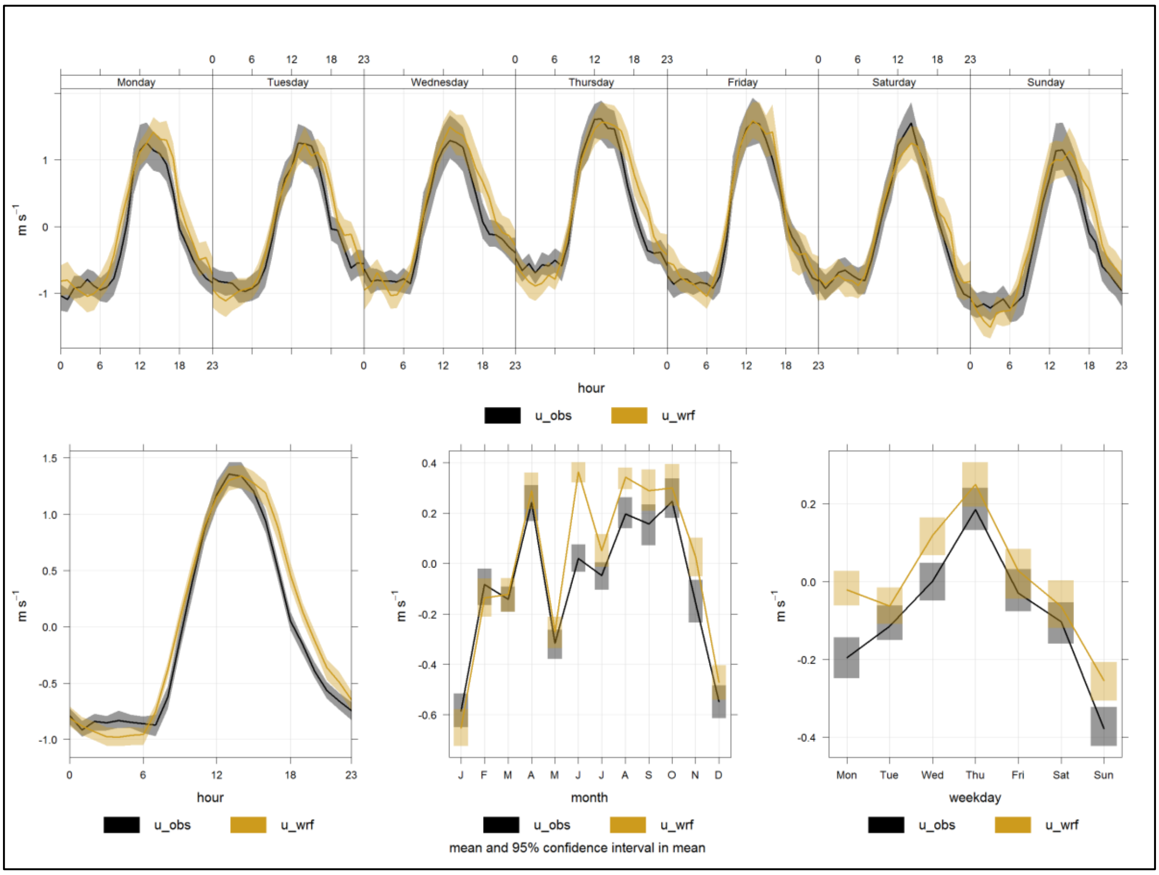


Figure 5-92: timeVariation plot of WRF and DEA station U Wind (all stations averaged)

WRF simulates U Wind (the East-West component) very well – only small over-estimates are seen.

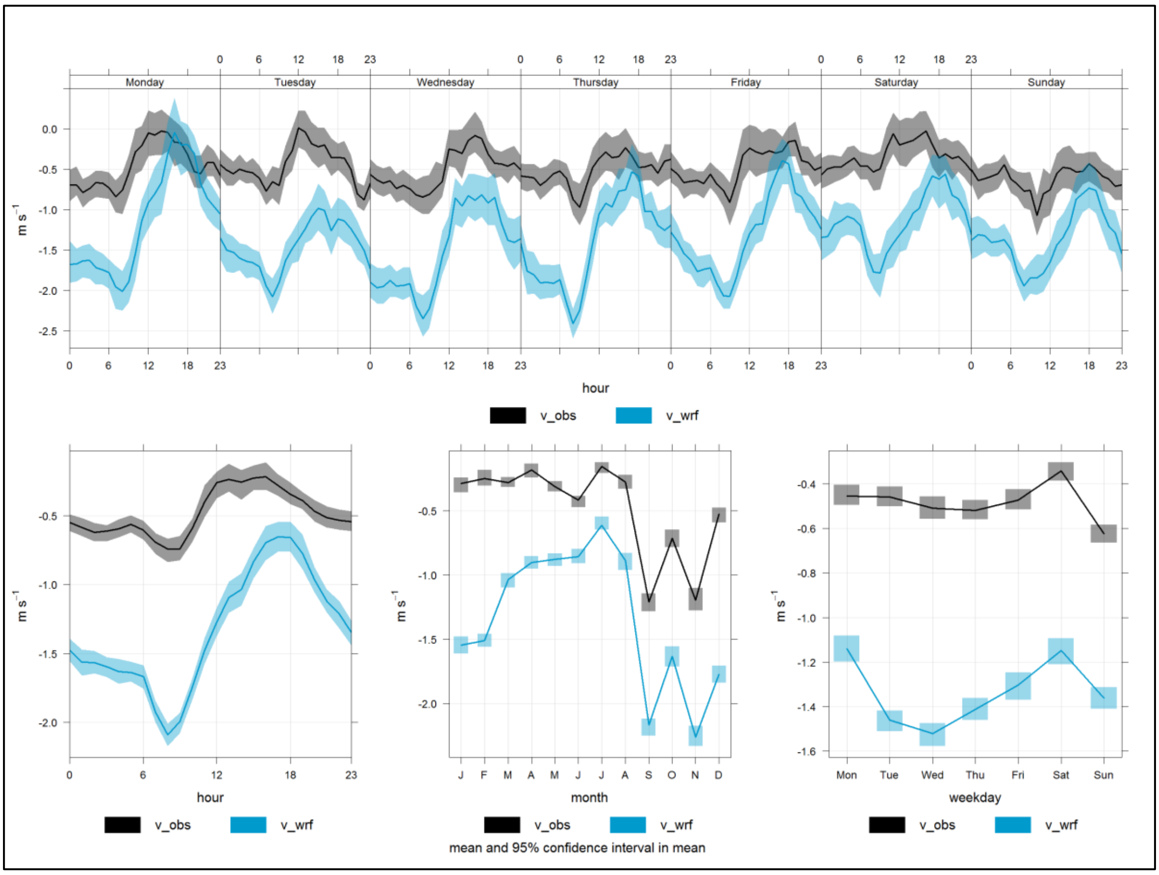


Figure 5-93: timeVariation plot of WRF and DEA station V Wind (all stations averaged)

The V Wind component (North-South) contributes to the over-estimates seen in wind speed. The over-estimate is seen as at most a ~1m/s in the southern direction (negative V). This artefact is likely related to the over-estimates in temperature (even though slight); of which primary drivers are the land surface scheme and land surface model.

In terms of rainfall, even though the magnitude captured by the DEA monitoring stations is insufficient for comparing with WRF rainfall, a timeVariation plot using a normalized y-axis can show a comparison of timing; and that WRF simulates the timing of rainfall quite accurately.

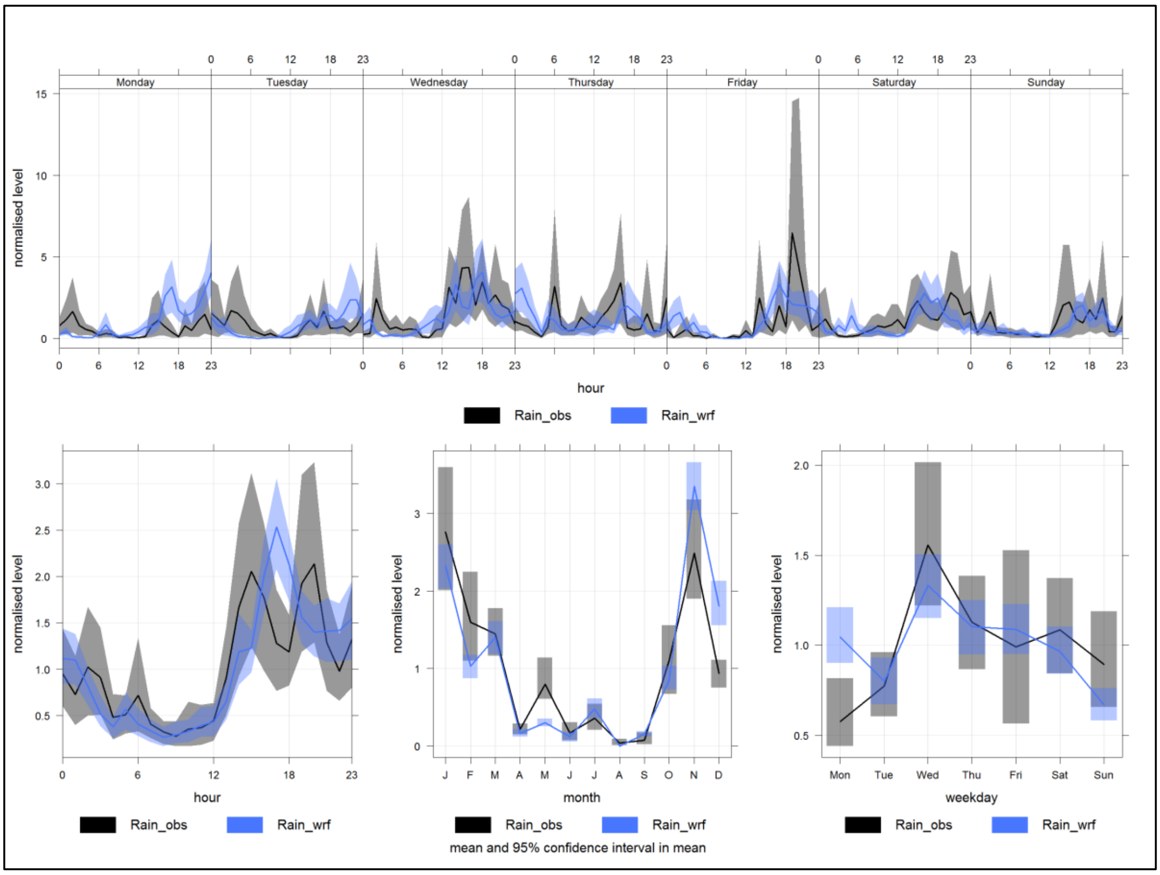


Figure 5-94: timeVariation plot of WRF and DEA station rainfall (all stations averaged; y-axis normalized)

In terms of rainfall magnitude, a comparison of WRF and CRU TS data shows a reasonable simulation with some over-estimation (Figure 5-95). Note that the CRU TS data covers 1910 – 2014 for Pretoria and 1951 – 2007 for Johannesburg. The error bars are the 5th and 95th percentile values for that time period. WRF rainfall is averaged (of monthly sum) over the five DEA station locations; with error bars showing 5th and 95th percentile across locations.

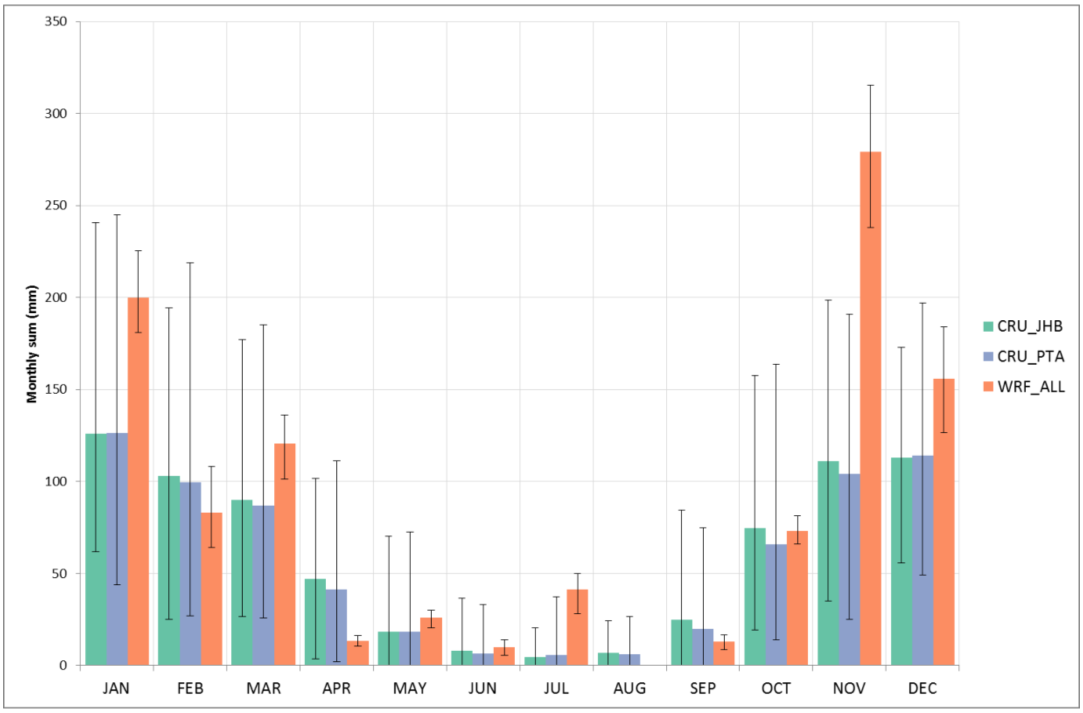


Figure 5-95: Comparison of WRF simulated rainfall for 2016 (error bars are 5th and 95th percentile over stations) and CRU TS at Pretoria and Johannesburg (error bars are 5th and 95th percentile for the periods covered)

The WRF rainfall simulation falls within an acceptable range for most months, however for November rainfall is clearly over-estimated.

Impacts on air quality modelling

In general, a higher simulated temperature may enhance ozone production in an air quality model. However, this is an oversimplification as temperature influences other chemical reactions that may or may not lead to ozone destruction. Over-estimates in wind speed tend to reduce simulated ambient concentrations that are heavily impacted by surface emission sources (by increased boundary layer depth and the fact that pollutants once emitted are blown away); however for tall stacks over-estimates are possible as the enhanced turbulence brings the stack plume to the surface more often. Over-estimates in rainfall will also serve to reduce simulated concentrations since wet deposition will be enhanced.

Both the over-estimates in WRF (and other meteorological models) and the impact on air quality model simulations have been discussed previously at length (Brunner et al., 2015). It is common experience that wind speed and rainfall are over-estimated, resulting in lower simulated ambient concentrations. Ngan et al. (2013) discuss possible reasons for wind speed and surface temperature bias, particularly for night hours. Through planetary boundary layer and land surface scheme (and land surface model) sensitivity analysis some improvements are made but the wind speed bias still persists. Research done for the Wind Atlas of South Africa (Hahmann et al., 2015) conclude that the key driver of the wind bias in WRF is the choice of land surface model; as surface roughness is controlled there. With regard to meteorological modelling for air quality model input, in South Africa specifically, there is much research to be done. Not only does a sensitivity analysis using the latest WRF 4.0 need to be completed; but also custom parameterization of land cover and land surface models. The results of these need to be tested in light of local air quality modelling.

5.3.3 Initial and boundary conditions

CAMx simulates the transport and transformation of air pollutants in a one-atmosphere simulation; and thus aims to represent a realistic state of atmospheric chemistry and processes. The model is also a limited-area model, i.e. it is not a global model, and therefore requires lateral boundary conditions to realistically simulate air quality by accounting for pollutant species entering the domain. Initial conditions are also necessary; these however influence mainly a short time after initialization, after which input emissions and chemistry dominate. The impact of initial conditions is minimized through a model spin-up period. Boundary conditions primarily impact areas near the domain edges, and it is often the practice to apply a buffer region along the model domain such that these concentrations are not included in further analysis. Air quality models are initialized at the start of a simulation, while boundary conditions are fed to the model continuously throughout the simulation. Ideally the concentrations that make up initial and boundary conditions should be based on measurements. However, it is rarely the case when there are enough measurements to represent each boundary of the model domain adequately.

For the CAMx simulation in this AQMP baseline characterisation, the air quality model was initialized at the start of each month of the simulation with a 5-day spin-up period; for example, the month of February was run by starting on 26 January. This enables each month to be run concurrently, thereby reducing run time considerably. The impact of initializing this often is reduced by the 5-day spin-up. Boundary conditions were provided for both lateral (north, south, east and west) and top (highest model level) boundaries for the larger 3 km domain. Boundary conditions for the 1 km VTAPA domain are not required since this domain is a nest. This also further highlights the importance in using a parent/nest configuration as any impacts from the boundary on the VTAPA domain are minimized.

There are no adequate measurements around the 3 km regional domain to be used as boundary conditions; or at least none that can represent each domain side for the entire length. It is apparent here that single monitoring stations have limited use for deriving boundary conditions for domains of this size; added to this, the varying air quality characteristics of the surrounding regions; therefore initial and boundary conditions were derived from a Global Chemical Transport Model (GCTM).

GCTMs are integrated over long periods of time globally. They are thus most often run at coarse resolutions; and include input datasets of equally coarse resolution. The aim of these models is to simulate global atmospheric chemistry, and to an extent larger regional influence. For input into CAMx, initial and boundary conditions are based on the Model for Ozone and Related Chemical Tracers (MOZART-4; Emmons et al., 2010) output provided to the WRF-Chem community via the NCAR Atmospheric Chemistry, Observations and Modelling (ACOM) MOZART download page (http://www.acom.ucar.edu/wrf-chem/mozart.shtml). The ACOM MOZART simulation utilizes NASA GMAO GEOS-5 meteorological fields to drive MOZART-4. The emission inventory used includes MEGAN biogenic emissions, FINN biomass burning, and global anthropogenic emissions based on Streets et al (2003). Model output is provided at a resolution of 1.9x2.5 degree (approximately 190x250 km) with 56 vertical levels.

The use of a coarsely resolved global model (which utilizes a global emission inventory) output carries inherent limitations. Only a few GCTM cells (at least 32) will be used if one considers the extent of the 3 km domain. However, this is still better than using single monitoring stations to describe spatially large regions. The GCTM also allows one to derive a top boundary input. In terms of MOZART-4 simulated species concentrations, the coarse resolution and global inventory lead to a regional (at best) representation. However, it is assumed that while emissions from smaller emitters near the 3 km boundary will not be captured in high detail, emissions from regional sources that feature in global inventories (such as regional biomass burning) will be well-represented in the GCTM. It is thus useful to note that the 3 km CAMx domain (Figure 5-1) covers a majority of source regions that may impact the VTAPA; and therefor will not leave these impacts to the GCTM forced boundary conditions. Such sources include biomass burning for the northern and eastern boundaries and wind-blown dust for the western boundary.

5.3.4 Photolysis rates

Photolysis rates are applied to chemical reactions that are heavily dependent on sunlight. These are initially determined by modifying standard photochemical reaction rates according to how much solar radiation is available. These must be provided to the CAMx model at each grid point and vertical level.

Photolysis rates are initially estimated by NCAR's TUV radiative transfer model (see http://cprm.acd.ucar.edu/Models/TUV/ and http://www.camx.com/download/support-software.aspx) and various look-up tables developed by the CAMx model developer. TUV calculates clear sky photolysis rates for the most important photochemical reactions to be used during the CAMx model run. The TUV model determines the state of the atmosphere by considering total column ozone, which in this study was based on the NASA OMI instrument (Veefkind, 2012). These are fed to CAMx as an initial estimate. Further modifications are made to the photolysis rates in-line within a CAMx run by considering the simulated aerosol impact and cloud cover on atmospheric radiative transfer within the model column.

5.3.5 Source tracking

In general air quality models aim to simulate ambient air quality. Therefore emissions from all significant sources need to be accounted for; and the model simulates the transport and transformation of all pollutants in "one atmosphere". This may be contrasted to the commonly used approach for Lagrangian or Gaussian plume dispersion modelling, where individual emission sources are modelled separately. While this is not strictly the best approach for simulating ambient air quality (and indeed is not the goal of plume dispersion modelling), it does offer insight into contribution of sources (or entire sectors) to air pollutant concentrations. However this depends entirely on the comprehensiveness of the sources included in simulations. In the context of an AQMP, this feature of plume dispersion modelling is desirable as it has the potential to identify key sources or sectors to guide interventions. Thus CAMx contains a source tracking feature which enables use of chemically active tracers to track both primary and secondary pollutant contribution from user defined source groupings. Source tracking may be applied to ozone (and precursors) and aerosols (and precursors; such as NOx and SO_2).

For the application in this VTAPA AQMP source tracking was utilized to track contribution to ozone and PM_{10} from industry within and outside the VTAPA. Thus two groups were actively tracked, that being industry located within the VTAPA and those outside. Note that this will include sources in the parent domain as well; and therefor includes influence from the Highveld Priority Area.

5.3.6 CAMx model run specifics

The CAMx model was run with the input data prepared using the methodologies detailed in the sections preceding. In order to allow for faster run completion each month of 2016 was run in parallel on the Centre for High Performance Computing (CHPC). To reduce the impact of model initialization 5 spin-up days were used (see Section 5.3.3 for more detail). Total time taken to simulate a year was approximately 96 hours.

5.3.7 Results

The aim of air quality modelling within the context of a baseline assessment is to simulate current ambient concentrations of pollutants within the VTAPA such that the general air quality of the area can be deduced. Areas of elevated concentrations can be identified for expanded monitoring; and when viewed within the context of the emission inventory, likely contributing sources targeted for intervention strategies. The source tracking also enables targeted analysis of source contributions.

This section will provide this analysis through a presentation of model performance (as gauged by comparison with DEA monitoring station data) and time averaged concentration maps. Concentrations maps are also available for the parent domain and may be found in Appendix C.

5.3.7.1 *Comparison to measurements*

Model performance for the baseline assessment is based on comparison of simulated concentrations with measurements at various monitoring stations within the VTAPA. Figure 5-96 shows the relative locations while Table 5-27 provides further details of the stations.

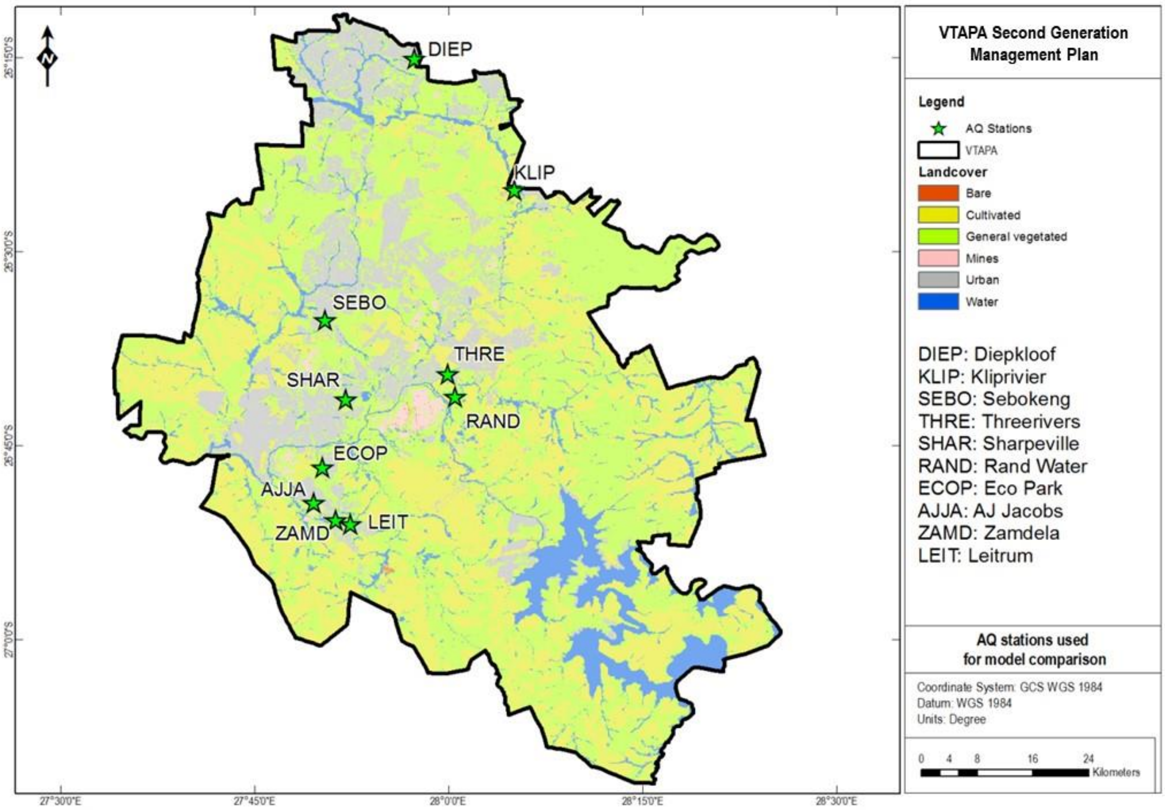


Figure 5-96: Location of monitoring stations used for model comparison

Table 5-27: List of air quality monitoring stations used for model comparison

			% completeness				
Owner	**Name**	**Short Name**	**NO_2**	**O_3**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**
DEA	Diepkloof	DIEP	94	94	65	70	94
DEA	Kliprivier	KLIP	51	51	46	47	46
DEA	Sebokeng	SEBO	78	78	73	73	73
DEA	Sharpeville	SHAR	86	90	79	48	80
DEA	Three Rivers	THRE	91	87	85	76	91
DEA	Zamdela	ZAMD	88	89	78	63	87
ESKOM	Randwater	RAND	99	89	92	72	99
SASOL	AJ Jacobs	AJJA	95	0	95	74	96
SASOL	EcoPark	ECOP	98	96	78	81	98
SASOL	Leitrim	LEIT	91	0	21	23	94

Notes: Red shading indicating data completeness less than 70%

Note that completeness does not necessarily indicate reliability. As much quality control was applied as possible without going into further investigation with network owners around possible issues. However, data quality could still be questionable; and an indication of this are the time-series plots of hourly data, where it is often obvious that data quality is questionable. These are provided together with comparison of model simulated daily averages and R Statistics/OpenAir timeVariation plots. All of the plots are located in Appendix B; and only those most pertinent/illustrative are shown in the main text. Model performance statistics are also provided (see Section 5.3.2.1 for definition of statistical parameters).

NO_2

Table 5-28 provides statistics regarding comparison of NO_2 measurements and simulated concentrations at the station locations. These are based on hourly model output and measurements.

Table 5-28: Model vs measurements statistics for NO_2 (based on hourly data)

station	pollutant	% completeness	MB	MGE	NMB	NMGE	r
DIEP	NO_2	94	-13.53	14.83	-0.56	0.62	0.58
ZAMD	NO_2	88	1.69	13.11	0.10	0.75	0.32
SHAR	NO_2	86	-4.41	9.16	-0.28	0.58	0.52
SEBO	NO_2	78	-2.87	7.58	-0.21	0.56	0.60
THRE	NO_2	91	-3.42	8.60	-0.24	0.61	0.40
KLIP	NO_2	51	-2.57	9.38	-0.16	0.60	0.42
AJJA	NO_2	95	5.66	11.11	0.52	1.03	0.42
ECOP	NO_2	98	-0.93	8.57	-0.08	0.78	0.36
LEIT	NO_2	91	3.18	10.39	0.26	0.86	0.32
RAND	NO_2	99	0.41	7.51	0.04	0.81	0.21

Notes: Red shading indicating data completeness less than 70%

In general, the model performs well with the highest under-estimate at Diepkloof and highest over-estimate at AJ Jacobs. The best performance is seen at Eco Park. Figure 5-97 shows time-series plots at Diepkloof. This site is heavily influenced by on-road vehicular traffic; as evidenced by the lower NO_2 concentrations on the weekend. While the emission inventory is influenced by SANRAL counts on the N1 nearby, traffic on Ben Naude Street (a major 3 lane route where the station is located) is based on the top-down approach. It is also possible that the emission inventory does not represent the exact mix of vehicles travelling on that road section. The over-estimate in wind speed (Section 5.3.2.1) also plays a role in reducing simulated concentrations that are primarily contributed by a localized surface emissions source.

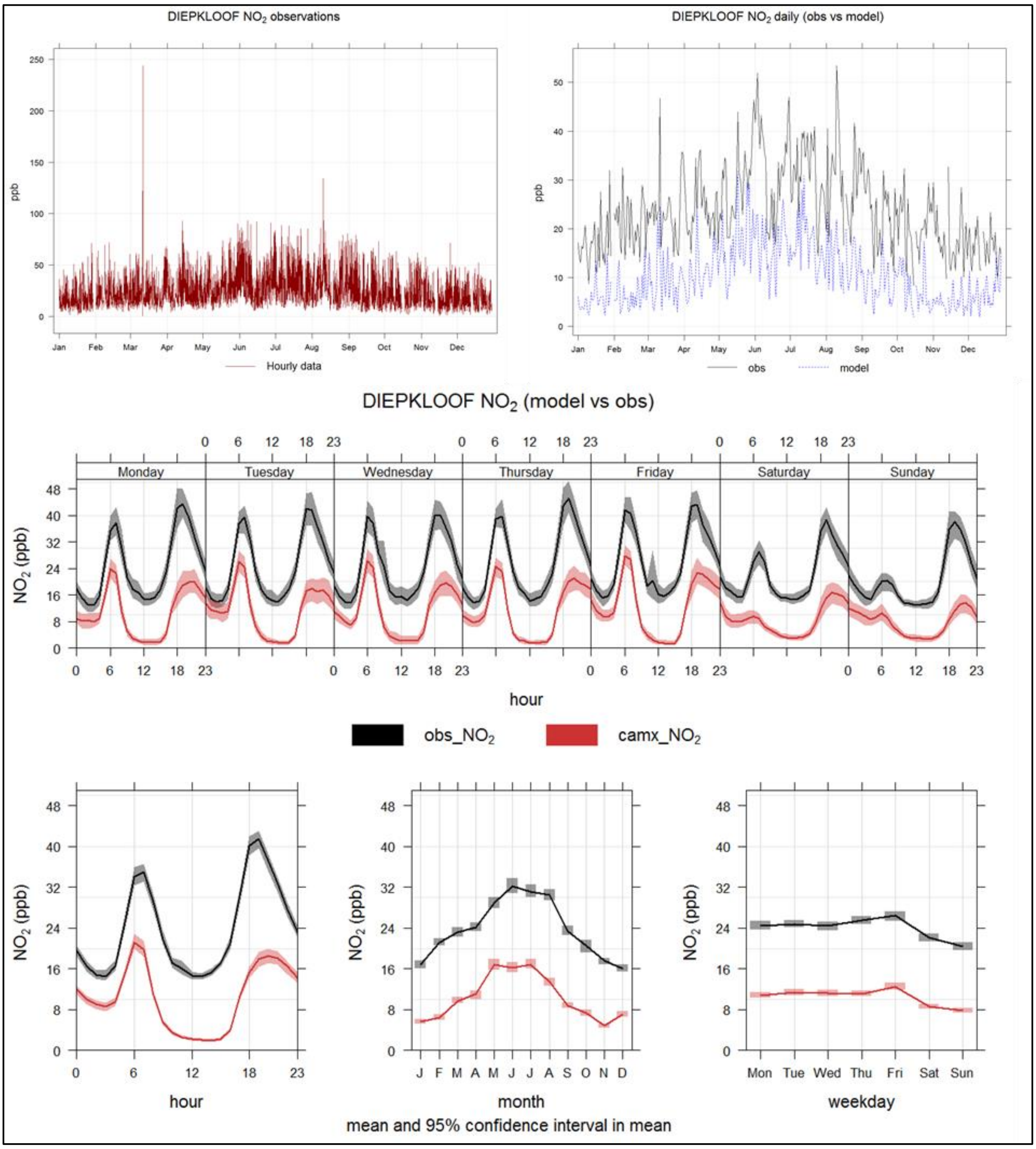


Figure 5-97: Time-series plots of simulated vs measured NO_2 at Diepkloof

In terms of over-estimates seen at AJ Jacobs, it is likely that the model is simulating enhanced mixing from higher layers (once again due to over-estimate in wind speed and increased planetary boundary layer height) which bring down plumes from Sasol and Lethabo Power station. Nearby sites such as Zamdela and Leitrum also show over-estimated NO_2.

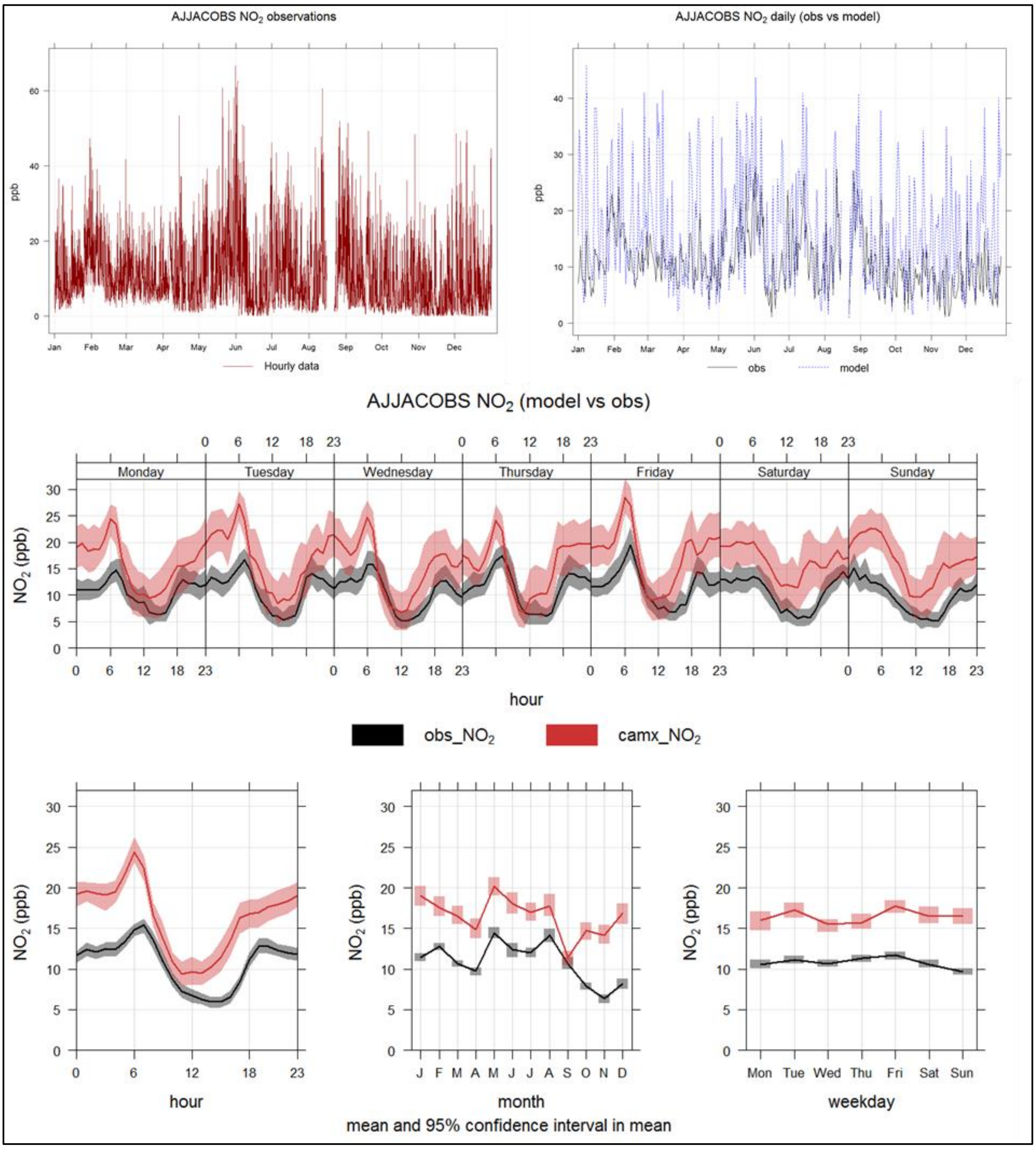


Figure 5-98: Time-series plots of simulated vs measured NO$_2$ at AJ Jacobs

However at Eco Park, another site near AJ Jacobs shows very good performance. This site is also north of Sasol; and the model typically over-estimates V component wind blowing south.

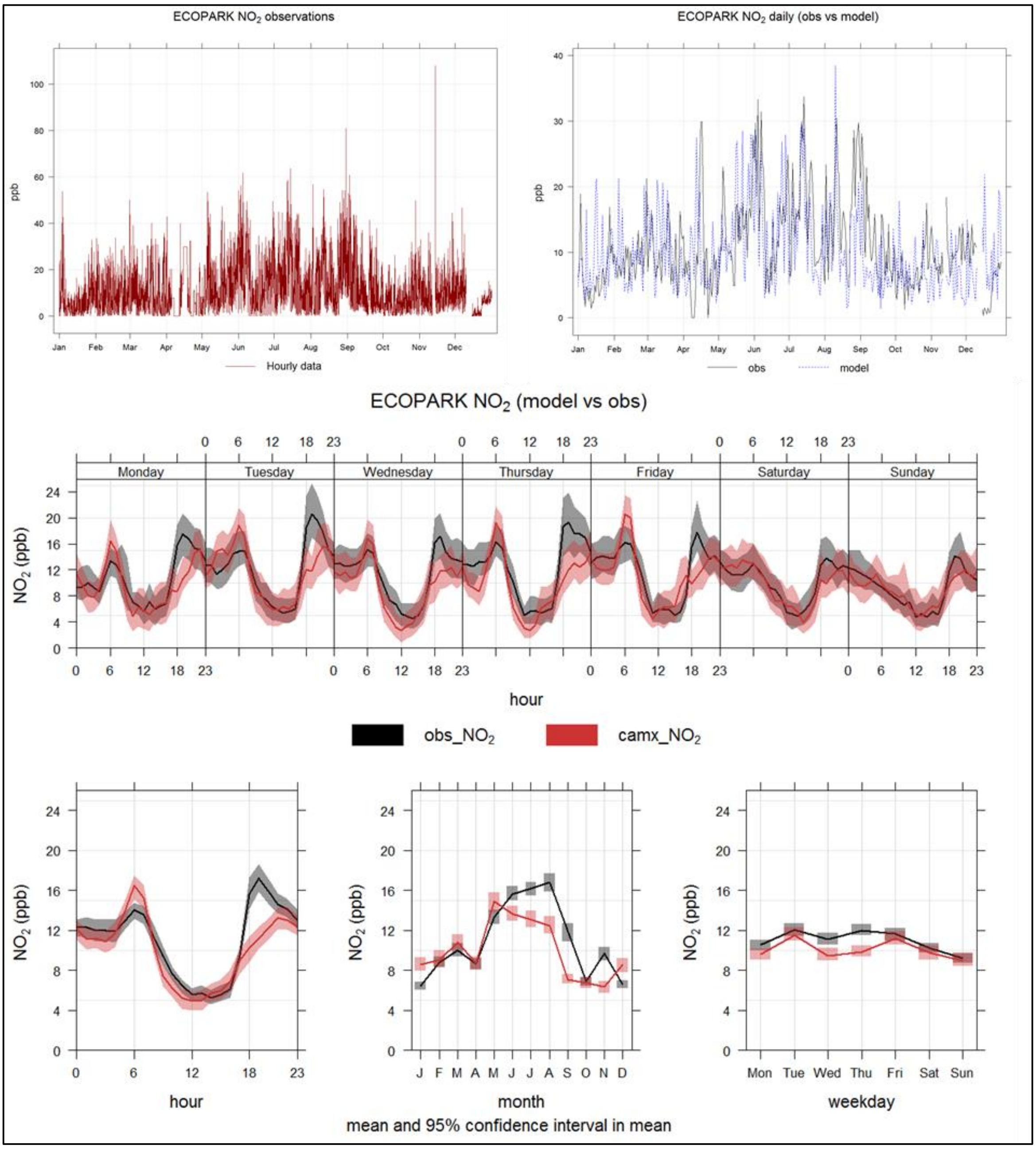


Figure 5-99: Time-series plots of simulated vs measured NO_2 at Eco Park

O_3:

Table 5-29 provides statistics regarding comparison of O_3 measurements and simulated concentrations at the station locations. These are based on hourly model output and measurements.

Table 5-29: Model vs measurements statistics for O_3 (based on hourly data)

station	pollutant	% completeness	MB	MGE	NMB	NMGE	r
DIEP	O_3	94	0.25	13.53	0.01	0.41	0.47
ZAMD	O_3	89	0.36	12.56	0.02	0.55	0.39
SHAR	O_3	90	6.18	11.65	0.26	0.48	0.66
SEBO	O_3	78	4.44	9.99	0.16	0.37	0.68
THRE	O_3	87	2.30	11.78	0.08	0.42	0.66
KLIP	O_3	51	7.84	12.84	0.38	0.62	0.65
AJJA	O_3	0	NA	NA	NA	NA	NA
ECOP	O_3	96	0.29	12.24	0.01	0.40	0.51
LEIT	O_3	0	NA	NA	NA	NA	NA
RAND	O_3	89	0.14	11.95	0.00	0.39	0.60

Notes: Red shading indicating data completeness less than 70%

The model performs reasonably well at a majority of station locations. Over all stations there is an over-estimate; however it should be noted that this is primarily due to model simulating higher evening O_3, and not an over-estimate of peak daytime concentrations. The highest over-estimation is seen at Kliprivier, however data completeness for that station is very low. The next highest over-estimation is seen at Sharpeville (Figure 5-100 below). There it is seen that there are enhanced concentrations simulated during evenings, however with an accurately simulated peak. There also seem to be spuriously low measurements during autumn and winter (values such as 0.001 etc.). If these are indeed spurious, it may temper the over-estimate somewhat.

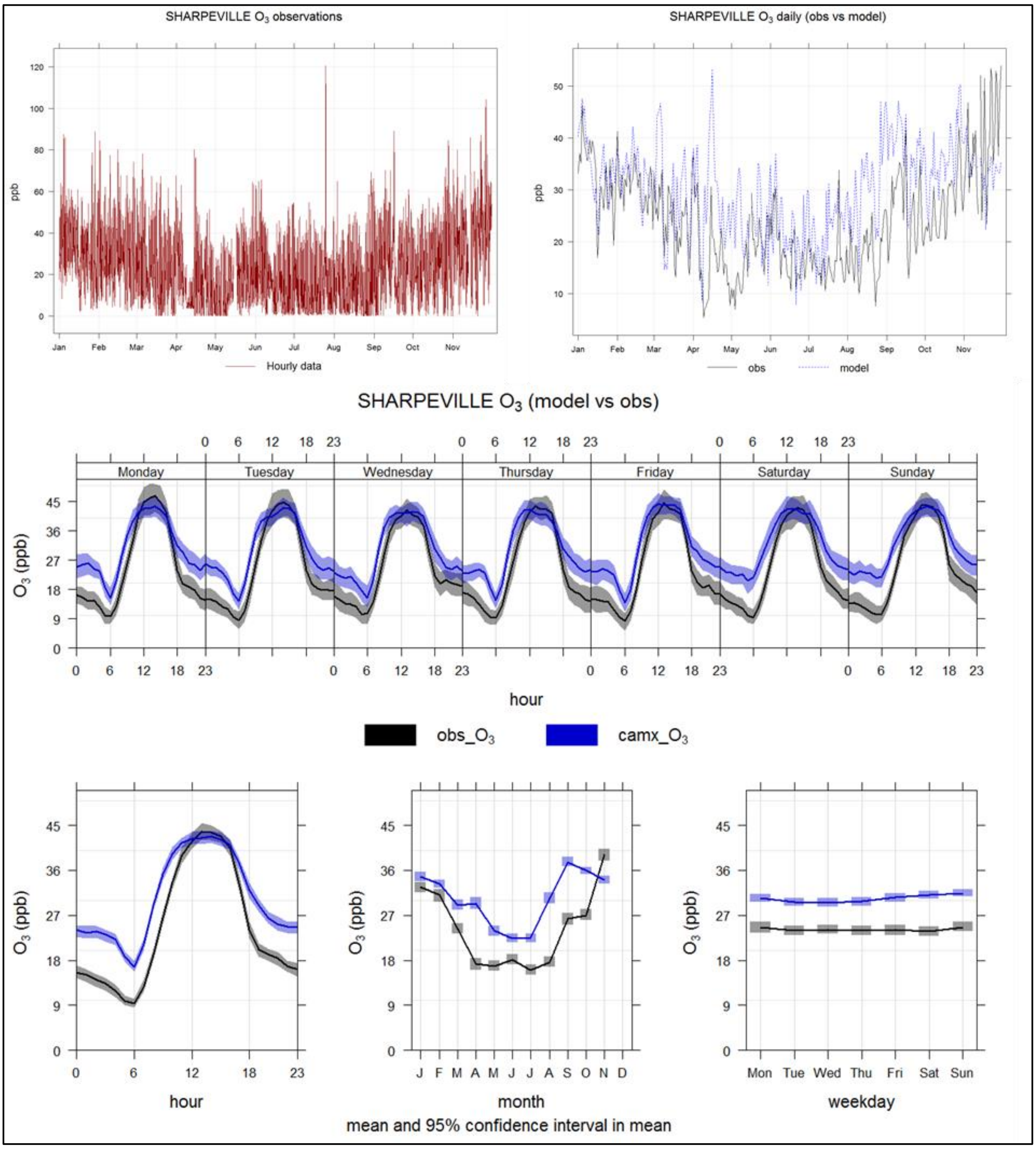


Figure 5-100: Time-series plots of simulated vs measured O_3 at Sharpeville

Figure 5-101 shows one of the better performing stations; that being Sebokeng.

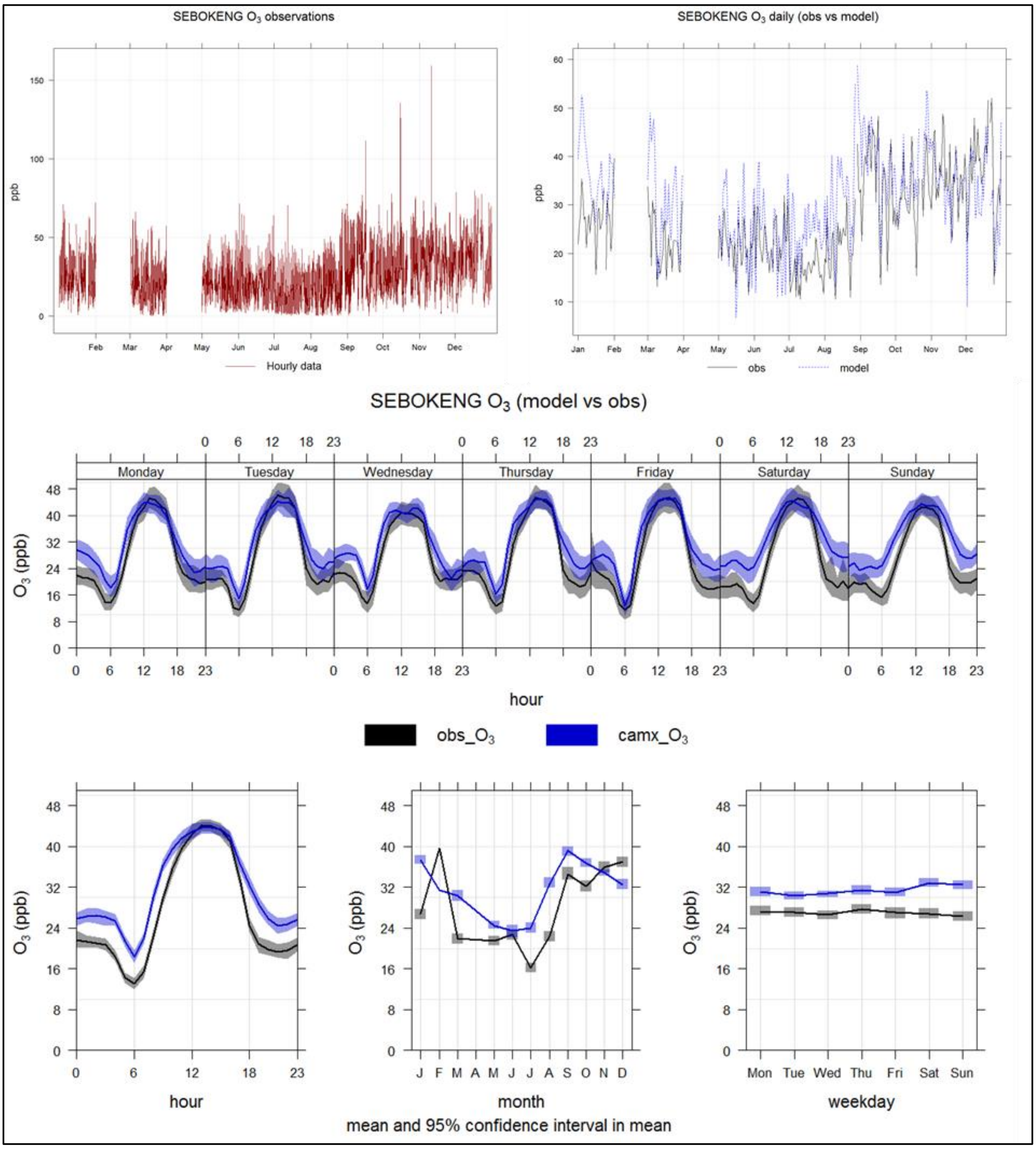


Figure 5-101: Time-series plots of simulated vs measured O_3 at Sebokeng

PM$_{10}$:

Table 5-30 provides statistics regarding comparison of PM_{10} measurements and simulated concentrations at the station locations. These are based on hourly model output and measurements. It should be noted that PM data quality for AJ Jacobs, Eco Park, Leitrum and Rand Water are highly questionable (See Appendix B).

Table 5-30: Model vs measurements statistics for PM_{10} (based on hourly data)

station	pollutant	% completeness	MB	MGE	NMB	NMGE	r
DIEP	PM_{10}	65	-15.46	26.19	-0.44	0.74	0.02
ZAMD	PM_{10}	78	-48.91	58.31	-0.68	0.81	0.12
SHAR	PM_{10}	79	-61.04	75.95	-0.62	0.77	0.22
SEBO	PM_{10}	73	-14.26	35.93	-0.32	0.80	0.19
THRE	PM_{10}	85	-28.02	49.91	-0.44	0.79	0.07
KLIP	PM_{10}	46	-57.08	59.32	-0.71	0.74	0.24
AJJA	PM_{10}	95	-19.66	33.99	-0.45	0.78	0.09
ECOP	PM_{10}	78	-14.08	30.49	-0.38	0.82	0.10
LEIT	PM_{10}	21	-16.31	33.96	-0.43	0.89	0.16
RAND	PM_{10}	92	-22.14	52.21	-0.38	0.90	-0.01

Notes: Red shading indicating data completeness less than 70%

The model under-estimates at all stations. Best performance is seen at Sebokeng (Figure 5-103) while the worst is at Kliprivier (Figure 5-104). The Kliprivier site is located at a police station near Everite Building Products. While the emission inventory does include Everite, the very nearfield impacts of the facility on the station may not be captured at 1km resolution. Additionally, the site may be impacted by open field burning, waste burning, unpaved roads and vehicle emissions at the police station. The station data (Figure 5-104) does seem to indicate very high short-lived peaks throughout the year.

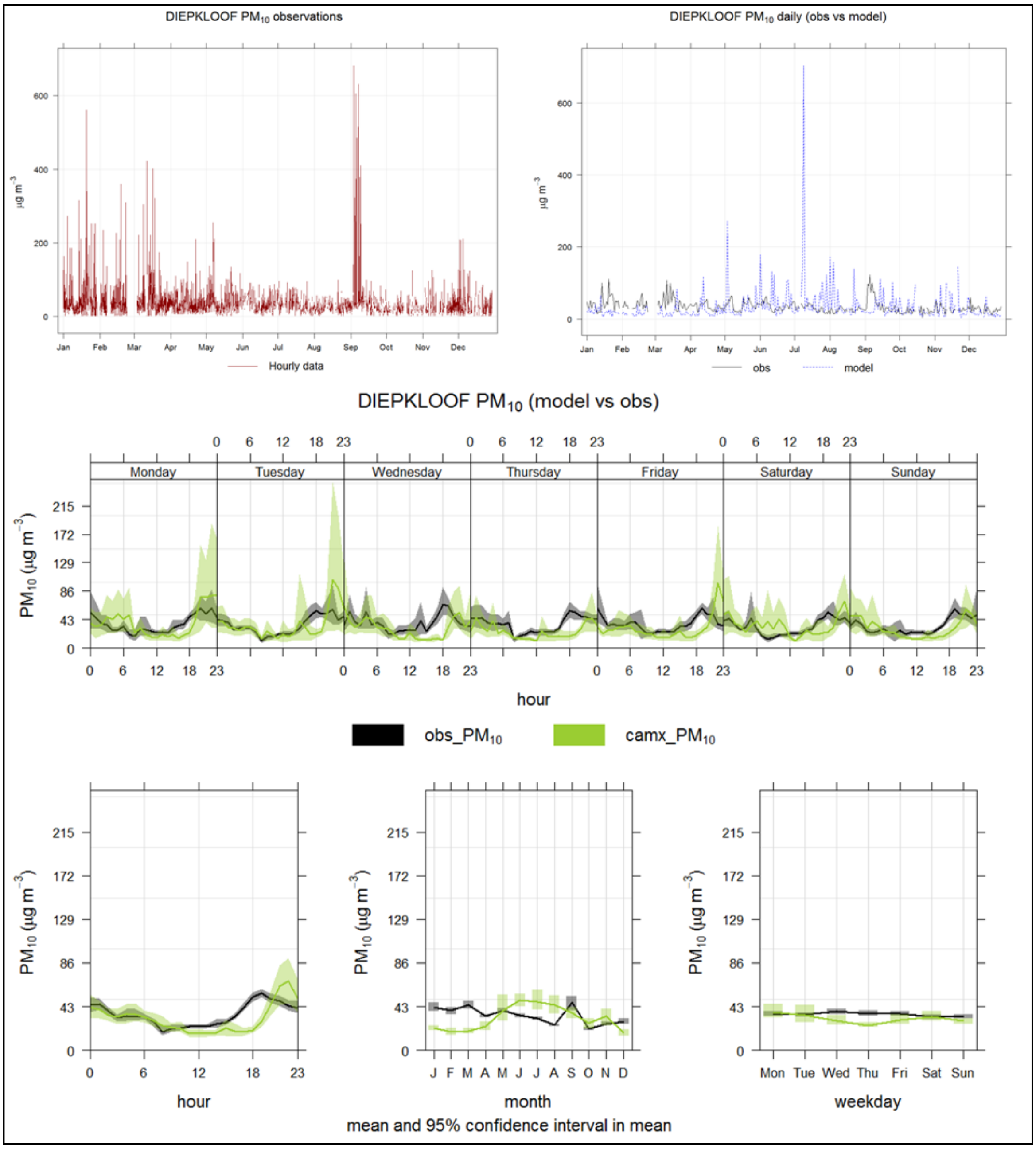


Figure 5-102: Time-series plots of simulated vs measured PM10 at Diepkloof

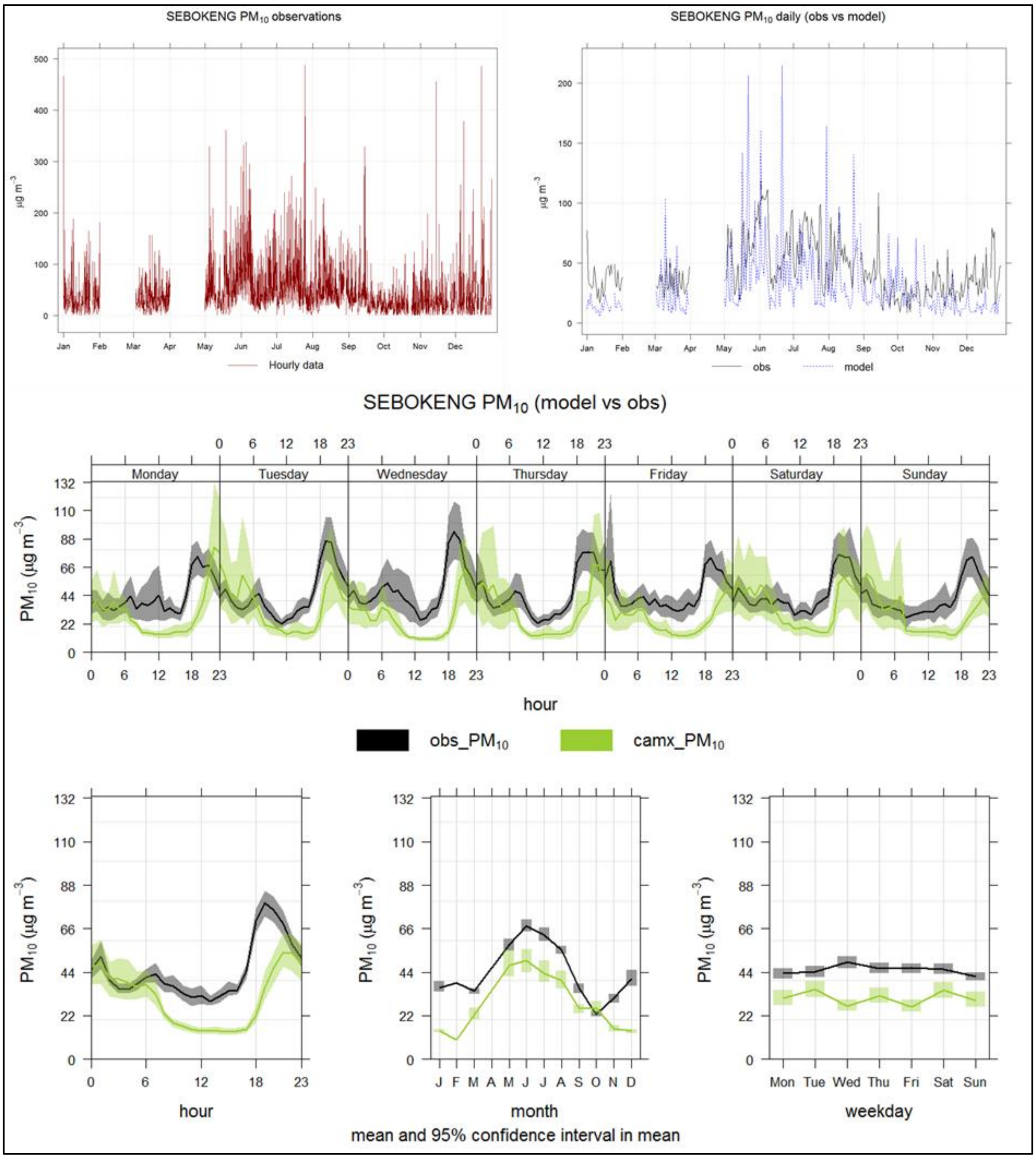


Figure 5-103: Time-series plots of simulated vs measured PM$_{10}$ at Sebokeng

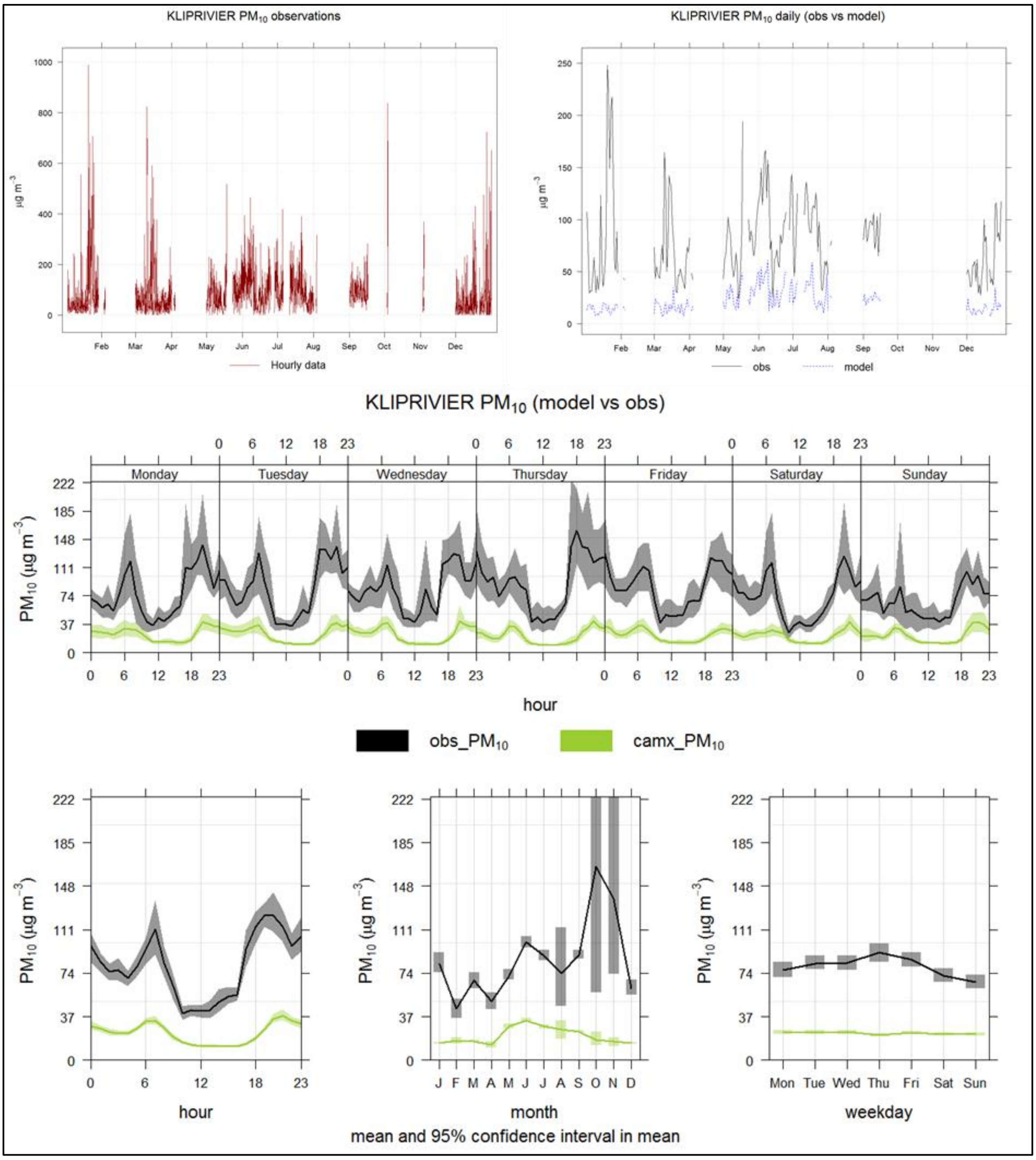


Figure 5-104: Time-series plots of simulated vs measured PM_{10} at Kliprivier

<u>$PM_{2.5}$:</u>

Table 5-31 provides statistics regarding comparison of $PM_{2.5}$ measurements and simulated concentrations at the station locations. These are based on hourly model output and measurements.

Table 5-31: Model vs measurements statistics for $PM_{2.5}$ (based on hourly data)

station	pollutant	% completeness	MB	MGE	NMB	NMGE	r
DIEP	$PM_{2.5}$	69	-9.78	15.13	-0.42	0.65	0.14
ZAMD	$PM_{2.5}$	63	-24.07	26.61	-0.66	0.73	0.29
SHAR	$PM_{2.5}$	48	-17.11	20.01	-0.56	0.66	0.28
SEBO	$PM_{2.5}$	73	-15.24	18.56	-0.50	0.61	0.48
THRE	$PM_{2.5}$	76	-13.58	18.27	-0.47	0.63	0.28
KLIP	$PM_{2.5}$	47	-21.91	26.68	-0.56	0.68	0.19
AJJA	$PM_{2.5}$	74	-5.54	10.87	-0.31	0.62	0.22
ECOP	$PM_{2.5}$	81	-4.61	11.24	-0.29	0.70	0.12
LEIT	$PM_{2.5}$	23	-0.46	10.93	-0.04	0.87	0.45
RAND	$PM_{2.5}$	72	-2.58	11.13	-0.14	0.60	0.35

Notes: Red shading indicating data completeness less than 70%

$PM_{2.5}$ is under-estimated at all stations; the worst of which occurs at Zamdela (although much of the summer's measurements are missing). It should be noted that PM data quality for AJ Jacobs, Eco Park, Leitrum and Rand Water is highly questionable (See Appendix B). Two stations stand out as having relatively good data combined with good data coverage; that being Three Rivers and Sebokeng (Figure 5-105 and Figure 5-106 respectively). Sebokeng station is likely impacted by domestic combustion (energy production and waste; included in emission inventory) and potentially dust from bare land (not included in emission inventory). ArcelorMittal Vanderbijlpark is located 8 km to the south. Three Rivers is a more sub-urban environment with impacts from biomass burning (included in emission inventory), dust from open fields (not in emission inventory) and New Vaal colliery (included in emission inventory). Lethabo power-station lies 9km to the south. Performance at both locations is similar, in that the model can capture the temporal variation relatively well, however the under-estimation is consistent. For Three Rivers influence from regional scale $PM_{2.5}$ is likely considering the high concentrations throughout the evenings/early mornings and decreasing during the day once the planetary boundary layer increases in height. This is possibly not simulated by the model due to the over-estimate in wind speed.

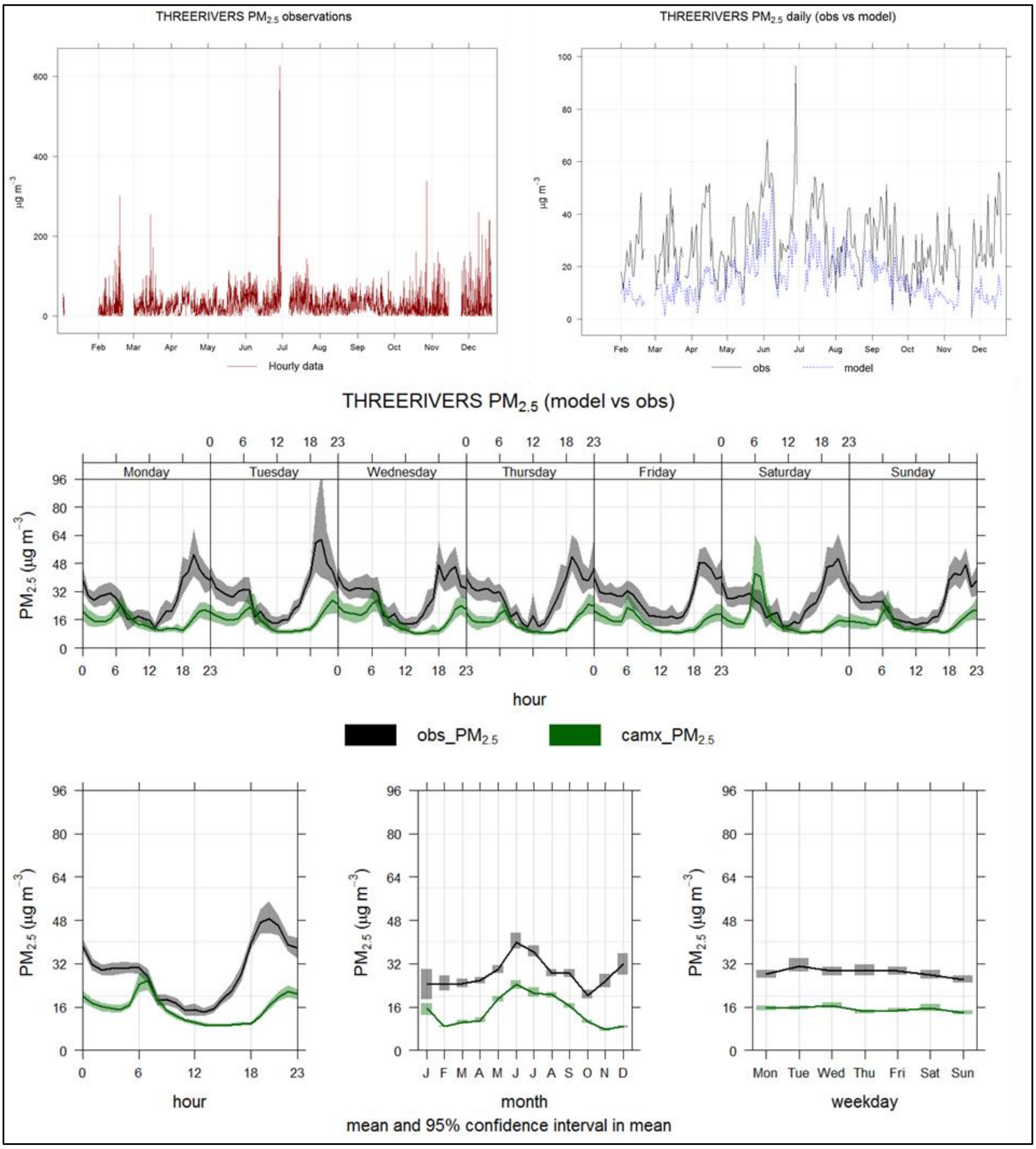


Figure 5-105: Time-series plots of simulated vs measured $PM_{2.5}$ at Three Rivers

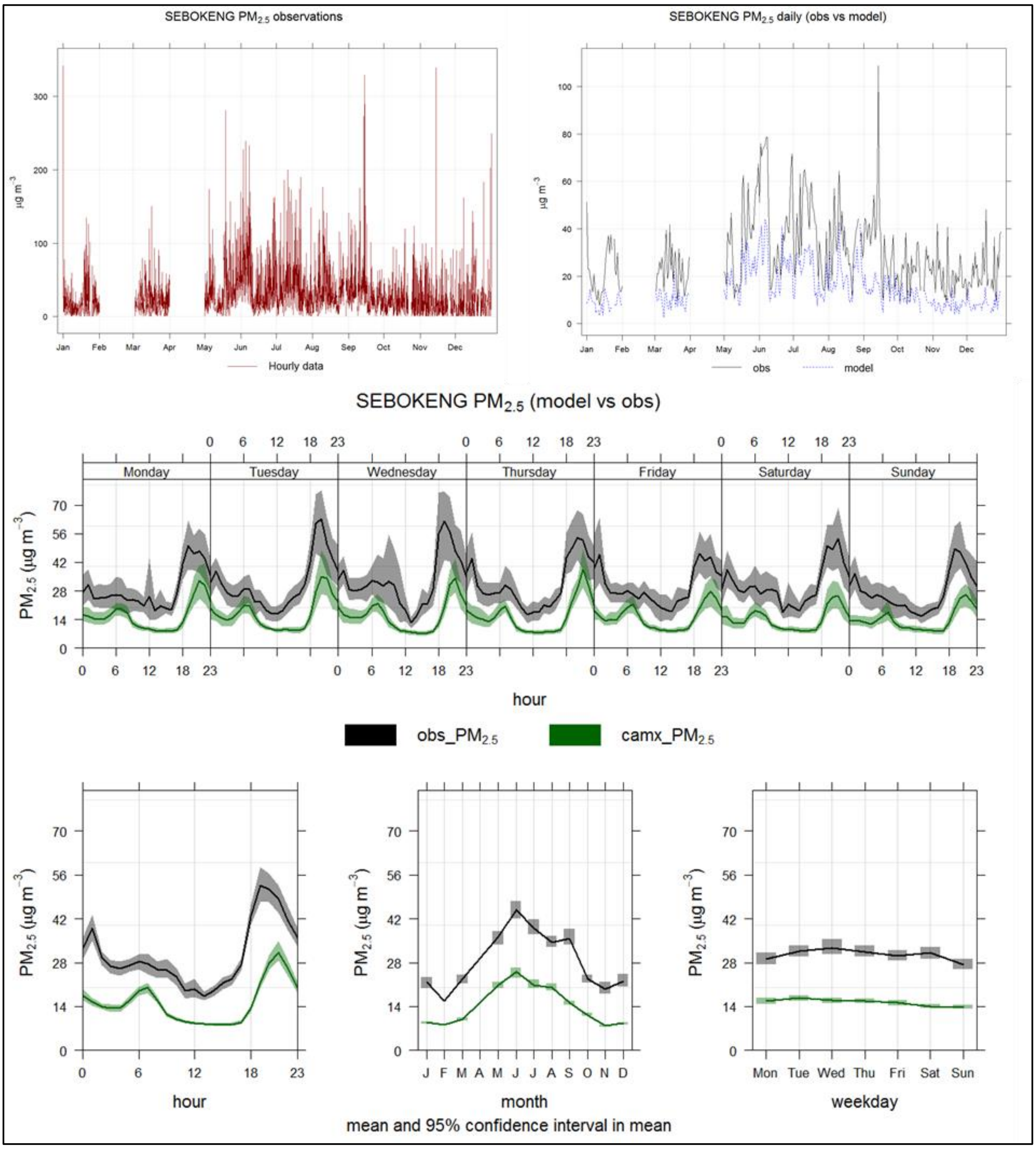


Figure 5-106: Time-series plots of simulated vs measured $PM_{2.5}$ at Sebokeng

SO_2:

Table 5-32 provides statistics regarding comparison of SO_2 measurements and simulated concentrations at the station locations. These are based on hourly model output and measurements. It should be noted that data quality for Eco Park, AJ Jacobs and Leitrum is highly questionable (see Appendix B).

Table 5-32: Model vs measurements statistics for SO_2 (based on hourly data)

station	pollutant	% completeness	MB	MGE	NMB	NMGE	r
DIEP	SO_2	94	1.58	4.30	0.38	1.03	0.33
ZAMD	SO_2	87	8.70	14.26	1.03	1.68	0.22
SHAR	SO_2	80	4.90	8.51	0.85	1.47	0.30
SEBO	SO_2	73	1.62	6.23	0.27	1.04	0.32
THRE	SO_2	91	4.41	8.53	0.74	1.44	0.29
KLIP	SO_2	46	1.84	5.77	0.35	1.11	0.25
AJJA	SO_2	96	-5.04	17.73	-0.23	0.81	0.39
ECOP	SO_2	98	-6.72	13.30	-0.42	0.83	0.22
LEIT	SO_2	94	-1.70	12.10	-0.11	0.81	0.22
RAND	SO_2	99	5.75	9.42	1.18	1.93	0.23

Notes: Red shading indicating data completeness less than 70%

For locations where stations have good data coverage and good quality data, the model over-estimates SO_2. According to time-series plots (Appendix B), performance for SO_2 looks very good for Leitrum and AJ Jacobs; however data quality for those sites is erratic, with a few months showing a shift in baseline concentrations. For Eco Park it is possible that better data would show even better performance since addressing the sensor drift would reduce measured concentrations (closer to what is simulated).

As mentioned in Section 5.3.2.1, an over-estimate in wind speed could indicate enhanced turbulence in the boundary layer, leading to the plume from elevated stacks reaching the ground more often in the simulation. An example of this may be seen in the time-series plots for Rand Water (an Eskom site 6.5km north east of Lethabo power-station). This brings the Eskom (or Sasolburg) plume to the ground slightly earlier and with greater magnitude. This is particularly apparent during winter months.

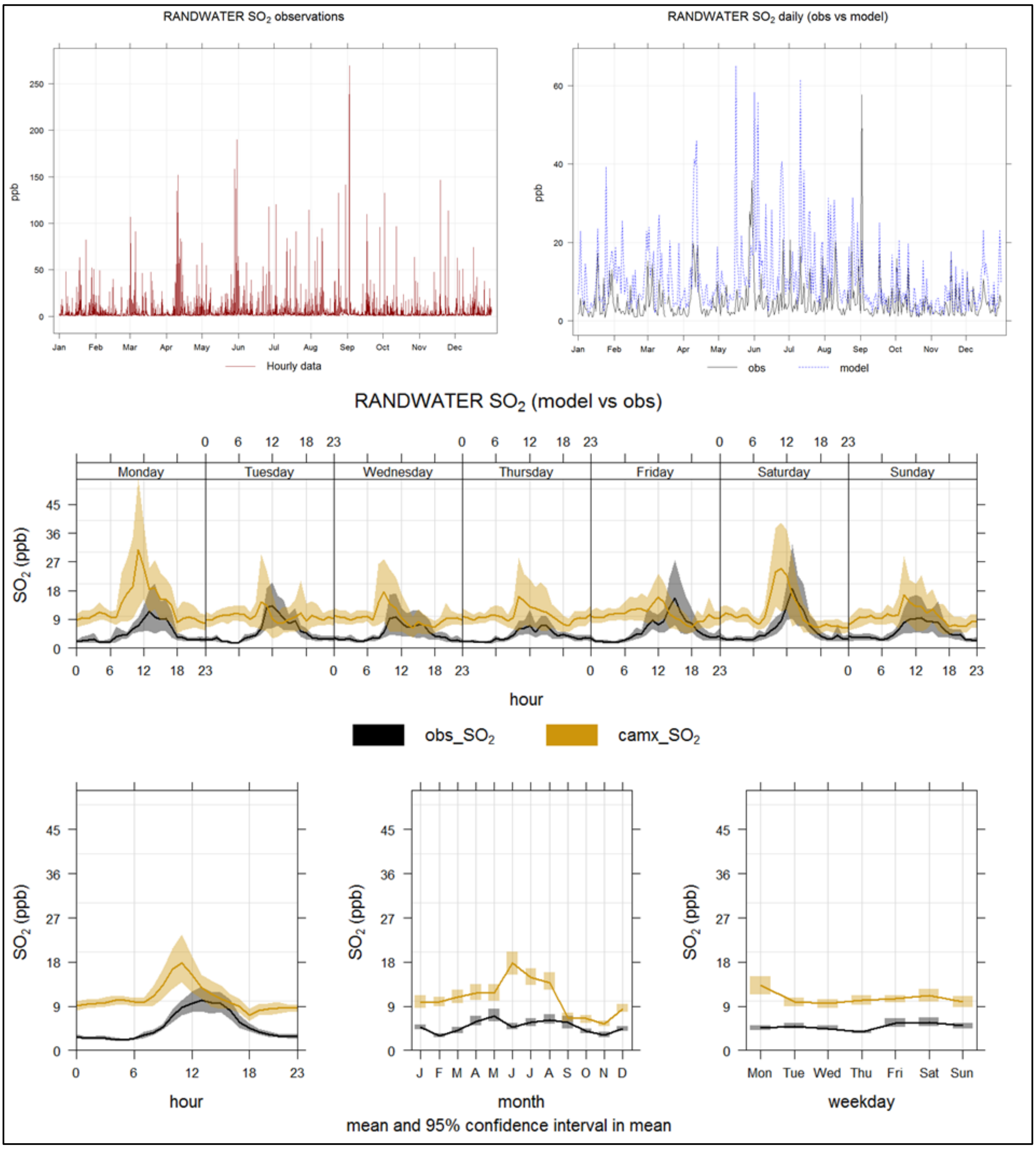


Figure 5-107: Time-series plots of simulated vs measured SO_2 at Rand Water

Performance at other locations, such as Sebokeng, show better results.

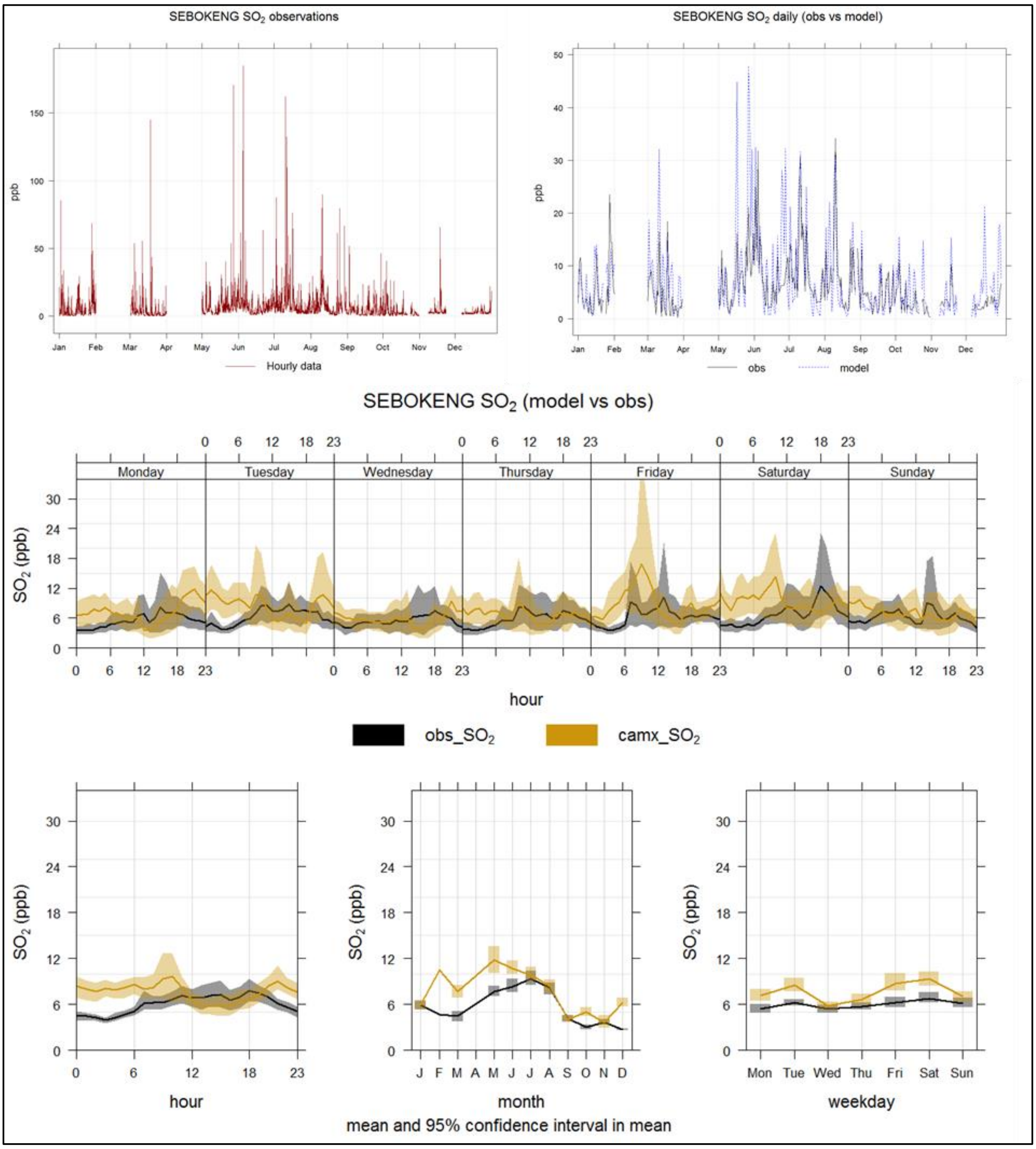


Figure 5-108: Time-series plots of simulated vs measured SO$_2$ at Sebokeng

5.3.7.2 *Time averaged concentration maps*

These maps show simulated concentrations averaged according to the NAAQS averaging period for that pollutant. This would thus be:

- PM_{10} – 24-hr and annual
- $PM_{2.5}$ – 24-hr and annual
- NO_2 – 1-hr and annual
- O_3 – 8-hr running
- SO_2 – 1-hr, 24-hr and annual

For 1-hr, 24-hr and 8-hr averaging periods the 99th percentile is taken as representative and is a worst-case view. The maps also show the location of monitoring stations together with the normalized mean bias for that pollutant (NMB would be the same for all averaging periods).

PM_{10}

As seen in the preceding section (i.e. comparison with measurements), PM_{10} is generally under-estimated at the station locations. Figure 5-109 and Figure 5-110 show simulated PM_{10} for the 99th percentile of 24 hour averages and annual average respectively. The negative normalized mean bias (seen in parentheses in the station labels) shows the extent of under-estimation. Even so, high concentrations and exceedances are simulated over large regions of VTAPA. The majority of these are in close proximity to industrial facilities, mines and the old tailings areas in CoJ. The lower exceedance concentrations (i.e. still within the exceedance bands; coloured orange) simulated in northern VTAPA are located around high emitting residential fuel combustion areas.

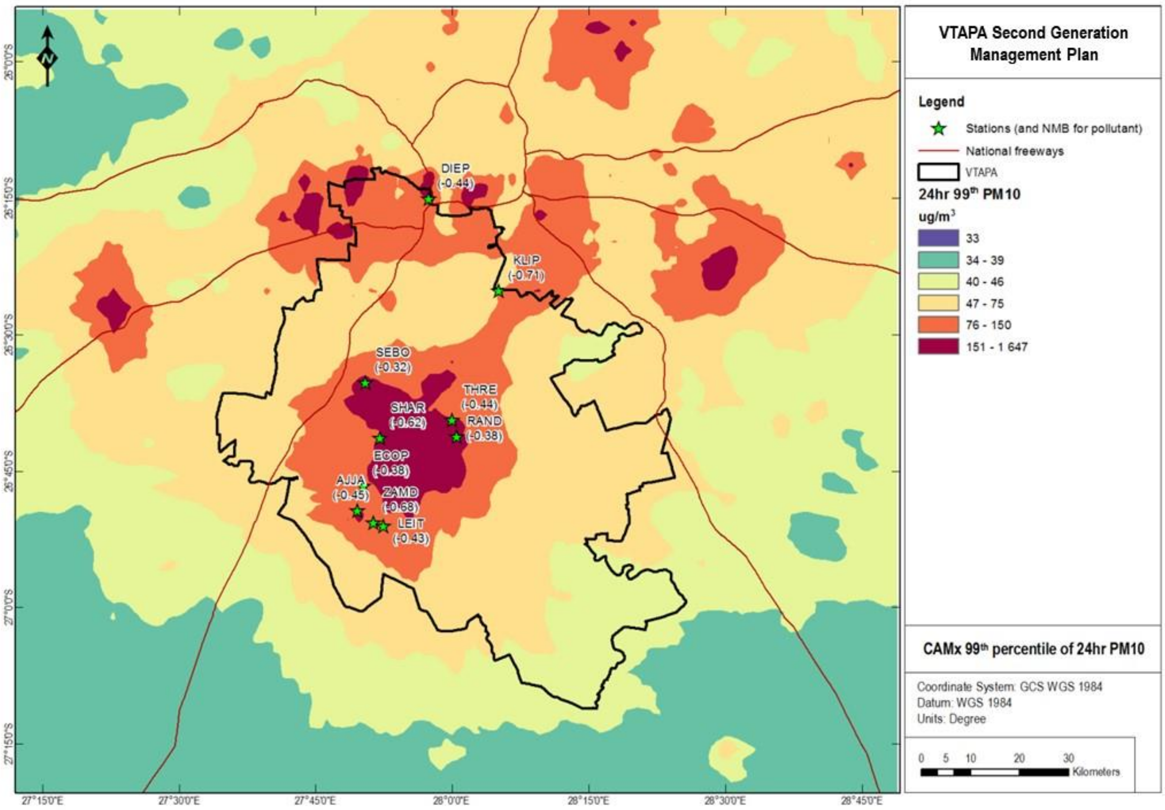


Figure 5-109: CAMx simulated 99th percentile of 24-hr PM_{10} (note exceedance shown in both orange and red)

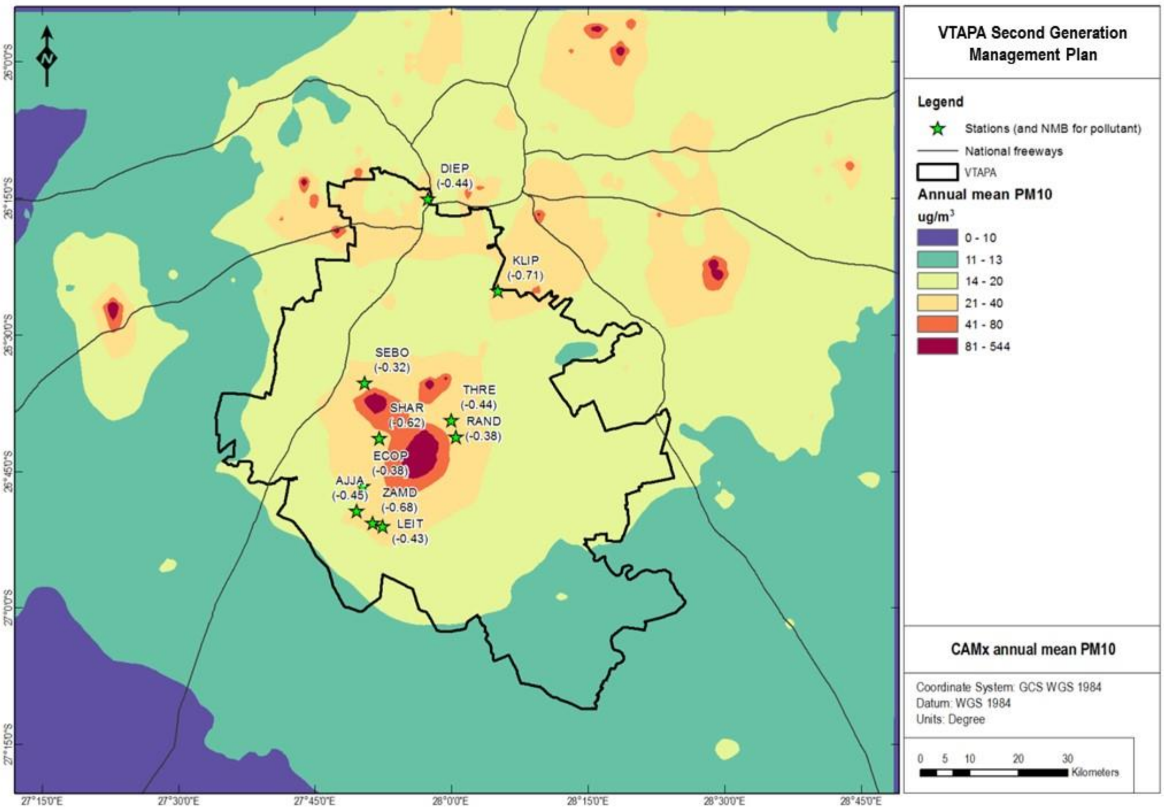


Figure 5-110: CAMx simulated annual mean PM_{10} (note exceedance shown in both orange and red)

$PM_{2.5}$

Similar to PM_{10} the $PM_{2.5}$ simulation exhibits a general under-estimate. Note that AJ Jacobs, Eco Park and Leitrum PM data are unreliable; while data completeness for Kliprivier and Sharpeville is not high.

The 24-hr NAAQS is simulated to be exceeded (for the 99th percentile thereof) in much of the domain. For the VTAPA this includes the central highly populated region and the area to the east of this. Exceedances are predicted even in spite of the general under-estimation. For the annual mean, exceedances are confined to specific areas along the central region.

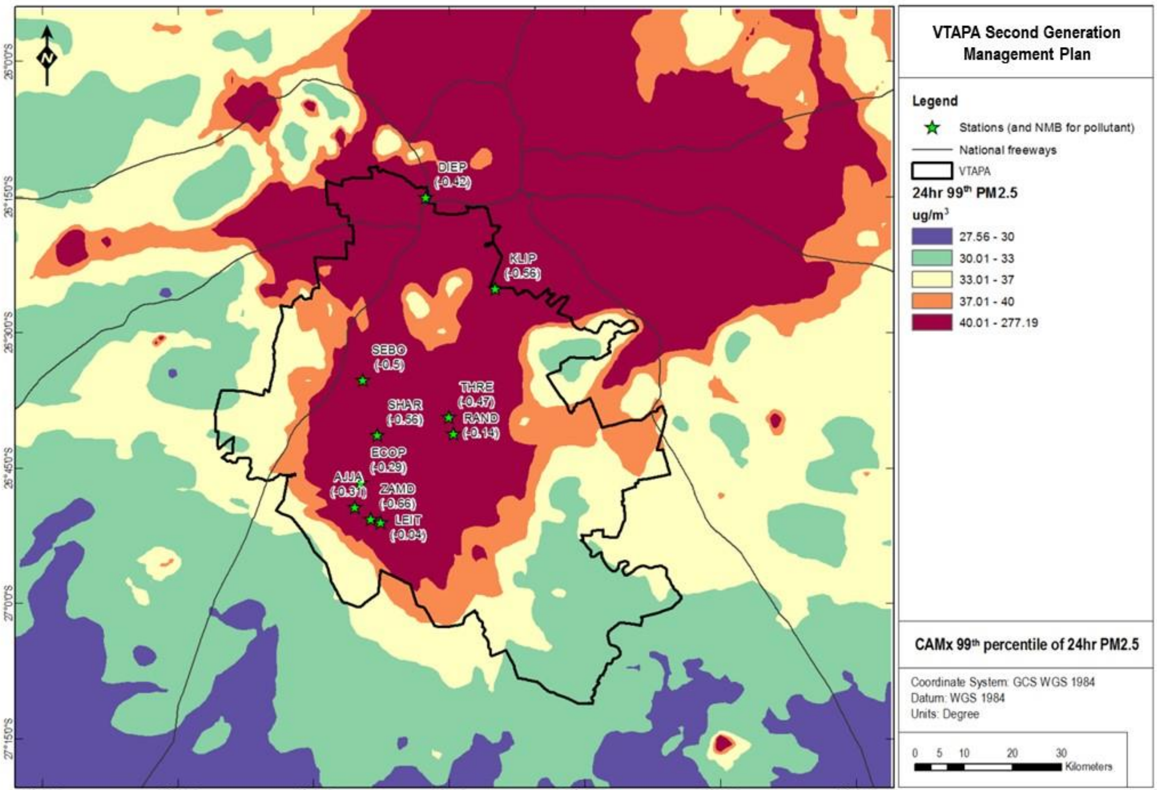


Figure 5-111: CAMx simulated 99th percentile of 24-hr $PM_{2.5}$

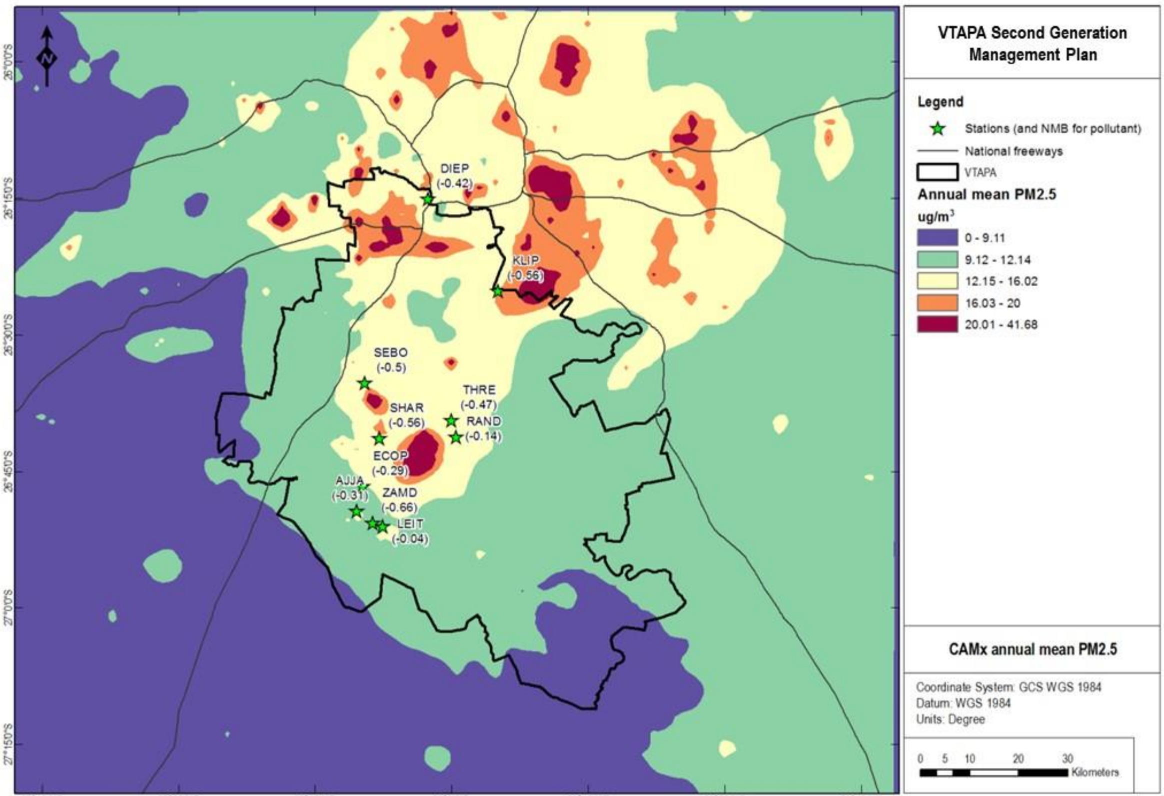


Figure 5-112: CAMx simulated annual mean $PM_{2.5}$

NO_2

Exceedances of the 1-hr NAAQS, due to modelled 99th percentile of 1-hour concentrations, are not simulated within the VTAPA. This is likely to be true as monitoring stations do not show exceedances either. Higher values are simulated around Sasolburg and Soweto.

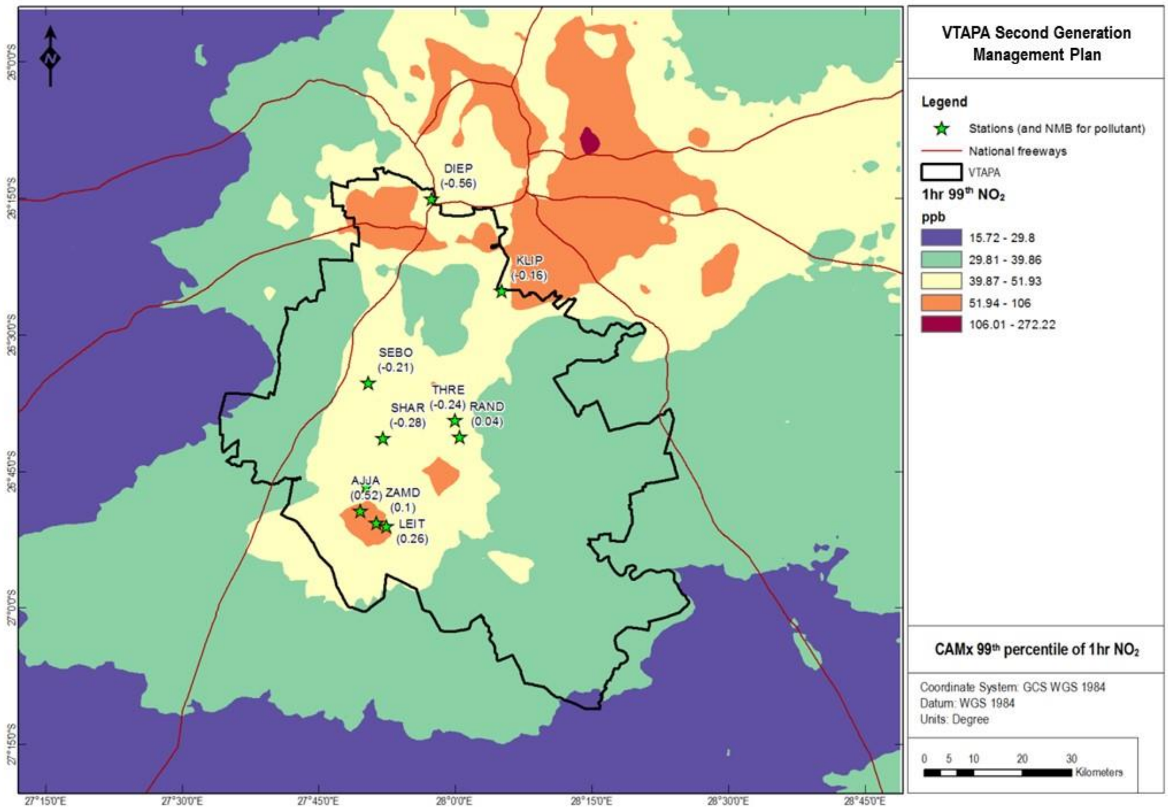


Figure 5-113: CAMx simulated 99th percentile of hourly NO_2

An exceedance of the annual mean is simulated around Zamdela, although the affected area is very small. The Diepkloof monitoring station does show an exceedance of the annual mean, however the simulated values do not reach this level.

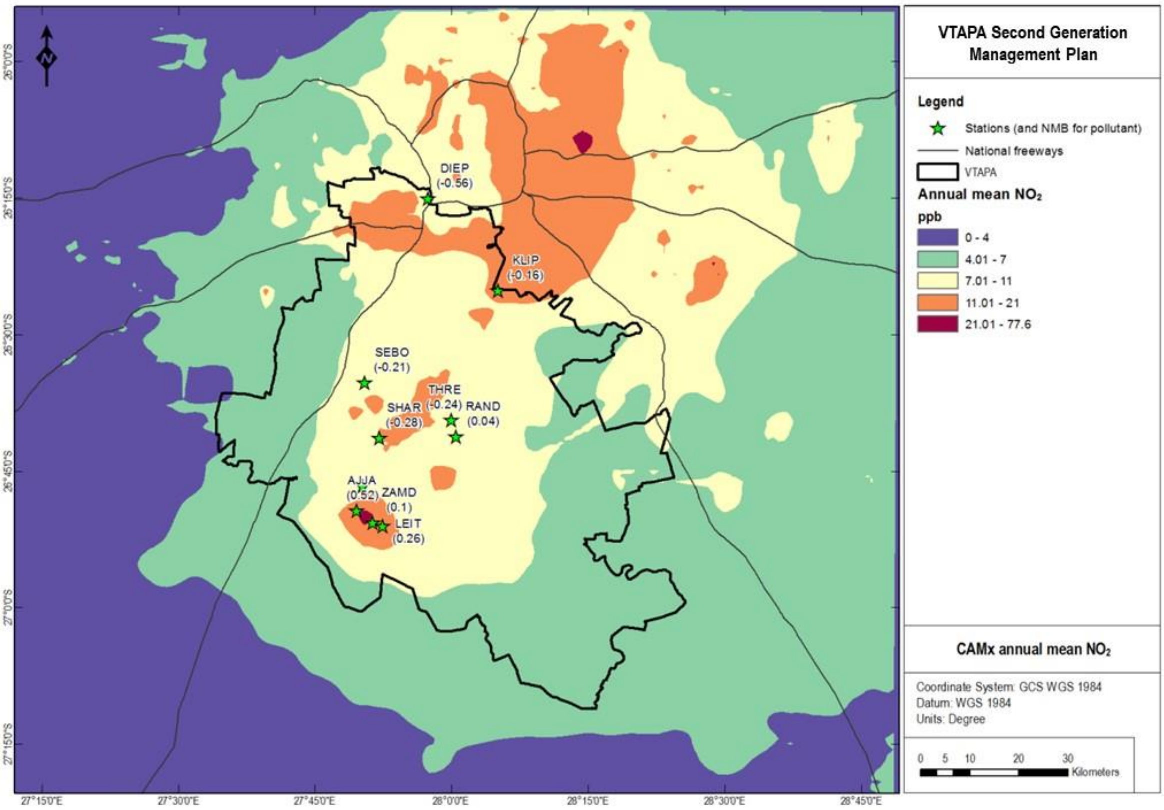


Figure 5-114: CAMx simulated annual mean NO_2

O_3:

Exceedances of the 8-hr NAAQS are simulated over most of the domain. This is plausible since 8 hourly running averages are used; which may exceed the NAAQS more than once per day. For cells/pixels in the map below to show red, the NAAQS of 61 ppb would have to be exceeded for at least 87 hours in a year. Considering O_3 could exceed the NAAQS for at least 2 – 3 hours in a day, this equates roughly to 43 – 29 days in the year. It is also possible that localized areas of titration are not simulated as the model does under-predict NOx for example at Diepkloof. That said the NMB exhibited by simulated O_3 (over all hours) is very low, indicating good performance.

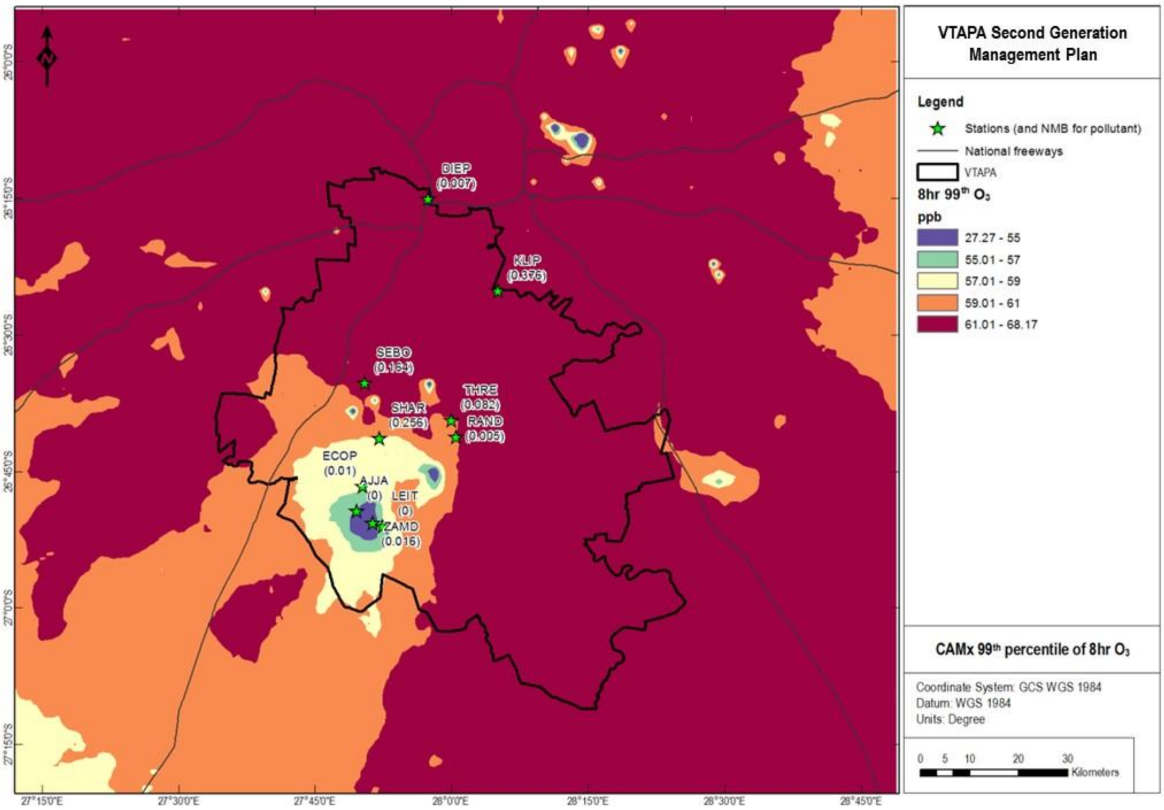


Figure 5-115: CAMx simulated 99th percentile of 8-hr (running) O_3

SO$_2$:

Elevated concentrations are simulated around the central region of VTAPA. These are primarily around Sasolburg and the Lethabo power station. In general, the sites where the model over-estimates are not simulated as in exceedance; meaning the over-estimation has little effect on areas of actual exceedance. The only exception of this is at Rand Water. It is also interesting to note that exceedances are simulated away from monitoring stations.

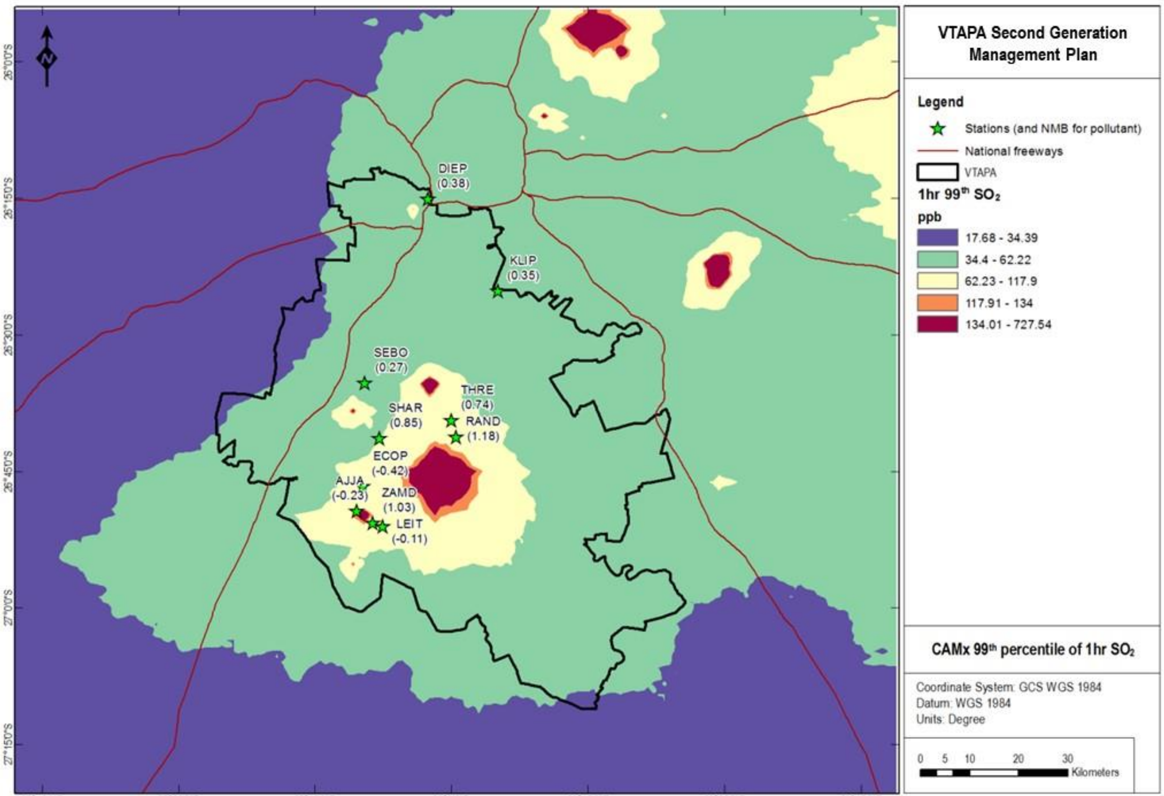


Figure 5-116: CAMx simulated 99th percentile of hourly SO_2

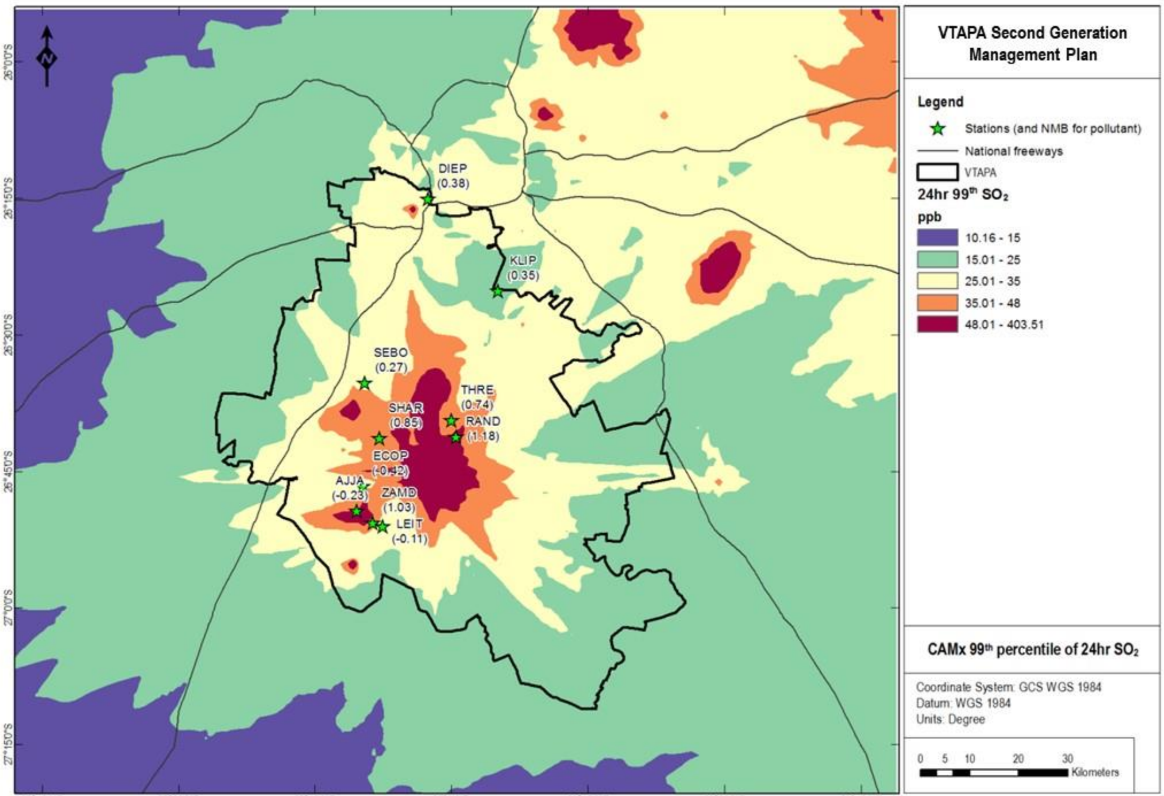


Figure 5-117: CAMx simulated 99th percentile of 24-hr SO_2

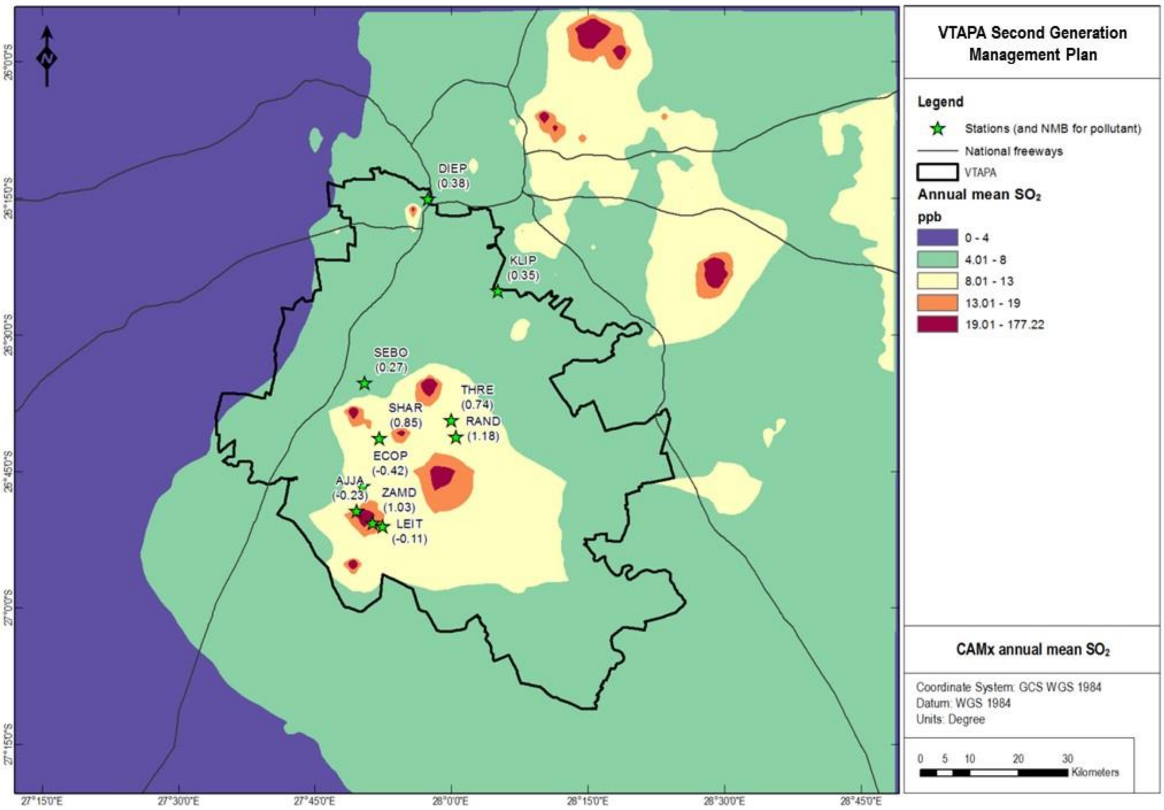


Figure 5-118: CAMx simulated annual mean SO_2

5.3.7.3 Source Tracking

Source tracking was utilized to investigate the relative contribution of industries within (group is called VIND herein) and outside (group is called NVIND herein) VTAPA to ozone and PM_{10} concentrations. Note that this means only contributions from industry (which excludes wind-blown dust) are analysed and presented here. Therefor it should be kept in mind that other sources not tracked may contribute to ambient exceedances (possibly significantly depending on time and space). Maps of annual exceedance count contributions are shown. These are derived from hourly source tracking output on the fine 1km resolution grid; which are time averaged as necessary (8 hour running for O_3 and 24hr averages for PM_{10}).

For each grid cell, when an exceedance is detected, if the VIND contribution in that cell is higher than the NVIND contribution, it is counted towards VIND; and vice-versa if the NVIND contribution is higher. These counts (including the ambient exceedance count) are summed up for the year. Therefore this means that only the fact that a certain industry group contributed more than the other is important, i.e. it is irrelevant as to how much either contributed to actually creating the exceedance; or if another source actually led to the exceedance.

<u>PM_{10}:</u>

Figure 5-119 shows the total ambient exceedance count for 24hr average PM_{10}. These exceedances are due to all sources in the model; and thus represent ambient exceedances. These basically correspond spatially to the map of 99th percentile 24hr average PM_{10} (Figure 5-109), in that exceedances occur near tailings storage facilities, mines and industry in general. There are also areas in northern VTAPA that represent domestic fuel combustion.

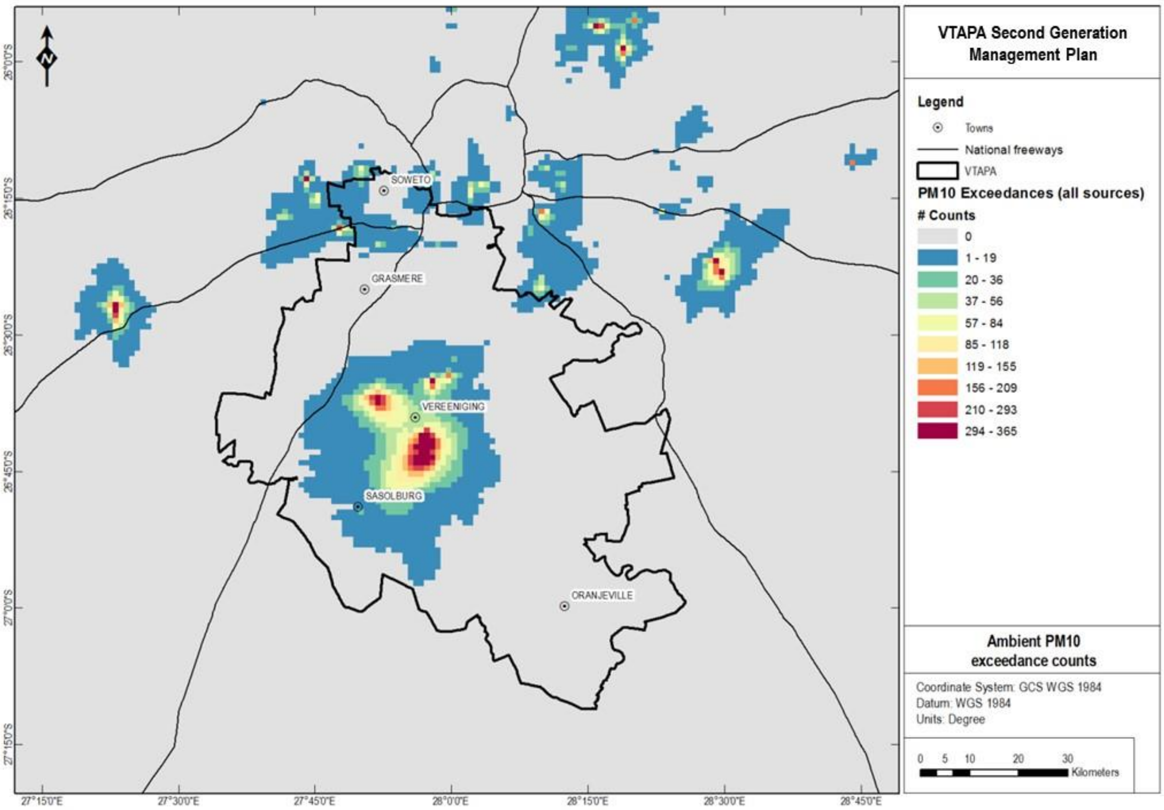


Figure 5-119: Ambient (i.e. due to all sources) PM_{10} 24hr average exceedance counts

Figure 5-120 shows a map of counts when VIND (concentration of PM_{10} from industry within the VTAPA) were higher than NVIND (concentration of PM_{10} from industry outside the VTAPA) during an exceedance. This illustrates that impact on exceedances from VIND is generally limited to within the VTAPA, except for when VTAPA industry are located near the boundary of the PA.

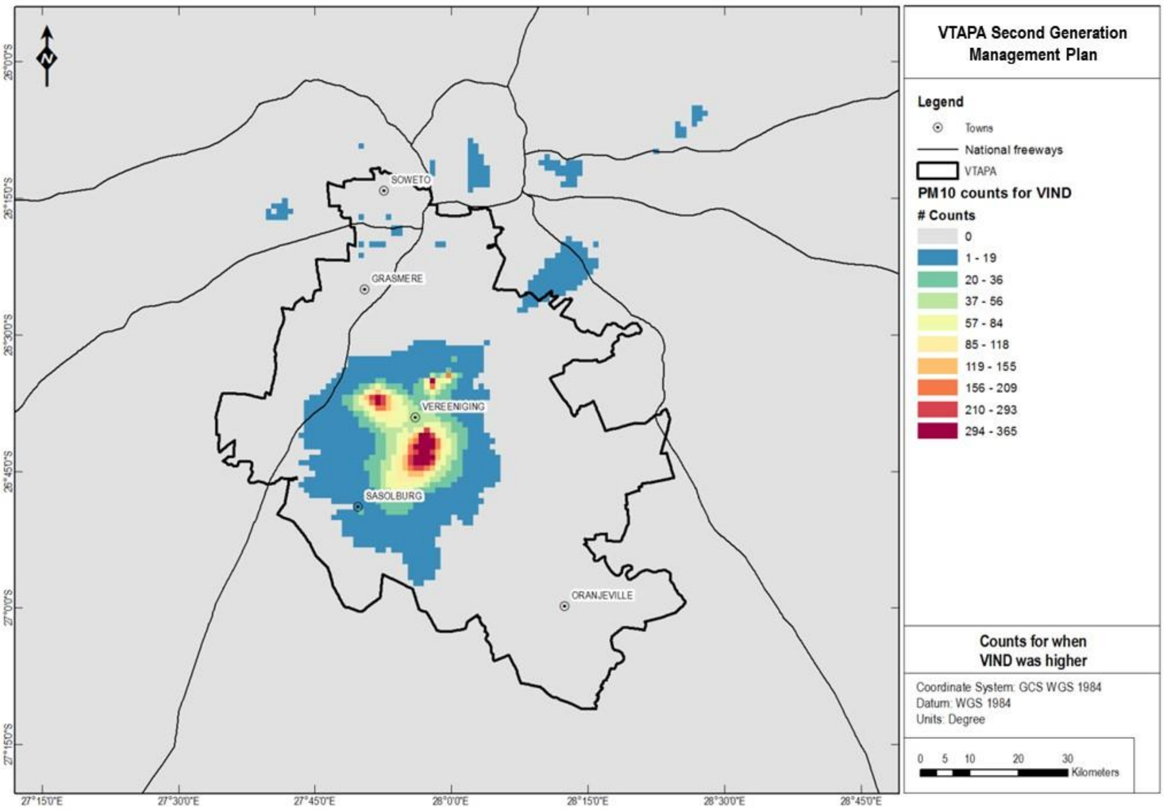


Figure 5-120: Counts for when VIND PM_{10} was higher during an exceedance (note same scale as exceedance counts; to provide context of contribution)

Figure 5-121 shows a map of counts when NVIND (concentration of PM_{10} contributed from industry outside the VTAPA) were higher than VIND (concentration of PM_{10} contributed from industry inside the VTAPA) during an exceedance. PM_{10} from NVIND rarely impact VTAPA.

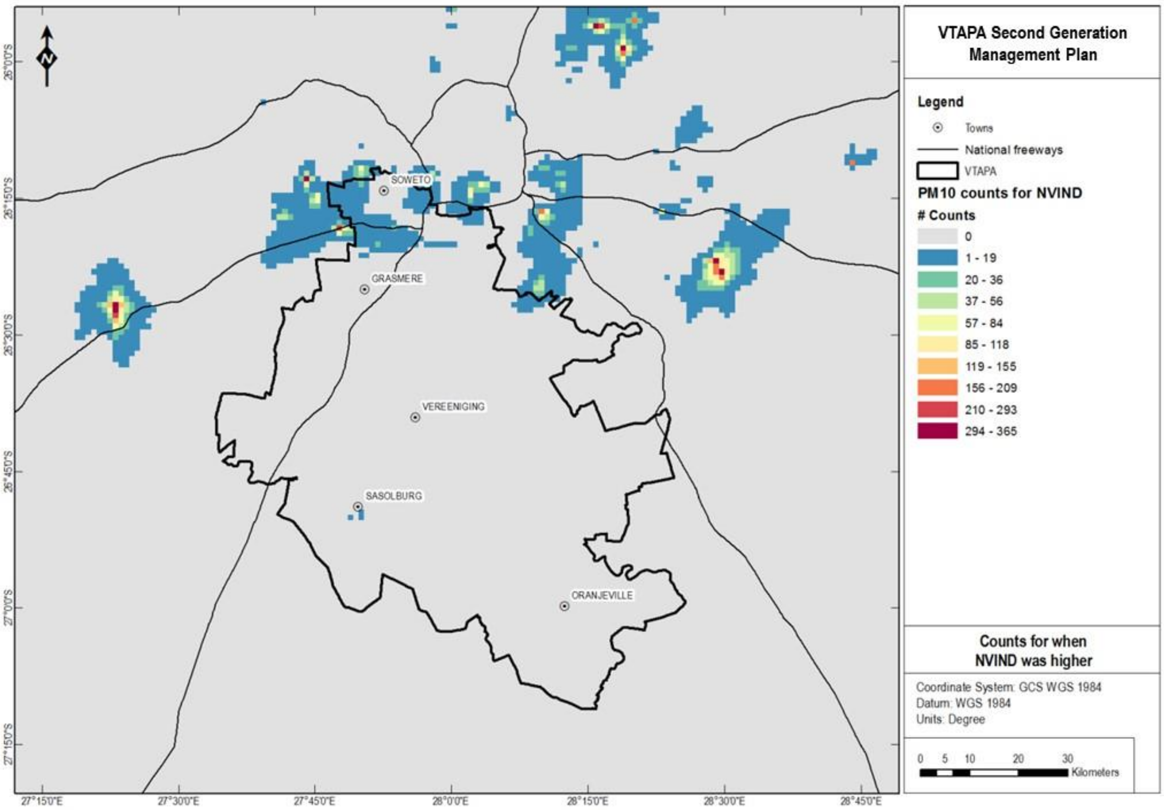


Figure 5-121: Counts for when NVIND PM_{10} was higher during an exceedance (note same scale as exceedance counts; to provide context of contribution)

O_3:

Figure 5-122 shows the total ambient exceedance count for 8hr running average O_3. These exceedances are due to all sources in the model; and thus represent ambient exceedances. These basically correspond spatially to the map of 99th percentile 8hr running average O_3 (Figure 5-115), in that exceedances are prolific throughout the domain; with lower counts occurring near Sasolburg and Lethabo Power Station.

O_3 is more complex since it is a secondary pollutant and forms downwind of high intensity NO emitters. Additionally, many of the high intensity NOx emitters are tall stacks, which increase the reach of NOx emissions, and thus O_3 formation. Therefore there is a higher potential for impacts within the VTAPA to originate from outside. Here source tracking aims to quantify contribution VIND and NVIND has (exclusively; i.e. only between those two groupings) on exceedances.

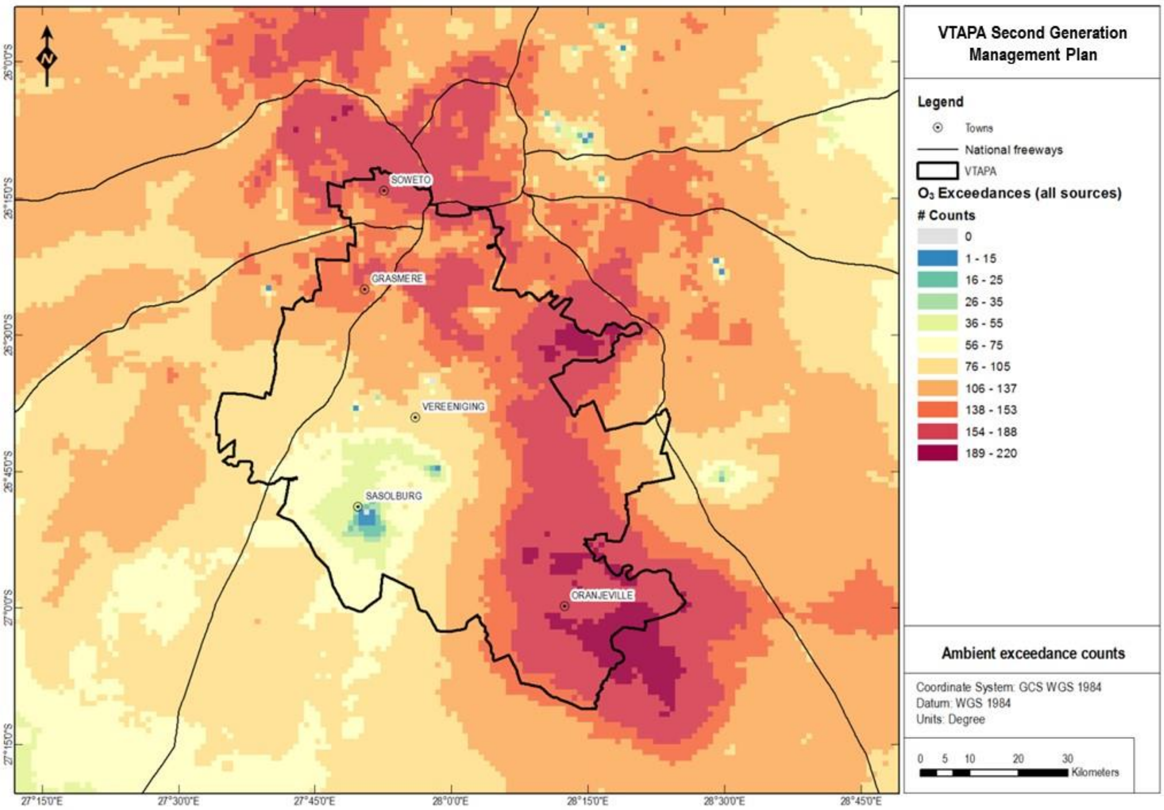


Figure 5-122: Ambient (i.e. due to all sources) O_3 8hr running average exceedance counts

Figure 5-123 shows a map of counts when VIND (concentration of O_3 formed due to industry within the VTAPA) were higher than NVIND (concentration of O_3 formed due to industry outside the VTAPA) during an exceedance. VIND impacts are mainly within in the south eastern VTAPA, around Oranjeville. It is likely that Lethabo Power Station and Sasol NOx emissions play a large role in O_3 formation in this area. There are impacts seen outside of VTAPA, and these are primarily to the south east in the domain. However, this map must be seen in context of both ambient exceedances (noting the colour scale and the light yellow colouring of VIND O_3 counts) and the contribution of NVIND.

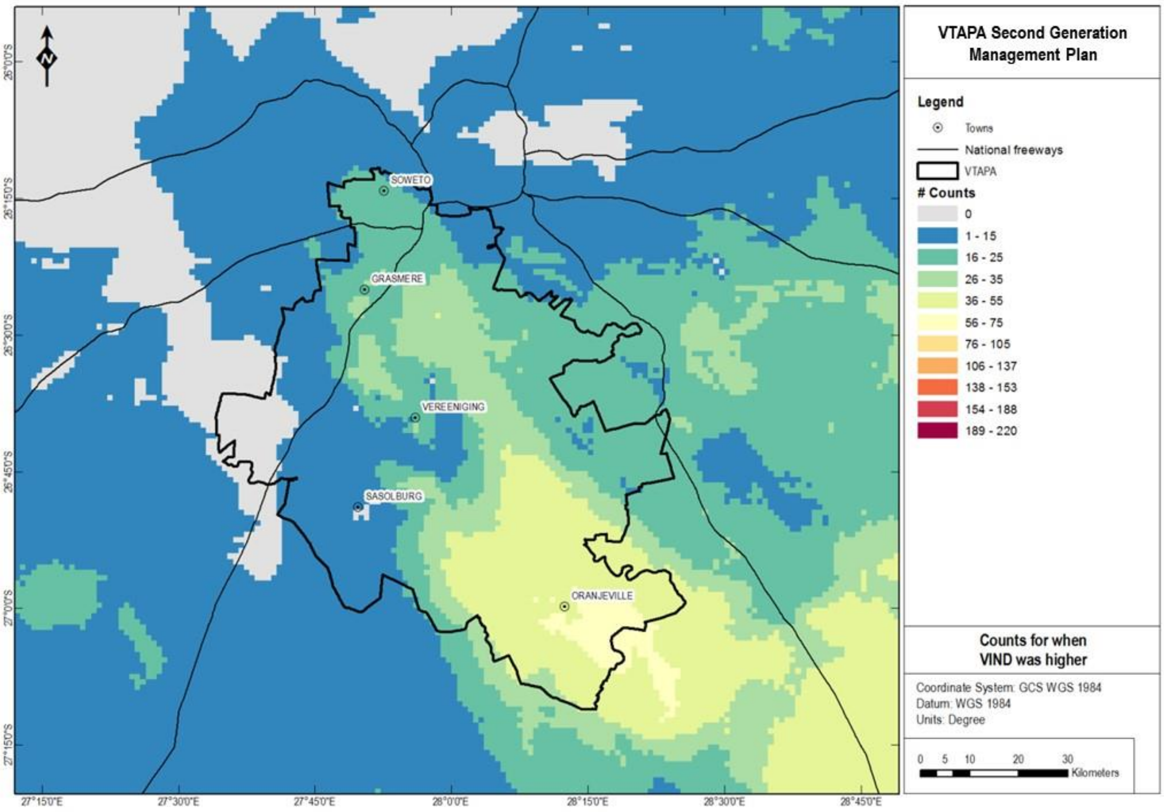


Figure 5-123: Counts for when VIND contributed O_3 was higher during an exceedance (note same scale as exceedance counts; to provide context of contribution)

Figure 5-124 shows a map of counts when NVIND (concentration of O_3 formed due to industry outside the VTAPA) were higher than VIND (concentration of O_3 formed due to industry inside the VTAPA) during an exceedance. Through the colour scale it is clear that NVIND plays a larger role (comparing only to VIND) in O_3 exceedances in all areas except those immediately around Sasolburg and Lethabo Power Station. For example, for VIND counts around Oranjeville are between 56 and 75 (light yellow), while for NVIND they are between 76 and 105 (light orange).

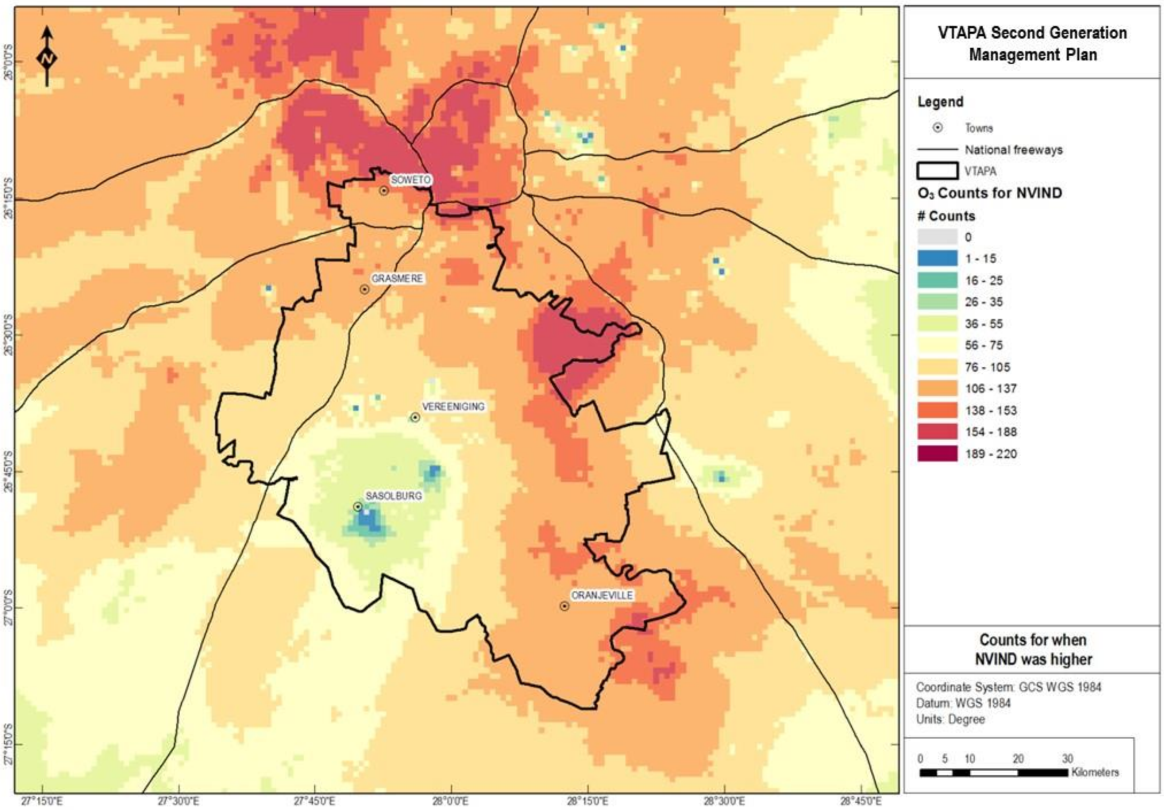


Figure 5-124: Counts for when NVIND O_3 was higher during an exceedance (note same scale as exceedance counts; to provide context of contribution)

5.4 VTAPA 2013 Health Study

A baseline health assessment study was conducted in the VTAPA during 2013 and 2014. The study comprised of a community survey in four communities within the priority area and a child respiratory health study (including lung function tests) in four schools within the community study areas, as well as an assessment of human health risks resulting from exposure to air pollution. The community survey and child health study took place in Diepkloof, Sebokeng, Sharpeville and Zamdela. The approach and results of each part of the study are summarised in the following sections.

5.4.1 Human Health Risk Assessment (HHRA)

The HHRA was performed using monitored ambient air quality data from DEA stations for 2013 to determine the potential for adverse effects to people in the VTAPA from exposure to the criteria air pollutants sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter with an aerodynamic diameter of 10 micrometre or less (PM_{10}). The population of concern was identified through estimating the sphere of influence of the stations using back trajectories. The sphere of influence around the air quality monitoring stations represented a specified area seen to be represented by the station's readings, i.e. where air will always pass over to reach the monitoring station. This was achieved by use of the US National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (NOAA ARL, 2010). Using HYSPLIT, 12 hour back-trajectories ending at each monitoring station were created for 2013. This was done to ascertain air flow to the stations representative of the evening and day (i.e. ending at 21:00 or 12:00 respectively).

A trajectory is composed of hourly endpoints during the air parcel's 12-hour journey to the station. A year of these trajectories will represent the general air flow possible during a year and will contain those endpoints. Using the end-points it was possible to deduce a radius by establishing endpoint frequency within a 0.25 degree (~25 km) resolution grid for various time periods, i.e. annual and seasonal. A region with 100% frequency meant that 100% of a station's trajectories pass over this region. This may be seen as the representative radius of influence of each station, since air will always pass over this area to get to a station (over a 12-hour period).

These radii of influence were then used to select Census 2011 sub-place regions around a station from which census data could be extracted and fed into the HHRA. Sub-place selection was done over two iterations. Firstly, sub-places were selected if their centroid fell within the radius. This selection yielded a very broad area, some of which fell outside the VTAPA. Then, since the radii did not follow legislative boundaries, the VTAPA boundary was used to constrain the selection to those within the priority area. The concentrations seen at the station would thus be representative of such an area. The HHRA was thus considered a worst-case scenario because the station with the highest concentration of a pollutant was considered as the station's sphere of influence for that sub-place.

The HHRA was done based on ambient concentrations of pollutants in relation to their respective National Ambient Air Quality Standards (NAAQS). The relationships between the pollutant concentrations and their respective benchmark values were used to derive Hazard Quotients (HQs) as an indication of the potential for developing adverse health effects. An HQ greater than 1 indicates that adverse health effects are likely while a HQ below 1 indicates that the potential for developing health effects is low.

5.4.1.1 Human health risks

The acute effects of exposure to SO_2 include upper respiratory irritation and bronchoconstriction, which will also exacerbate asthma. The results of the HHRA showed that it would be unlikely for people to experience these health effects from exposure at the concentrations measured during 2013.

The acute health effects of exposure to NO_2 include upper and lower respiratory symptoms (such as inflammation and exacerbation of asthma) and chronic effects are associated with an increase in the susceptibility of respiratory infections and a reduction in lung function growth. Based on 2013 data, the HHRA indicated a potential for acute effects in the communities within the Zamdela station's sphere of influence (Figure 5-125a). The communities most at risk of chronic health effects from exposure to NO_2 were those in the Diepkloof, monitoring stations' sphere of influence (Figure 5-125b).

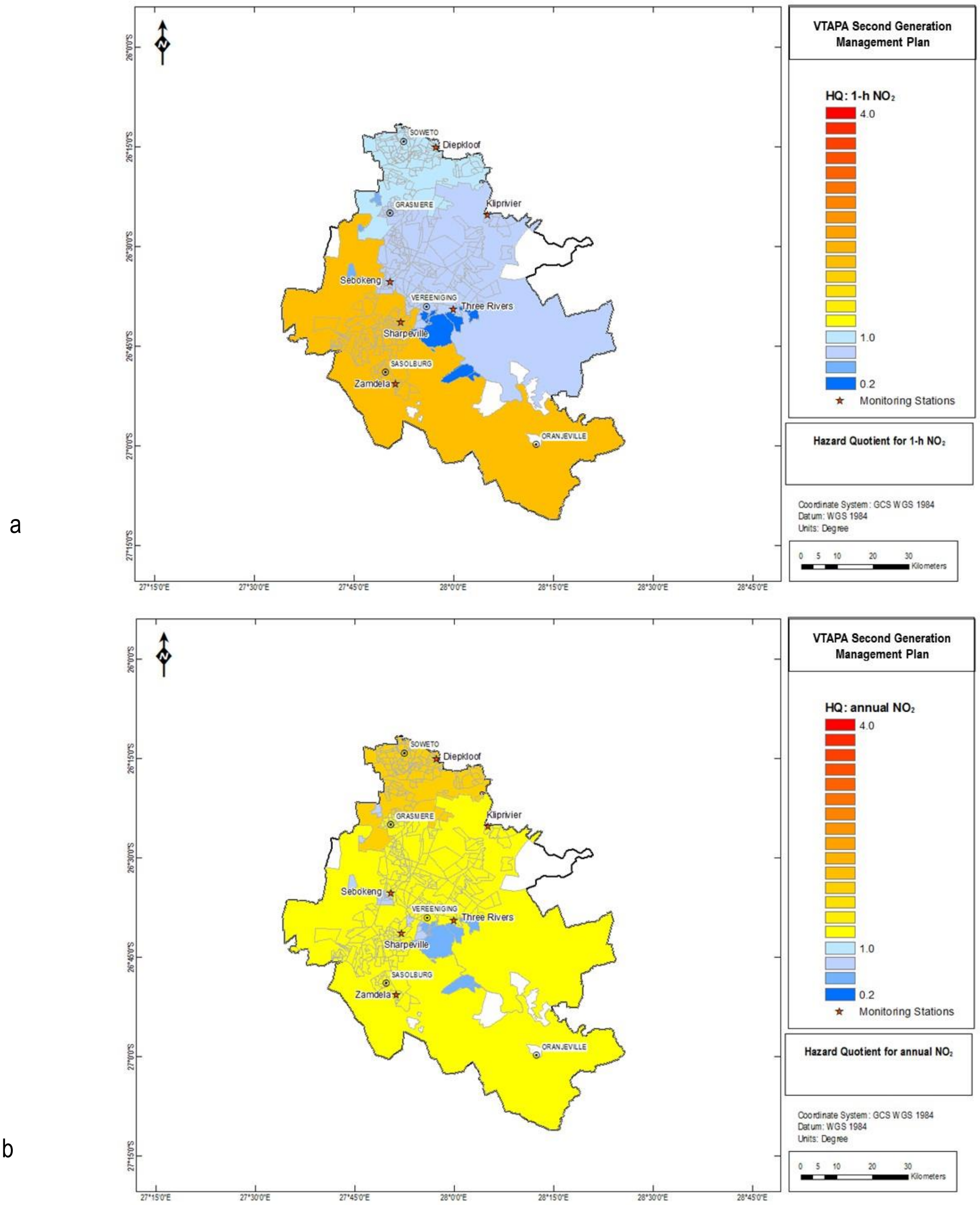


Figure 5-125: HQs for (a) 1-h NO_2 and (b) annual NO_2 in the communities of concern, considering the 99th percentile.

The health effects of particulate matter are related to the size (the smaller the particle the deeper it may penetrate into the lungs) and chemical composition of the particles. People with existing respiratory diseases such as asthma and or cardiovascular diseases will be more at risk of the exposure to particulate matter since it is believed that the detrimental effects are as a result of exacerbation of existing symptoms or progression of underlying illnesses (WHO, 2013). The whole of VTAPA may be considered to be potentially at risk of acute and chronic health effects due to exposure to particulate matter, except in the Diepkloof monitoring station's sphere of influence where the potential for adverse effects due to acute PM_{10} exposure was low (HQ<1). The communities most at risk were largely those within the Sharpeville and Zamdela spheres of influence and those west and north-west of the Sebokeng monitoring station (Figure 5-126).

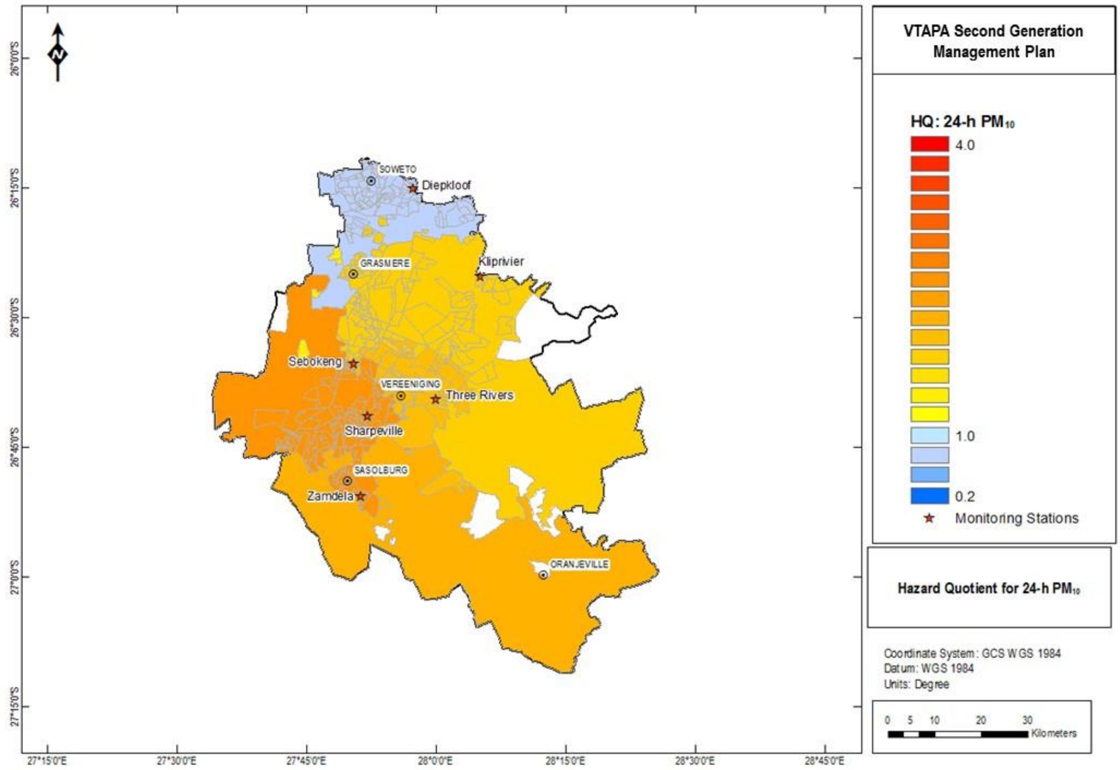


Figure 5-126. HQs for 24-h PM_{10} in the communities of concern, considering the 99th percentile.

5.4.2 Vulnerability

The vulnerability of these communities was assessed at the Census sub-place level by means of a "cumulative" human health risk, where, in addition to exposure to air pollution, factors affecting susceptibility and coping capacity of the communities were considered. Examples include age, existing illnesses and socio-economic conditions. These data were sourced from Census 2011 (StatsSA, 2011). The California Environmental Protection Agency (Cal-EPA)'s "Environmental Health Screening Tool Version 2" was used as guide to select relevant and readily available indicators of population characteristics and pollution burden.

5.4.2.1 Pollution burden

The pollution burden of each sub-place was represented by the HQs determined for the 99th percentile of the 24-hr PM_{10} concentrations (Figure 5-126). The 24-hr PM_{10} concentrations were chosen as a worst–case scenario, as most areas potentially at risk from exposure to air pollution were at risk due to the 24-hr PM_{10} concentrations.

5.4.2.2 Vulnerability Score

The vulnerability score for population characteristics for each sub-place in the VTAPA is presented in Figure 5-127a. These scores were normalised to the difference between the highest and lowest value in the domain, and thus are an indication of relative vulnerability. The most vulnerable communities are situated to the middle and north of the VTAPA. It must be noted that a score of 0 simply indicates that such a community is the least vulnerable in comparison to the other communities considered. The five sub-places ranked most vulnerable in this assessment, were the following (red in Figure 5-127a):

- Eikenhof
- Boiketlong
- Freedom Charter Square
- Kapok Informal
- Hopefield Informal

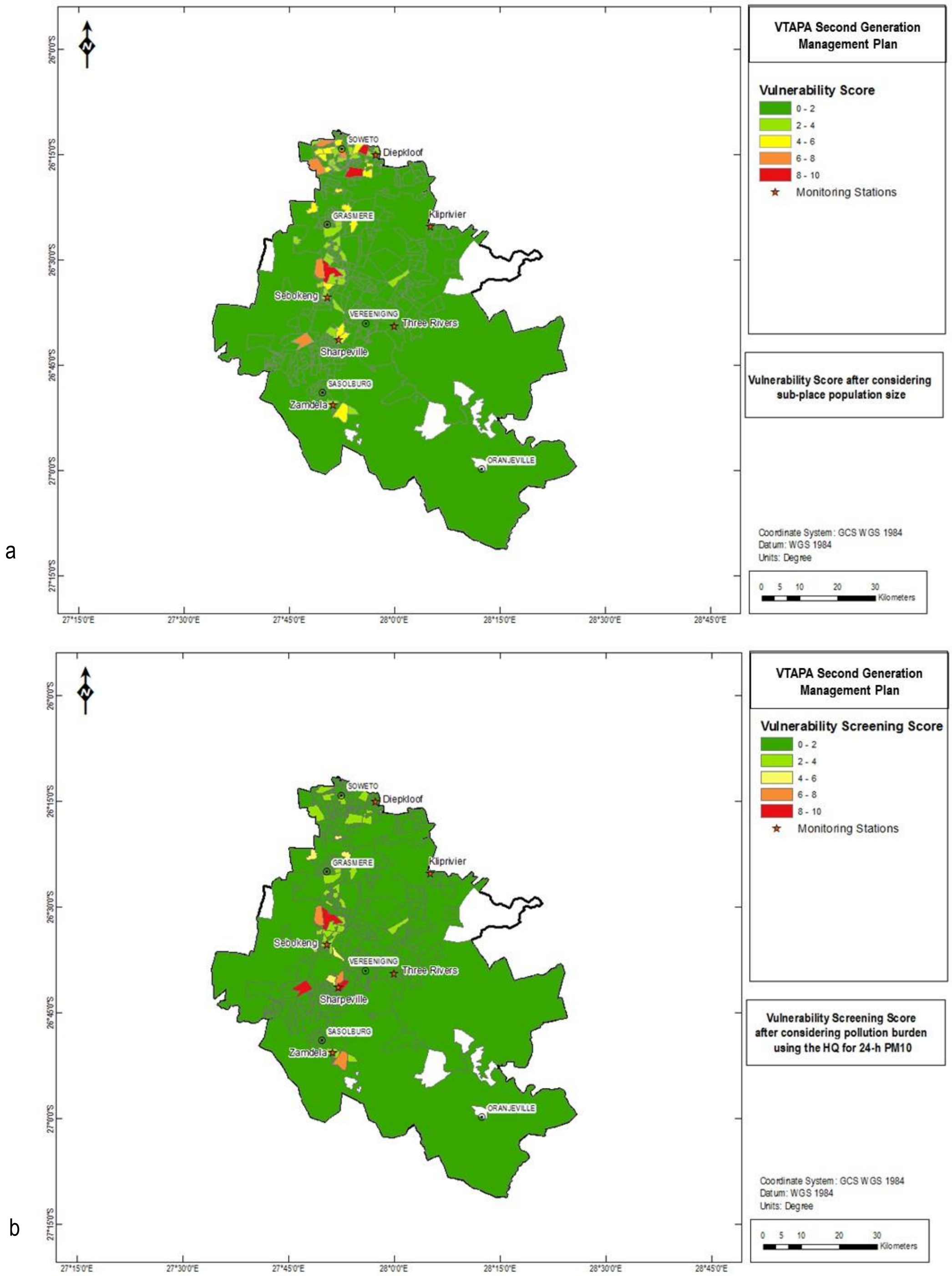


Figure 5-127: (a) Vulnerability Scores after considering population size (b) and Vulnerability Screening Scores after considering the pollution burden for the communities of concern.

It was found that the factors driving the vulnerability score for these sub-places were largely the type of dwelling and the energy carrier used for cooking and heating. Population size of each sub-place (using 2011 StatsSA data) also impacts on the score, which gives a vulnerable sub-place with a large population a higher score than a sub-place with the same vulnerability score but with a smaller population.

5.4.2.3 Vulnerability Screening Score

The score for the pollution burden for each sub-place was multiplied by the vulnerability score, to obtain a Vulnerability “Screening Score” (Figure 5-127b). From the figure, it is evident that the communities of main concern are those directly north and north-west of Evaton (north of the Sebokeng monitoring station), those directly north, north-east and north-west of the Sharpeville monitoring station and an area further west of this station (west of Vanderbijlpark) as well as an area south-east of the Zamdela monitoring station (south of Coalbrook).

The main vulnerable areas of concern as per the vulnerability screening score were those north of the Sebokeng and Sharpeville monitoring stations and south-east of the Zamdela monitoring station. These areas are more vulnerable because of two factors, i.e. (i) are experiencing a high pollution level while (ii) they are having a relatively high density of vulnerable population groups (children, elderly, low income earners etc.).

5.4.3 Community Study

The community study was a cross-sectional study and was conducted in four areas within a 3 km radius from the nearest air quality monitoring stations. A questionnaire was designed and administered to a total of 1 219 households; of which, 319 households were in Diepkloof, 337 in Sebokeng, 277 in Sharpeville, and 286 in Zamdela. Questions related to the household's experience of a set of chronic and acute illnesses that can be related to exposure to air pollution that any member of the household has experienced in the past weeks or year were included in the questionnaire.

The results showed a relatively low prevalence of reported respiratory illnesses - most respondents perceived their health and that of their household members to be good. The prevalence of bronchitis, pneumonia, lung infection, cancer and pus from ear were all below 1% and the prevalence of chronic cough and wheezing which was around 3%, implying that less than 5% of the study sample had these health effects. For acute health impacts (ear infection, sinusitis, runny nose and coughing), the prevalence was also less than 5%. The highest prevalence of asthma, e.g., was 1.4%, recorded in Zamdela. The 2011 General Household Survey found the asthma prevalence in South Africa to be 2.3%, with Asian/Indian people having the highest prevalence (4.8%), followed by whites with 3.1%. The prevalence among black Africans (the majority group of the current study) was lower at 1.9%. The same household survey found the prevalence of TB in South Africa to be 0.8% in 2011.

Sebokeng recorded the highest prevalence of symptoms experienced by individuals during the 12 months preceding the study survey, symptoms related to coughing and wheezing, as well as the most people (0.37%) who had been hospitalised for lung infection during the year preceding the study.

Very limited clinic data available for all four communities studied. The only respiratory related data available were for pneumonia in children below the age of 5 years. The highest was 1.3% of those children below 5 years who visited the clinic (n = 29 600) in Diepkloof in that year (2013).

5.4.4 Child Health Study

The child health study involved a medical survey among 290 Grade 3 and 4 children. Information gathering included parent-administered questionnaires about the living conditions of the children to identify other risk factors than air pollution (e.g. any individuals smoking in the house, rodents in the house, if the child had other illnesses etc.). These children were also given a lung function test on two occasions, including a summer (Phase I) and winter (Phase II) campaign to assess any changes in lung function as daily pollution concentration changes.

The pollutants, oxides of nitrogen (NOx), sulphur dioxide (SO_2) and particulate matter equal to or below 2.5 µm in aerodynamic diameter ($PM_{2.5}$), from schools near the Diepkloof, Sharpeville, Sebokeng and Zamdela stations were investigated in this study, using SAAQIS data. There were no data available from the Sebokeng monitoring station for the entire Phase I (10 to

28 March 2014). During Phase II, data for all three pollutants were missing for the Sharpeville and Zamdela stations for the period 4 to 9 June 2014 and half of 26 May 2014.

Concentrations for all pollutants measured were below NAAQS applicable during Phase I (10 to 28 March 2014). However, when considering the concentrations of PM_{10}, it was found that these exceeded the 24-hr NAAQS twice at Zamdela during this time.

Concentrations of pollutants were, in general, higher during Phase II (27 May to 10 June 2014). This is expected, due to climatic conditions and possibly more coal being burnt in winter. Although NO_2 and SO_2 did not exceed daily national ambient air quality standards during this period, particulate matter did (both $PM_{2.5}$ and PM_{10}) exceed between one and three times. To comply with NAAQS, the 24-hr average concentrations of the different pollutants are not allowed to exceed the NAAQS more than four times per year.

5.4.4.1 Health status of participating children

A high proportion (88%) of primary caregivers perceived the general health status of participating children to be good to excellent while 75% considered the children to be of normal weight. About 60% of participating children were not absent from school during the 12 months preceding the study, which may indicate that they were healthy.

Questionnaire findings indicate that the caregiver-reported prevalence of respiratory symptoms (i.e. chronic cough, chronic wheeze, chronic phlegm and shortness of breath, etc.) was low (ranging from 4.6% to 6.1%). The prevalence of doctor-diagnosed respiratory illnesses such as asthma (3.6%) was also considered to be low. However, when questions from the US National Asthma Education and Prevention Programme (NAEPP, 1991) were used to classify asthma as “any”, “mild intermitted”, “persistent” or “moderate to severe”, the prevalence of asthma was found to be 9.6%.

This difference between the prevalence of doctor-diagnosed asthma and symptoms-defined disease prevalence could imply that children are not accessing appropriate health care services for these symptoms, and thus not being diagnosed. Some families may rather seek help from other sources than health care professionals. This theory is strengthened by the fact that approximately 55% of caregivers reported not to have sought any health care for two years or more, which may imply that a number of participants are likely to have undiagnosed asthma.

The 2011 General National Household Survey found that the majority (78%) of the population surveyed had consulted a doctor or nurse when they were ill and those who did not were mostly young adults; the reason was that it was either not serious enough or they used self-medication. This may be an indication that illnesses and conditions, including symptoms of asthma, are often not considered serious enough to consult a doctor or nurse or people are using self-medication and only seek help when the situation is critical.

The study also established a link between air pollution and children’s’ acute health symptoms such as cough, tight chest and wheeze. The lung function tests showed significant declines in daily lung function (therefore poorer health) and increased odds/ chance of having negative respiratory symptoms in relation to fluctuations in the concentrations of the various pollutants.

Results showed that the probability of having certain respiratory illnesses when a child was from the selected primary school in Sharpeville was higher than that for children at any of the other schools. In addition, the parameters of lung function (FEV1 and FVC) were also lower at the Sharpeville primary school when compared to the other schools. No other school showed a similar reduction (therefore poorer health) in lung function outcomes.

5.5 VTAPA Source Apportionment Study

The VTAPA-Source Apportionment Study aims to apportion the contribution of sources to the overall PM_{10} and $PM_{2.5}$ loading in the VTAPA. The project components include,

- Ambient sampling
- Emission inventory update for use in source apportionment
- Source profile development
    - Collection of grab samples and re-suspension in laboratory chamber
    - Collection of PM samples
    - Chemical characterisation
- Laboratory analysis of ambient PM filter samples
    - Gravimetric
    - Chemical composition: XRF (for identification of inorganic elemental composition), Ion Chromatography, EC/OC for elemental and organic carbon
- Receptor modelling
    - Chemical Mass Balance modelling
    - Positive Matrix Factorization (PMF) and Principal Component Analysis (PCA)

Ambient filter samples for PM_{10} and $PM_{2.5}$ analysis were collected during the two intensive field campaigns. The summer campaign sampled 28 February – 21 March 2018 and the winter campaign sampled 20 June – 6 July 2018 in Sebokeng, Sharpeville, Kliprivier and Zamdela. Instrumentation to develop local source profiles were developed in this project; this includes a stack monitoring system to collect PM_{10} and $PM_{2.5}$ samples from point sources (e.g. industrial sources).

Preliminary results indicate that PM_{10} and $PM_{2.5}$ masses were higher in the winter at sampling sites compared to summer. Preliminary XRF analyses of the summer samples show inorganic content from crustal and anthropogenic activities.

A waste burning qualitative survey was conducted in Sharpeville 9-13 July 2018. This included scheduled walk-throughs in the community where the project team observed and recorded evidence of historic, potential, and active veld fires and waste burning. Dumped waste was also collected for further characterization. The initial data found (over the 5 days observing period):

- Of the active fires, 68% were domestic waste burning in a public place
- 296 observations of historical waste burning
- 229 potential waste burning sites
- 90 historical veld fires

These data highlight the large scale of local waste burning and veld fires in this community and reinforces the strong need for improved activity and emission factor data on burning.

In addition, through discussions with communities, the project team found local community-driven projects to clean up waste dumping sites. This highlights an example of the important opportunity to partner with communities in air quality improvement interventions.

6 MAIN FINDINGS AND THE WAY FORWARD

The objective of the baseline characterisation was two-fold: to determine the current state of air quality in the VTAPA, and to assess whether the interventions set by the 2009 VTAPA AQMP resulted in ambient air quality improvements, and if not, what the reason for this is. The main findings set out in this section are primarily based on the background assessment, the evaluation of ambient air quality in the VTAPA, the 2017 emission inventory and the associated dispersion modelling. These provided a good understanding of the current state of air quality within the VTAPA and to some extent, the source contributions to the ambient pollution levels. The results of the source apportionment study currently being conducted will allow for a more specific link between source and effect to allow for the identification of desired intervention strategies.

6.1 Geography and Demographics

The 2009 VTAPA AQMP study made use of the 2001 Census data, which indicated the population in the VTAPA to be 2 532 362 at the time. The current study made use of the 2011 Census data, which indicated a population growth of 12% over the 10-year period to 2 848 140, and the 2016 Community Survey statistics, which indicated a population of 3 127 907 implying a growth of 10% over five years. According to the census data, the only Local Municipalities within VTAPA with more than 10% of households using coal, wood or dung for cooking were Emfuleni (17.8%) and Metsimaholo (12.6%). Due to changes in the boundaries between the census years a quantitative comparison was not possible.

6.2 Regional Climate and Existing Ambient Air Quality

The DEA operates six ambient monitoring stations within the VTAPA, located at Diepkloof, Sharpeville, Three Rivers, Zamdela, Kliprivier and Sebokeng. These stations record meteorological parameters and ambient air quality concentrations for SO_2, NOx, PM_{10} and $PM_{2.5}$. Data was obtained from these stations for the period 2013-2015 to determine dispersion conditions and for the period 2007-2016 to assess ambient air quality trends. In addition, data from the three Sasol ambient monitoring stations was obtained for the same period as well as from the Eskom station and the four ArcelorMittal stations. The Sedibeng DM stations were not included since data was only available for one year (2017).

The main findings are:

- There was some variability in wind fields across the VTAPA monitoring stations, however a predominance of wind from the north-easterly and north-westerly sectors was evident at all stations, with possible exception of Eco Park, where a south-easterly flow was dominant. Winds exceeding 4 m/s were more frequently recorded at Sharpeville, Leitrim, and Eco Park. The Leitrim station recorded the fewest calm conditions (6%), while calm periods were most frequent at the AJ Jacobs station (30%).
- Long term trends, from 2007 to 2016, in SO_2 concentrations showed compliance with the NAAQSs at most of the stations for most of the time. Trends in SO_2 concentrations over the 10 years showed small decreases at Diepkloof, Zamdela, Randwater and Eco Park but slight increases over time at Kliprivier, Three Rivers and AJ Jacobs. Concentrations at Sebokeng, Sharpeville and Leitrim showed more annual variability and no distinct long-term trends.

  At AJ Jacobs a distinct pattern of contribution from the north-east was noted with two sources contributing at the Leitrim station, one to the north-west and one to the north-east of the station. At Kliprivier station the contribution was mostly from the south and at Sebokeng and Sharpeville it was from the south-east. North-east and easterly winds resulted in higher SO_2 concentrations at Diepkloof whereas north-east and southerly winds contributed to the Three Rivers station. The Zamdela station recorded elevated SO_2 concentrations from the north-east, north and north-west.

- Annual average NO_2 concentrations were non-compliant with the NAAQSs at Diepkloof (all the years except 2011), Kliprivier (2009 and 2010), Sebokeng (2015) and Sharpeville (2015). Hourly NO_2 concentrations were also non-compliant with NAAQS at Sebokeng in 2015, with the lowest concentrations recorded at the Randwater station. Monthly NO_2 concentrations have decreased slightly at the Leitrim station, while concentrations have increased at Diepkloof; Three Rivers; Zamdela; and AJ Jacobs stations. At the other stations the ambient NO_2 concentrations remained the same.

  Higher concentrations at Diepkloof were associated with winds from the north-east, south-west, and west during periods of higher wind speeds whereas strong winds from the west and north-west contributed to higher NO_2 concentrations at the Kliprivier station. NO_2 concentrations at the Sebokeng and Three Rivers stations persist mainly during low wind speeds. The Sharpeville station was influenced by stronger winds from the north-west, west and north-east while the Zamdela station recorded higher concentrations during winds from the north-west and north-east. NO_2 concentrations at the Randwater station were mostly during strong winds from the north-west, north-east and east-southeast. Most of the stations recorded NO_2 concentrations from all directions at low wind speeds. Observations from the stations located in high traffic areas with a strong contribution during low wind speeds were most likely from vehicular exhaust emissions.

- PM_{10} concentrations were in exceedance of the NAAQSs at most of the stations for most of years assessed except at Eco Park where annual PM_{10} had been compliant with NAAQS since establishment of the station. The highest concentrations were recorded at Zamdela.

  The stations of Kliprivier, Sebokeng, Three Rivers, Sharpeville, Zamdela, and to a lesser extent, Randwater and Diepkloof showed significant PM_{10} contributions at low wind speeds from all directions suggesting local contributing sources. During high wind speeds the contributing directions vary at the different stations, with winds from the northerly sector contributing mainly at the Diepkloof station and winds from the south-west at the Kliprivier station. The Sebokeng, Three Rivers and Sharpeville stations recorded elevated particulate concentrations from the northerly sector under strong winds. PM_{10} concentrations at Zamdela showed high concentrations from the west, north-west, north-east, east, and south. At the Eco Park station elevated PM_{10} concentrations were associated with northerly winds whereas winds from north and west contribute at AJ Jacobs station.

- Annual average $PM_{2.5}$ concentrations were in non-compliance with NAAQS, for most of the period assessed, except for AJ Jacobs where no annual exceedances were noted between 2014 and 2016. AJ Jacobs and Three Rivers had the lowest annual average concentrations whereas Leitrim, Sharpeville, Kliprivier, and Sebokeng had the highest. Annual average concentrations appeared to have decreased at Diepkloof and Sebokeng but monthly average $PM_{2.5}$ concentrations did not show substantive improvements with slight increases at Kliprivier, Sharpeville, Zamdela and AJ Jacobs stations.

  The stations of Diepkloof, Kliprivier, Sebokeng, Three Rivers, Sharpeville, Zamdela, and to a lesser extent Randwater had persistent $PM_{2.5}$ contributions at low wind speeds equally distributed in direction.

6.3 VTAPA Emissions

Emissions were quantified for all main sources within the VTAPA, as well as sources from the surrounding areas to form input into air quality modelling. The emission inventory reported on are for the sources within the VTAPA. These include:

- ***Industrial Sources***: sources of air pollutants represent mostly stationary facilities operating under licenses or registration where emissions are reported to the authorities annually (Section 21 and Section 23 sources). A total of 452 individual point sources were identified, across 117 facilities, in the VTAPA, mostly in the Emfuleni Local Municipality of which 40 facilities operate listed activities under Section 21 of NEM: AQA and 48 individual point sources are classified as Section 23 Controlled Emitters. Data reported on in NAEIS for the 2017 calendar year was used.

- ***Mining Sources***: including opencast and underground mines and quarries. Two open-cast mines (one dolomite and one coal) and one underground coal mine were identified. Activity data reported on in NAEIS for the calendar year 2017 was used.
- ***Mobile Sources***: accounting for vehicles traveling on arterial- and main roads, national freeway, secondary roads, slipways, off- and on ramps and streets. Use was made of SANRAL national counts for 2016 and GAUTRANS Gauteng Manual counts for 2015. A top-down and bottom-up approach was followed.
- ***Domestic Fuel Burning***: fuel combustion for energy use in the domestic environment in VTAPA. Both a top-down (for gas, paraffin and coal) and bottom-up (for wood) approach was used for domestic fuel use emissions. Community Survey 2016 and Census 2011 data were used to proportionally disaggregate national fuel consumption to provincial and then SAL geographic units.
- ***Waste***: open burning in residential areas were quantified based on available information (no information was available on landfills and waste water treatment facilities to quantify these emissions).
- ***Windblown Dust***: from mine waste facilities, product stockpiles, as well as ash storage facilities for large combustion sources. Windblown dust from denuded areas were not included.
- ***Biogenic VOC Emission***: plants emitting numerous VOC compounds, primarily isoprene, due to stress responses were included due to the important role in the atmospheric chemistry.
- ***Biomass Burning***: large scale agricultural burning and natural fires. FINN data was extracted for the year 2016 and processed, with erroneous fires due to surface coal mines removed.
- ***Airfields:*** there are no major commercial airports within the VTAPA and the occasional use of airstrips in the area were not regarded to result in significant emissions.
- ***Agriculture***: including mainly for its contribution to ammonia emissions used in the dispersion model.

6.3.1 Synopsis of VTAPA Emissions

Emissions from the various sources identified and quantified in the VTAPA are provided in

Table 6-1 and in Figure 6-1. Based on the quantified emissions, industrial sources were the main contributors of SO_2 (99.8%) and NOx (93%) emissions within the VTAPA. Mobile sources were the only other significant contributors to NOx emissions at 7%. Total PM_{10} emissions were mainly a result of mining operations (49%) followed by industrial sources (31%), with windblown dust the third most significant contributing source group at 16%. For the sources for which $PM_{2.5}$ emissions were reported and/or quantified, mining was the main contributing source (39%) followed by windblown dust (33%) and domestic fuel burning (17%). CO emissions were a result of domestic fuel burning (28%), mobile sources (27%), biomass burning (26%) and industrial sources (19%). Biogenic VOC emissions were unsurprisingly the main contributor to NMVOC emissions followed by biomass burning. Ammonia emission (NH_3) sources were mainly (soil) biogenic, with contributions from agriculture (87%) and to a lesser extent mobile sources (11%).

Table 6-1: Emissions from the various source groups in VTAPA (tonnes per annum)

	SO_2	NOx	PM_{10}	$PM_{2.5}$	CO	NMVOC	NH_3
Industrial Sources	232 669	118 459	16 808	256	6 761	830	70
Mining Sources	-	-	26 586	2 921	-	-	-
Mobile Sources	251	8 299	245	-	9 635	967	493
Domestic Fuel Burning	261	184	1 310(a)	1 242	9 982	1 404	0
Waste	12	90	287	-	-	544	27
Windblown Dust	-	-	8 444	2 449	-	-	-
Biogenic VOC Emissions	-	-	-	-	-	9 727	-
Biomass Burning	44	589	729(a)	589	9 359	4 057	-
Agriculture	-	-	-	-	-	-	3 890
TOTAL	**233 237**	**127 621**	**54 409**	**7 456**	**35 737**	**17 529**	**4 480**

Note:

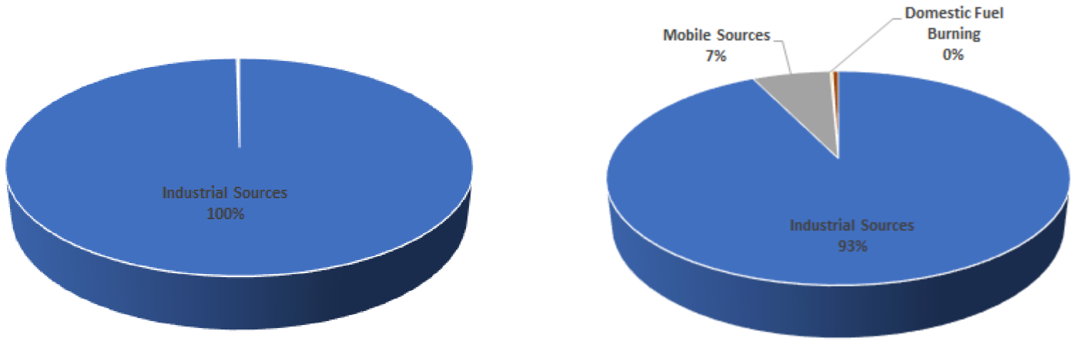
(a) PM_{10} represents only the coarse fraction (i.e. PM with diameter 2.5 µm to 10 µm)

Compared to the 2009 and 2013 medium-term review inventories, the total emissions within the VTAPA remained similar for SO_2 but reduced significantly for NOx (Table 6-2). This is primarily a result of lower estimated mobile source emissions and domestic fuel burning emissions. PM_{10} emissions increased from the 2009 and 2013 inventories mainly due to the high PM_{10} emissions reported for the opencast coal mine. Industrial PM_{10} emissions reduced from the 2009 VTAPA, and even though the cause of this reduction is not clear, it could be an actual reduction in industrial PM_{10} emissions since the 2017 emission inventory is regarded more comprehensive than the one for 2009.

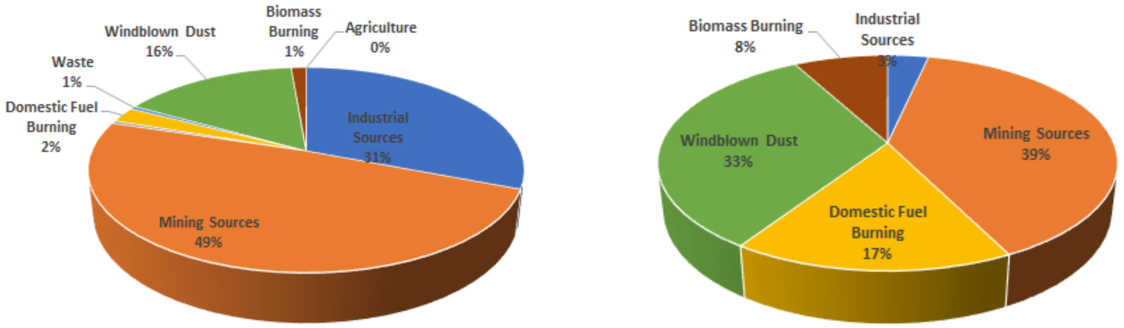
Table 6-2: Medium-term VTAPA AQMP review versus 2018 VTAPA AQMP total emissions (tpa)

	SO_2	NOx	PM_{10}
2009 AQMP	221 361	188 640	37 033
2013 Medium-term review	248 583	149 748	22 743
2018 VTAPA AQMP	233 237	127 621	54 404^(a)^

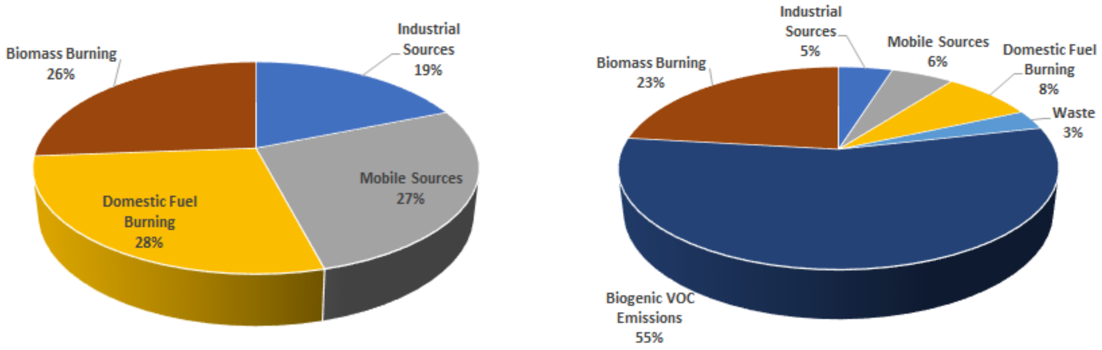
Notes: (a) Excluding Section 21 Category 5 sources (Mineral Processing, Storage and Handling) tile factories



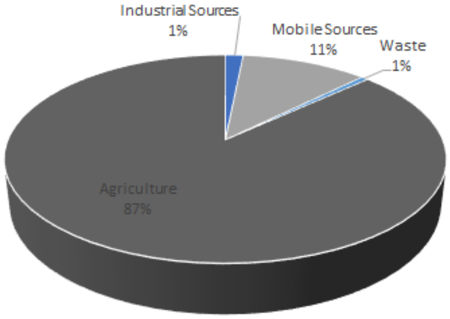
(a) SO_2 (b) NOx



(c) PM_{10} (d) $PM_{2.5}$



(e) CO (f) NMVOC



(g) NH_3

Figure 6-1: Source contributions to the total emissions for (a) SO_2; (b) NOx; (c) PM_{10}; (d) $PM_{2.5}$; (e) CO; (f) NMVOC and (g) NH_3

6.4 Dispersion Model

The aim of air quality modelling within the context of a baseline assessment was to simulate current ambient concentrations of pollutants within the VTAPA to assess ambient air quality on a more comprehensive spatial scale than what can be provided with monitoring stations. Areas of elevated concentrations can be identified for expanded monitoring; and when viewed within the context of the emission inventory, likely contributing sources targeted for intervention strategies. Through the use of source tracking features in the model, it was also possible to quantify relative contribution between tracked sources.

CAMx, a chemical air quality model, was used to simulate baseline ambient air quality. A regional 3 km resolution modelling domain aimed to capture Highveld regional sources that may impact in the VTAPA, while a finer resolution 1 km domain over VTAPA aimed to simulate ambient air quality in more detail.

6.4.1 Summary of findings

The primary aim of air quality modelling in this AQMP was to assess ambient air quality in the VTAPA on a more comprehensive spatial scale than what can be provided with monitoring stations and provide directed source tracking analyses. The CAMx air quality model was run to aid in the baseline assessment of the VTAPA. To this end a comprehensive emission inventory was developed for both management purposes and as input into the air quality model. The WRF meteorological model was also used to simulate the necessary meteorological parameters that form additional input to the air quality model. A comparison of model output to measurements from monitoring stations was done to ascertain performance. The comparison took the form of both statistics and time-series plots. For source tracking, two groups were tracked; industry located within the VTAPA and those outside. Source tracking output was analysed for O_3 and PM_{10} impacts.

Concentrations of PM_{10} were in general under-estimated by, looking at hourly data, between 32% (at Sebokeng) and 71% (Kliprivier). This was primarily due to the potential impact of much localized sources near stations. High exceedances (for both 24hr and annual averages) were still simulated. The majority of these were in close proximity to industrial facilities, mines and the old tailings areas in CoJ. Exceedances were also simulated in northern VTAPA, located around high emitting residential fuel combustion areas. $PM_{2.5}$ results were also in general under-estimated where monitoring data was good enough for a comparison, although performance was better than for PM_{10}. Under-estimation ranged from as low as 14% (at Randwater) to 50% (at Sebokeng). Even though $PM_{2.5}$ was under-estimated, a majority of the VTAPA was simulated to be in exceedance of the 24hr NAAQS for $PM_{2.5}$. However, for the annual mean, the exceedance levels were seen to be more limited to the immediate vicinity of mines, tailings facilities and areas of heavy domestic fuel combustion. The model did not simulate annual exceedances measured at Sebokeng and Three Rivers. Elevated $PM_{2.5}$ concentrations measured during hours between ~21:00 - ~05:00 (i.e. very late evening and very early morning) were not simulated by the model. This may be related to the over-estimate in wind speed.

The over-estimate in wind speed also resulted in over-estimate of SO_2; since in the model the tall stack impacts tend to dominate due to enhanced turbulence. However, this did not impact the ability of the model to simulate areas of exceedance (or lack thereof according to the monitoring data, when the monitoring data was of good quality). The exception to this is at the Rand Water location, where the model simulated an exceedance of the annual mean while the monitoring data (relatively good quality and completeness) did not show an exceedance. In general exceedances were seen around Lethabo power-station and Sasolburg.

Performance of NO_2 and O_3 simulations were good; particularly for O_3. For NO_2 the highest under-estimate was at Diepkloof, as the model did not capture micro-scale emissions activity on roads around the monitoring station. On the other hand, at AJ Jacobs, over-estimates were due to enhanced turbulence leading to Lethabo power-station and Sasol Sasolburg plumes impacting ground concentrations. In general, the model simulated the lack of exceedances seen in the monitoring data; the only exception being at Diepkloof for the annual mean. The model simulated highest (though not necessarily in exceedance) concentrations around Sasolburg. For O_3 the modelled concentrations resulted in 8-hr NAAQS exceedances over the majority of the VTAPA. There is a zone of titration around Sasolburg where concentrations were simulated to be lower.

The air quality model simulations indicated widespread exceedances of O_3 and PM over the majority of the VTAPA. Exceedances were seen for short-term/acute time scale periods (24-hr and 8-hr running) indicating high variability and magnitude.

In terms of source tracking it must be noted that only two industry groups were tracked; and therefor results were only relative to industry contribution. It is possible that other sources could play a significant role in actual ambient exceedances for a given time and place. PM_{10}, impacts within VTAPA were primarily due to industry within VTAPA; which was expected since PM_{10} concentrations were generally highest immediately around sources. For O_3 it was more complex since highest concentrations may be found near the sources if NO emissions are low, or further downwind if NO emissions are high. Thus, there is a regional aspect to O_3 formation when related to the precursor contributing sources. For the VTAPA there was a mix of contribution from local industry and those outside. However simulations indicated that industry outside the VTAPA plays a larger role in O_3 formation than within the VTAPA.

6.5 Conclusions from the VTAPA Health Study

A baseline health assessment study was conducted in the VTAPA during 2013 and 2014. The study comprised of a community survey in four communities within the priority area and a child respiratory health study (including lung function tests) in four schools within the community study areas, as well as an assessment of human health risks resulting from exposure to air pollution.

The main findings of the study may be summarised as follows:

- Given the ambient concentrations measured at DEA/SAWS stations in 2013, no risk from SO_2 was found. NO_2 was estimated to pose a health risk in Zamdela. The risk to health from exposure to particulate matter (PM_{10}) was found to be s more of a concern than the risk from exposure to SO_2 and NO_2. Sharpeville in particular recorded the highest concentrations of PM_{10} during 2013.
- From the community survey, risk factors for respiratory illnesses were mostly associated with energy use (coal for cooking and paraffin for heating), overcrowding and hygiene practices (burning or burying of refuse or failure to regularly remove refuse) as well as lifestyle (active and passive smoking and alcohol use).
- The main conditions affecting vulnerability of areas to the effects of air pollution involved socio-economic conditions and energy use. The main vulnerable areas of concern were north of the Sebokeng and Sharpeville monitoring stations and south-east of the Zamdela monitoring station.
- Although the socio-economic conditions and exposure at the schools were similar, the odds of having chronic symptoms (such as cough, wheeze and phlegm and asthma) were significantly higher at the school in Sharpeville. Pollutant concentrations at the Sharpeville monitoring station were also consistently among the highest.

Significant declines in daily lung function (therefore poorer respiratory health) and an increased chance of having negative respiratory symptoms were associated with changes in the concentrations of the various pollutants. Given that these adverse respiratory outcomes were observed within the context of some pollution levels complying with the national ambient air quality standards, there is reason for concern that air pollution in the VTAPA may be affecting child health.

6.6 Preliminary findings on the VTAPA Source Apportionment Study

The VTAPA Source Apportionment Study aims to apportion the contribution of sources to the overall PM_{10} and $PM_{2.5}$ loading in the VTAPA.

Preliminary results indicated that PM_{10} and $PM_{2.5}$ mass were higher in the winter at sampling sites compared to summer. Preliminary XRF analyses of the summer samples showed inorganic content from crustal and anthropogenic activities.

A qualitative waste burning survey conducted in Sharpeville highlighted the large scale of local waste burning and veld fires in this community and reinforces the strong need for improved activity and emission factor data on burning.

6.7 Way Forward

The VTAPA Source Apportionment study is currently being conducted with results expected by the end of February 2019. These results, as indicated, will be integrated into the baseline assessment to inform the cause and effect relationship.

In parallel to the Source Apportionment study, the GAINS model will be run for a set of intervention scenarios. These scenarios are based on the same emission inventory used in this study. Up to three scenarios were selected for the following source groups:

- Industry
- Mobile sources
- Domestic Fuel Burning
- Waste Burning
- Windblown sources
- Biomass Burning

These results are also expected to be available by the end of February 2019. The aim with the GAINS model intervention scenarios is that it will provide an indication of the expected air quality improvement associated with a specific intervention, as well as the cost benefit thereof. This will allow for a selection of feasible interventions likely to result in the greatest air quality benefit. These selected interventions will then be modelled using the VTAPA CAMx model.

The strategy analysis will be conducted during a workshop once the preferred interventions have been identified. The outcome will be action plans for implementation within a set timeframe.

7 REFERENCES

Akagi, S., Yokelson, R., Burling, I., Meinardi, S., Simpson, I., Blake, D., . . . Weise, D. (2013). easurements of reactive trace gases and variable O3 formation rates in some South Carolina biomass burning plumes. *Atmos. Chem. Phys., 13*, 1141-1165.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., . . . Winiwarter, W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modeling & Software, 26*, 1489-1501.

Anyamba, A., Justice, C., Tucker, C., & Mahoney, R. (2003). Seasonal to interannual variability of vegetation and fires at SAFARI 2000 sites inferred from advanced very high resolution radiometer time series data. *J. Geophys. Res., 108*(D13), 8507. doi:10.1029/2002JD002464

Balk, D., Deichman, U., Yetman, G., Pozzi, F., Hay, S., & Nelson, A. (2006). Determining global population distributions: Methods, applications and data. *Adv Parasitol., 62*, 119-156.

Ballard-Tremeer, G. (1997). *Emissions of Rural Wood-Burning Cooking Devices. PhD Thesis (Engineering).* Johannesburg: University of the Witwatersrand.

Britton, M. (1998). *Low Smoke Fuel Programme: Laboratory Technical Tests, Determination of Emission Factors. .* Pretoria: Department of Minerals and Energy, Report No ES9606.

Brunner, D., Nicholas Savage, Oriol Jorba, Brian Eder, Lea Giordano, Alba Badia, Alessandra Balzarini, Rocío Baró, Roberto Bianconi, Charles Chemel, Gabriele Curci, Renate Forkel, Pedro Jiménez-Guerrero, Marcus Hirtl, Alma Hodzic, Luka Honzak, Ulas Im, Christoph Knote, Paul Makar, Astrid Manders-Groot, Erik van Meijgaard, Lucy Neal, Juan L. Pérez, Guido Pirovano, Roberto San Jose, Wolfram Schröder, Ranjeet S. Sokhi, Dimiter Syrakov, Alfreida Torian, Paolo Tuccella, Johannes Werhahn, Ralf Wolke, Khairunnisa Yahya, Rahela Zabkar, Yang Zhang, Christian Hogrefe, Stefano Galmarini. (2015) Comparative analysis of meteorological performance of coupled chemistry-meteorology models in the context of AQMEII phase 2. Atmospheric Environment, Volume 115, 2015,Pages 470-498, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2014.12.032.

Burger, L. (2010). Complexities in the Estimation of Emissions and Impacts of Wind generated fugitive dust. *Proceedings of the National Association for Clean Air Conference, Polokwane 13 – 15 October 2010.* Polokwane: National Association for Clean Air.

Burger, L., Held, G., & Snow, N. (1997). *Ash Dump Dispersion Modeling Sensitivity Analysis of Meteorological and Ash Dump Parameters.* Cleveland: Eskom Report TRR/S95/077.

Cal-EPA Draft California Communities Environmental Health Screening Tool Version 2. (CalEnviroScreen 2**)**. Available: http://oehha.ca.gov/ej/pdf/CES20PublicReview04212014.pdf (Accessed July 2014)

Carslaw, D. (2015). *The openair manual - open-source tools for analysing air pollution data. Manual for version 1.1-4.* King's College London.

Carslaw, D., & Ropkins, K. (2012). openair - an R package for air quality data analysis. *Environmental Modelling and Software, 27-28*, 52 - 61.

Carter, W. (2000). *Implementation of the SAPRCC-99 Chemical Mechanism into the Models-3 Framework. Report to the United States Environmental Protection Agency.* Retrieved 11 22, 2017, from http://www.cert.ucr.edu/%7Ecarter/absts.htm#s99mod3

Committee of Transport Officials. (2012). *TRH 26: South African Road Classification and Access Management Manual, version 1.0.* Roads Coordinating Body of the Committee of Transport Officials, South African National Roads Agency Limited. Retrieved 01 12, 2018, from at http://www.roadclass.co.za/wp-content/uploads/2014/02/TRH26-RCAM.pdf

Demuynck, J., Bosteels, D., De Paepe, M., Favre, C., May, J., and Verhelst, S. (2012). Recommendations for the new WLTP cycle based on an analysis of vehicle emission measurements on NEDC and CADC, Energy Policy 49 (2012) pp234–242, 2012, doi: 10.1016/j.enpol.2012.05.081.

DEA, (2009). Vaal Triangle Airshed Priority Area Air Quality Management Plan. Report compiled by: Airshed Planning Professionals (Pty) Ltd and Gondwana Environmental Solutions (Pty) Ltd, March 2009 on behalf of the Department of Environmental Affairs and Tourism, Environmental Quality and Protection, Chief Directorate: Air Quality Management and Climate Change.

DEA, (2013). The Medium Term Review of the 2009 Vaal Triangle Airshed Priority Area Air Quality Management Plan. Final Review Report. Report compiled by: Escience Associates Consulted (Pty) Ltd, June 2013 on behalf of the Department of Environmental Affairs Climate Change and Air Quality Chief Directorate: Air Quality Management.

DOE. (2014). *Commodity flows and energy balances for 2014.* . Department of Energy, South Africa. Retrieved 12 21, 2017, from (http://www.energy.gov.za/files/media/explained/Native_units/2014-Native-Units.xlsx).

Emmons, L. K., Walters, S., Hess, P. G., Lamarque, J.-F., Pfister, G. G., Fillmore, D., Granier, C., Guenther, A., Kinnison, D., Laepple, T., Orlando, J., Tie, X., Tyndall, G., Wiedinmyer, C., Baughcum, S. L., and Kloster, S. (2010). Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4), Geosci. Model Dev., 3, 43-67, doi:10.5194/gmd-3-43-2010, 2010.

European Environment Agency. (2013). *EMEP/EEA air pollutant emission inventory guidebook 2013: Technical guidance to prepare national emissions inventories. Part B: sectoral guidance chapters, Section 1.A.3.b.i-iv Exhaust emissions from road transport.* Luxemborg: Publications Office of the European Union. Retrieved 12 21, 2017, from http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport

Formenti, P., W. Elbert, W. Maenhaut, J. Haywood, S. Osborne , & M. O. Andreae. (2003). Inorganic and carbonaceous aerosols during the Southern African Regional Science Initiative (SAFARI 2000) experiment. *Chemical characteristics, physical properties, and emission data for smoke from African biomass burning, 108*(D13), 8488.

GEA. (2012). *Global Energy Assessment: Toward a Sustainable Future.* UK: Cambridge University Press.

Giglio, L. (2007). Characterization of the tropical diurnal fire cycle using VIRS and MODIS observations. *Remote Sensing of Environment, 108*, 407-421.

Guenther, A., Karl, T, Harley, P, Wiedinmyer, C, Palmer. P.I, & Geron, C. (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics, 6*, 3181–3210.

Hahmann, A. N., Lennard, C., Badger, J., Vincent, C. L., Kelly, M. C., Volker, P. J. H., ... Refslund, J. (2015). Mesoscale modeling for the Wind Atlas of South Africa (WASA) project. Technical University of Denmark (DTU) Wind Energy. (DTU Wind Energy E; No. 0050 (updated))

Hély, C., K. Caylor, S. Alleaume, R. J. Swap , & H. H. Shugart. (2003). Release of gaseous and particulate carbonaceous compounds from biomass burning during the SAFARI 2000 dry season field campaign. *J. Geophys. Res, 108*(D13), 8470.

IPCC. (2006). Country-Specific Number of MSW, Annex 2A.1 from Chapter 2: Waste Generation, Composition and Management Data. *IPCC Guidelines for National Greenhouse Inventories, 5*. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html

Jeffares and Green (Pty) Ltd. (2016). The Diversion of Municipal Solid Waste Away from Landfills In 6 South African Municipalities, Waste Analysis and Composition Survey (Report). Climate Support Programme - Waste Management Flagship, Commissioned by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Email: emeryr@jgi.co.za.

Jiang, X., C. Wiedinmyer, & A.G. Carlton. (2012). Aerosols from fires: an examination of the effects on ozone photochemistry. *Environmental Science & Technology, 46*(21), 442-460. doi:10.1021/es301541k

Kaoma, H., & Shackleton, C.M. (2015). The direct-use value of urban tree non-timber forest products to household income in poorer suburbs in South African towns. *Forest Policy and Economics, 61*, 104-112. doi:org/10.1016/j.forpol.2015.08.005

Klimont, Z., Smith, S.J, & Cofala, J. (2013). *The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions.* Environmental Research Letters. doi:org/10.1088/1748-9326/8/1/014003

Kornelius, G., de Jager, C, & Kariyatty, P. G. (2015). Fuel from invader species for domestic gasification stoves: Processing and emission factors. *National Association for Clean Air Conference, October 2015.* Bloemfontein, South Africa.

Lamarque, J.-F. (2010). Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols. *Methodology and application. Atmospheric Chemistry and Physics, 10*(2), 7017–7039. doi:10.5194/acp-10-7017-2010

Liebenberg-Enslin, H. (2014). *A Functional Dependence Analysis of Wind Erosion Modelling System Parameters to Determine a Practical Approach for Wind Erosion Assessments. PhD Thesis.* Johannesburg: University of Johannesburg. .

Makonese, T., Masekameni, D. M, Annegarn, H. J, & Forbes, P. B. (2015). Influence of fire-ignition methods and stove ventilation rates on gaseous and particle emissions from residential coal braziers. *Journal of Energy in Southern Africa, 26*(4), 16-25.

Marticorena, B., & Bergametti, G. (1995). Modelling the Atmospheric Dust Cycle 1 Design of a Soil-Derived Dust Emission Scheme. *Journal of Geophysical Research, 100*, 16415-16430.

Merven, B., Stone, A, Hughes, A, & Cohen, B. (2012). *Quantifying the energy needs of the transport sector for South Africa: A bottom-up model.* South African National Energy Development Institute (SANEDI). Cape Town: Energy Research Cente, University of Cape Town.

National Asthma Education and Prevention Program (NAEPP). 1991. Expert Panel Report: Guidelines for the Diagnosis and Management of Asthma. National Institutes of Health, Bethesda, MD.

Ngan, F., Kim, H., Lee, P., Al-Wali, K. and Dornblaser, B. (2013). A Study of Nocturnal Surface Wind Speed Overprediction by the WRF-ARW Model in Southeastern Texas. Journal of Applied Meteorology and Climatology, Volume 52, pp 2638-2653. DOI: 10.1175/JAMC-D-13-060.1.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E. (2011). NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Dataset. Available at: http://dx.doi.org/10.5065/D61C1TXF. Article available at: https://doi.org/10.1175/JCLI-D-12-00823.1 (Last accessed 12/12/2017).

Scheepers, J. (2013). *Energy sources of the Bela-Bela township and the impacts of their usage on the environment. Short dissertation for the degree Magister Artium in Environmental Management.* Johannesburg, South Africa: Faculty of Humanities, University of Johannesburg.

Schroeder, W., Oliva, P, Giglio, L, Quayle, B, Lorenz, E, & Morelli, F. (2016). Active fire detection using Landsat-8/OLI data. *Remote Sensing of the Environment, 185*, 210-220. doi:org/10.1016/j.rse.2015.08.032

Schulze, R. (1986). *Climate of South Africa. Part 8: General Survey, WB28.* Pretoria, RSA: South African Weather Bureau.

Schutze, R. E., & Lynch, S. D. (2007). Monthly Rainfall and its Inter-Annual Variability. In R. (. Schulze, *South African Atlas of Climatology and Agrohydrology, WRC Report 1489/1/06, Section 6.6.* Pretoria, RSA: Water Research Commission.

Scorgie, Y., Annegarn, H.J, & Burger, L.W. (2004). *Fund for research into industrial development growth and equity (FRIDGE). Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion.* Pretoria, South Africa: Trade and Industry Chamber.

Silverman, D. S. (2012). The Diesel Exhaust in Miners Study: A Nested Case–Control Study of Lung Cancer and Diesel Exhaust. *Journal of the National Cancer Institute, 104*(11), 855–868. doi:org/10.1093/jnci/djs034

Simon, H., Beck, L., Bhave, P.V., Divita, F., Hsu, Y., Luecken, D., Mobley, J.D., Pouliot, G.A., Reff, A., Sarwar, G. and Strum, M. (2010). The development and uses of EPA's SPECIATE database. Atmospheric Pollution Research 1 (2010) 196-206. doi: 10.5094/APR.2010.026.

Stats SA. (2013). *National Household Travel Survey, 2013. Statistics South Africa.* Pretoria, South Africa: Stats SA Nesstar portal. Retrieved from http://interactive.statssa.gov.za:8282/webview

StatsSA. (2011). *Census 2011.* Pretoria: StatsSA. Retrieved 12 20, 2017, from http://www.statssa.gov.za/?page_id=3839

Stone, A. (2000). *South African Vehicle Emissions Project: Phase II, Final Report: Diesel Vehicles.* Department of Mineral & Energy Affairs unpublished report accessed with permission of VEP project manager. Retrieved 02 2000

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H. and Yarber, K.F. (2003). An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. Atmos., 108 (2003).

South African Air Quality Information System (SAAQIS). 2014. Available: (http://www.saaqis.org.za/NAAQM.aspx) (Accessed August 2015)

South African General Household Survey. 2011. Available: http://beta2.statssa.gov.za/publications/P0318/P03182011.pdf (Accessed August 2015)

Tsiakmakis, S., Ciuffo, B., Fontaras, G., Cubito, C., Pavlovic, J., and Anagnostopoulos, K. (2017) From NEDC to WLTP: effect on the type-approval CO_2 emissions of light duty vehicles, EUR 28724 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-71642-3, doi:10.2760/93419, JRC107662.

Turner, D., Chico, T, & Catalano, A. (1986). *TUPOS: A Multiple Source Gaussian Dispersion Algorithm Using On-Site Turbulence Data.* Research Triangle Park, North Carolina: U.S. Environmental Protection Agency.

University of East Anglia Climatic Research Unit; Harris, I.C.; Jones, P.D. (2017): CRU TS4.01: Climatic Research Unit (CRU) Time-Series (TS) version 4.01 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2016). Centre for Environmental Data Analysis, 04 December 2017. doi:10.5285/58a8802721c94c66ae45c3baa4d814d0. http://dx.doi.org/10.5285/58a8802721c94c66ae45c3baa4d814d0

US EPA United States Environmental Protection Agency. (2009). Risk and Exposure Assessment to Support the Review of the SO2 National Ambient Air Quality Standards: Final Report. Available: http://www.epa.gov/ttn/naaqs/standards/so2/data/200908SO2REAFinalReport.pdf (Accessed August 2014).

US EPA. (2004). *Review of Ammonia Emission Modeling Techniques for Natural Landscapes and Fertilized Soils.* EC/R Incorporated. EPA Contract no. 68-D02-064.

Val Martin, M., Heald, C. L, Ford, B, Prenni, A. J, & Wiedinmyer, C. (2013). A decadal satellite analysis of the origins and impacts of smoke in Colorado. *Atmos. Chem. Phys, 13*, 7429-7439. doi:10.5194/acp-13-7429-2013

Veefkind, P. (2012). OMI/Aura Ozone (O3) DOAS Total Column L3 1 day 0.25 degree x 0.25 degree V3, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC). Accessed 30/11/2017. 10.5067/Aura/OMI/DATA3005.

Western Regional Air Partnership. (2005). *2002 Fire emission inventory for the WRAP Region—Phase II.* Western Governors Association/Western Regional Air Partnership.

WHO. (2012).). *International Agency for Research on Cancer: Diesel engine exhaust carcinogenic.* Retrieved 02 01, 2018, from https://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf

Wiedinmyer, C., S.K. Akagi, R.J. Yokelson, L.K. Emmons, J.A. Al-Saadi, J.J. Orlando, & A.J. Soja. (2011). The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning. *Geoscientific Model Development, 4*, 625-641.

Wiedinmyer, C., Yokelson, R.J, & Gullett, B.K. (2014). Global emissions of trace gases, particulate matter and hazardous air pollutants from open burning of domestic waste, ES&T, 48. *Environ. Sci. Technol.,, 48*(16), 9523-9530. doi:Dx/doi.org/10.1021/es502250z

Wong, C. (1999). *Vehicle Emissions Project (Phase II). Volume I, Main Report, Engineering Research.* Department of Minerals and Energy, Pretoria, South Africa. Retrieved 02 1999

Wong, C., & Dutkiewicz, R.K. (1998). *Vehicle Emissions Project (Phase II). Volume I, Main Report, Engineering Research.* Department of Minerals and Energy, Pretoria, South Africa. Retrieved 11 1998

Wooster, M., Zhukov, B, & Oertel, D. (2003).). Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. . *Remote Sensing of Environment, 86*, 83-107.

WHO World Health Organization. (2013). Review of evidence on health aspects of air pollution – REVIHAAP Project. Technical report. Available: http://www.euro.who.int/__data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf. (accessed August 2014)

World Bank. (2012). *What a Waste: A global review of solid waste management.* Retrieved from http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/Chap3.pdf

World Bank. (2013). *Update, Population total and Urban Population, Table S1*. Retrieved from http://data.worldbank.org/indicator/SP.POP.TOTL

Yarwood, G., Jung, J, Whitten, G.Z, Heo, G, Mellberg, J, & Estes, M. (2010). Updates to the Carbon Bond Mechanism for Version 6 (CB6). *Presented at the 9th Annual CMAS Conference.* Chapel Hill, NC. Retrieved 11 13, 2010

Yarwood, G., Rao, S, Yocke, M, & Whitten, G.Z. (2005). *Updates to the Carbon Bond chemical mechanism: CB05. Final Report prepared for United States Environmental Protection Agency.* Retrieved 11 22, 2017, from http://www.camx.com/publ/pdfs/CB05_Final_Report_120805.pdf

Yokelson, R., I.R. Burling, J.B. Gilman, C. Wameke, C.E. Stockwell, J. de Gouw, . . . D. R. Weise. (2013). Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires. *Atmos. Chem. Phys, 13*, 89-116.

8 APPENDIX A – LONG-TERM AMBIENT AIR QUALITY DETAILED COMPLIANCE TABLES

Table 8-1: Summary of ambient measurements at Diepkloof – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No. of recorded hourly exceedances
		99th Percentile		
		NO_2		
2007	**68%**	70.3	**24.5**	-
2008	92%	67.0	**22.4**	2
2009	92%	74.4	**24.4**	2
2010	**12%**	89.3	**24.5**	2
2011	**53%**	54.1	16.7	-
2012	85%	73.4	19.4	31
2013	94%	98.6	**29.3**	71
2014	81%	63.0	**22.3**	-
2015	92%	82.0	**30.2**	14
2016	94%	70.9	**24.0**	2
Average		*74.3*	***23.8***	
		SO_2		
2007	83%	43.0	7.7	-
2008	92%	37.8	6.2	1
2009	93%	33.5	6.2	-
2010	**58%**	39.0	7.9	-
2011	**57%**	33.7	5.2	1
2012	89%	28.9	4.6	-
2013	94%	28.4	4.6	-
2014	**71%**	33.5	5.2	7
2015	91%	25.4	4.6	-
2016	94%	23.0	4.2	-
Average		*32.6*	*5.7*	
		Benzene		
2007	**67%**	2.4	0.3	
2008	96%	0.6	0.1	
2009	**25%**	5.1	0.4	
2010	**40%**	7.0	1.3	
2011	**51%**	193.0	23.9	
2012	**75%**	2.5	0.3	
2013	85%	3.3	0.6	
2014	78%	2.6	0.6	
2015	**60%**	2.8	0.4	
2016	**61%**	0.8	0.1	
Average		*22.0*	*2.8*	

Table 8-2: Summary of ambient measurements at Diepkloof – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007	83%	23.4	7.7	-
2008	92%	22.6	6.2	-
2009	93%	21.1	6.2	-
2010	**58%**	22.5	7.9	-
2011	**57%**	22.7	5.2	-
2012	89%	17.6	4.6	-
2013	94%	18.8	4.6	-
2014	**71%**	19.1	5.2	1
2015	91%	17.1	4.6	-
2016	94%	13.7	4.2	-
Average		*19.8*	*5.7*	
PM_{10}				
2007	88%	103.0	47.6	2
2008	97%	98.8	45.2	-
2009	99%	98.1	45.2	1
2010	79%	175.0	**57.2**	**13**
2011	**58%**	112.4	38.6	1
2012	96%	148.9	47.7	**6**
2013	96%	82.8	41.1	-
2014	85%	152.0	40.0	**6**
2015	95%	114.4	**41.7**	**19**
2016	94%	88.0	31.5	**9**
Average		*117.3*	*43.6*	
$PM_{2.5}$				
2007	**56%**	57.0	**26.5**	-
2008	**2%**	0.0	0.0	-
2009	94%	111.4	**44.0**	**37**
2010	**42%**	160.0	**58.0**	**50**
2011	**58%**	533.0	**92.8**	**32**
2012	98%	87.0	**27.4**	**11**
2013	90%	46.3	23.2	-
2014	86%	45.3	22.3	-
2015	95%	49.6	22.9	-
2016	97%	56.6	**23.9**	**31**
Average		*114.6*	*34.1*	
O_3				
2007	84%	98.7	23.8	
2008	89%	45.5	24.1	
2009	91%	42.9	22.3	
2010	**59%**	36.3	20.2	
2011	**63%**	176.7	24.2	
2012	93%	50.6	22.0	
2013	84%	68.4	37.3	
2014	79%	61.0	32.5	
2015	91%	59.9	30.6	
2016	98%	56.9	33.0	
Average		*69.7*	*27.0*	

Table 8-3: Summary of ambient measurements at Kliprivier – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
NO_2				
2007	88%	236.3	19.0	-
2008	78%	201.9	15.8	-
2009	78%	202.9	**23.5**	24
2010	82%	186.8	**22.4**	2
2011	**0%**			-
2012	90%	223.3	**21.2**	4
2013	90%	213.3	20.9	1
2014	94%	196.9	19.8	1
2015	**58%**	296.7	19.8	1
2016	**52%**	353.9	15.7	-
Average		*234.7*	*19.8*	
SO_2				
2007	89%	9.3	5.6	-
2008	95%	1.1	4.6	-
2009	80%	0.2	4.3	-
2010	**69%**	0.5	5.0	-
2011	**0%**			-
2012	98%	0.1	4.5	-
2013	84%	0.1	4.7	-
2014	81%	0.1	5.1	1
2015	**64%**	0.0	4.8	2
2016	**47%**	0.1	5.2	1
Average		*1.3*	*4.9*	
Benzene				
2007	91%	1.0	0.1	
2008	96%	0.3	0.1	
2009	**71%**	1.5	0.2	
2010	96%	0.7	0.1	
2011	**0%**			
2012	94%	1.2	0.2	
2013	90%	2.6	0.5	
2014	86%	1.7	0.3	
2015	**57%**	3.2	0.8	
2016	**49%**	1.2	0.4	
Average		*1.5*	*0.3*	

Table 8-4: Summary of ambient measurements at Kliprivier – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007	89%	17.6	5.6	-
2008	95%	19.6	4.6	-
2009	80%	17.3	4.3	-
2010	**69%**	14.8	5.0	-
2011	**0%**			-
2012	98%	16.0	4.5	-
2013	84%	15.7	4.7	-
2014	81%	16.7	5.1	-
2015	**64%**	16.5	4.8	-
2016	**47%**	18.3	5.2	-
Average		*17.0*	*4.9*	
PM_{10}				
2007	91%	145.3	**63.1**	**21**
2008	98%	151.9	**66.1**	**21**
2009	87%	247.2	**69.8**	**32**
2010	92%	172.3	**63.8**	**11**
2011	**0%**			-
2012	97%	213.8	**65.2**	**24**
2013	92%	126.1	**53.5**	**6**
2014	98%	120.8	**51.6**	4
2015	**73%**	149.1	**63.3**	**72**
2016	**75%**	250.0	**84.9**	**139**
Average		*175.2*	*64.6*	
$PM_{2.5}$				
2007	91%	85.9	**36.5**	**20**
2008	96%	100.8	**45.9**	**43**
2009	96%	233.4	**54.8**	**81**
2010	**54%**	138.5	**48.8**	**42**
2011	**0%**			-
2012	85%	99.9	**37.9**	**28**
2013	88%	72.3	**30.7**	**11**
2014	98%	83.0	**35.4**	**21**
2015	**73%**	95.5	**37.7**	**19**
2016	**74%**	196.3	**47.4**	**122**
Average		*122.8*	*41.7*	
O_3				
2007	75%	42.0	23.0	
2008	94%	41.7	20.4	
2009	93%	39.1	19.2	
2010	95%	35.1	17.7	
2011	**0%**			
2012	98%	44.2	19.4	
2013	88%	44.2	19.4	
2014	97%	44.2	15.1	
2015	76%	44.3	18.3	
2016	77%	42.6	16.4	
Average		*41.9*	*18.8*	

Table 8-5: Summary of ambient measurements at Sebokeng – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
NO$_2$				
2007	83%	50.8	14.9	-
2008	**75%**	54.2	15.8	-
2009	82%	60.6	15.1	-
2010	89%	56.4	15.9	1
2011	**18%**	73.5	14.0	2
2012	**67%**	45.3	14.0	-
2013	87%	46.6	13.7	-
2014	85%	47.0	14.9	-
2015	83%	133.3	**22.7**	**156**
2016	78%	51.0	13.5	-
Average		*61.9*	*15.4*	
SO$_2$				
2007	88%	33.4	5.5	-
2008	**65%**	28.0	3.9	-
2009	80%	33.5	5.2	1
2010	88%	41.5	6.3	2
2011	**21%**	22.6	4.7	-
2012	**42%**	27.7	4.0	1
2013	89%	37.2	5.2	-
2014	85%	40.1	6.0	-
2015	89%	30.7	4.9	2
2016	**74%**	42.8	5.9	6
Average		*33.7*	*5.2*	
Benzene				
2007	**73%**	2.2	0.4	
2008	**75%**	1.1	0.3	
2009	82%	1.8	0.3	
2010	79%	5.4	1.1	
2011	**11%**	6.0	1.2	
2012	**63%**	2.3	0.7	
2013	89%	3.2	0.8	
2014	83%	24.3	3.0	
2015	**73%**	9.2	2.3	
2016	79%	4.9	0.6	
Average		*6.0*	*1.1*	

Table 8-6: Summary of ambient measurements at Sebokeng – Part 2: daily and annual

Period	Data Availability	Daily 99th Percentile	Annual Average	No of recorded daily exceedances
		SO_2		
2007	88%	20.4	5.5	-
2008	**65%**	20.6	3.9	-
2009	80%	21.6	5.2	-
2010	88%	24.3	6.3	-
2011	**21%**	14.2	4.7	-
2012	**42%**	18.7	4.0	-
2013	89%	24.0	5.2	-
2014	85%	21.0	6.0	-
2015	89%	20.0	4.9	-
2016	**74%**	26.7	5.9	-
Average		*21.1*	*5.2*	
		PM_{10}		
2007	93%	141.8	**62.0**	**14**
2008	84%	151.5	**56.3**	**19**
2009	85%	111.6	38.6	2
2010	93%	144.9	**52.1**	**8**
2011	**16%**	132.1	**51.9**	2
2012	85%	106.9	46.6	1
2013	91%	100.9	46.5	1
2014	87%	110.1	40.4	-
2015	87%	100.2	40.7	**22**
2016	95%	104.2	**41.9**	**38**
Average		*120.4*	*47.7*	
		$PM_{2.5}$		
2007	84%	79.6	**28.2**	**10**
2008	**0%**			
2009	**53%**	141.6	**44.7**	**33**
2010	93%	170.1	**50.7**	**77**
2011	**23%**	266.6	**61.0**	**24**
2012	85%	104.6	**34.0**	**18**
2013	92%	71.0	**29.2**	**7**
2014	88%	86.8	**30.1**	**10**
2015	87%	62.2	**28.4**	1
2016	95%	75.7	**30.1**	**76**
Average		*117.6*	*37.4*	
		O_3		
2007	**69%**	48.9	28.2	
2008	83%	47.7	25.0	
2009	85%	41.3	23.5	
2010	85%	54.3	24.9	
2011	**24%**	30.3	16.0	
2012	**75%**	45.5	20.6	
2013	93%	49.3	22.5	
2014	88%	43.5	22.5	
2015	96%	48.8	22.0	
2016	95%	48.1	26.1	
Average		*45.8*	*23.1*	

Table 8-7: Summary of ambient measurements at Three Rivers – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
		NO_2		
2007	**58%**	43.6	11.9	-
2008	**42%**	50.6	13.5	-
2009	**0%**			-
2010	**36%**	69.7	17.3	3
2011	**13%**	24.7	9.3	-
2012	82%	44.7	11.6	1
2013	90%	38.7	11.4	-
2014	82%	40.4	12.0	-
2015	80%	55.6	16.8	-
2016	91%	49.0	14.0	-
Average		*46.3*	*13.1*	
		SO_2		
2007	**73%**	29.6	5.5	2
2008	**66%**	35.9	5.2	-
2009	**67%**	35.6	4.5	-
2010	82%	44.3	6.0	11
2011	**13%**	60.0	6.8	4
2012	78%	25.4	4.2	2
2013	91%	44.3	5.0	7
2014	86%	51.6	6.7	11
2015	84%	42.0	5.5	5
2016	91%	62.3	5.9	7
Average		*43.1*	*5.5*	
		Benzene		
2007	**58%**	0.3	0.1	
2008	**66%**	0.3	0.1	
2009	**25%**	0.3	0.1	
2010	**50%**	5.3	1.1	
2011	**4%**	1.6	0.3	
2012	**71%**	4.7	0.4	
2013	**71%**	4.8	0.4	
2014	**37%**	3.7	0.7	
2015	**51%**	2.1	0.3	
2016	83%	0.9	0.1	
Average		*2.4*	*0.4*	

Table 8-8: Summary of ambient measurements at Three Rivers – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007	**73%**	15.0	5.5	-
2008	**66%**	17.5	5.2	-
2009	**67%**	25.1	4.5	-
2010	82%	26.6	6.0	-
2011	**13%**	46.5	6.8	1
2012	78%	14.1	4.2	-
2013	91%	27.9	5.0	2
2014	86%	27.3	6.7	1
2015	84%	21.2	5.5	-
2016	91%	25.7	5.9	-
Average		*24.7*	*5.5*	
PM_{10}				
2007	90%	131.1	**51.7**	**7**
2008	80%	113.3	33.6	2
2009	**75%**	99.4	40.9	-
2010	80%	135.5	**52.0**	**6**
2011	**10%**	56.2	26.0	-
2012	82%	158.7	**60.7**	**14**
2013	95%	139.7	**56.5**	**10**
2014	90%	114.7	**50.2**	1
2015	86%	119.3	**51.4**	**54**
2016	90%	130.1	**61.1**	**87**
Average		*119.8*	*48.4*	
$PM_{2.5}$				
2007	89%	62.4	**26.3**	3
2008	86%	84.7	**26.0**	**10**
2009	76%	60.0	24.1	1
2010	85%	78.1	**30.5**	**7**
2011	**9%**	56.8	20.4	-
2012	77%	62.0	**25.9**	3
2013	95%	59.2	24.4	2
2014	87%	59.6	**25.4**	1
2015	92%	69.7	**27.7**	**5**
2016	82%	61.8	**28.7**	**58**
Average		*65.4*	*25.9*	
O_3				
2007	**74%**	46.8	20.2	
2008	76%	47.4	21.4	
2009	77%	40.3	21.5	
2010	78%	54.9	22.9	
2011	**15%**	305.1	25.1	
2012	**64%**	45.5	23.1	
2013	95%	41.0	21.7	
2014	84%	49.2	22.4	
2015	90%	52.6	27.8	
2016	89%	52.0	28.2	
Average		*73.5*	*23.4*	

Table 8-9: Summary of ambient measurements at Sharpeville – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
NO$_2$				
2007	**71%**	55.7	17.8	-
2008	81%	53.5	14.8	10
2009	96%	63.2	17.6	2
2010	**39%**	64.4	16.9	-
2011	**37%**	53.4	11.1	4
2012	75%	51.9	12.8	-
2013	83%	79.7	16.7	17
2014	97%	50.6	15.1	1
2015	86%	83.3	**23.3**	15
2016	86%	55.7	15.8	-
Average		*61.1*	*16.2*	
SO$_2$				
2007	82%	62.8	9.3	6
2008	96%	43.8	6.9	7
2009	91%	52.8	6.8	8
2010	**60%**	51.1	9.1	7
2011	**65%**	48.9	7.5	7
2012	93%	42.3	6.4	6
2013	95%	53.9	6.8	7
2014	96%	73.5	8.8	8
2015	87%	51.8	7.3	15
2016	80%	48.5	5.8	3
Average		*52.9*	*7.5*	
Benzene				
2007	80%	3.2	0.5	
2008	97%	4.7	0.9	
2009	97%	4.1	0.7	
2010	**30%**	10.6	3.4	
2011	**25%**	9.7	3.5	
2012	**32%**	4.7	0.9	
2013	83%	3.9	0.8	
2014	82%	1.9	0.3	
2015	**32%**	3.8	0.4	
2016	**6%**	0.0	0.0	
Average		*4.6*	*1.1*	

Table 8-10: Summary of ambient measurements at Sharpeville – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007	82%	33.6	9.3	1
2008	96%	26.8	6.9	1
2009	91%	31.9	6.8	-
2010	**60%**	41.0	9.1	2
2011	**65%**	35.1	7.5	-
2012	93%	29.9	6.4	1
2013	95%	33.1	6.8	-
2014	96%	35.7	8.8	-
2015	87%	35.9	7.3	2
2016	80%	28.4	5.8	-
Average		*33.1*	*7.5*	
PM_{10}				
2007	81%	222.2	**75.0**	**65**
2008	98%	207.8	**78.4**	**70**
2009	85%	182.2	**63.8**	**34**
2010	94%	232.7	**79.2**	**60**
2011	**59%**	220.1	**82.1**	**38**
2012	95%	184.8	**70.3**	**44**
2013	95%	187.8	**66.3**	**35**
2014	99%	173.8	**64.8**	**25**
2015	89%	153.6	**62.8**	**83**
2016	86%	234.8	**95.9**	**185**
Average		*200.0*	*73.9*	
$PM_{2.5}$				
2007	82%	136.2	**36.7**	**45**
2008	100%	90.7	**34.7**	**34**
2009	94%	103.9	**35.1**	**44**
2010	**72%**	138.0	**46.7**	**50**
2011	**54%**	107.0	20.0	**14**
2012	97%	124.1	**39.8**	**49**
2013	95%	97.7	**35.2**	**34**
2014	99%	112.5	**38.3**	**34**
2015	88%	97.9	**36.5**	**27**
2016	**53%**	77.2	**31.6**	**43**
Average		*108.5*	*35.4*	
O_3				
2007	88%	48.5	22.6	
2008	98%	43.1	22.4	
2009	88%	40.5	22.5	
2010	78%	37.2	20.2	
2011	**68%**	48.4	23.2	
2012	89%	57.3	27.8	
2013	76%	53.9	35.4	
2014	99%	51.6	23.7	
2015	88%	53.6	25.7	
2016	91%	51.9	24.2	
Average		*48.6*	*24.8*	

Table 8-11: Summary of ambient measurements at Zamdela – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
NO_2				
2007	**69%**	43.9	11.9	-
2008	93%	46.4	12.5	-
2009	**37%**	36.0	9.8	-
2010	**27%**	40.4	12.1	-
2011	**73%**	52.5	12.4	-
2012	80%	48.2	13.2	-
2013	**64%**	61.6	15.8	1
2014	82%	44.3	12.8	3
2015	87%	53.4	16.0	-
2016	88%	65.8	17.4	1
Average		*49.3*	*13.4*	
SO_2				
2007	**66%**	71.3	9.3	3
2008	**70%**	55.5	8.4	-
2009	93%	71.8	9.1	7
2010	89%	65.8	8.1	7
2011	86%	56.7	7.5	3
2012	90%	71.8	9.6	13
2013	83%	68.0	8.4	10
2014	85%	77.3	9.2	9
2015	87%	65.9	8.2	5
2016	87%	71.4	8.5	5
Average		*67.6*	*8.6*	
Benzene				
2007	**47%**	2.1	0.2	
2008	78%	1.3	0.2	
2009	**21%**	1.2	0.1	
2010	**66%**	1.6	0.2	
2011	**21%**	3.8	0.1	
2012	**74%**	1.2	0.1	
2013	80%	3.9	0.4	
2014	82%	7.6	1.3	
2015	**63%**	3.6	0.5	
2016	**67%**	194.8	16.4	
Average		*22.1*	*2.0*	

Table 8-12: Summary of ambient measurements at Zamdela – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007	**66%**	29.7	9.3	-
2008	**70%**	25.2	8.4	-
2009	93%	30.4	9.1	-
2010	89%	28.2	8.1	-
2011	86%	25.9	7.5	-
2012	90%	29.5	9.6	1
2013	83%	29.5	8.4	-
2014	85%	34.6	9.2	-
2015	87%	26.0	8.2	-
2016	87%	30.9	8.5	2
Average		*29.0*	*8.6*	
PM_{10}				
2007	**60%**	232.8	**91.5**	**57**
2008	76%	231.1	**81.6**	**67**
2009	78%	250.8	**102.4**	**95**
2010	**0%**			-
2011	**58%**	291.1	**99.5**	**68**
2012	87%	215.8	**81.6**	**70**
2013	76%	152.6	**59.8**	**15**
2014	89%	168.5	**57.8**	**25**
2015	**64%**	125.2	**46.0**	**35**
2016	92%	165.2	**64.7**	**106**
Average		*203.7*	*76.1*	
$PM_{2.5}$				
2007	76%	97.7	**35.7**	**25**
2008	92%	82.5		
2009	99%	78.6	**27.4**	**6**
2010	100%	86.8	**34.2**	**18**
2011	77%	108.9	**29.8**	**16**
2012	95%	67.2	**29.1**	**8**
2013	84%	70.4	**29.3**	**5**
2014	92%	86.0	**29.7**	**16**
2015	89%	73.2	**30.0**	**11**
2016	82%	95.8	**35.0**	**92**
Average		*84.7*	*31.1*	
O_3				
2007	**54%**	51.6	29.1	
2008	92%	46.1	25.6	
2009	99%	39.6	22.7	
2010	**55%**	36.4	20.7	
2011	78%	44.6	22.1	
2012	90%	42.8	25.0	
2013	**73%**	39.9	23.8	
2014	92%	45.3	28.8	
2015	94%	44.0	25.2	
2016	95%	41.7	23.0	
Average		*43.2*	*24.6*	

Table 8-13: Summary of ambient measurements at Randwater – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
		NO_2		
2007				
2008				
2009				
2010				
2011				
2012	100%	30.7	8.6	-
2013	88%	49.1	10.6	45
2014	98%	31.4	8.5	6
2015	91%	31.5	8.8	**2**
2016	99%	36.2	9.3	9
Average		*35.8*	*9.2*	
		SO_2		
2007				
2008				
2009				
2010				
2011				
2012	100%	34.1	4.3	1
2013	89%	33.5	6.4	23
2014	99%	33.1	5.1	12
2015	97%	35.7	4.1	13
2016	99%	35.2	4.9	12
Average		*34.3*	*5.0*	

Table 8-14: Summary of ambient measurements at Randwater – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2007				
2008				
2009				
2010				
2011				
2012	100%	19.7	4.3	-
2013	89%	272.3	6.4	**8**
2014	99%	24.4	5.1	-
2015	97%	29.8	4.1	1
2016	99%	21.9	4.9	1
Average		*73.6*	*5.0*	
PM_{10}				
2007				
2008				
2009				
2010				
2011				
2012	**63%**	47.5	31.6	-
2013	89%	323.2	**56.6**	**7**
2014	99%	124.2	47.2	4
2015	86%	95.1	**44.9**	**25**
2016	97%	238.8	**55.8**	**56**
Average		*165.8*	*47.2*	
$PM_{2.5}$				
2007				
2008				
2009				
2010				
2011				
2012	**0%**			-
2013	**0%**			-
2014	**0%**			-
2015	**0%**			-
2016	75%	41.2	18.8	**6**
Average		*41.2*	*18.8*	
O_3				
2007				
2008				
2009				
2010				
2011				
2012	100%	63.8	45.2	
2013	92%	388.2	53.0	
2014	99%	54.7	29.9	
2015	90%	66.3	35.4	
2016	94%	57.0	31.0	
Average		*126.0*	*38.9*	

Table 8-15: Summary of ambient measurements at Eco Park – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
NO_2				
2011	84%	40.9	10.2	5
2012	97%	47.9	12.0	**93**
2013	100%	43.4	10.7	45
2014	99%	45.0	12.0	53
2015	100%	44.8	11.1	43
2016	98%	45.2	11.1	**167**
Average		*44.5*	*11.2*	
SO_2				
2011	84%	129.2	26.4	28
2012	98%	105.2	16.1	60
2013	100%	78.2	10.2	24
2014	99%	254.1	20.5	**317**
2015	100%	91.4	19.6	31
2016	98%	99.9	16.0	41
Average		*126.3*	*18.1*	

Table 8-16: Summary of ambient measurements at Eco Park – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2011	84%	92.3	26.4	**15**
2012	98%	66.3	16.1	**6**
2013	100%	34.7	10.2	-
2014	99%	254.1	20.5	**14**
2015	100%	44.9	19.6	1
2016	98%	48.9	16.0	**5**
Average		*90.2*	*18.1*	
PM_{10}				
2011	**46%**	56.3	23.1	-
2012	87%	355.5	49.6	**18**
2013	99%	106.3	34.9	2
2014	98%	105.5	30.0	-
2015	94%	125.9	37.2	**45**
2016	98%	117.9	33.1	**29**
Average		*144.6*	*34.6*	
$PM_{2.5}$				
2011	**0%**			-
2012	**4%**	15.0	15.0	**77**
2013	**24%**	993.8	**80.1**	**50**
2014	93%	82.1	20.8	**28**
2015	95%	52.6	18.2	**64**
2016	98%	308.8	20.6	**23**
Average		*290.5*	*30.9*	
O_3				
2011	86%	234.1	40.0	
2012	99%	48.7	29.9	
2013	100%	51.9	28.1	
2014	100%	50.8	27.4	
2015	100%	54.8	30.1	
2016	99%	364.0	39.8	
Average		*134.0*	*32.6*	

Table 8-17: Summary of ambient measurements at AJ Jacobs – Part 1: hourly and annual

Period	Data Availability	Hourly	Annual Average	No of recorded hourly exceedances
		99th Percentile		
		NO_2		
2008	94%	44.0	12.3	-
2009	97%	43.9	11.7	1
2010	91%	40.3	10.9	2
2011	97%	43.3	10.8	-
2012	97%	35.4	8.9	-
2013	95%	29.1	7.1	-
2014	99%	46.2	13.5	-
2015	84%	42.3	11.2	-
2016	95%	39.1	10.8	-
Average		*40.4*	*10.8*	
		SO_2		
2008	96%	105.5	13.2	37
2009	96%	109.6	12.2	53
2010	92%	95.4	13.4	20
2011	95%	101.9	16.5	27
2012	98%	99.6	17.9	29
2013	96%	115.7	16.2	47
2014	99%	112.0	17.7	34
2015	98%	108.4	**21.5**	33
2016	96%	117.4	**21.8**	54
Average		*107.3*	*16.7*	

Table 8-18: Summary of ambient measurements at AJ Jacobs – Part 2: daily and annual

Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
		SO_2		
2008	96%	55.1	13.2	**7**
2009	96%	56.9	12.2	**8**
2010	92%	43.9	13.4	1
2011	95%	51.7	16.5	**9**
2012	98%	53.5	17.9	**11**
2013	96%	69.1	16.2	**18**
2014	99%	57.7	17.7	**19**
2015	98%	58.4	21.5	**12**
2016	96%	61.9	21.8	**23**
Average		*56.5*	*16.7*	
		PM_{10}		
2008	77%	108.7	46.4	1
2009	93%	130.6	41.6	**6**
2010	91%	119.5	43.2	4
2011	100%	112.6	41.6	3
2012	88%	103.1	38.5	1
2013	92%	128.7	**51.9**	**8**
2014	98%	118.4	**44.8**	4
2015	96%	119.9	**46.4**	**48**
2016	99%	105.1	**43.1**	**39**
Average		*116.3*	*44.2*	
		$PM_{2.5}$		
2008	**0%**			-
2009	**0%**			-
2010	**0%**			-
2011	**0%**			-
2012	**0%**			-
2013	**0%**			-
2014	85%	54.5	18.9	2
2015	93%	48.2	18.3	-
2016	82%	54.2	17.9	**14**
Average		*52.3*	*18.4*	

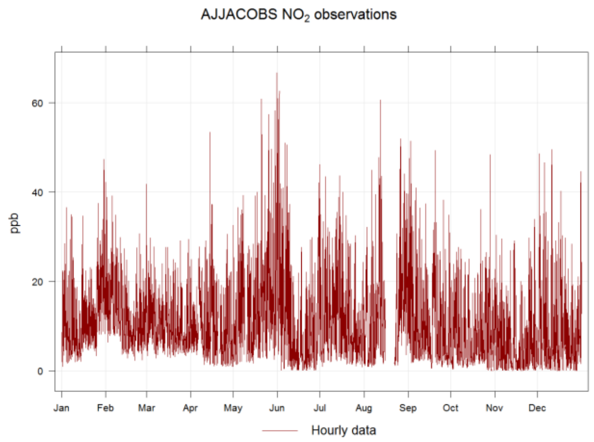
Table 8-19: Summary of ambient measurements at Leitrim – Part 1: hourly and annual

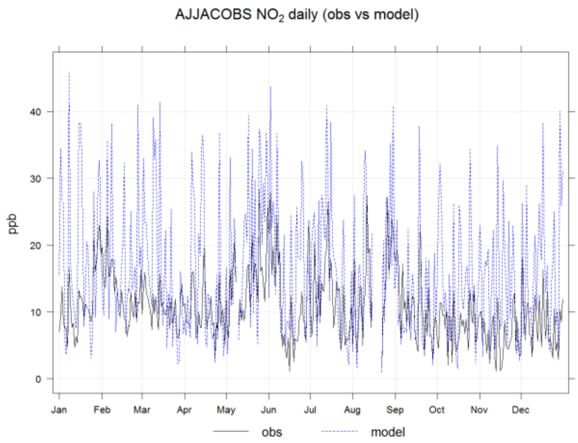
Period	Data Availability	Hourly 99th Percentile	Annual Average	No of recorded hourly exceedances
		NO_2		
2008	90%	50.6	15.5	14
2009	81%	47.1	13.1	1
2010	91%	44.0	11.4	-
2011	75%	42.6	11.1	3
2012	78%	46.0	12.1	-
2013	**68%**	39.8	11.2	-
2014	**26%**	88.0	10.0	13
2015	**21%**	34.5	11.3	-
2016	91%	46.4	12.1	-
Average		*48.8*	*12.0*	
		SO_2		
2008	90%	79.6	11.9	11
2009	81%	72.3	10.4	7
2010	92%	66.8	8.5	7
2011	**75%**	61.3	8.1	6
2012	77%	61.6	8.8	7
2013	**62%**	63.2	8.7	2
2014	**47%**	71.7	23.7	4
2015	85%	70.6	12.7	4
2016	94%	78.6	15.0	15
Average		*69.5*	*12.0*	
		Benzene		
2008	**70%**	5.4	1.3	
2009	79%	3.4	1.2	
2010	85%	2.9	1.3	
2011	**47%**	4.5	1.6	
2012	75%	3.4	1.4	
2013	**46%**	4.3	1.4	
2014	**22%**	6.3	1.8	
2015	**0%**			
2016	**0%**			
Average		*4.3*	*1.4*	

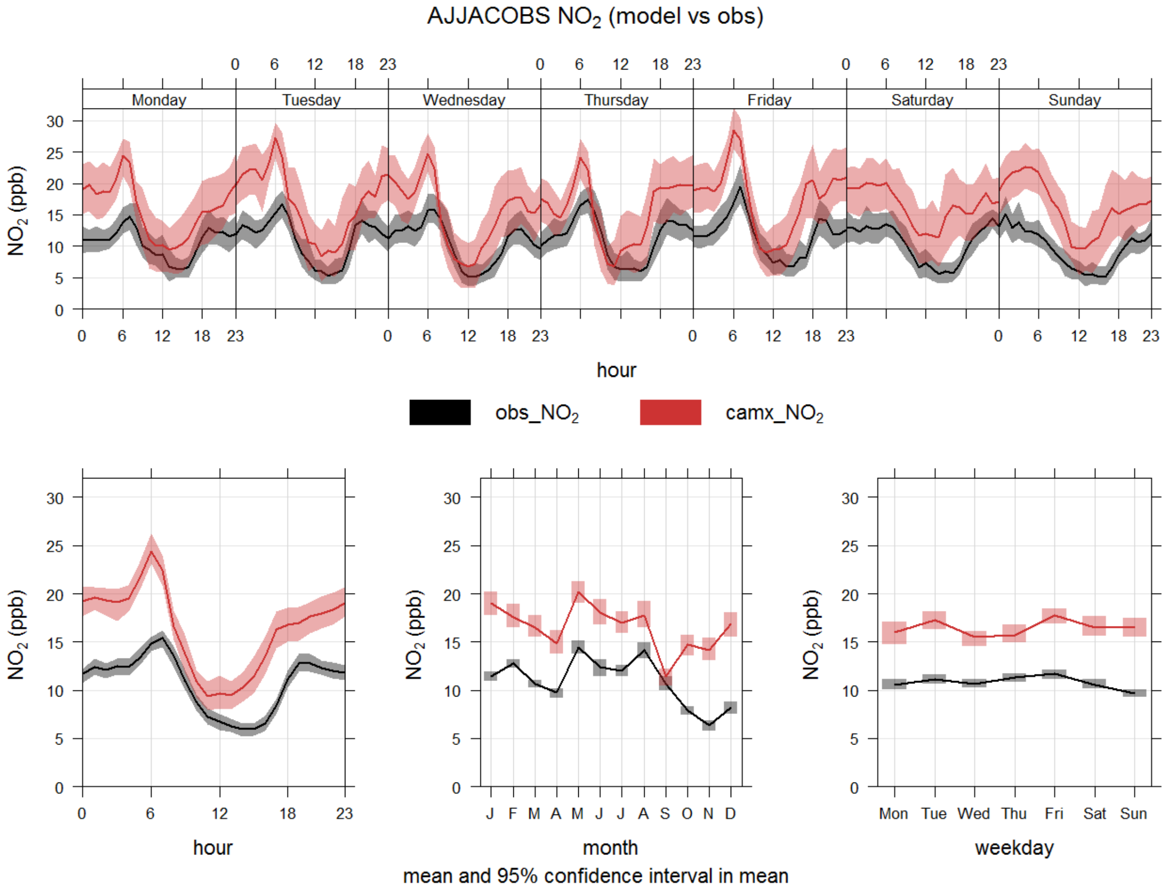
Table 8-20: Summary of ambient measurements at Leitrim – Part 2: daily and annual

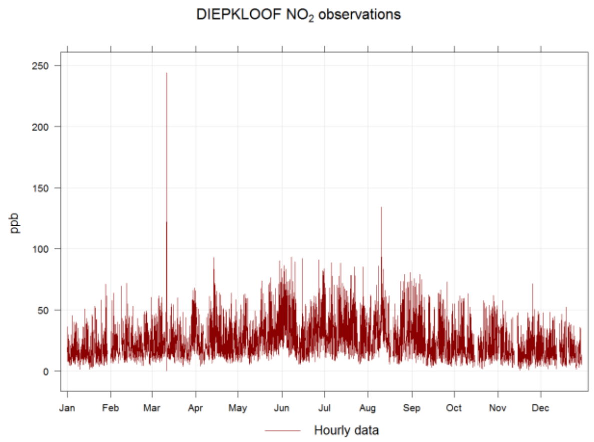
Period	Data Availability	Daily	Annual Average	No of recorded daily exceedances
		99th Percentile		
SO_2				
2008	90%	36.0	11.9	-
2009	81%	29.6	10.4	-
2010	92%	27.8	8.5	-
2011	**75%**	29.0	8.1	-
2012	77%	28.1	8.8	-
2013	**62%**	33.8	8.7	-
2014	**47%**	52.9	23.7	-
2015	85%	40.5	12.7	-
2016	94%	38.2	15.0	-
Average		*35.1*	*12.0*	
PM_{10}				
2008	99%	175.3	**63.9**	**43**
2009	99%	146.1	47.0	**11**
2010	99%	160.8	**53.5**	**20**
2011	97%	162.5	47.3	**10**
2012	95%	155.1	**50.5**	**16**
2013	76%	156.5	**56.3**	**17**
2014	79%	163.7	**45.1**	**10**
2015	81%	153.4	**49.2**	**57**
2016	**41%**	117.0	23.7	**21**
Average		*154.5*	*48.5*	
$PM_{2.5}$				
2008	**0%**			-
2009	**0%**			-
2010	**0%**			-
2011	**0%**			-
2012	**0%**			-
2013	**0%**			-
2014	**0%**			-
2015	**65%**	75.2	24.2	**5**
2016	**43%**	53.6	8.6	**8**
Average		*64.4*	*16.4*	
O_3				
2008	97%	46.4	29.8	
2009	88%	43.9	26.3	
2010	99%	36.0	20.7	
2011	86%	36.9	20.3	
2012	89%	39.5	24.4	
2013	77%	43.3	26.1	
2014	**28%**	20.2	9.6	
2015	**0%**			
2016	**0%**			
Average		*38.0*	*22.5*	

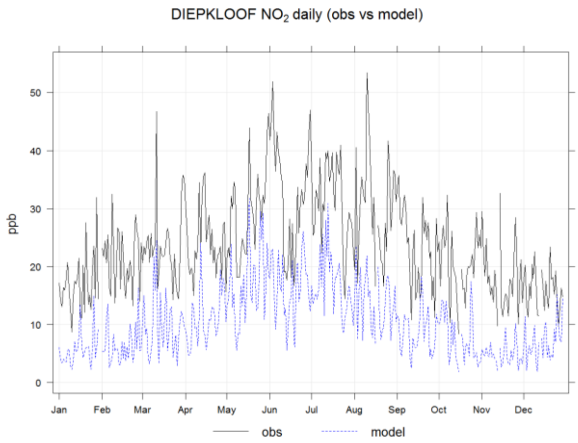
9 APPENDIX B – TIME-SERIES PLOTS OF MODEL VS MEASURED CONCENTRATIONS

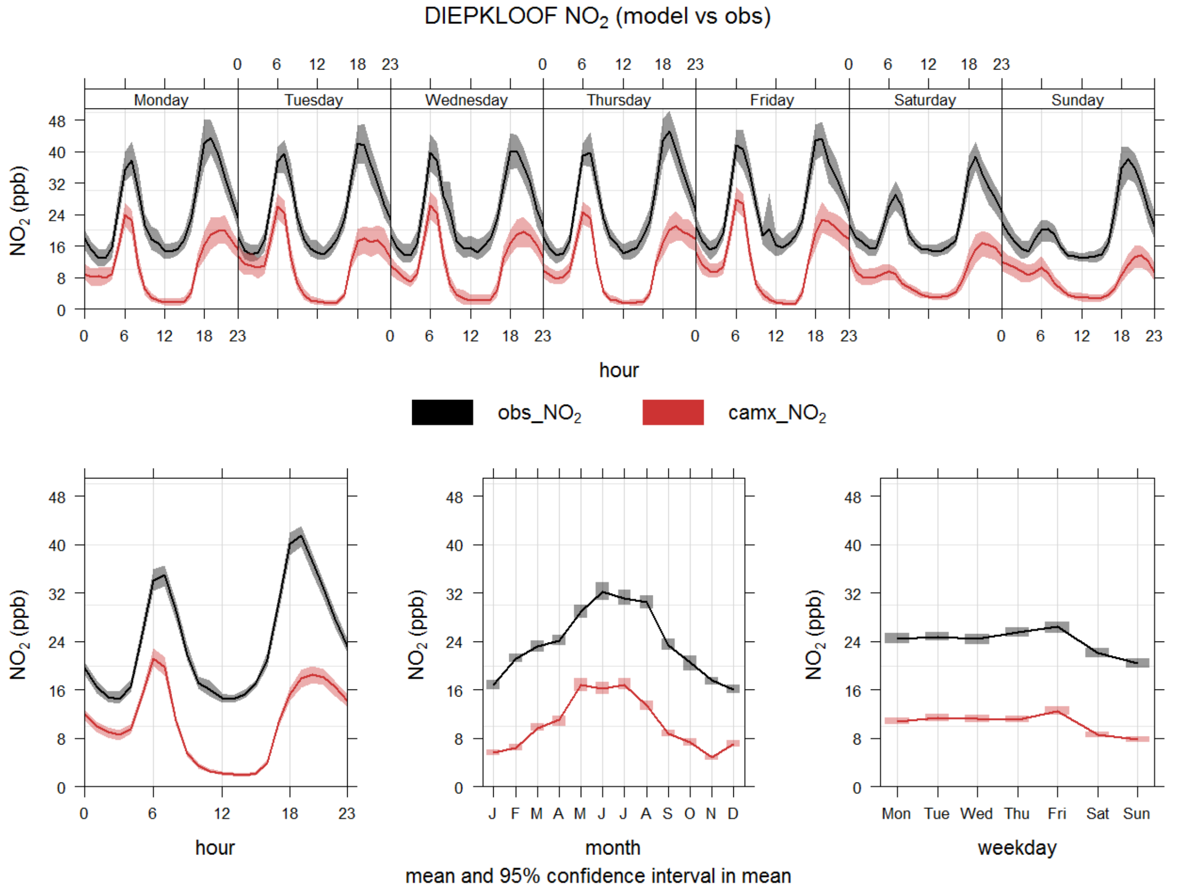

AJJACOBS NO$_2$ observations
ppb
0
20
40
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

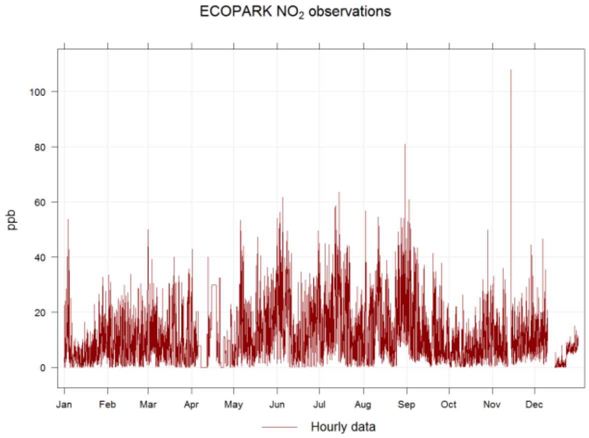

AJJACOBS NO$_2$ daily (obs vs model)
ppb
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

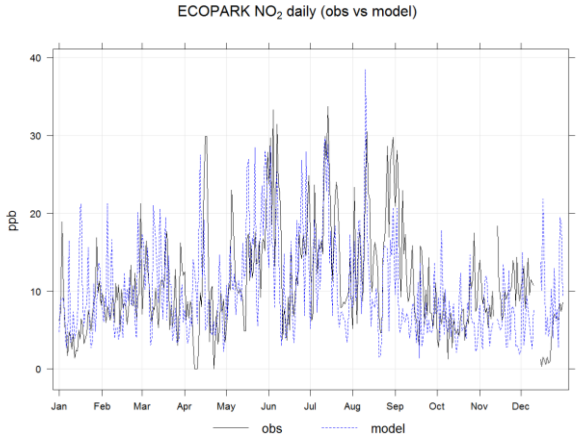

AJJACOBS NO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO$_2$ (ppb)
0
5
10
15
20
25
30
0
6
12
18
23
hour
obs_NO$_2$
camx_NO$_2$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

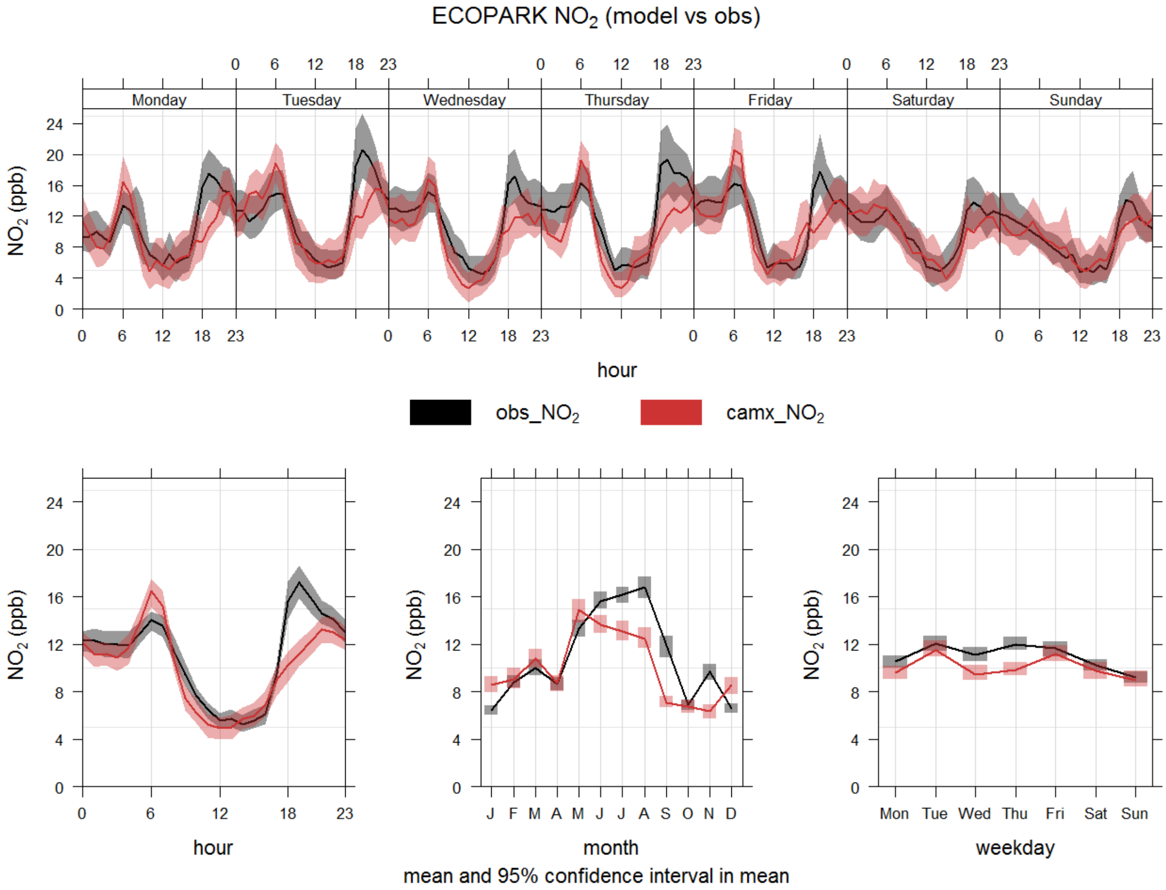

DIEPKLOOF NO$_2$ observations
ppb
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

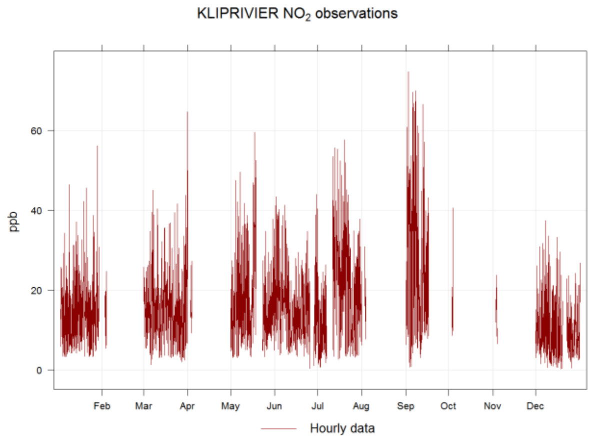

DIEPKLOOF NO$_2$ daily (obs vs model)
ppb
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

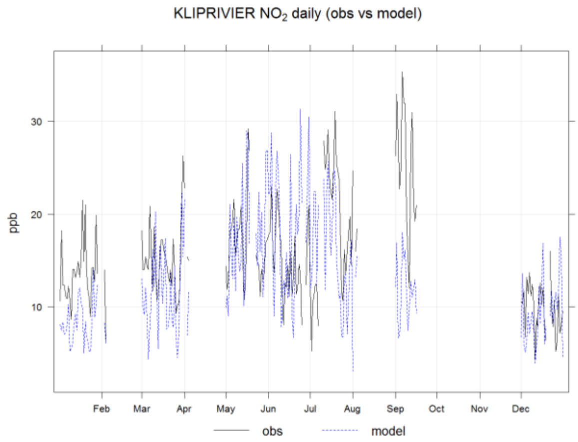

DIEPKLOOF NO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO$_2$ (ppb)
0
8
16
24
32
40
48
0
6
12
18
23
hour
obs_NO$_2$
camx_NO$_2$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

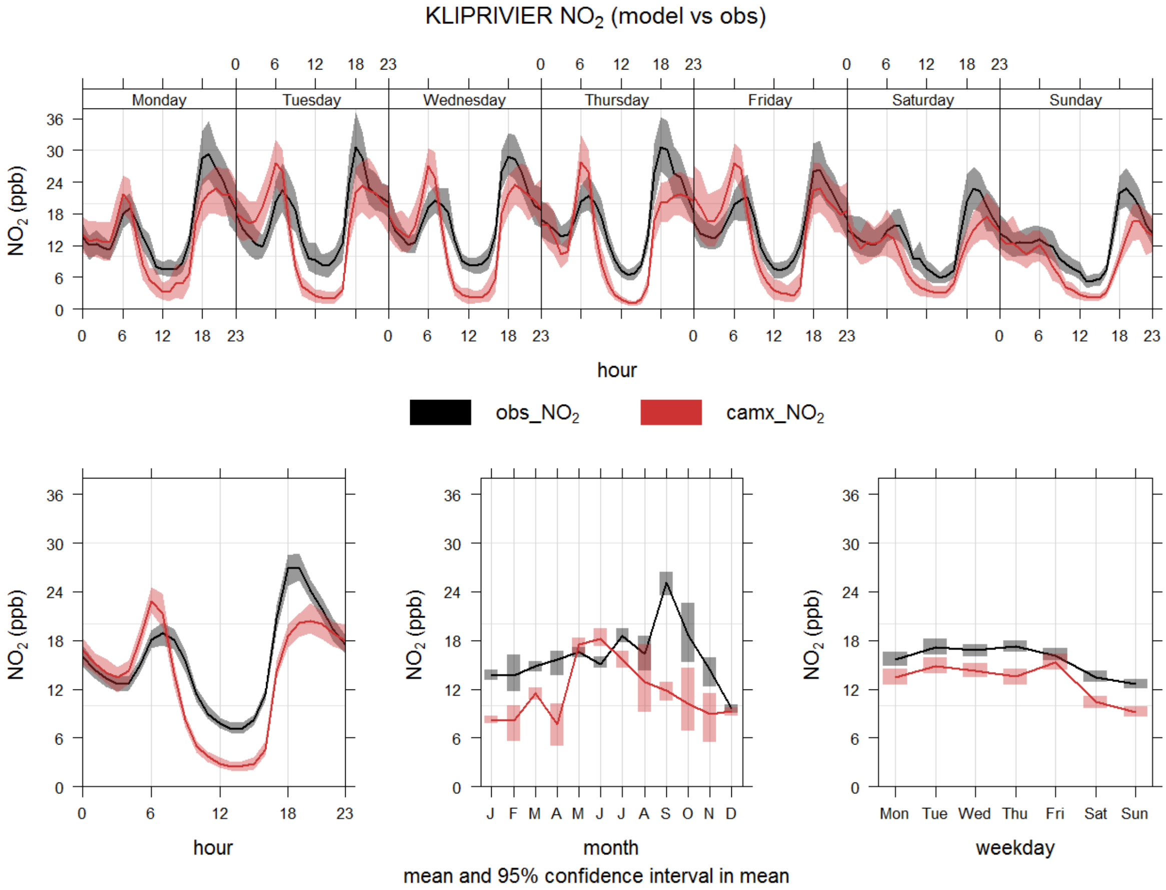

ECOPARK NO$_2$ observations
ppb
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data


ECOPARK NO$_2$ daily (obs vs model)
ppb
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

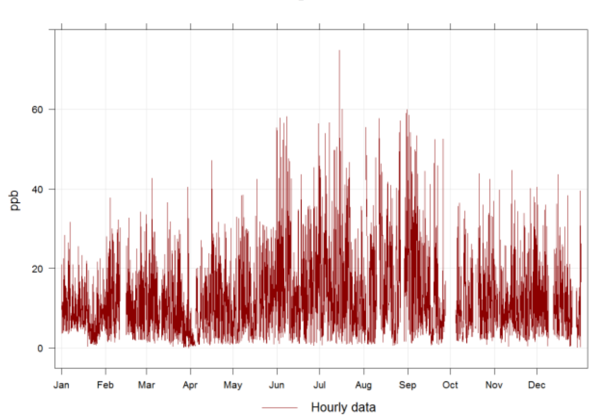

ECOPARK NO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO$_2$ (ppb)
0
4
8
12
16
20
24
0
6
12
18
23
hour
obs_NO$_2$
camx_NO$_2$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean


KLIPRIVIER NO$_2$ observations

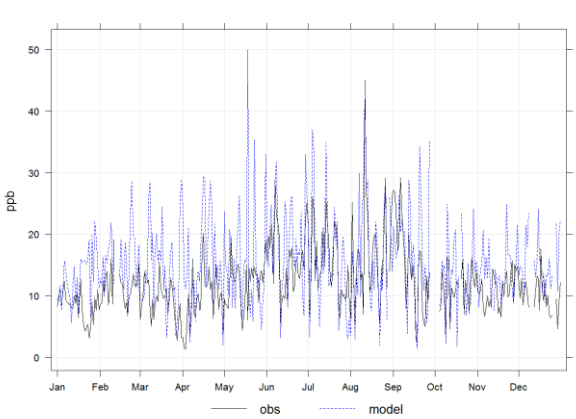

KLIPRIVIER NO$_2$ daily (obs vs model)


KLIPRIVIER NO$_2$ (model vs obs)

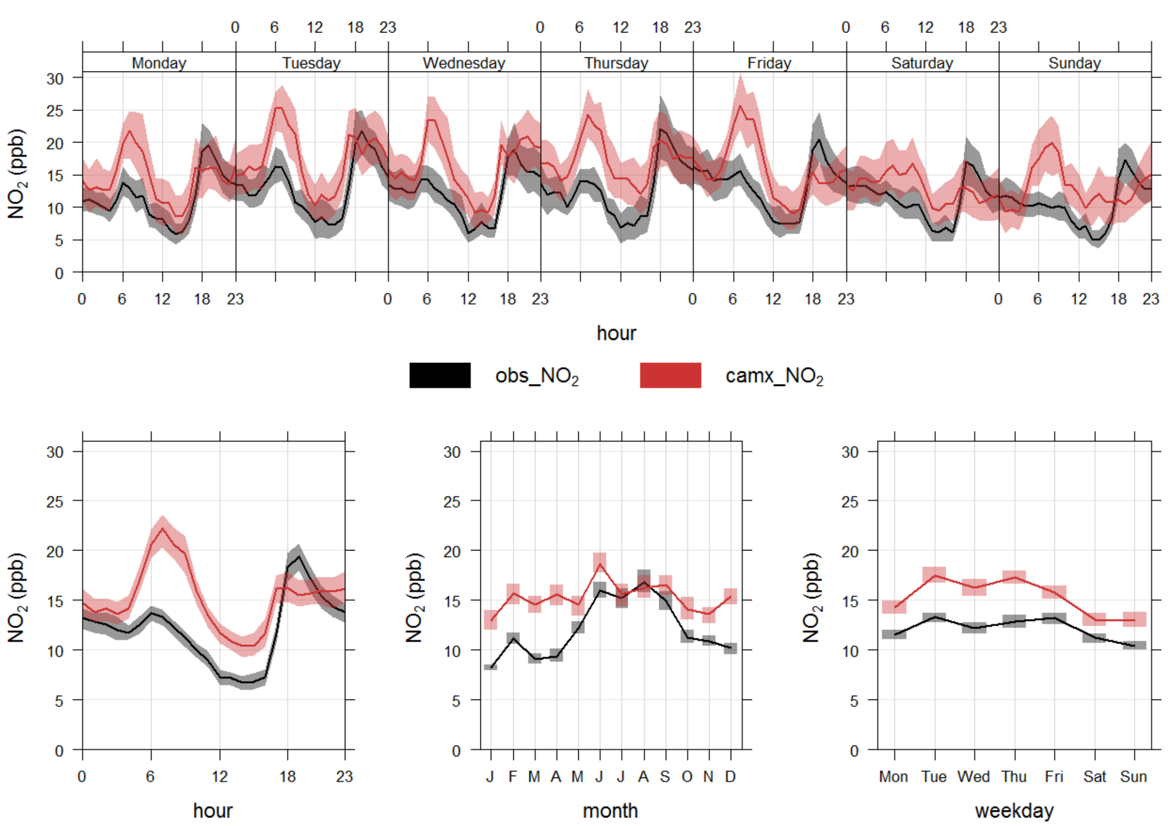
mean and 95% confidence interval in mean



LEITRUM NO_2 observations

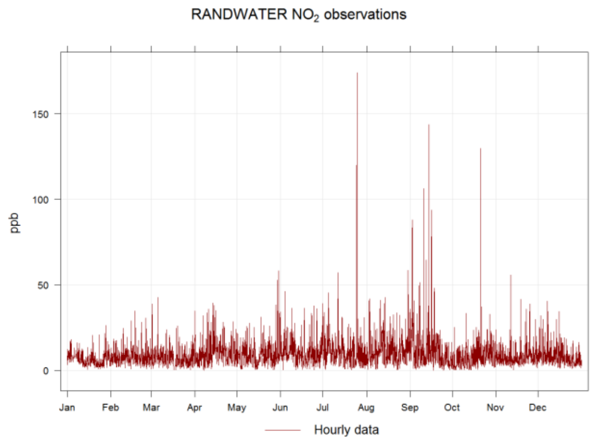


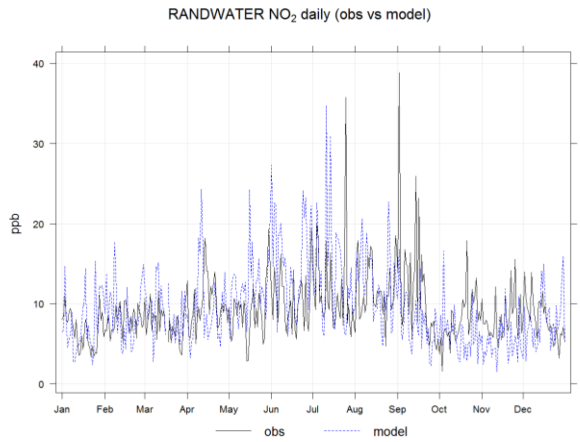
LEITRUM NO_2 daily (obs vs model)

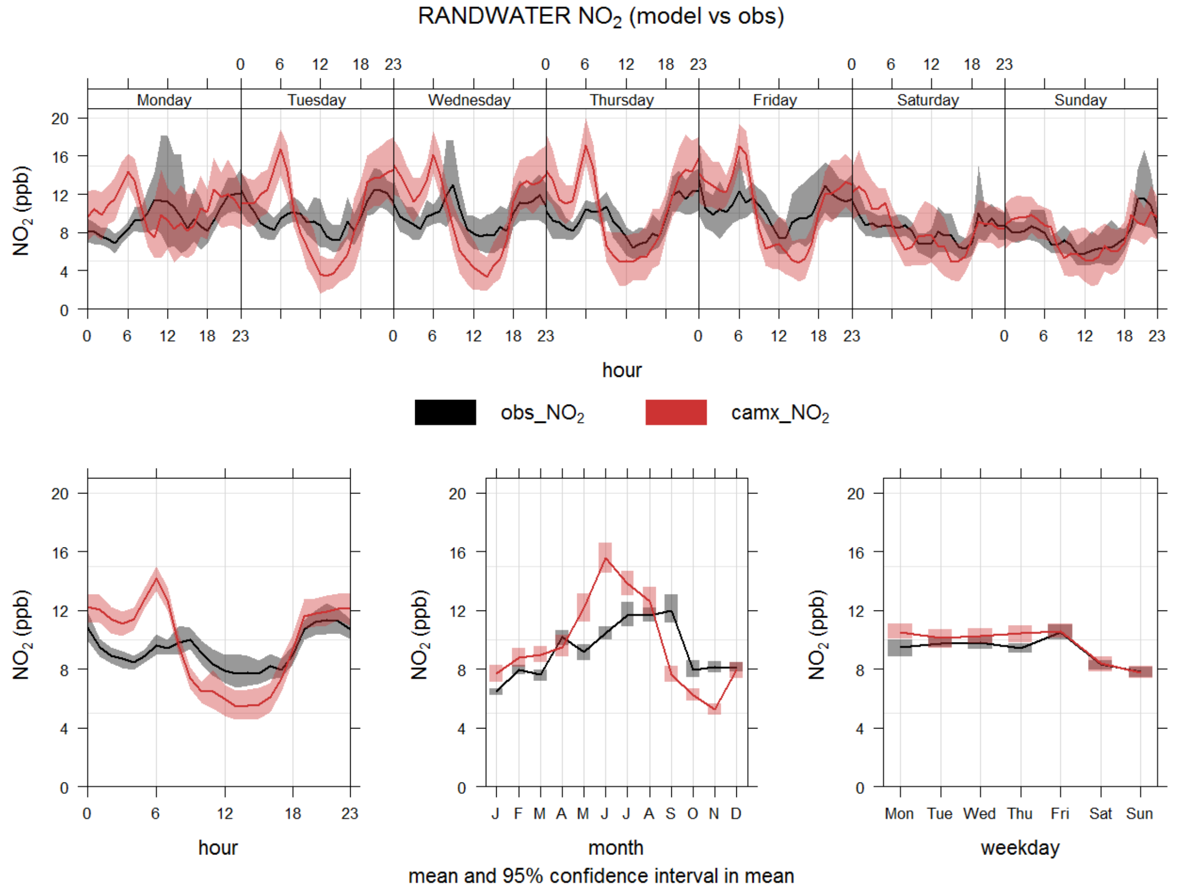


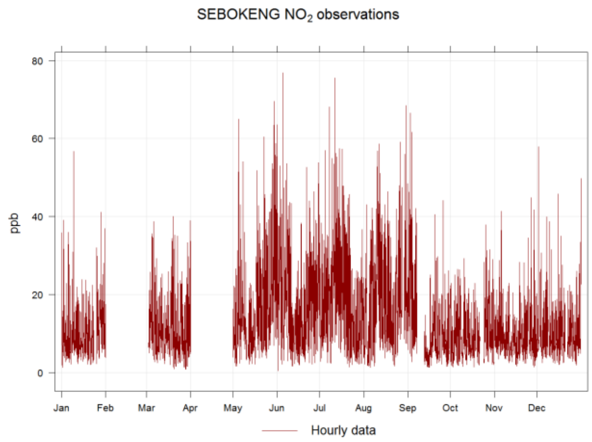
LEITRUM NO_2 (model vs obs)

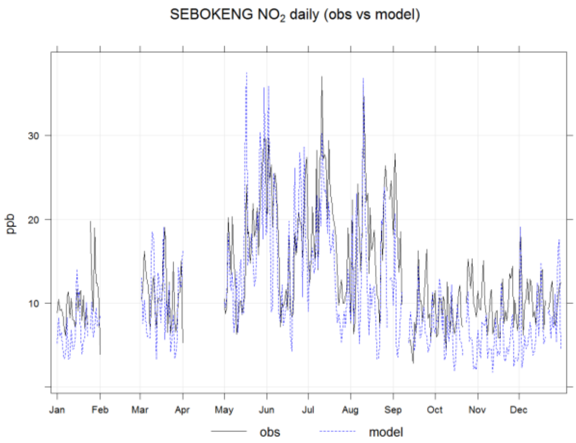
mean and 95% confidence interval in mean

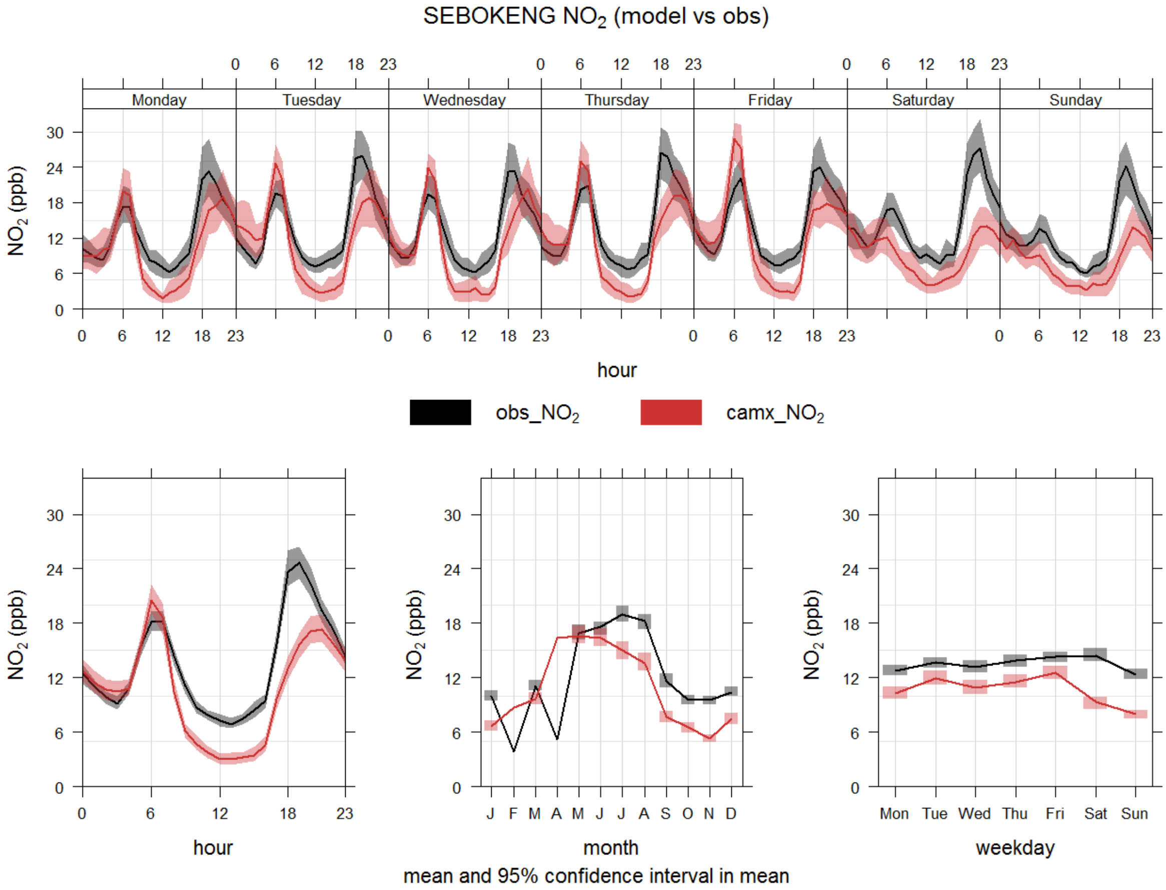

RANDWATER NO$_2$ observations
ppb
0
50
100
150
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

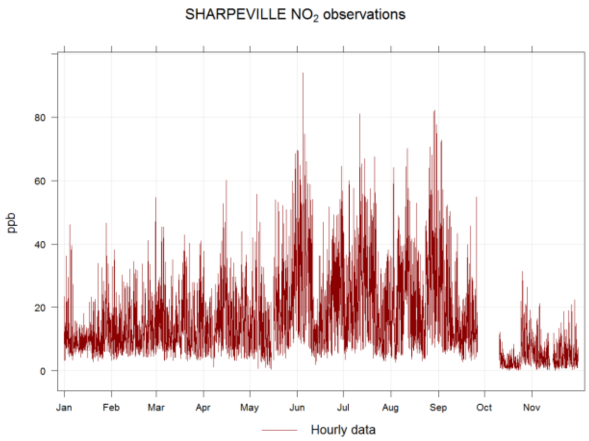

RANDWATER NO$_2$ daily (obs vs model)
ppb
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

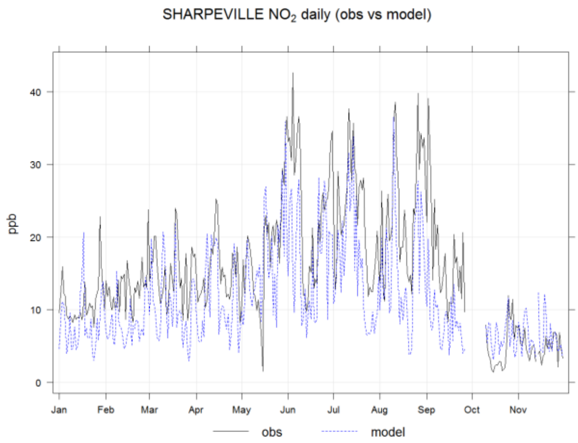

RANDWATER NO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO$_2$ (ppb)
0
4
8
12
16
20
0
6
12
18
23
hour
obs_NO$_2$
camx_NO$_2$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

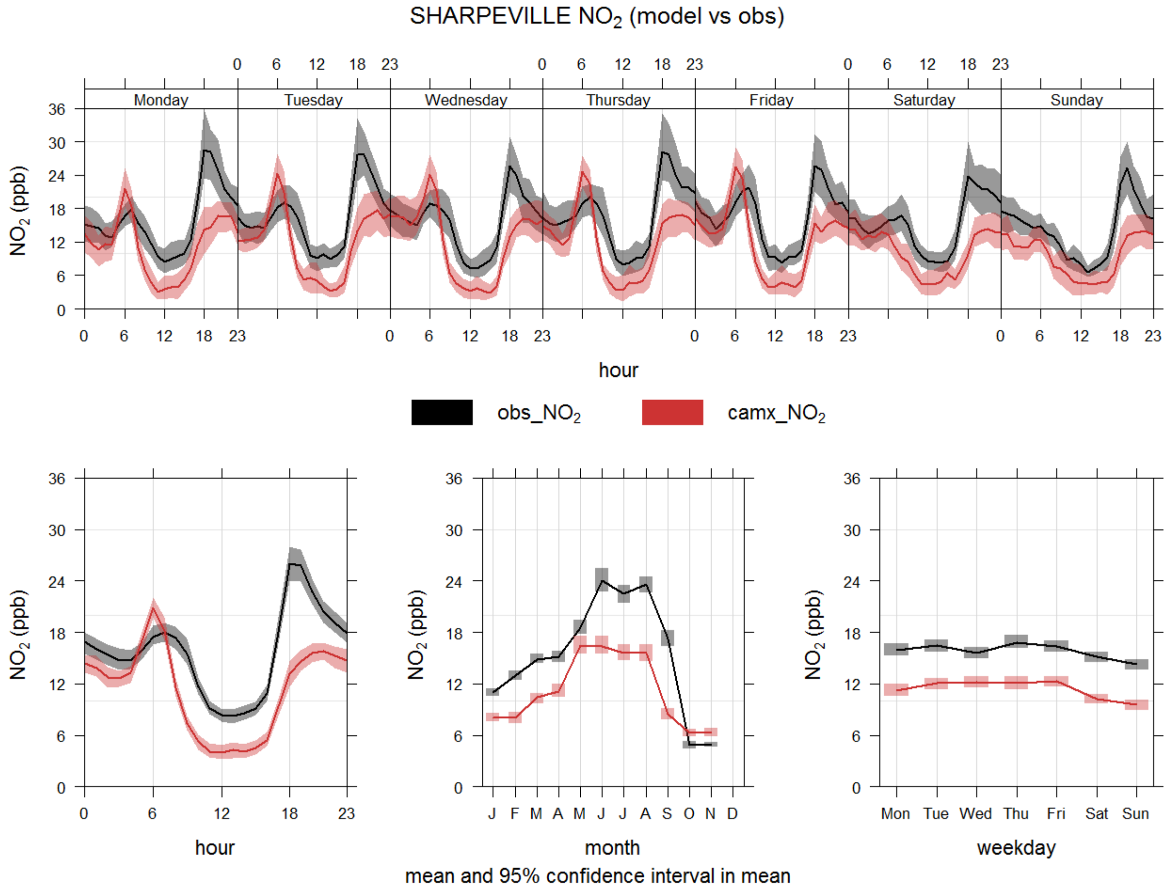

SEBOKENG NO$_2$ observations
ppb
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

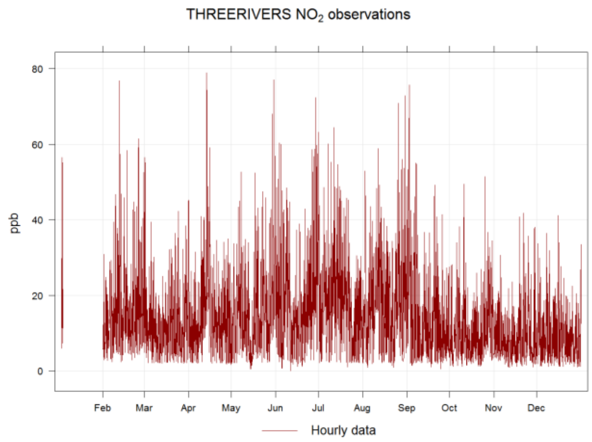

SEBOKENG NO$_2$ daily (obs vs model)
ppb
30
20
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

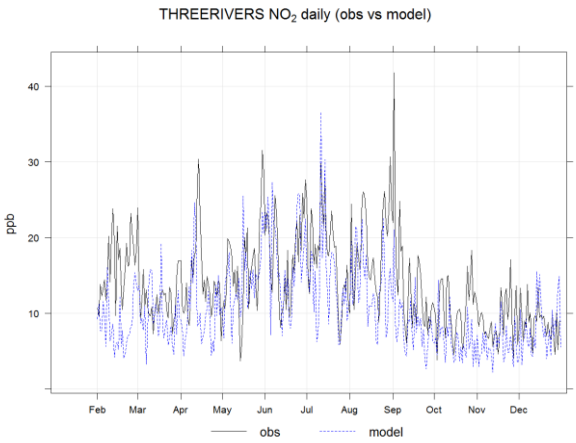

SEBOKENG NO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO$_2$ (ppb)
0
6
12
18
24
30
0
6
12
18
23
hour
obs_NO$_2$
camx_NO$_2$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

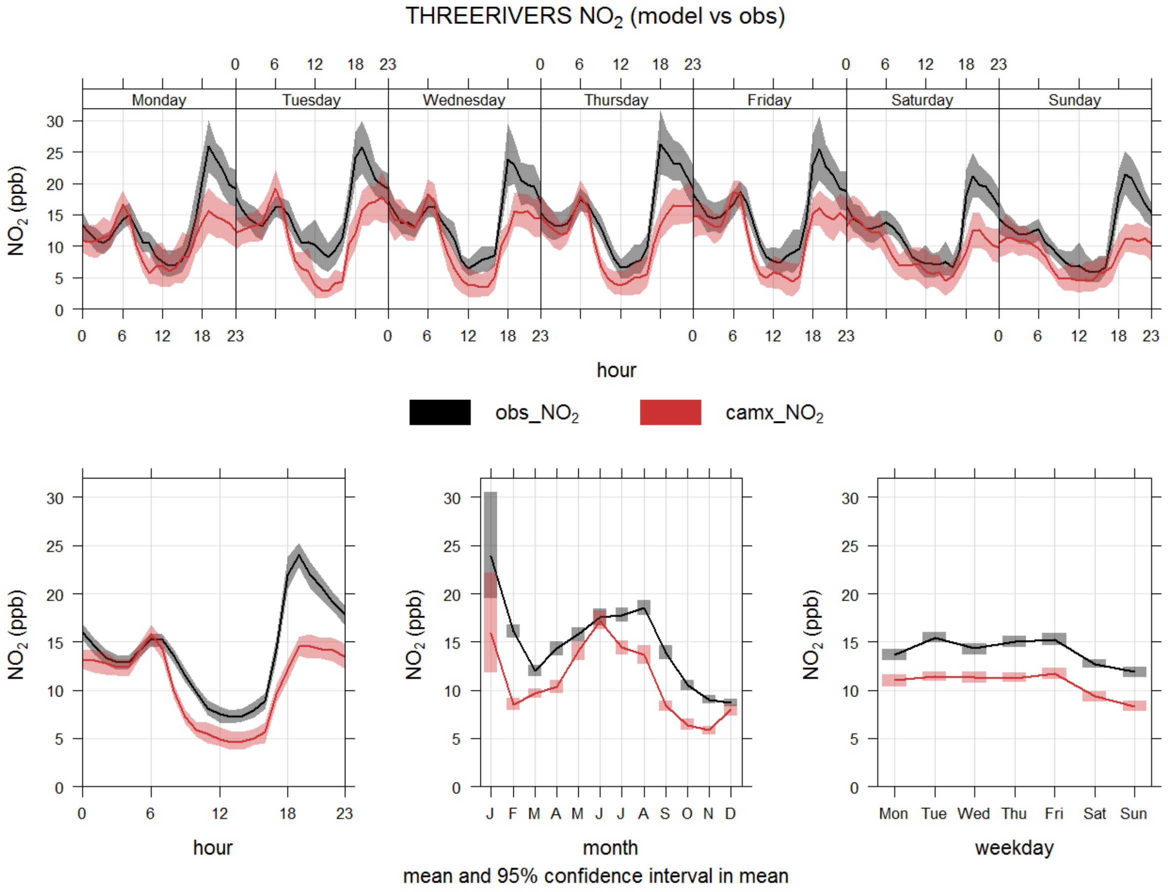

SHARPEVILLE NO_2 observations
ppb
0
20
40
60
80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Hourly data

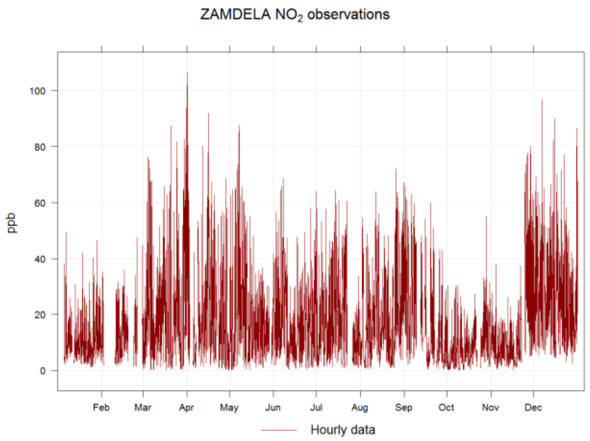

SHARPEVILLE NO_2 daily (obs vs model)
ppb
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
obs
model

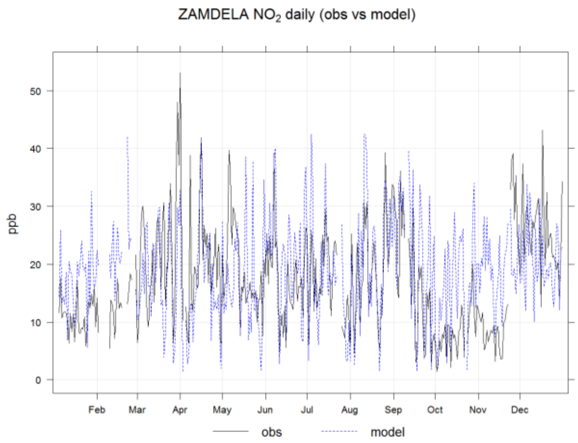

SHARPEVILLE NO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
NO_2 (ppb)
0
6
12
18
23
0
6
12
18
24
30
36
hour
obs_NO_2
camx_NO_2
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

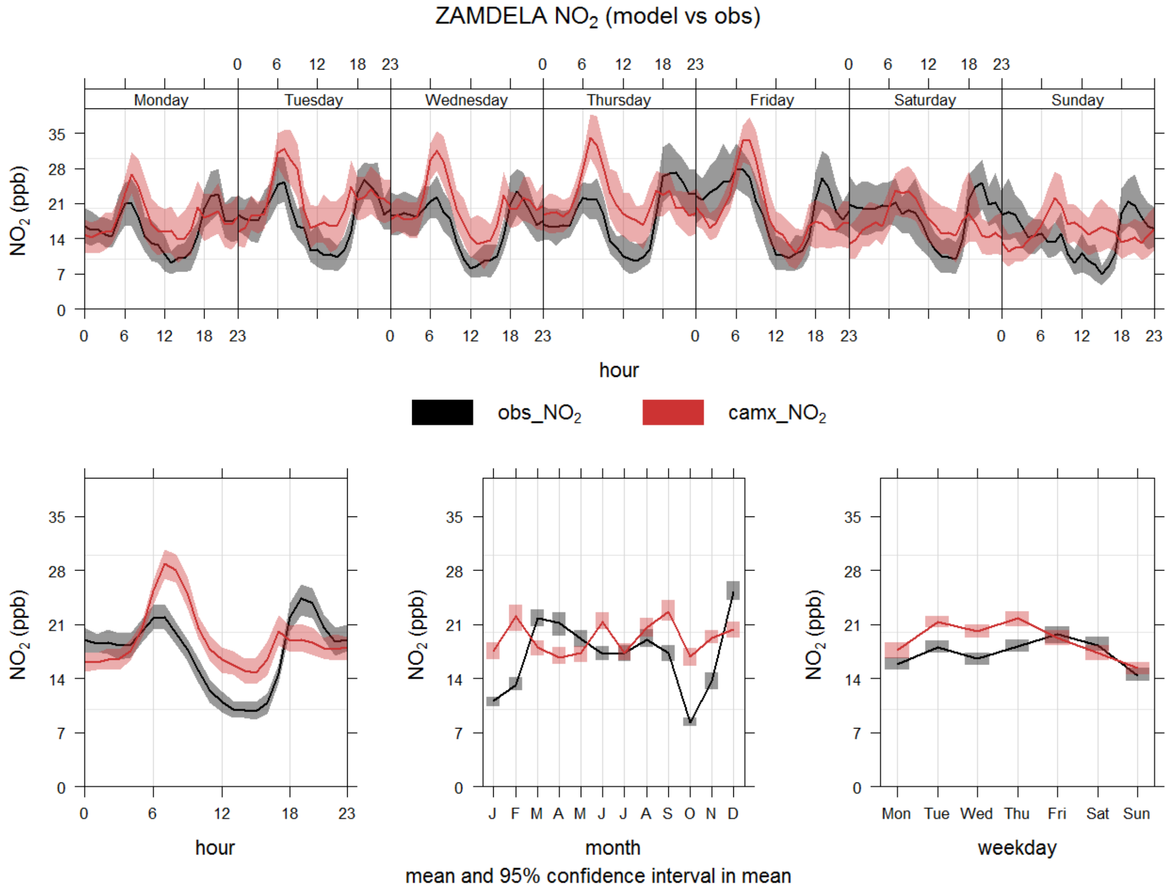

THREERIVERS NO_2 observations
ppb
0
20
40
60
80
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

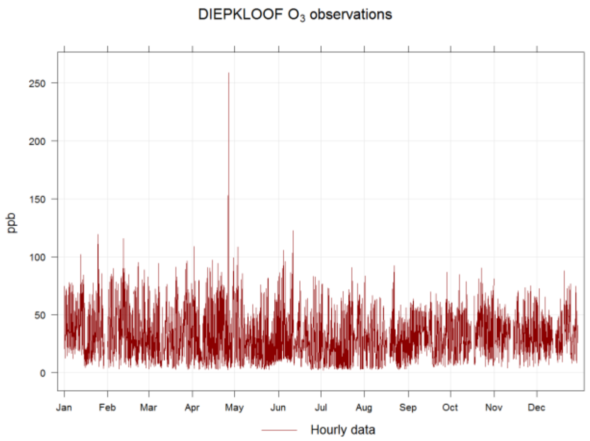

THREERIVERS NO_2 daily (obs vs model)
ppb
10
20
30
40
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

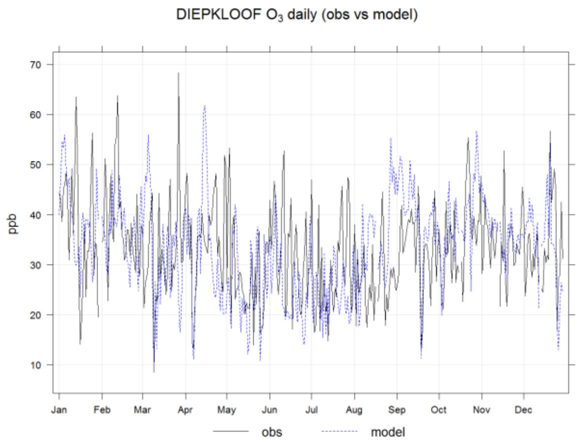

THREERIVERS NO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0 6 12 18 23
NO_2 (ppb)
0
5
10
15
20
25
30
hour
obs_NO_2
camx_NO_2
hour
month
J F M A M J J A S O N D
weekday
Mon Tue Wed Thu Fri Sat Sun
mean and 95% confidence interval in mean

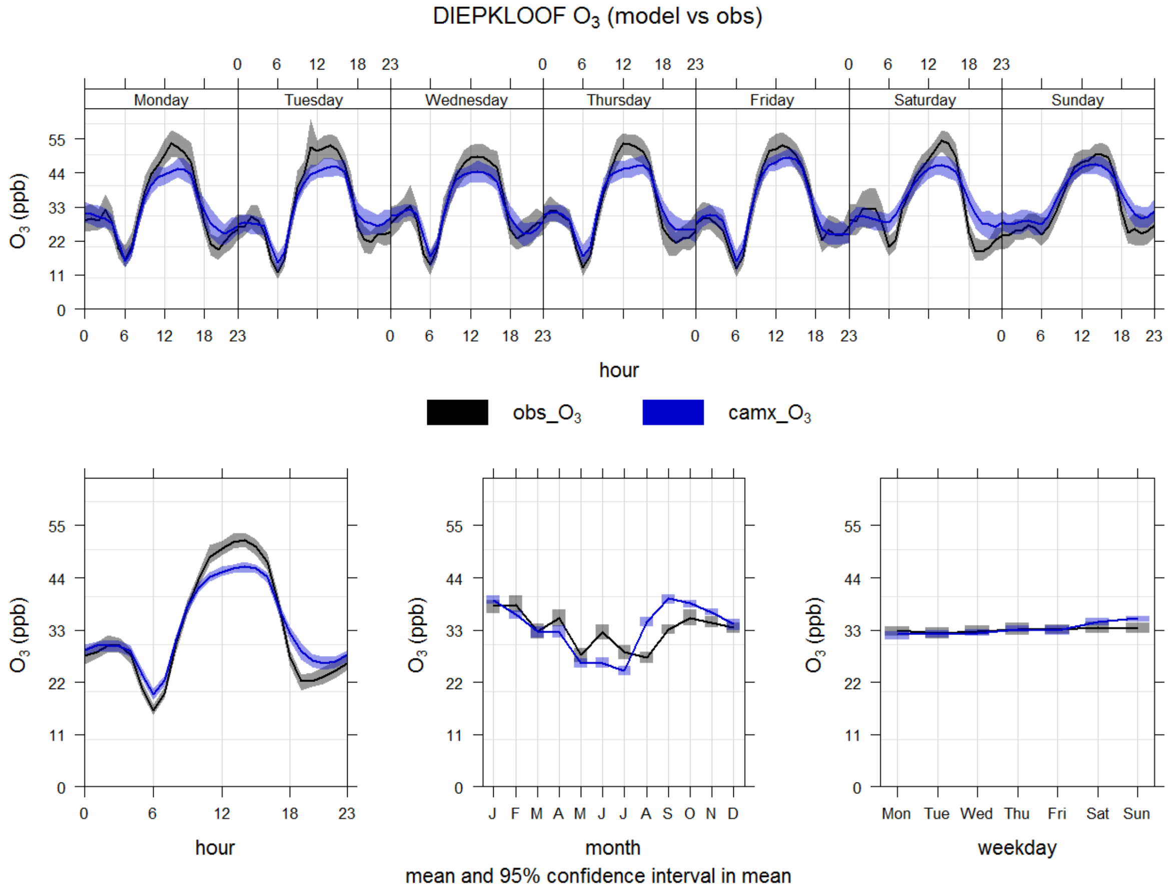

ZAMDELA NO_2 observations
ppb
0
20
40
60
80
100
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

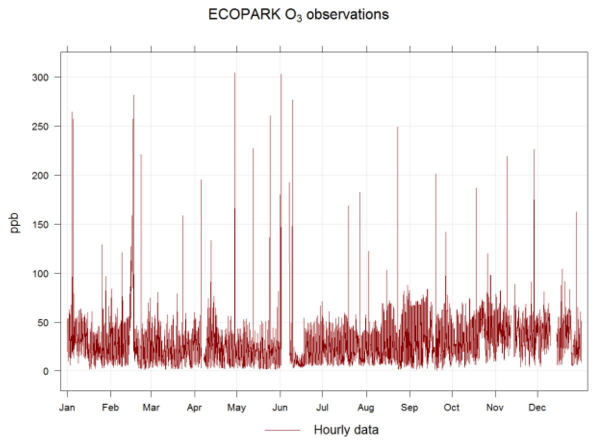

ZAMDELA NO_2 daily (obs vs model)
ppb
0
10
20
30
40
50
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

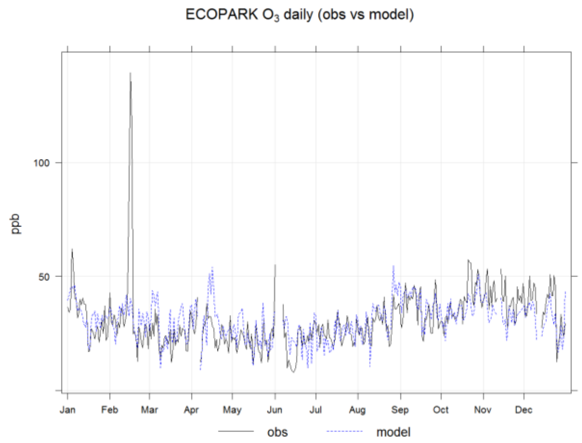

ZAMDELA NO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
NO_2 (ppb)
0
7
14
21
28
35
hour
obs_NO_2
camx_NO_2
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

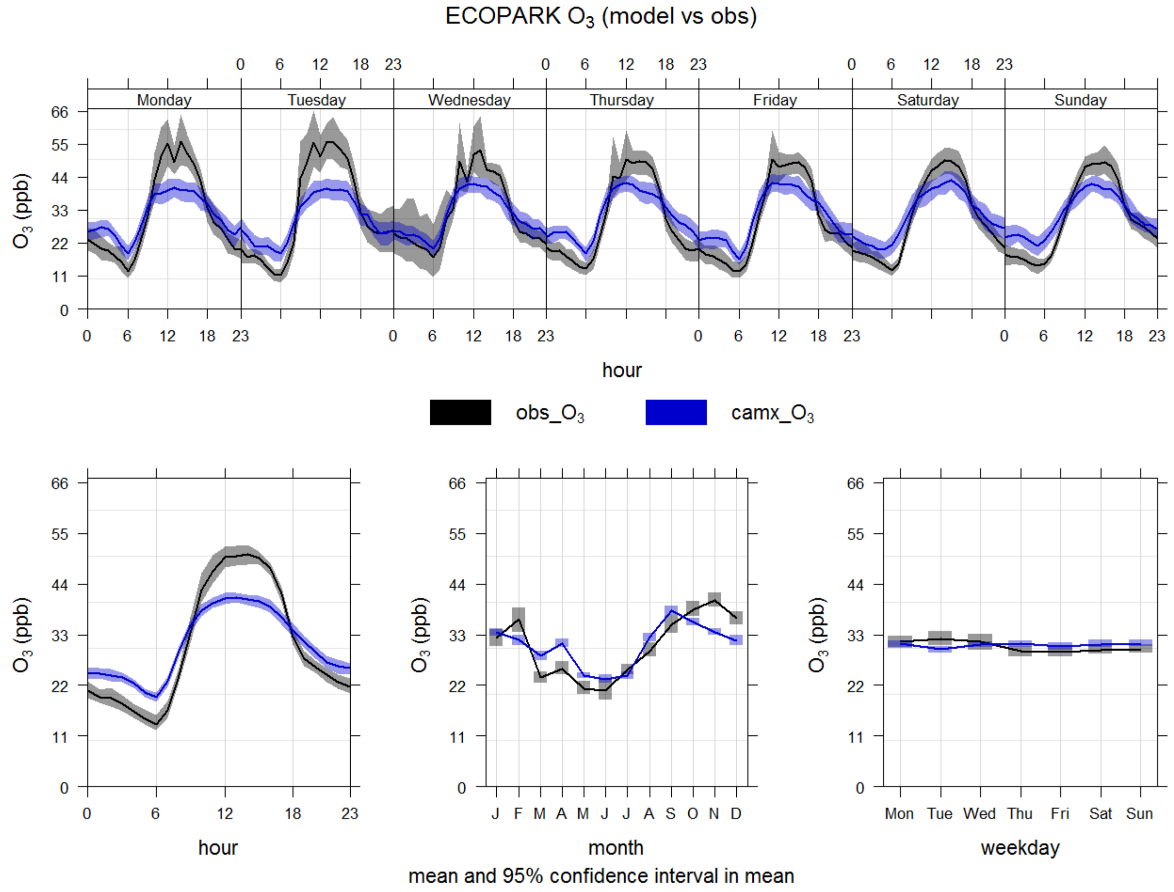

DIEPKLOOF O_3 observations
ppb
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

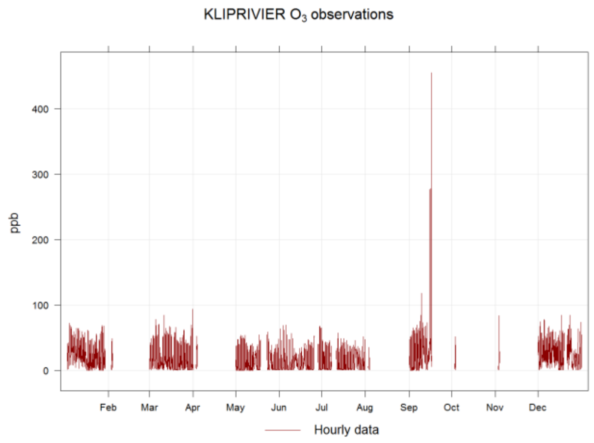

DIEPKLOOF O_3 daily (obs vs model)
ppb
70
60
50
40
30
20
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

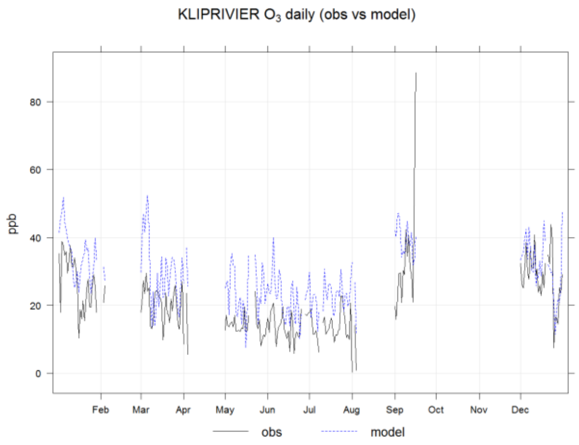

DIEPKLOOF O_3 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0 6 12 18 23
O_3 (ppb)
0
11
22
33
44
55
hour
obs_O_3
camx_O_3
hour
month
J F M A M J J A S O N D
weekday
Mon Tue Wed Thu Fri Sat Sun
mean and 95% confidence interval in mean

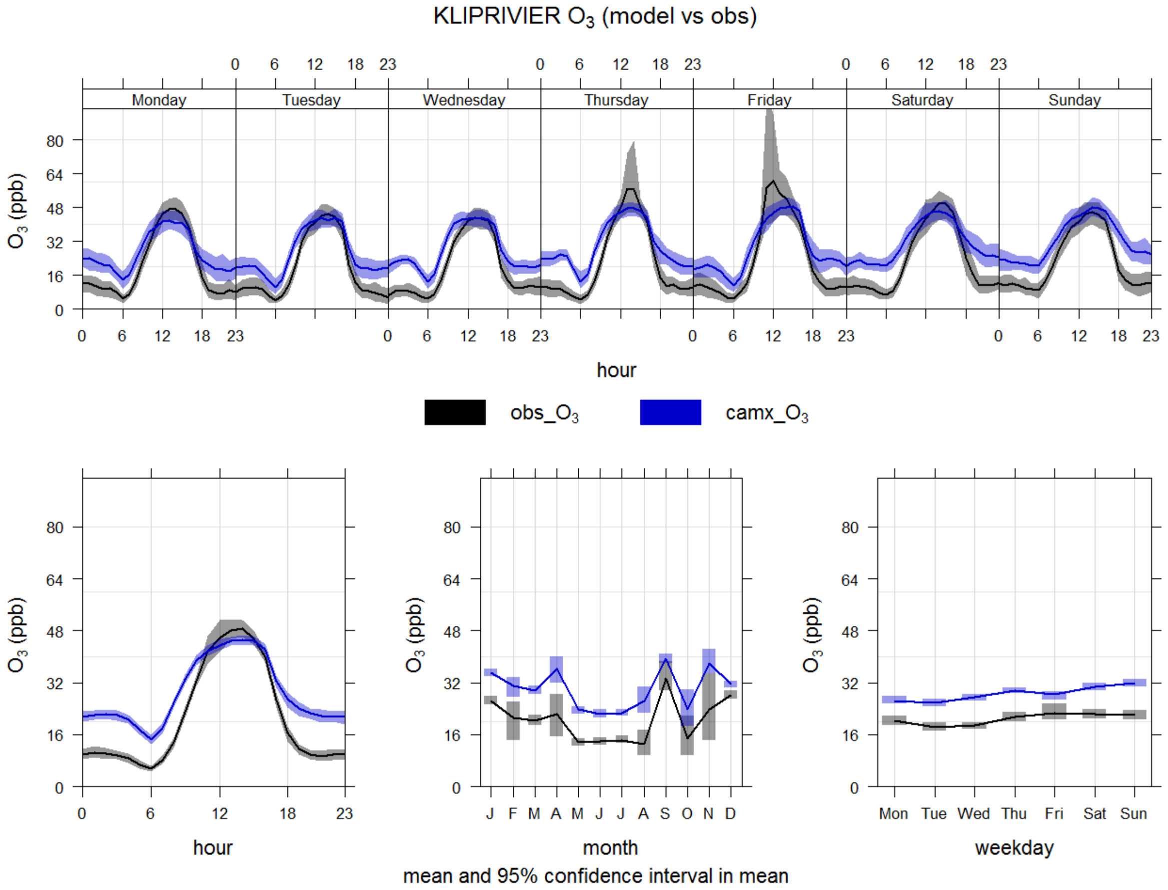

ECOPARK O_3 observations
ppb
300
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data


ECOPARK O_3 daily (obs vs model)
ppb
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

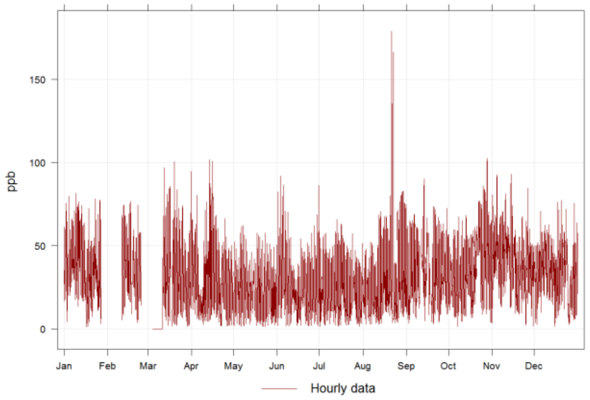

ECOPARK O_3 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
O_3 (ppb)
66
55
44
33
22
11
0
0
6
12
18
23
hour
obs_O_3
camx_O_3
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean


KLIPRIVIER O_3 observations

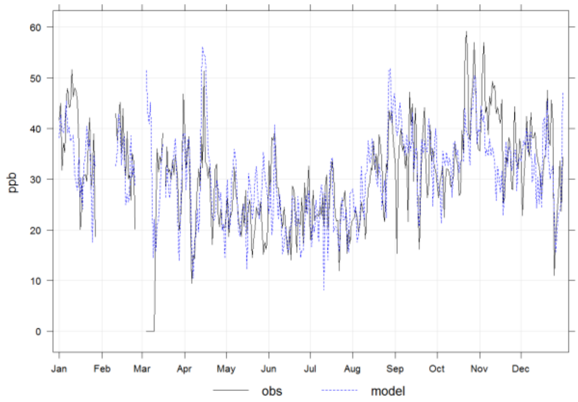

KLIPRIVIER O_3 daily (obs vs model)


KLIPRIVIER O_3 (model vs obs)

mean and 95% confidence interval in mean

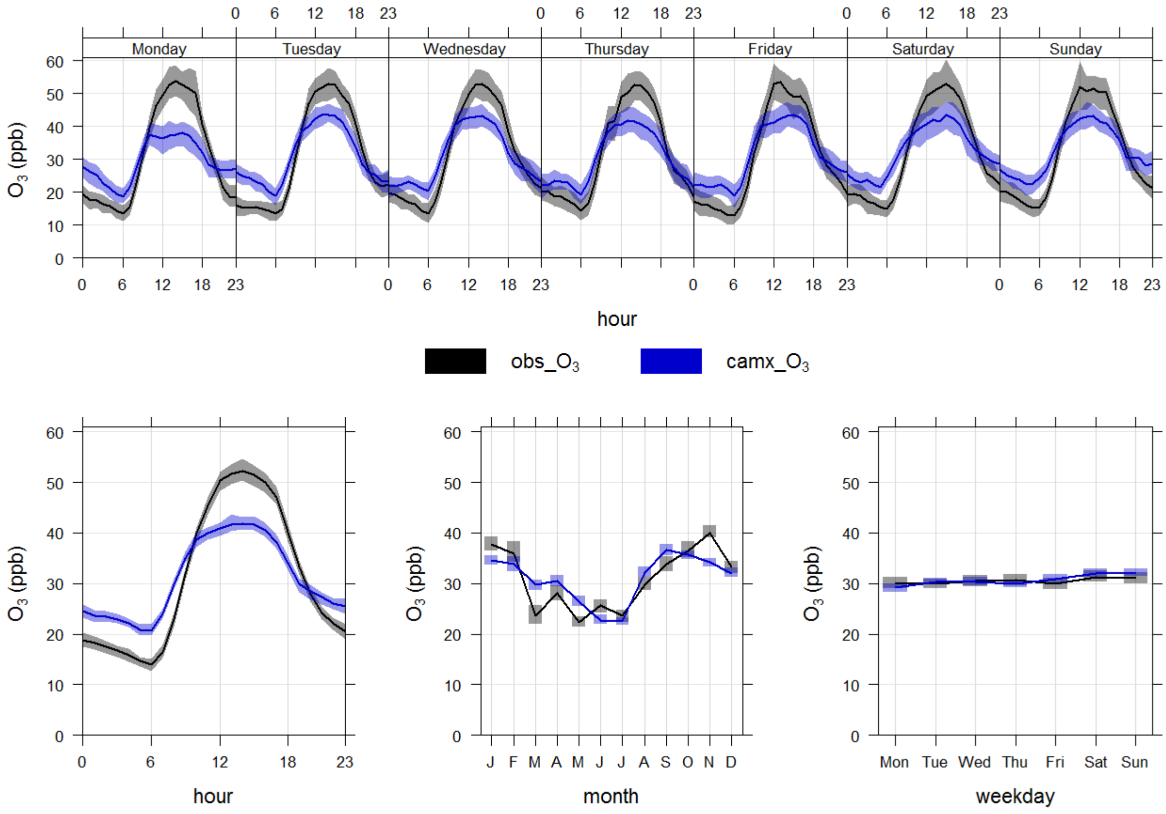


RANDWATER O_3 observations

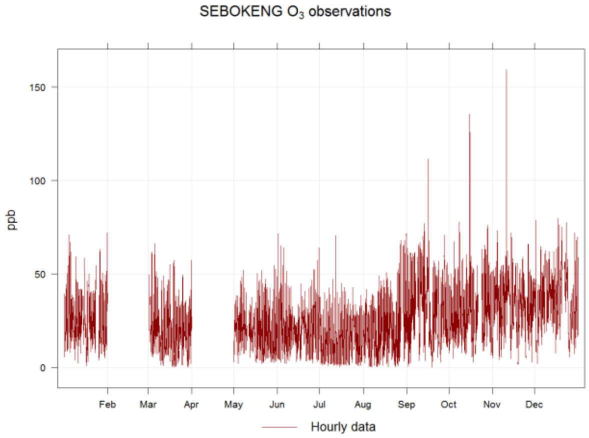


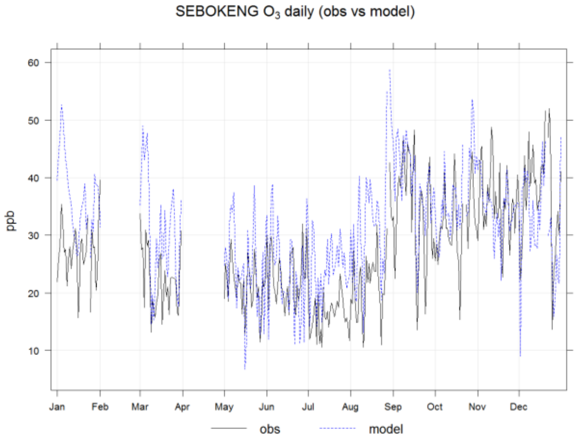
RANDWATER O_3 daily (obs vs model)

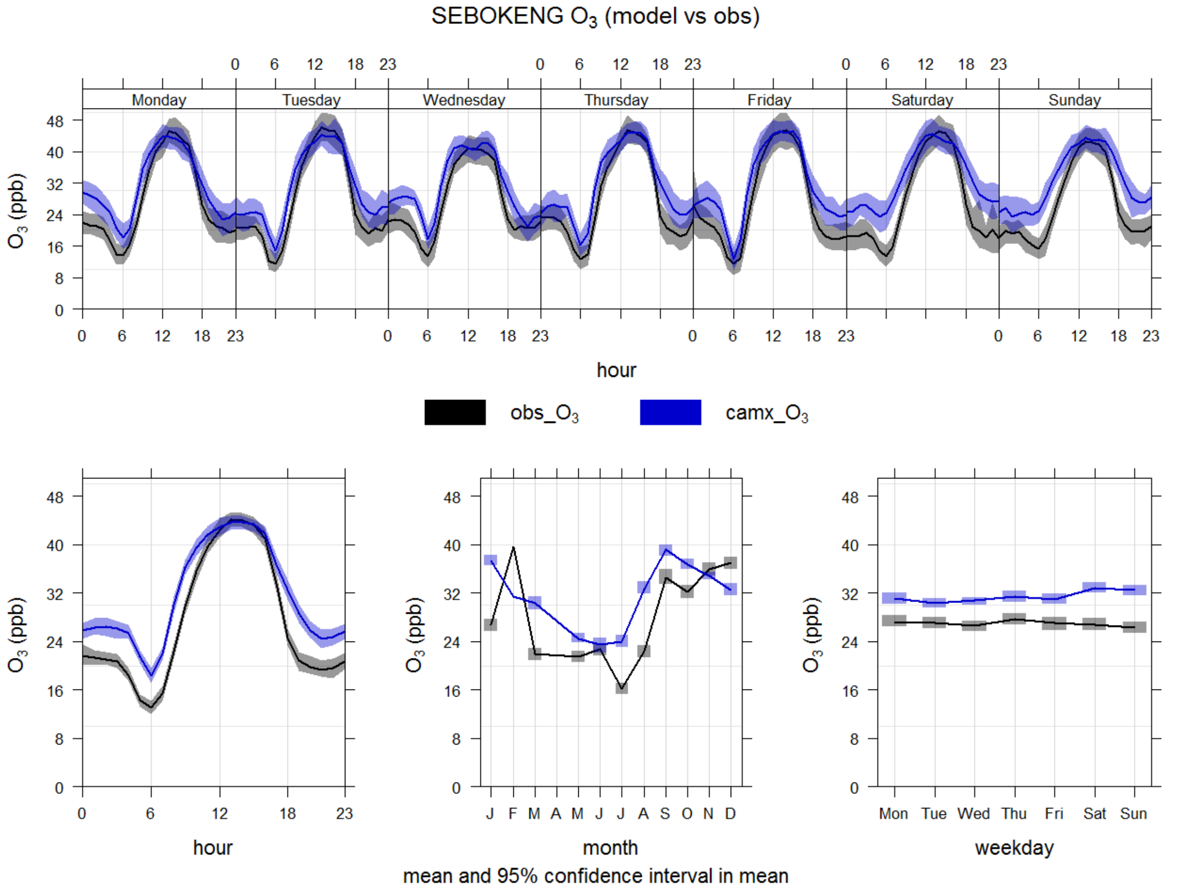
RANDWATER O_3 (model vs obs)

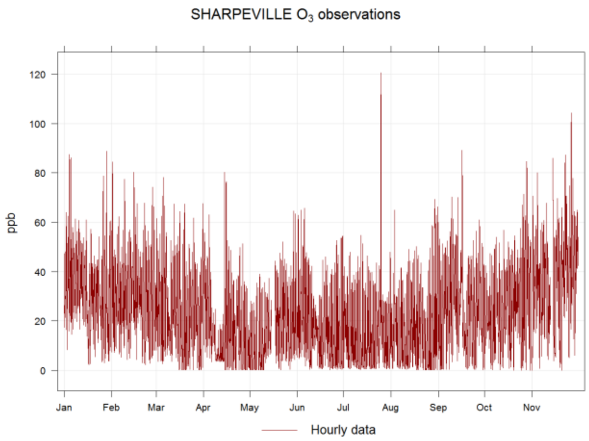


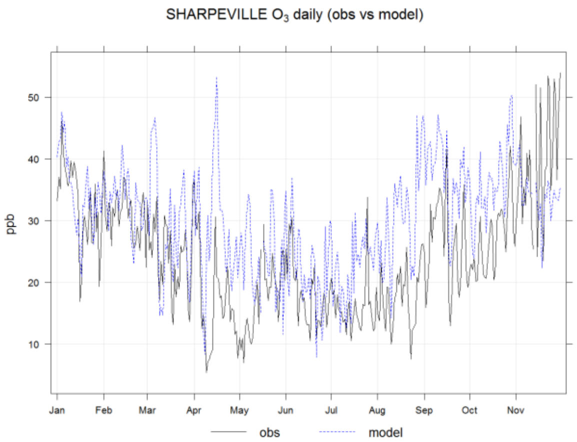
mean and 95% confidence interval in mean


SEBOKENG O$_3$ observations
ppb
150
100
50
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

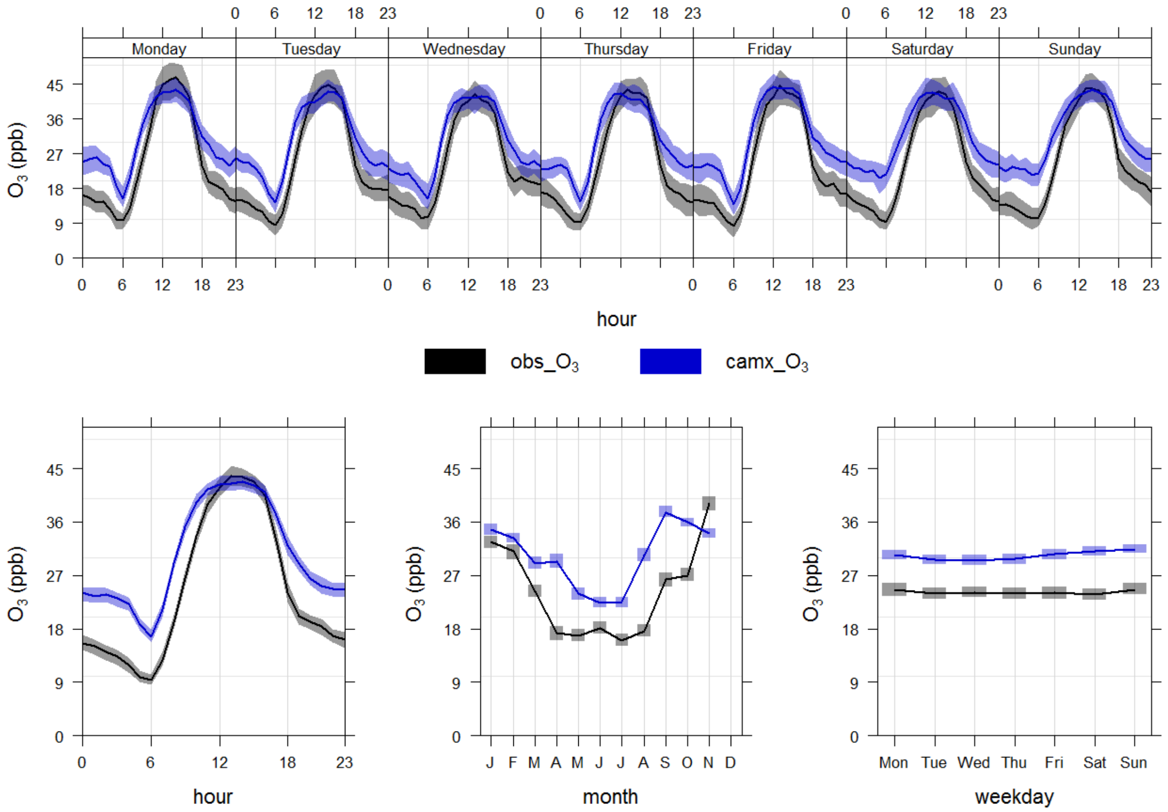

SEBOKENG O$_3$ daily (obs vs model)
ppb
60
50
40
30
20
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model


SEBOKENG O$_3$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
O$_3$ (ppb)
48
40
32
24
16
8
0
hour
obs_O$_3$
camx_O$_3$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

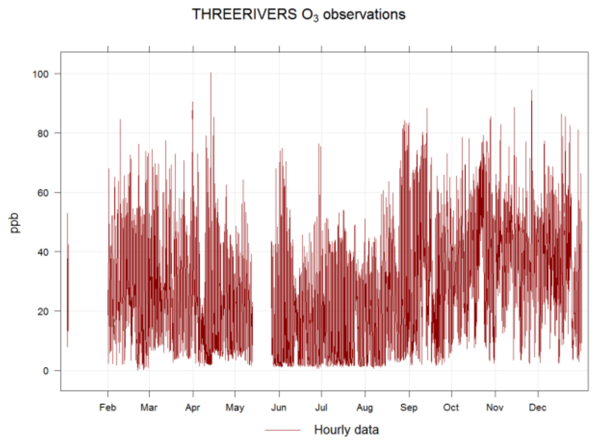

SHARPEVILLE O_3 observations

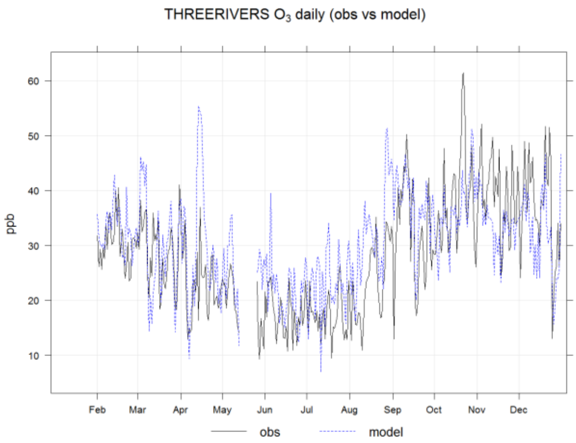

SHARPEVILLE O_3 daily (obs vs model)

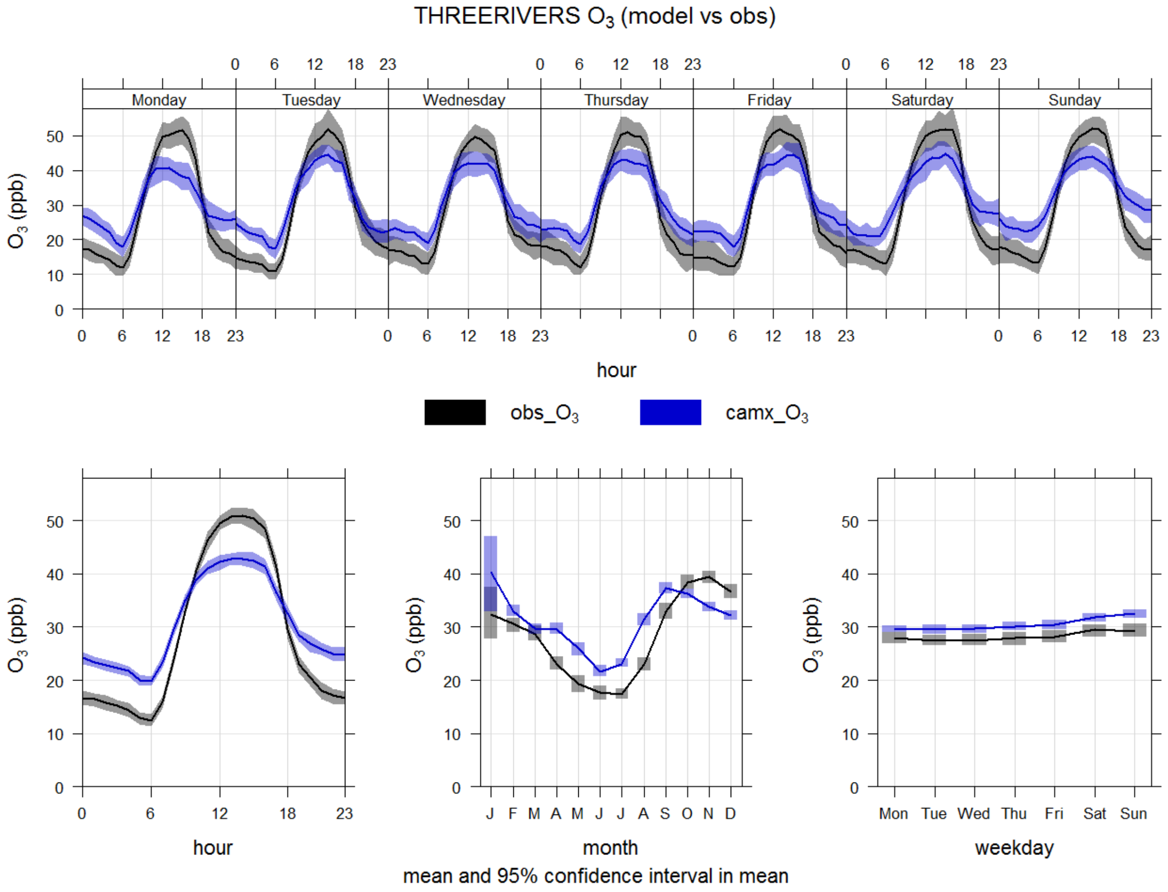
SHARPEVILLE O_3 (model vs obs)



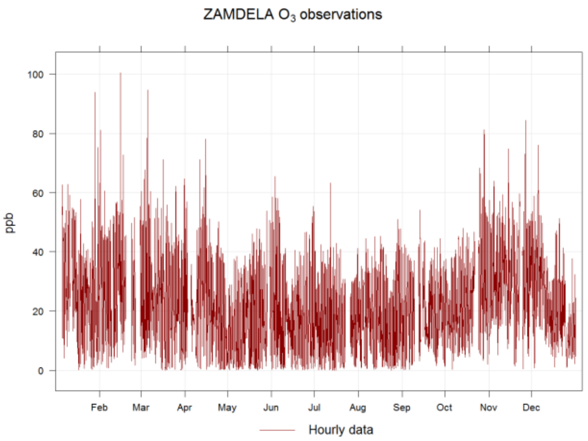
mean and 95% confidence interval in mean

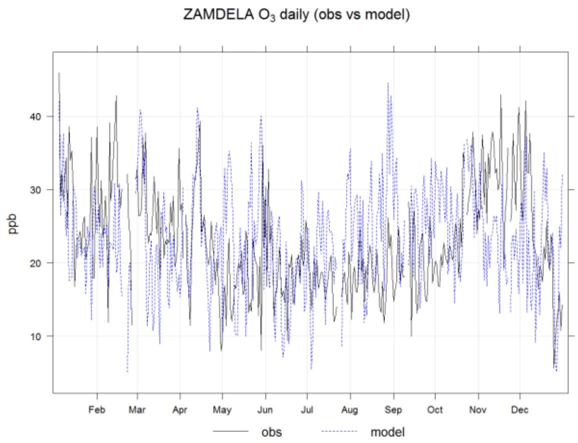

THREERIVERS O_3 observations

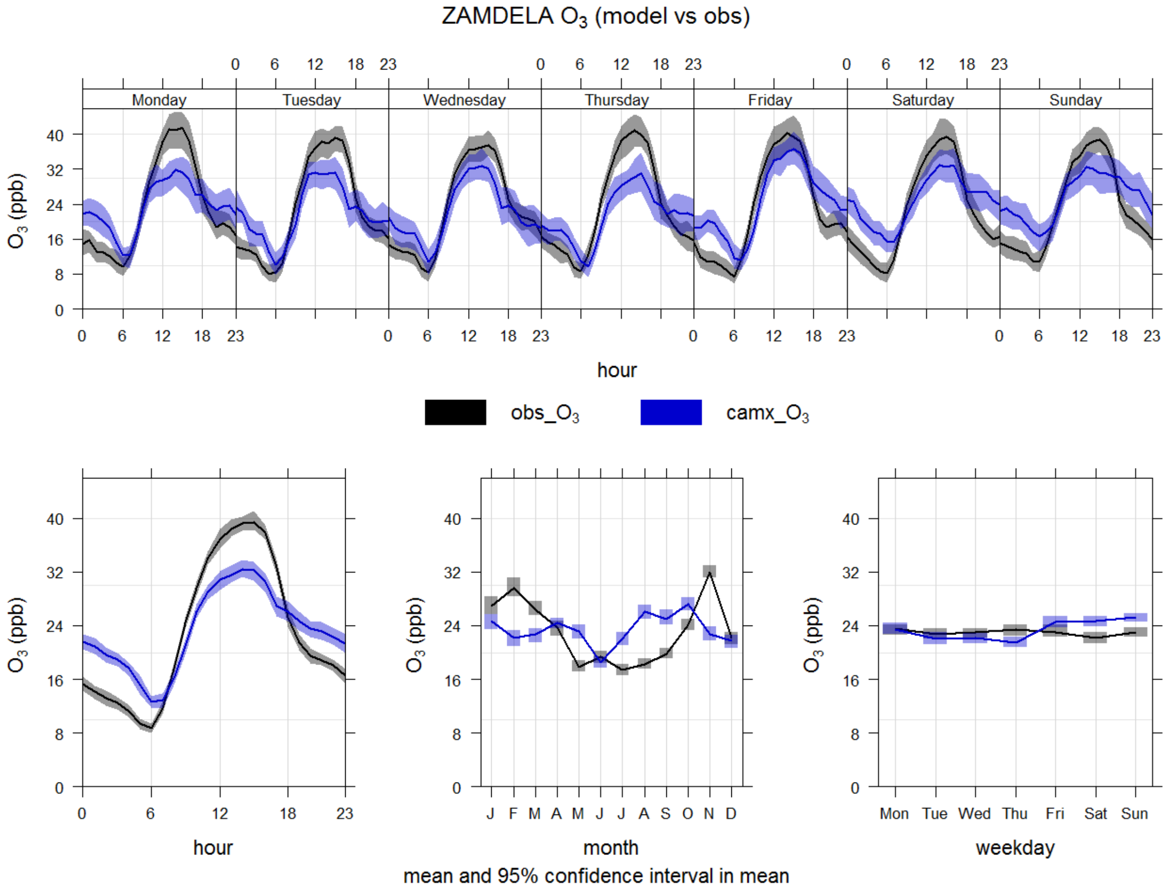

THREERIVERS O_3 daily (obs vs model)

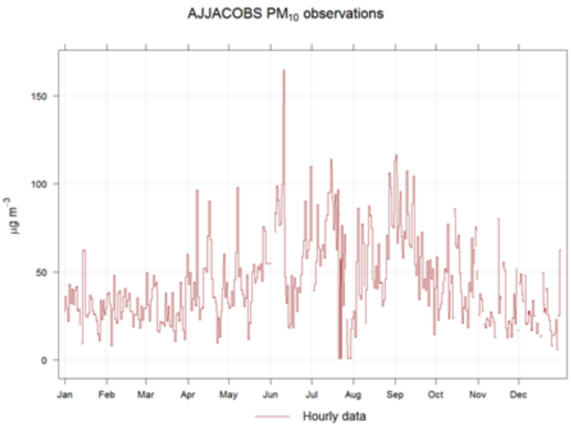

THREERIVERS O_3 (model vs obs)

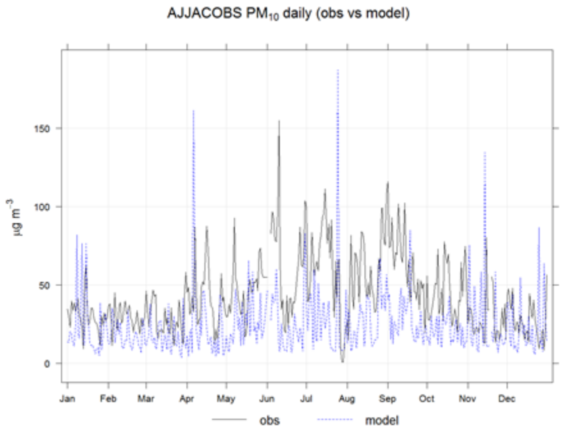
mean and 95% confidence interval in mean

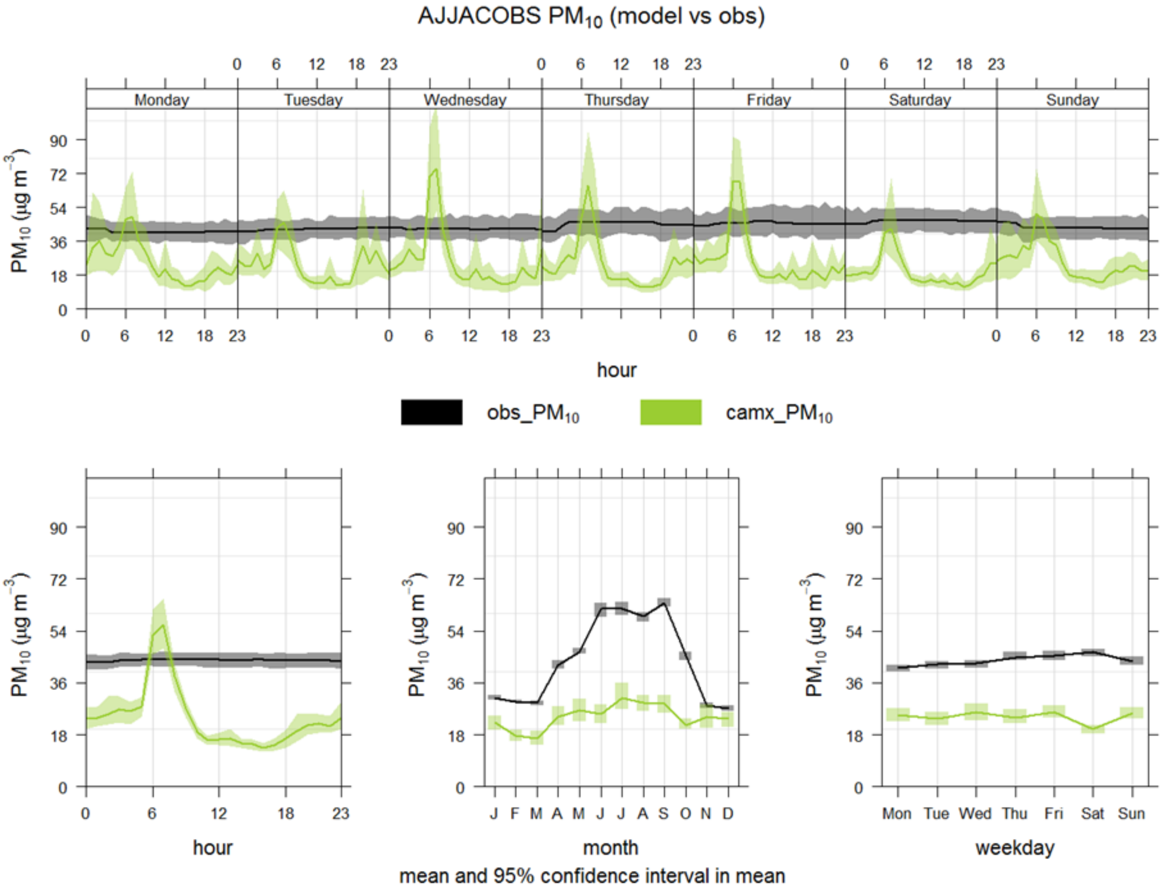

ZAMDELA O_3 observations
ppb
100
80
60
40
20
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

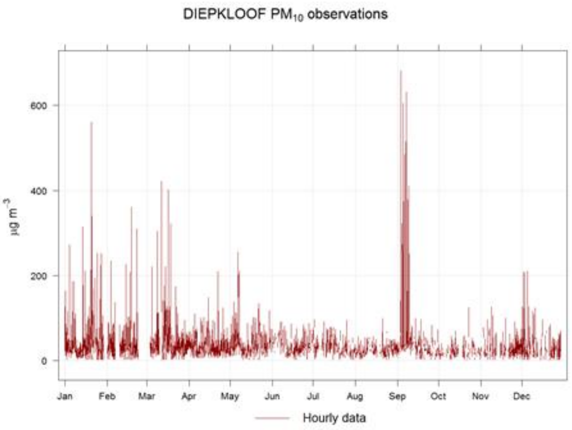

ZAMDELA O_3 daily (obs vs model)
ppb
40
30
20
10
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

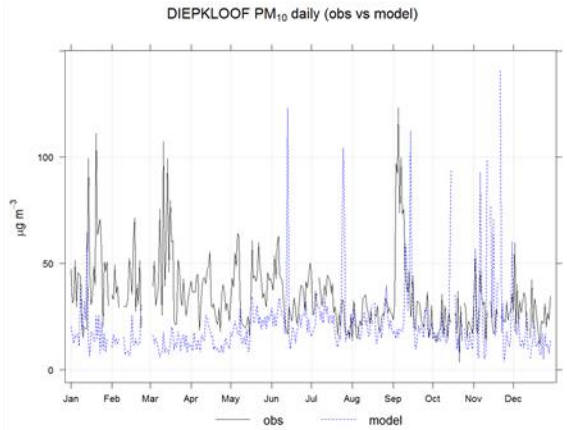

ZAMDELA O_3 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
O_3 (ppb)
40
32
24
16
8
0
hour
obs_O_3
camx_O_3
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

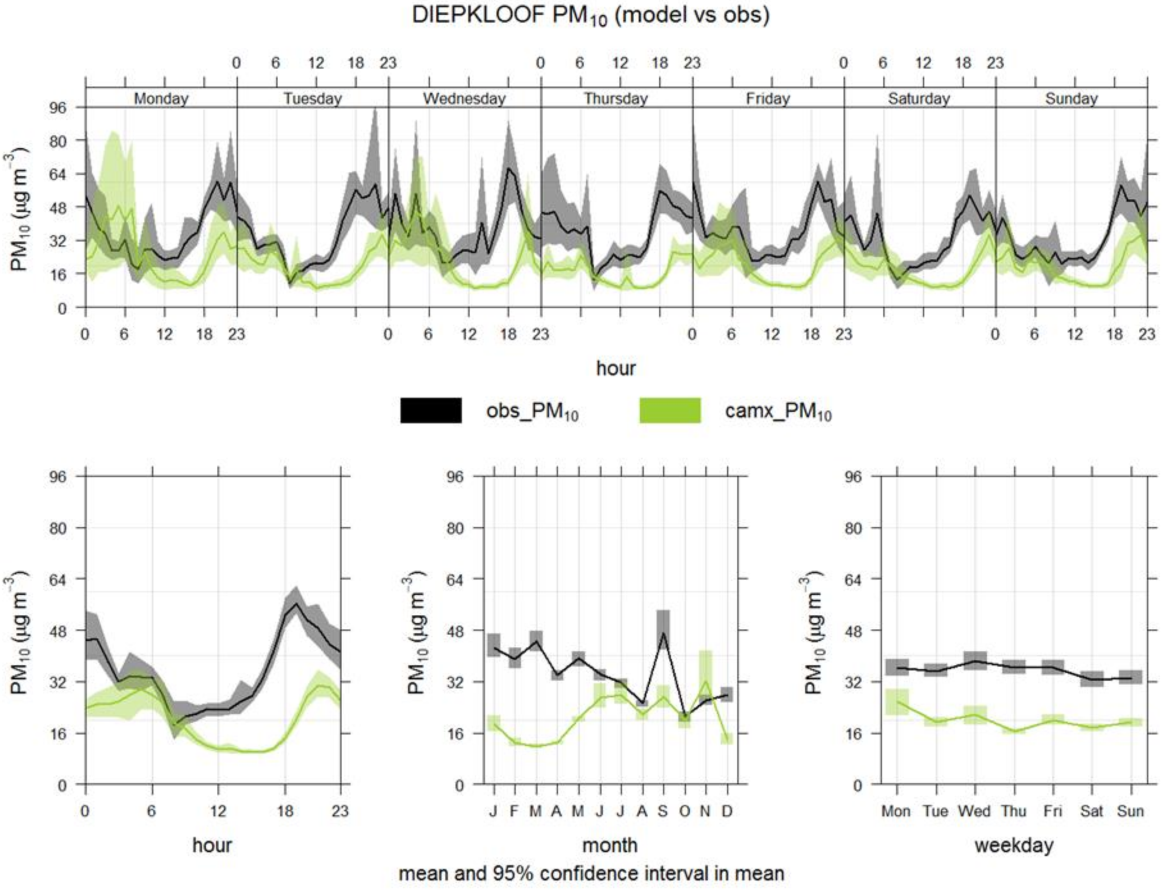

AJJACOBS PM$_{10}$ observations
µg m^{-3}
0
50
100
150
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Hourly data

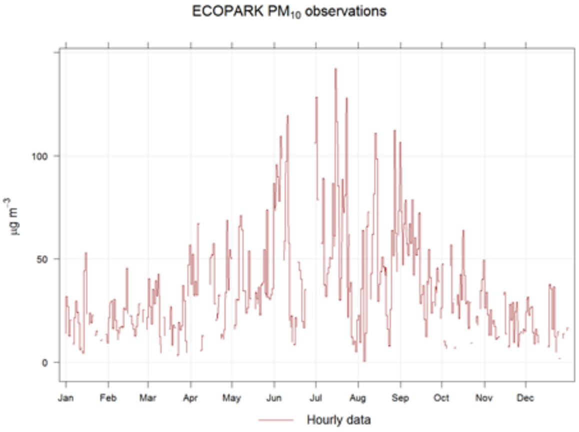

AJJACOBS PM$_{10}$ daily (obs vs model)
µg m^{-3}
0
50
100
150
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
obs
model

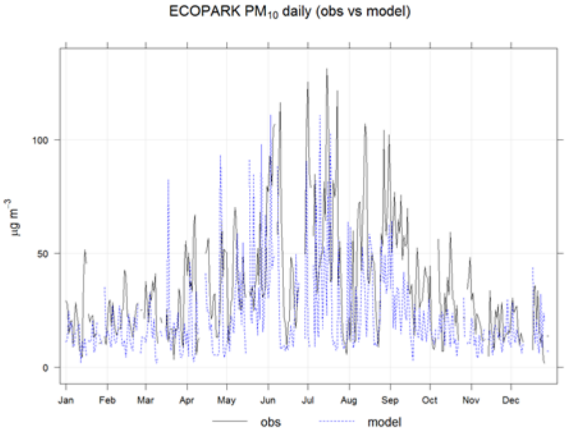

AJJACOBS PM$_{10}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
PM$_{10}$ (µg m^{-3})
0
18
36
54
72
90
0 6 12 18 23
hour
obs_PM$_{10}$
camx_PM$_{10}$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

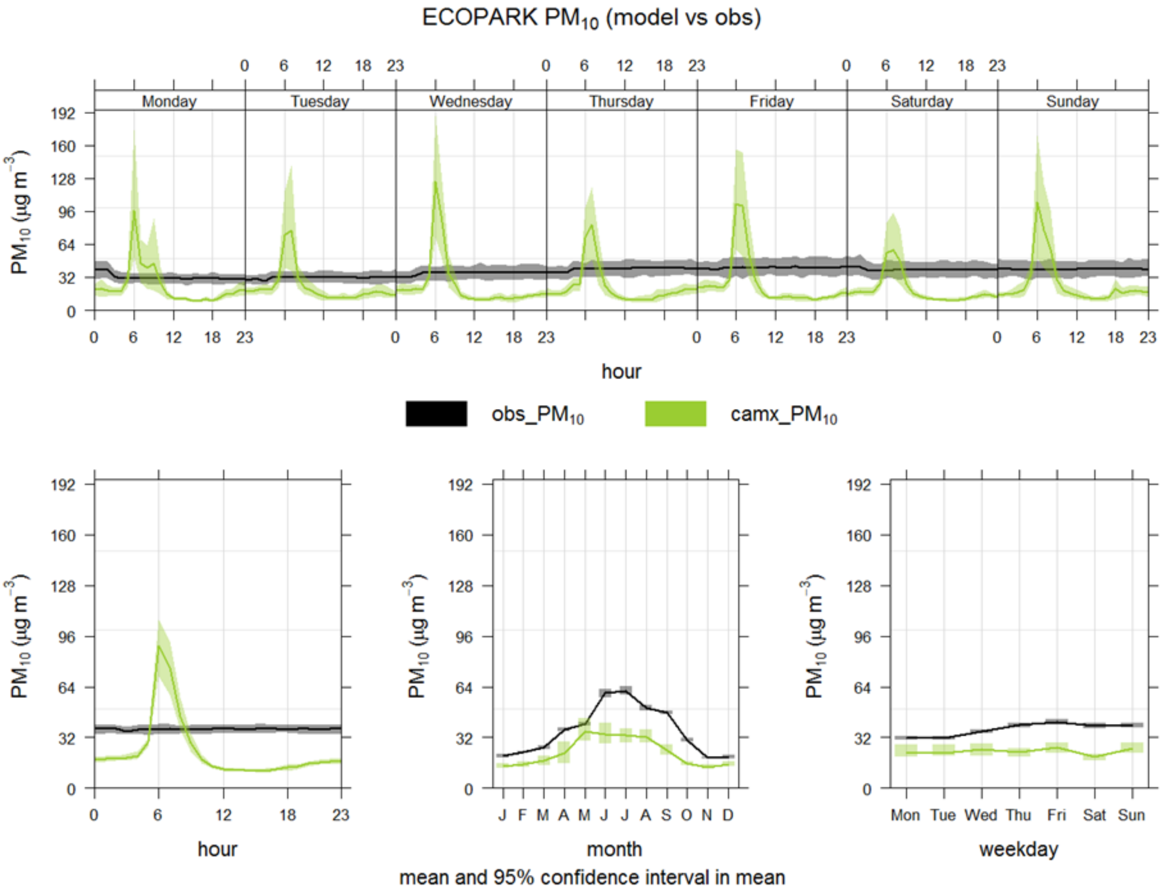

DIEPKLOOF PM_{10} observations
$\mu g\ m^{-3}$
0
200
400
600
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

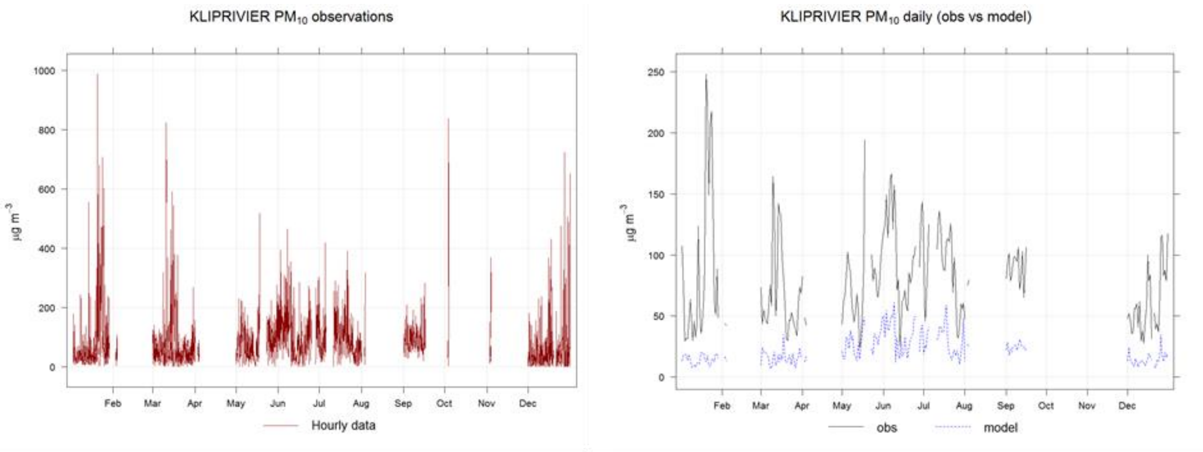

DIEPKLOOF PM_{10} daily (obs vs model)
$\mu g\ m^{-3}$
0
50
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

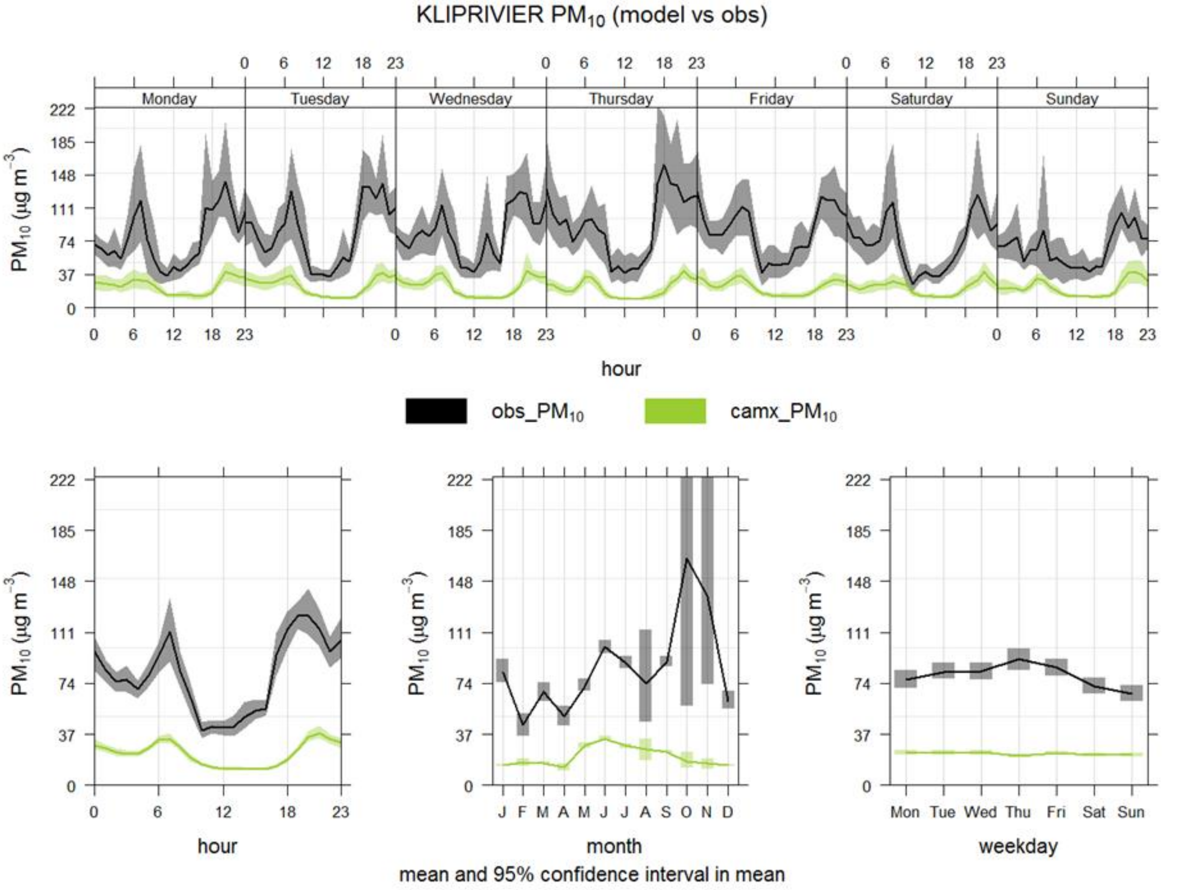

DIEPKLOOF PM_{10} (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM_{10} ($\mu g\ m^{-3}$)
0
16
32
48
64
80
96
hour
obs_PM_{10}
camx_PM_{10}
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

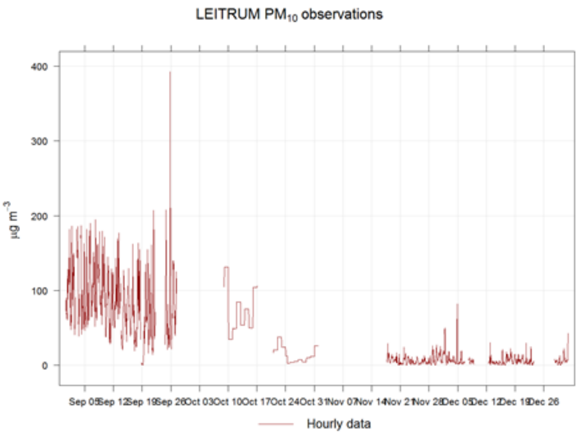

ECOPARK PM_{10} observations
μg m^{-3}
0
50
100
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Hourly data

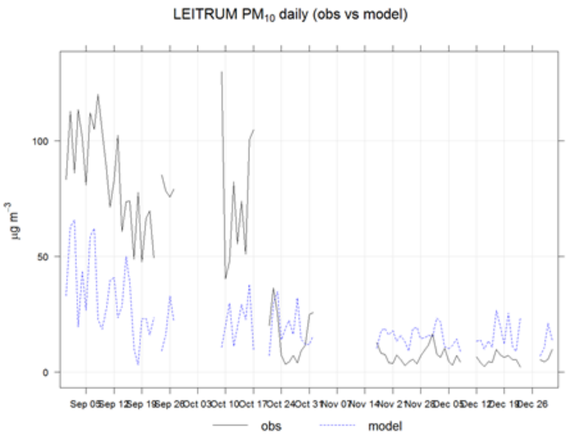

ECOPARK PM_{10} daily (obs vs model)
μg m^{-3}
0
50
100
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
obs
model

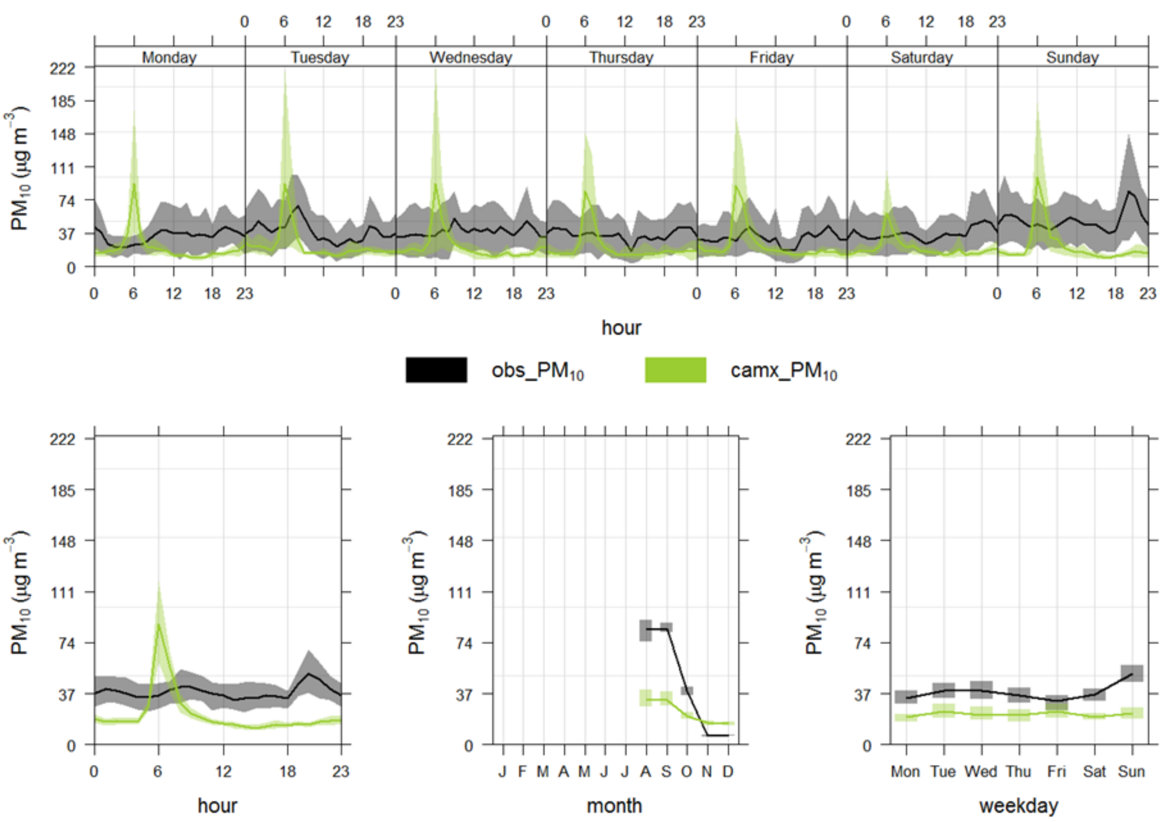

ECOPARK PM_{10} (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
PM_{10} (μg m^{-3})
0
32
64
96
128
160
192
0 6 12 18 23
hour
obs_PM_{10}
camx_PM_{10}
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean


KLIPRIVIER PM_{10} observations
µg m^{-3}
1000
800
600
400
200
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data
KLIPRIVIER PM_{10} daily (obs vs model)
µg m^{-3}
250
200
150
100
50
0
obs
model

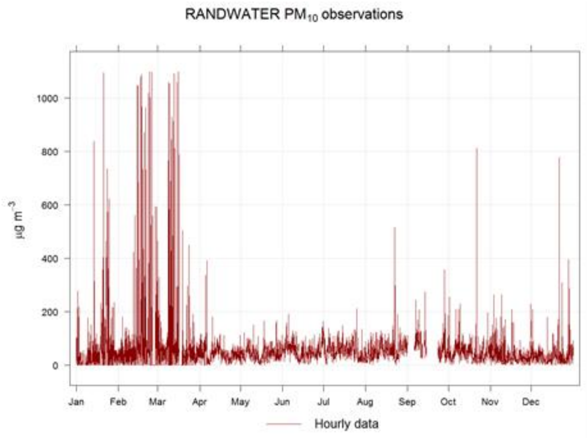

KLIPRIVIER PM_{10} (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM_{10} (µg m^{-3})
222
185
148
111
74
37
0
hour
obs_PM_{10}
camx_PM_{10}
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

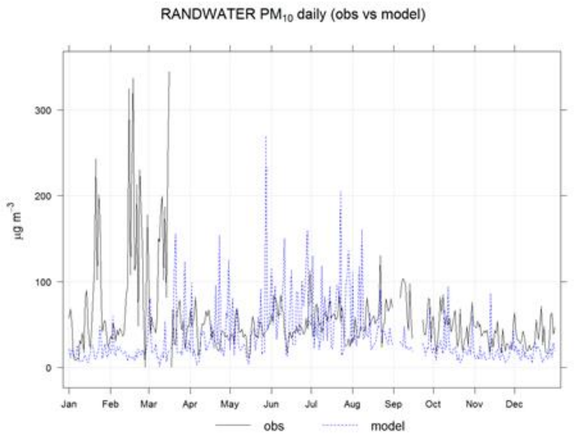

LEITRUM PM_{10} observations

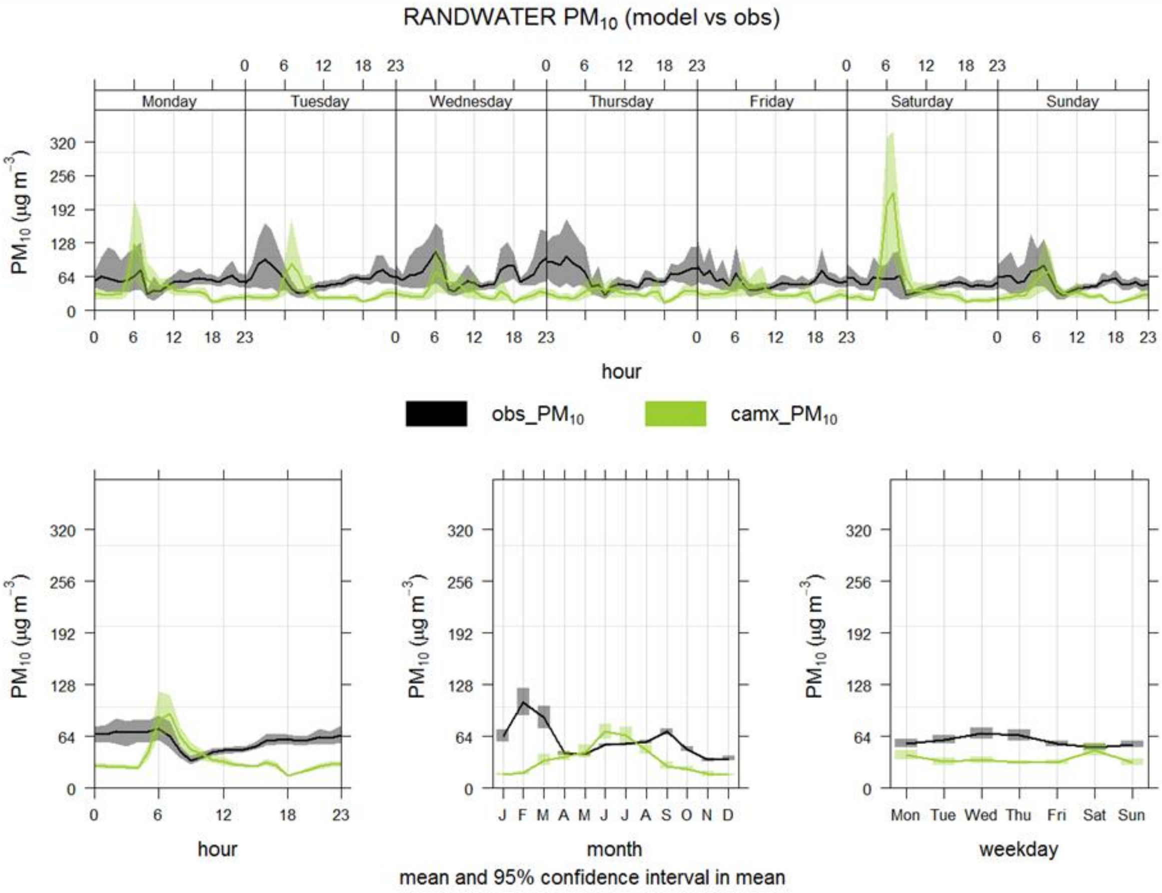

LEITRUM PM_{10} daily (obs vs model)

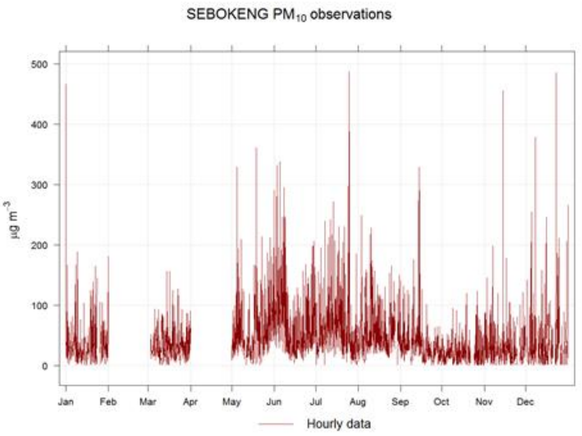

LEITRUM PM_{10} (model vs obs)

mean and 95% confidence interval in mean

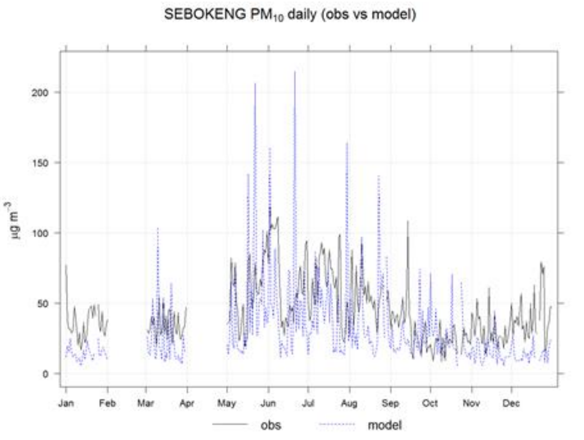

RANDWATER PM_{10} observations
µg m^{-3}
0
200
400
600
800
1000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data


RANDWATER PM_{10} daily (obs vs model)
µg m^{-3}
0
100
200
300
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model


RANDWATER PM_{10} (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
PM_{10} (µg m^{-3})
0
64
128
192
256
320
0
6
12
18
23
hour
obs_PM_{10}
camx_PM_{10}
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

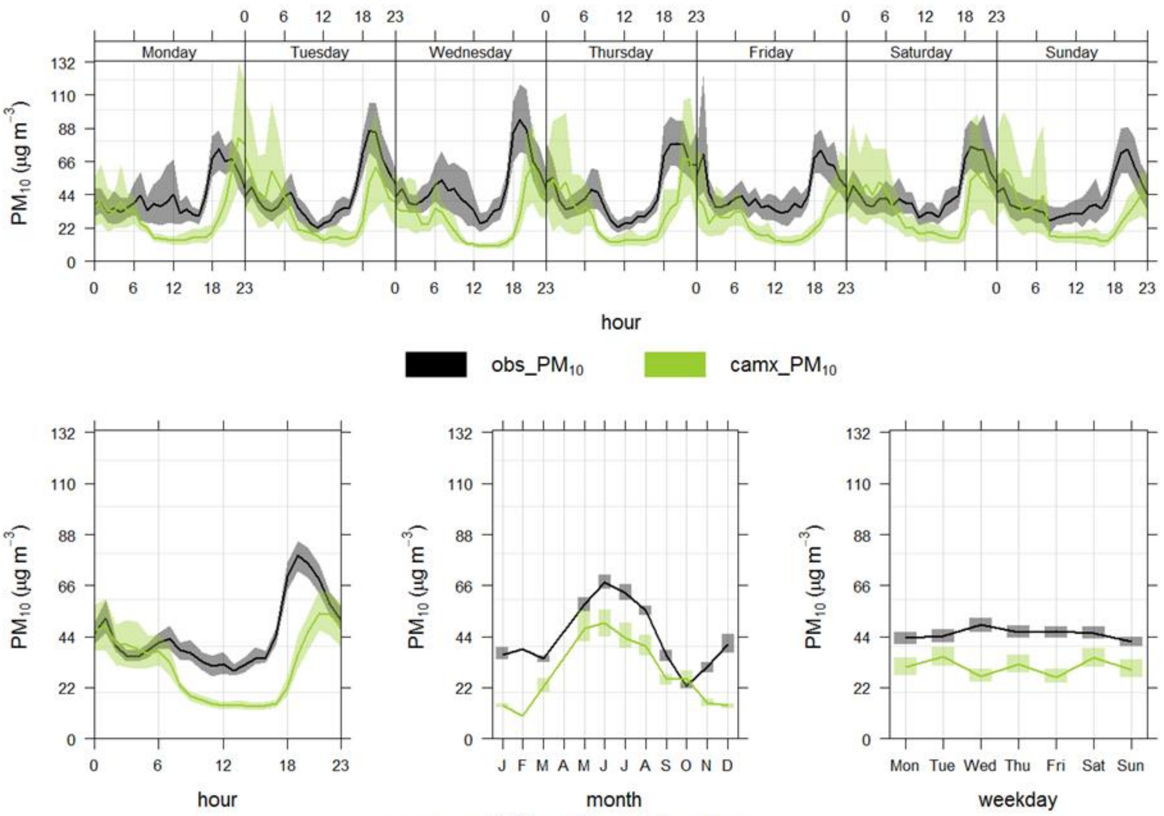


SEBOKENG PM_{10} observations

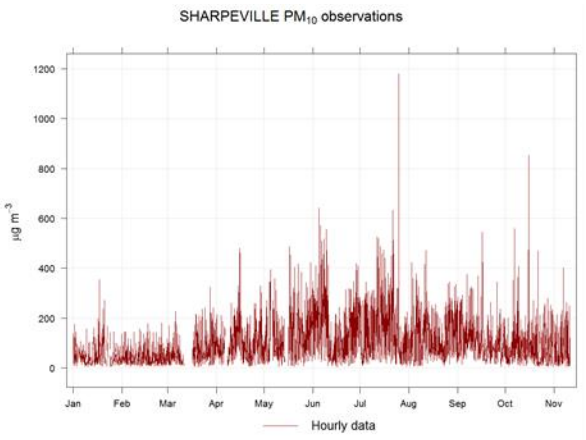


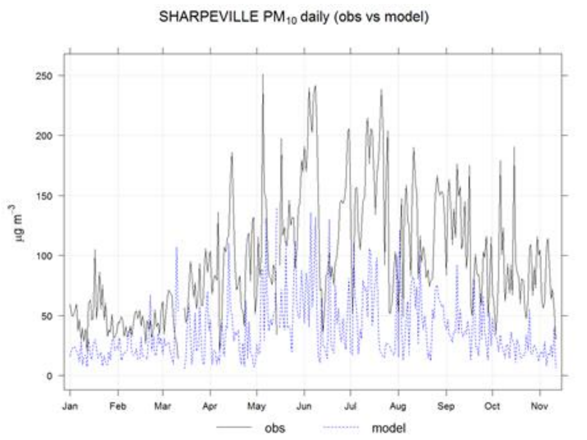
SEBOKENG PM_{10} daily (obs vs model)

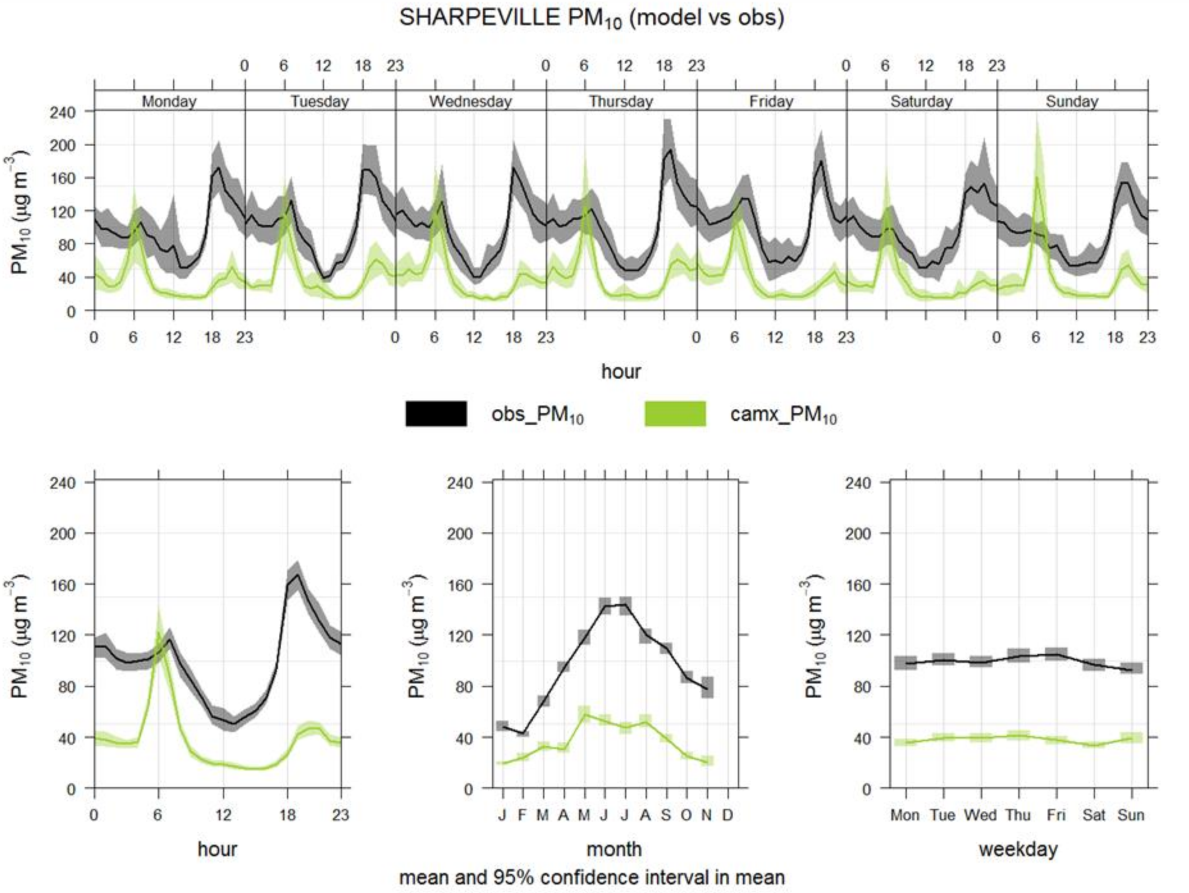
SEBOKENG PM_{10} (model vs obs)

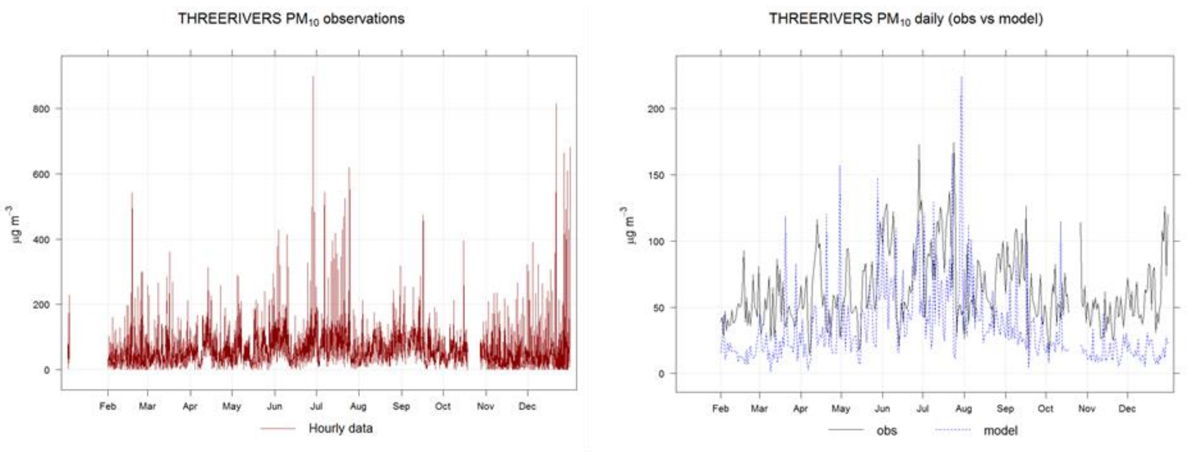


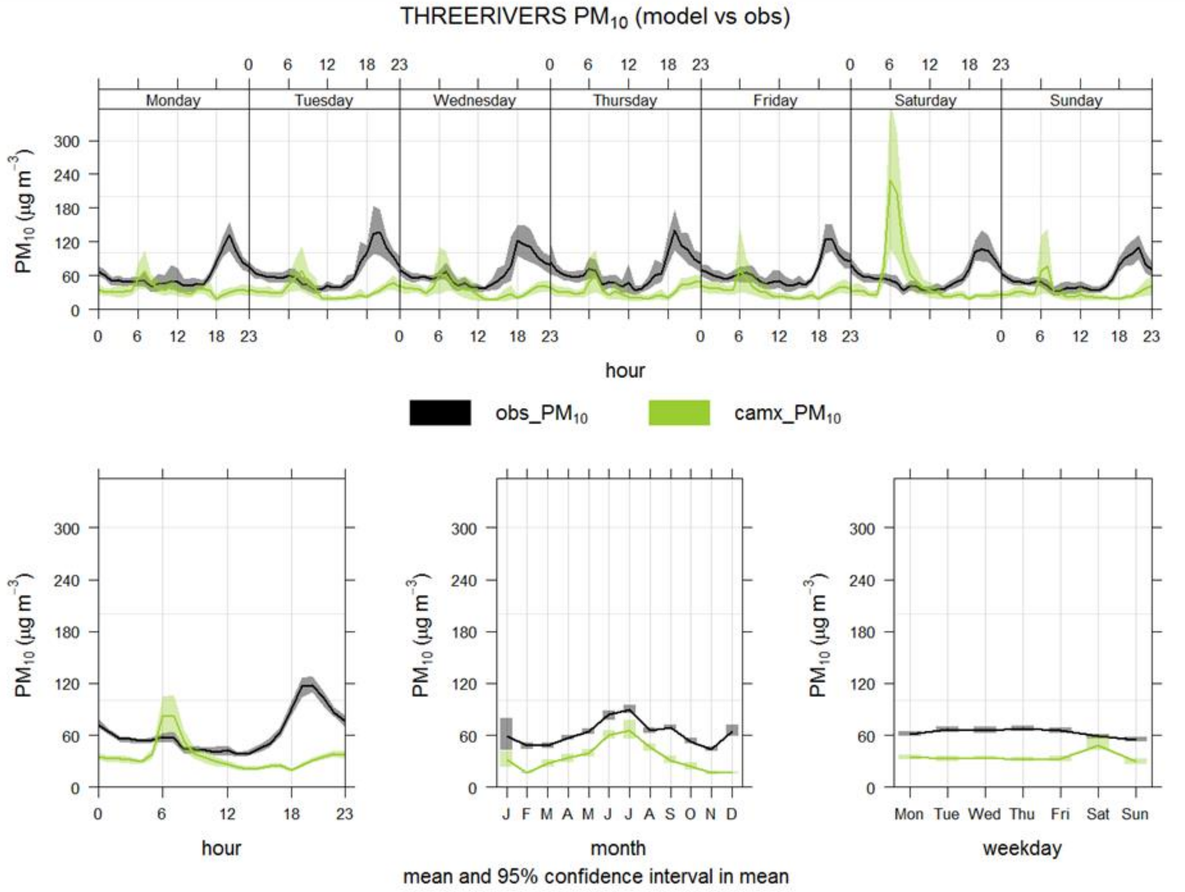
mean and 95% confidence interval in mean

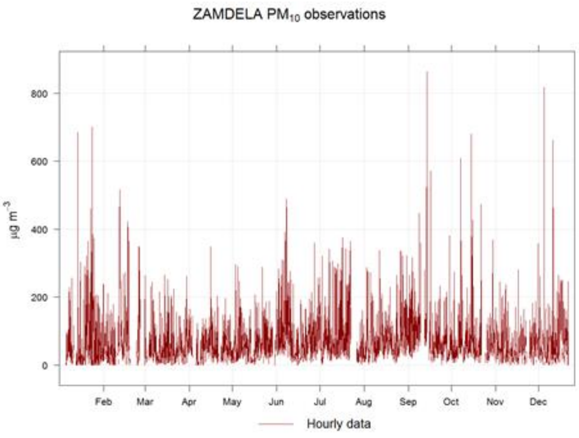

SHARPEVILLE PM$_{10}$ observations
µg m^{-3}
0
200
400
600
800
1000
1200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Hourly data

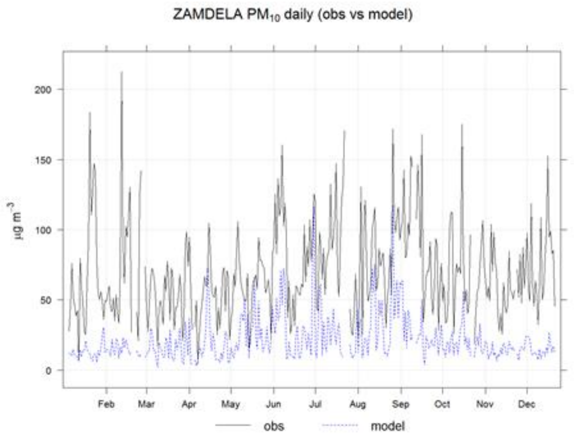

SHARPEVILLE PM$_{10}$ daily (obs vs model)
µg m^{-3}
0
50
100
150
200
250
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
obs
model

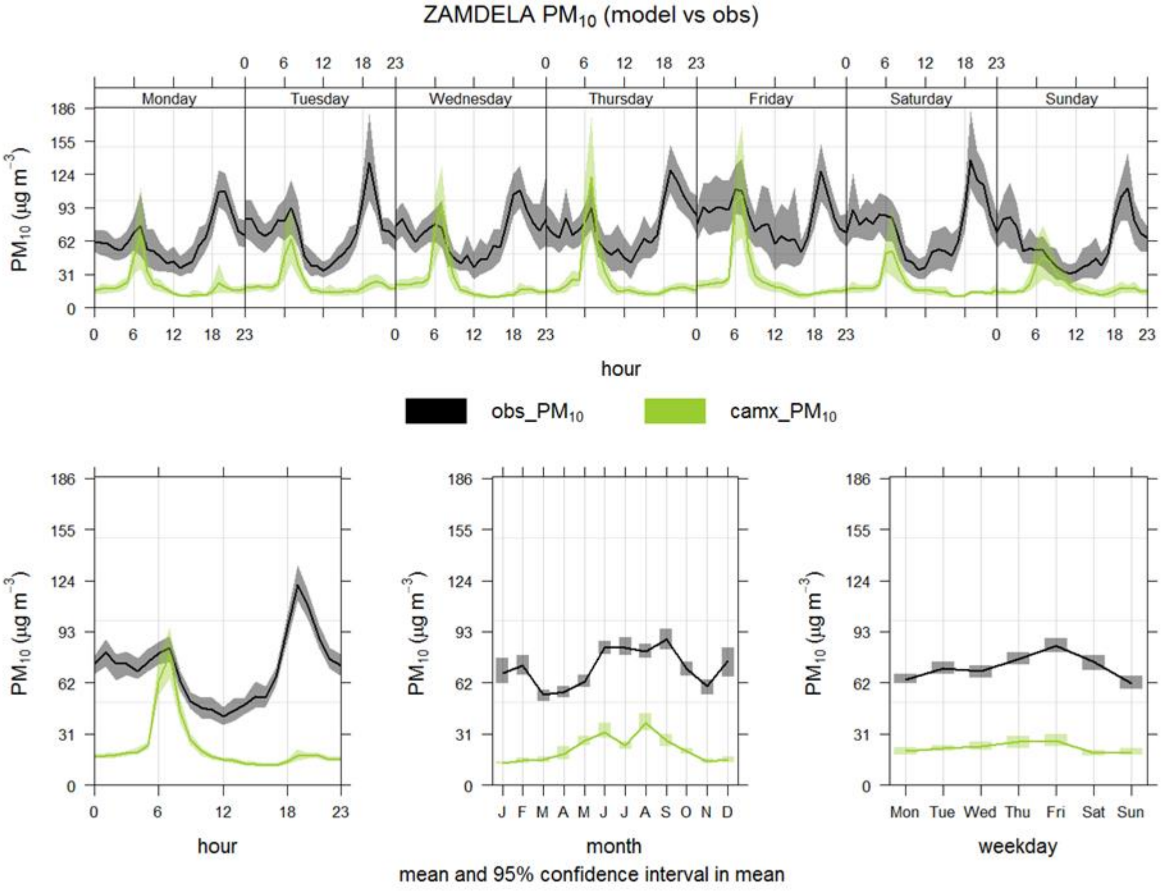

SHARPEVILLE PM$_{10}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM$_{10}$ (µg m^{-3})
0
40
80
120
160
200
240
hour
obs_PM$_{10}$
camx_PM$_{10}$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

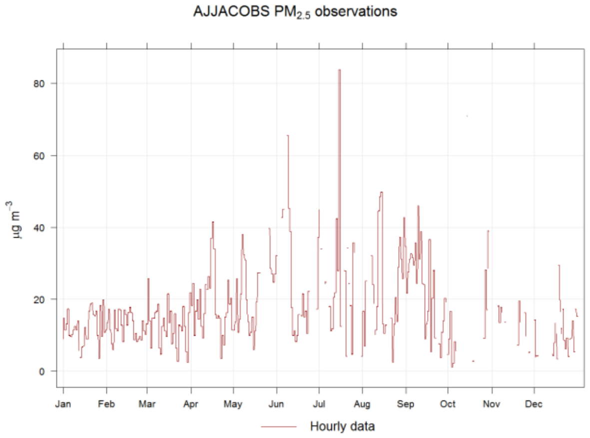

THREERIVERS PM$_{10}$ observations
µg m^{-3}
0
200
400
600
800
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data
THREERIVERS PM$_{10}$ daily (obs vs model)
µg m^{-3}
0
50
100
150
200
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

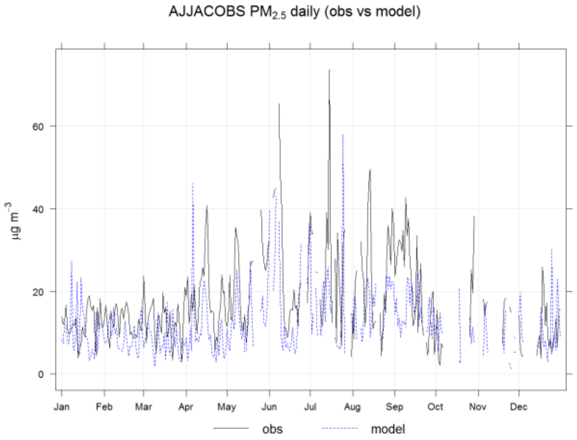

THREERIVERS PM$_{10}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM$_{10}$ (µg m^{-3})
0
60
120
180
240
300
hour
obs_PM$_{10}$
camx_PM$_{10}$
hour
month
J F M A M J J A S O N D
weekday
Mon Tue Wed Thu Fri Sat Sun
mean and 95% confidence interval in mean

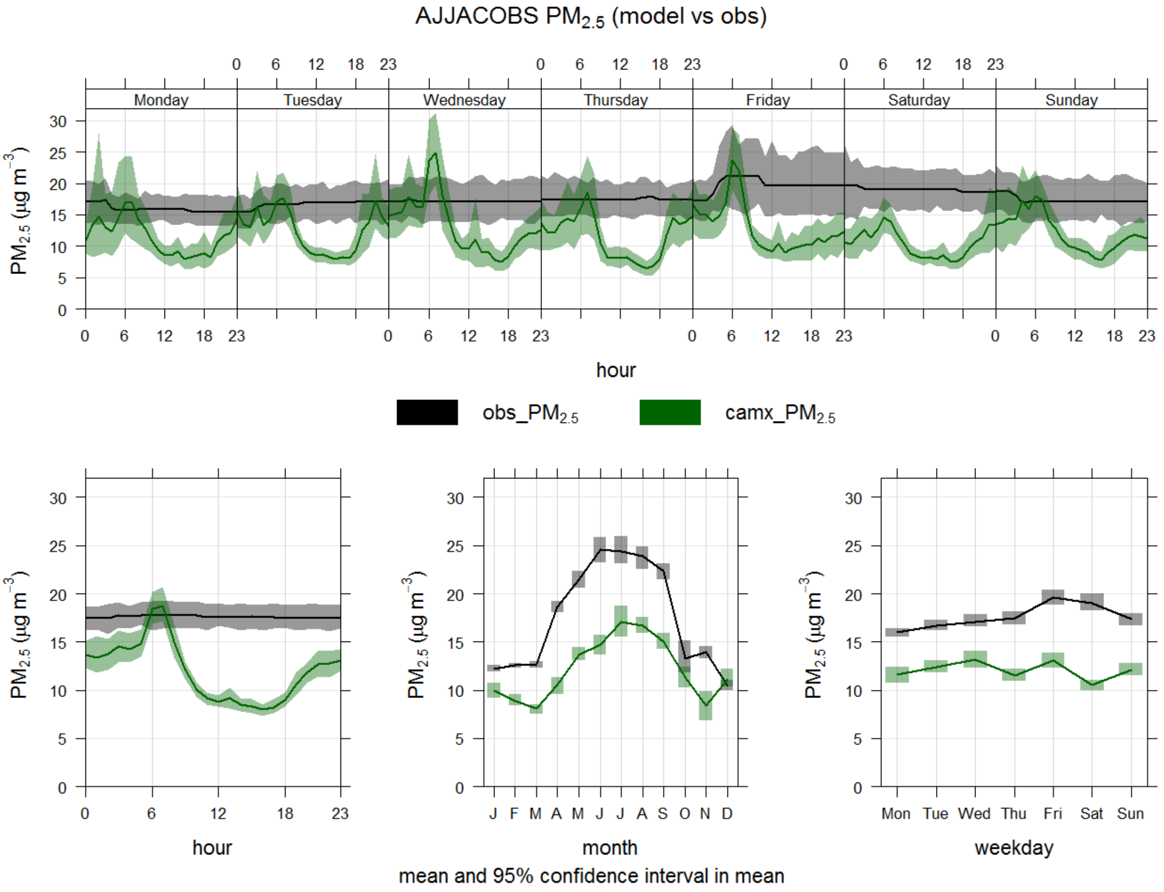

ZAMDELA PM$_{10}$ observations

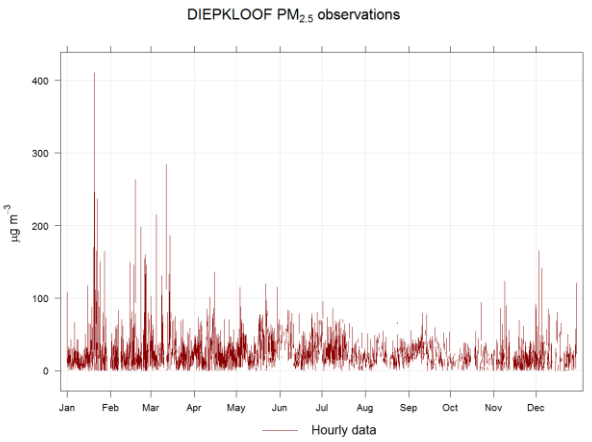

ZAMDELA PM$_{10}$ daily (obs vs model)


ZAMDELA PM$_{10}$ (model vs obs)

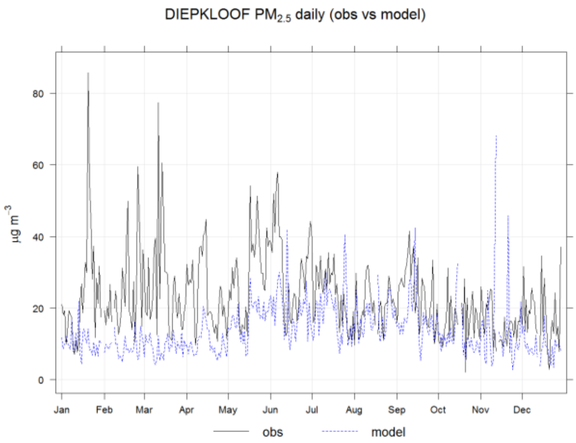

AJJACOBS $PM_{2.5}$ observations
µg m^{-3}
0
20
40
60
80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data


AJJACOBS $PM_{2.5}$ daily (obs vs model)
µg m^{-3}
0
20
40
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model


AJJACOBS $PM_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
$PM_{2.5}$ (µg m^{-3})
0
5
10
15
20
25
30
hour
obs_$PM_{2.5}$
camx_$PM_{2.5}$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

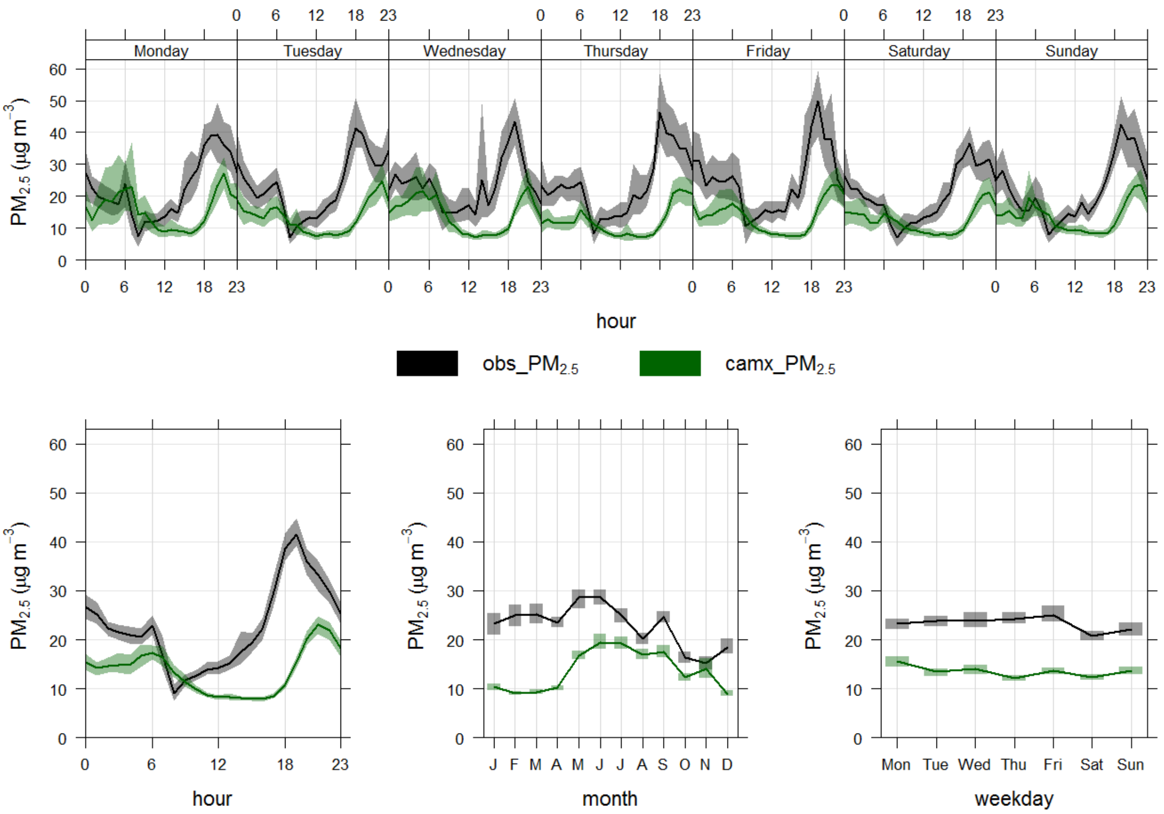


DIEPKLOOF $PM_{2.5}$ observations

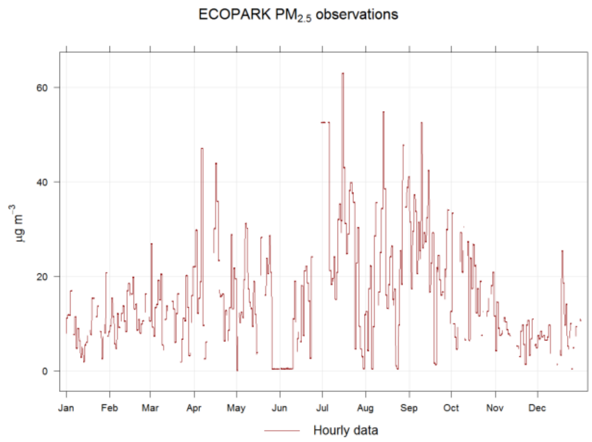


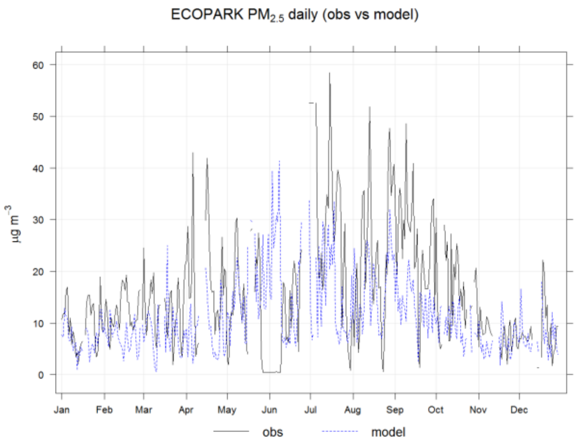
DIEPKLOOF $PM_{2.5}$ daily (obs vs model)

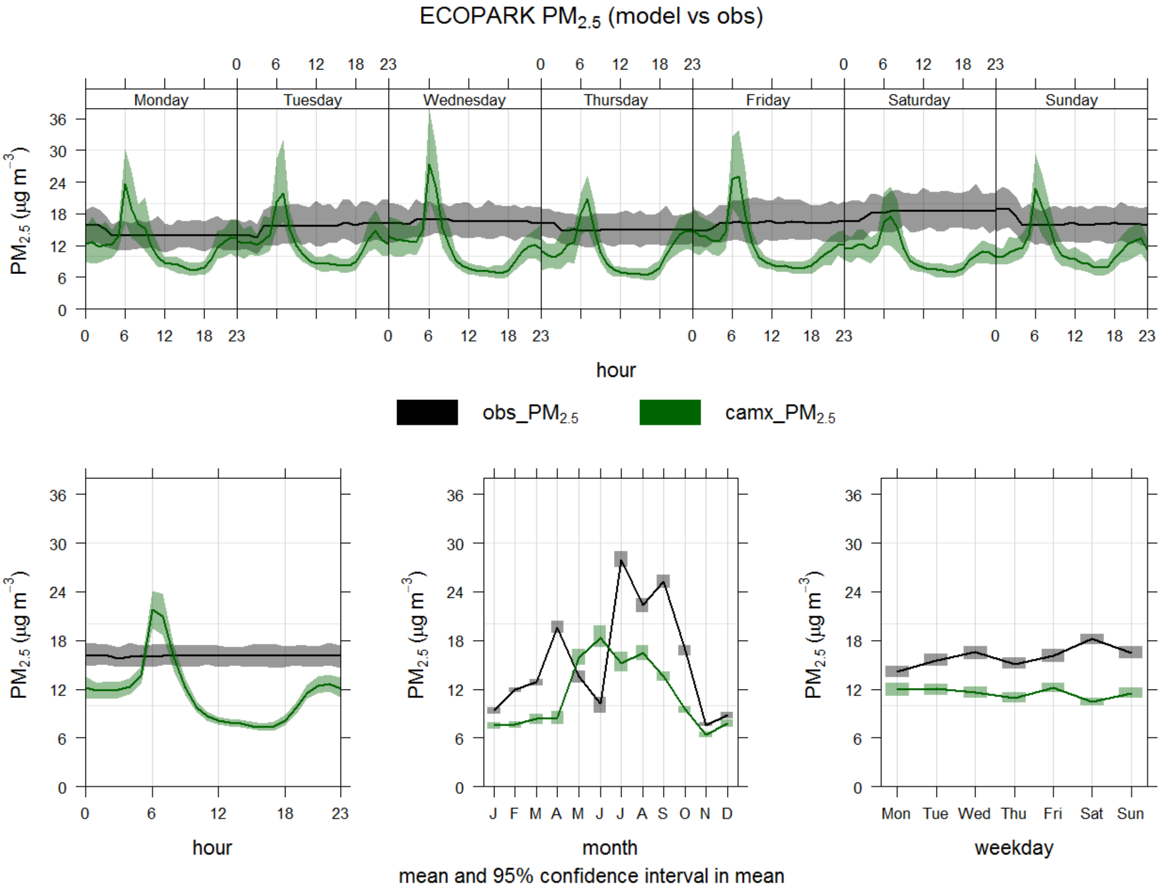
DIEPKLOOF $PM_{2.5}$ (model vs obs)

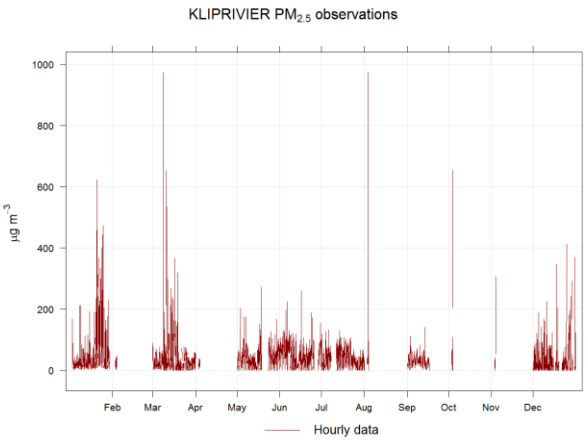


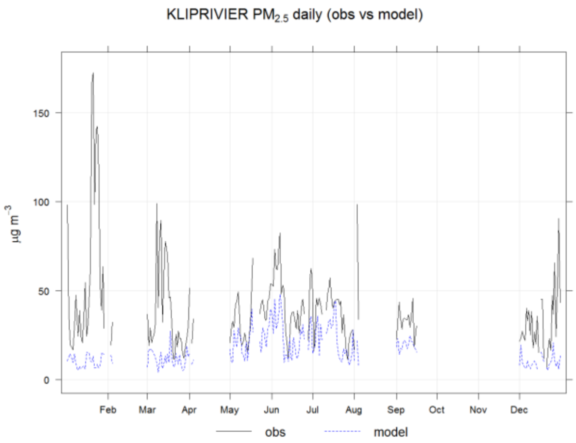
mean and 95% confidence interval in mean

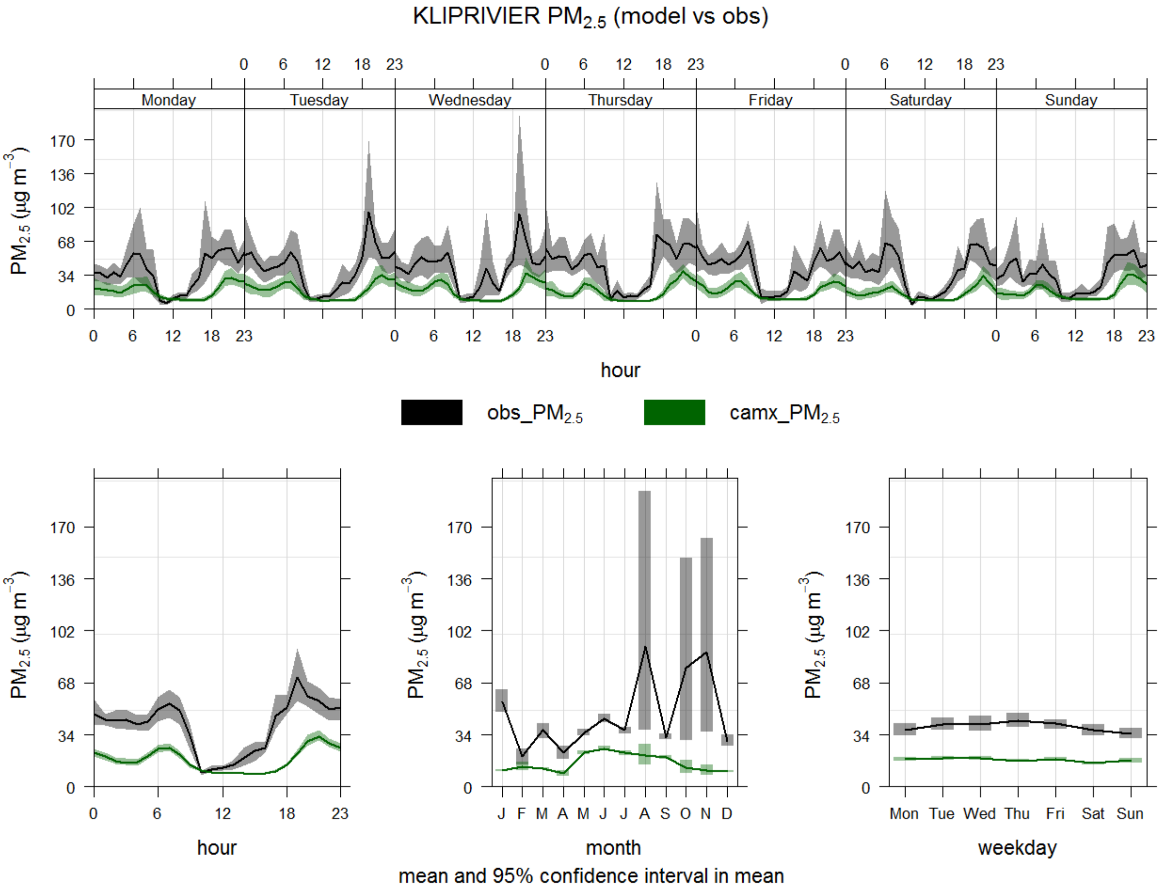

ECOPARK $PM_{2.5}$ observations
µg m^{-3}
0
20
40
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

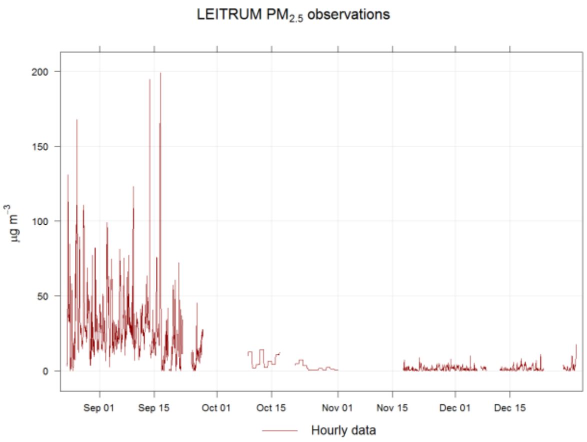

ECOPARK $PM_{2.5}$ daily (obs vs model)
µg m^{-3}
0
10
20
30
40
50
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

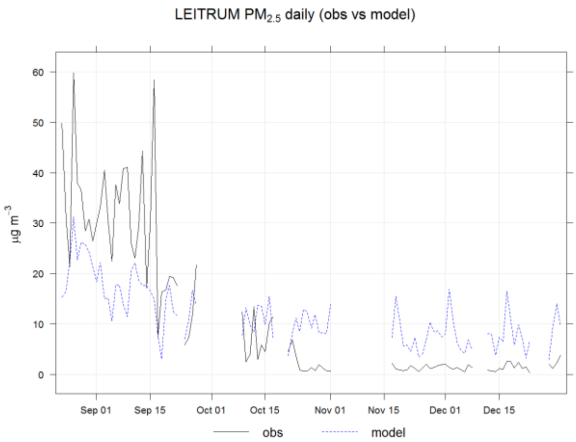

ECOPARK $PM_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
$PM_{2.5}$ (µg m^{-3})
0
6
12
18
24
30
36
hour
obs_$PM_{2.5}$
camx_$PM_{2.5}$
hour
month
J F M A M J J A S O N D
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

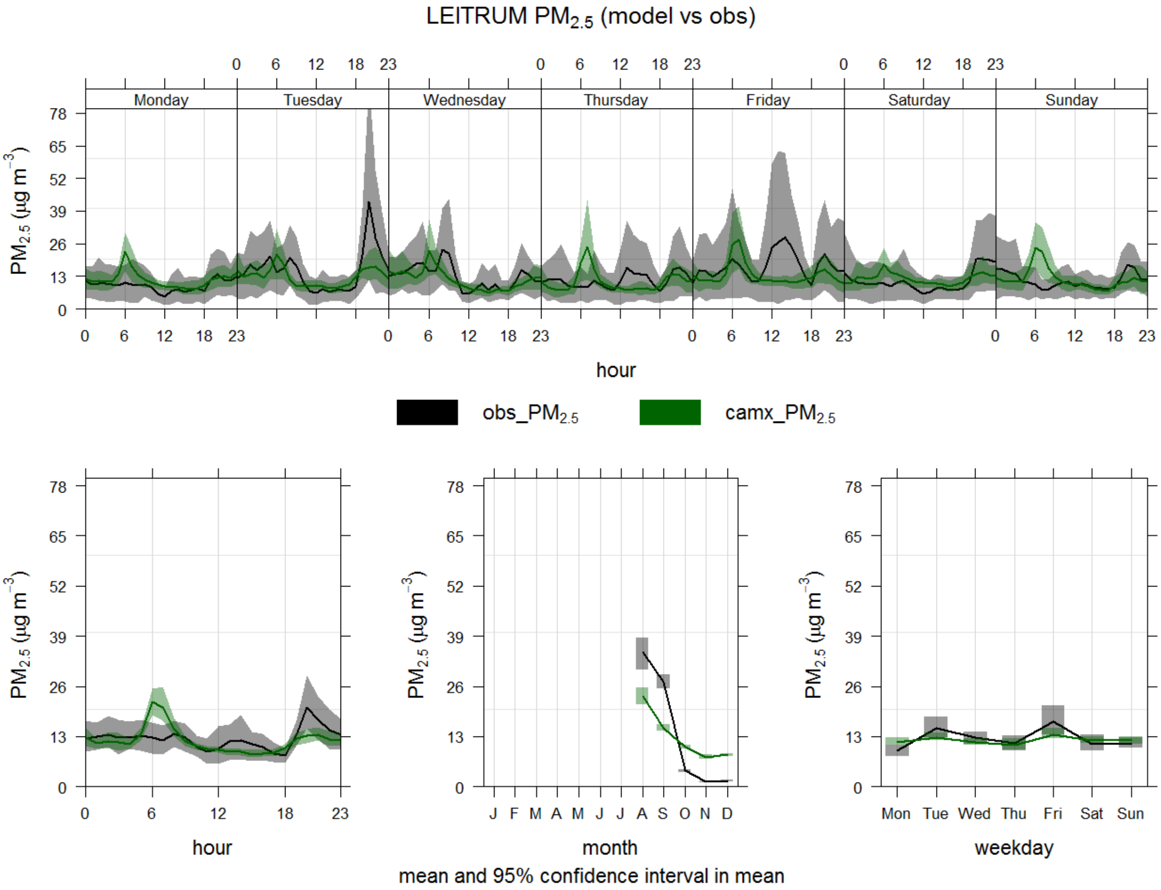

KLIPRIVIER PM$_{2.5}$ observations
µg m^{-3}
1000
800
600
400
200
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

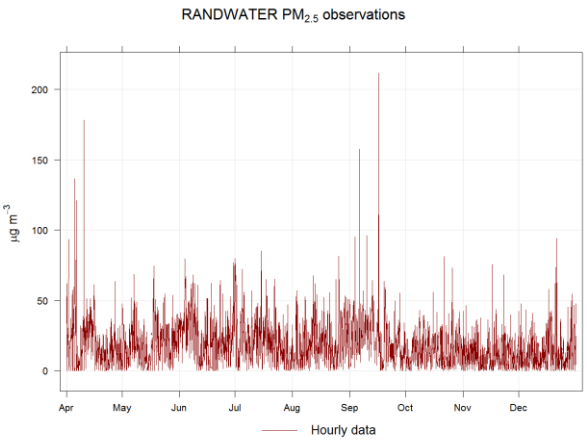

KLIPRIVIER PM$_{2.5}$ daily (obs vs model)
µg m^{-3}
150
100
50
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

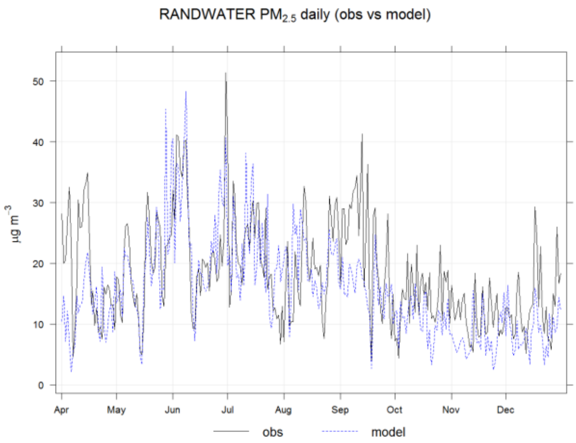

KLIPRIVIER PM$_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM$_{2.5}$ (µg m^{-3})
170
136
102
68
34
0
hour
obs_PM$_{2.5}$
camx_PM$_{2.5}$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

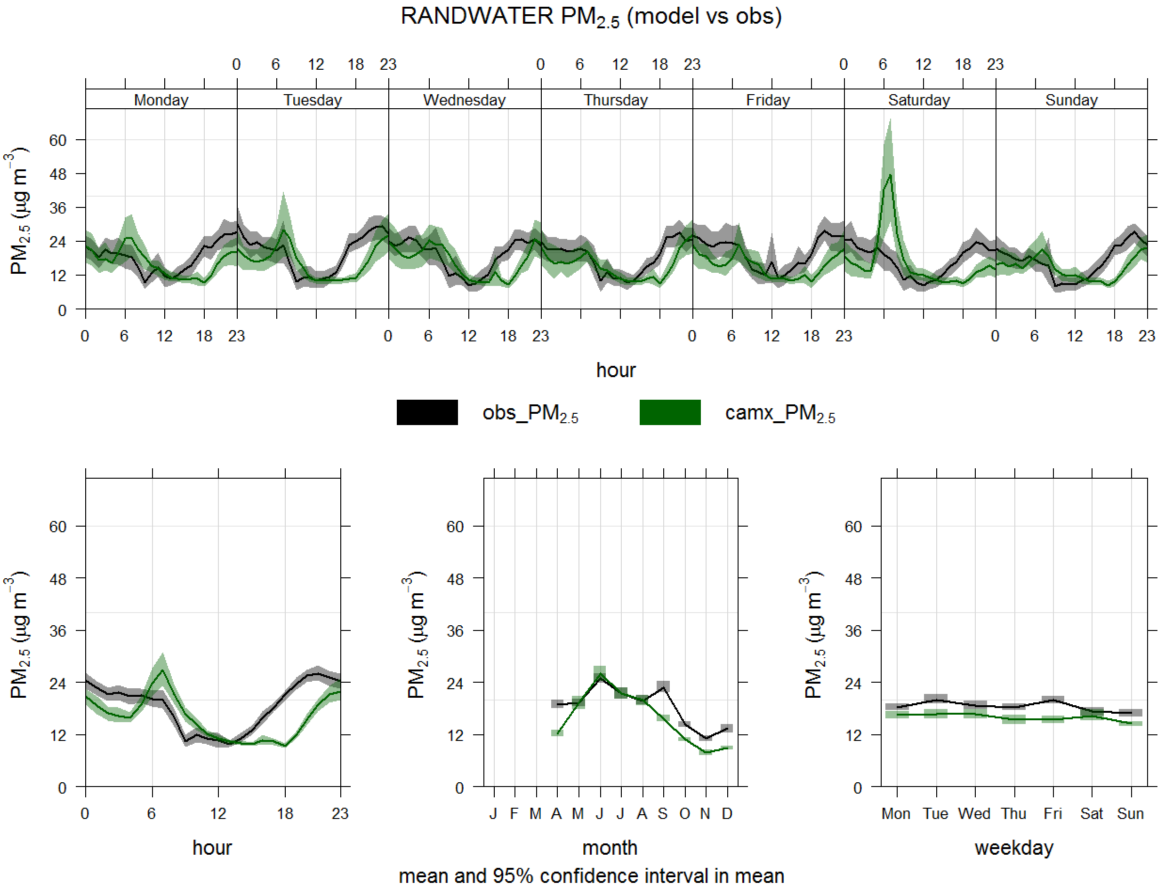

LEITRUM $PM_{2.5}$ observations
µg m^{-3}
200
150
100
50
0
Sep 01
Sep 15
Oct 01
Oct 15
Nov 01
Nov 15
Dec 01
Dec 15
Hourly data

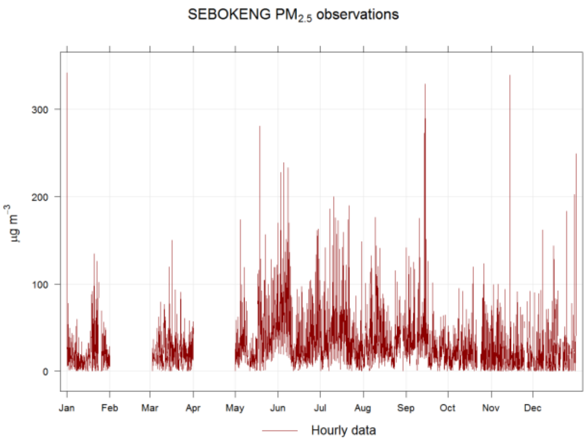

LEITRUM $PM_{2.5}$ daily (obs vs model)
µg m^{-3}
60
50
40
30
20
10
0
Sep 01
Sep 15
Oct 01
Oct 15
Nov 01
Nov 15
Dec 01
Dec 15
obs
model

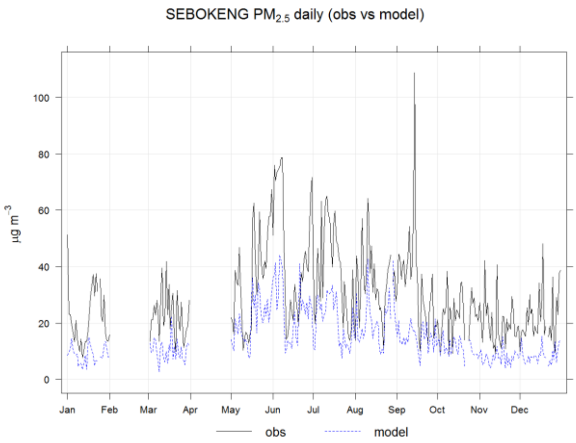

LEITRUM $PM_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
$PM_{2.5}$ (µg m^{-3})
78
65
52
39
26
13
0
0
6
12
18
23
hour
obs_$PM_{2.5}$
camx_$PM_{2.5}$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

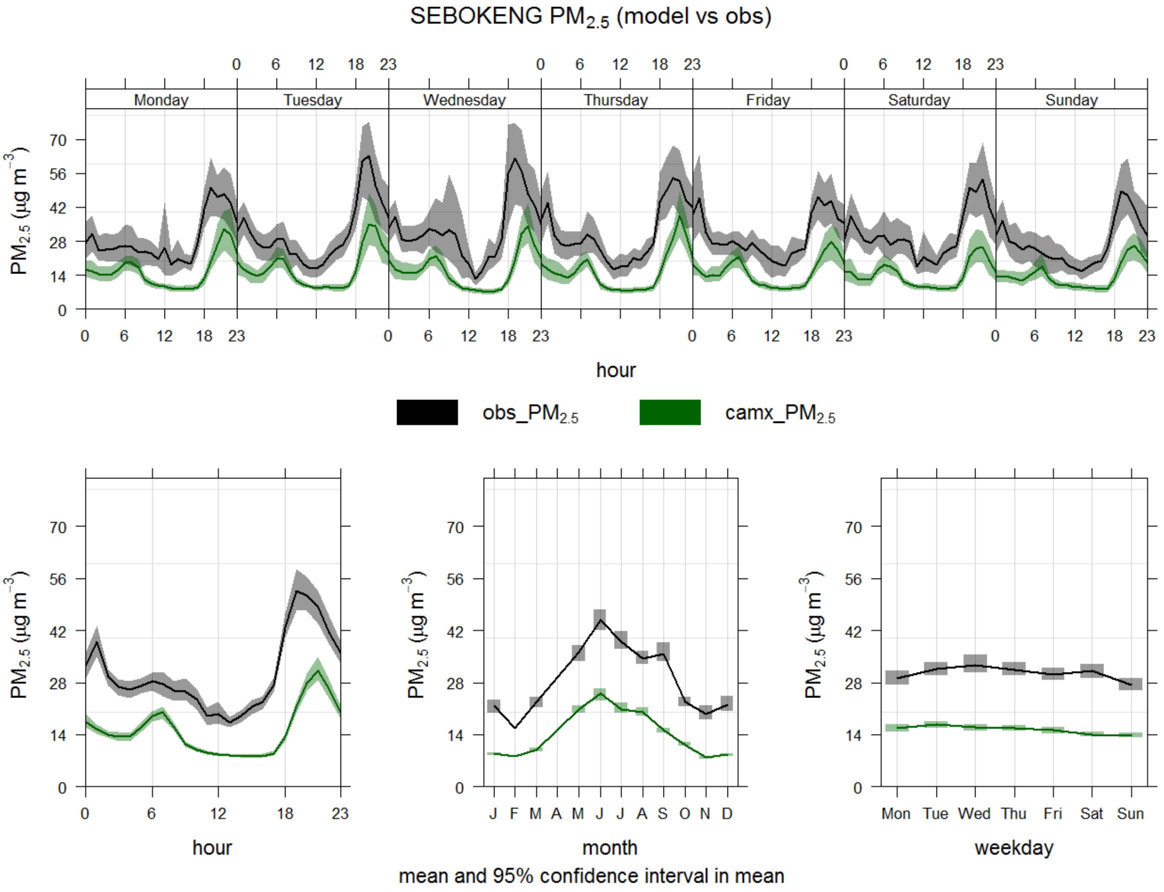

RANDWATER PM$_{2.5}$ observations
µg m^{-3}
0
50
100
150
200
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

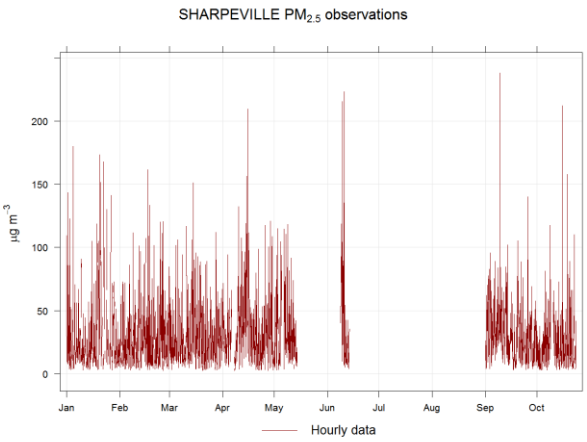

RANDWATER PM$_{2.5}$ daily (obs vs model)
µg m^{-3}
0
10
20
30
40
50
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

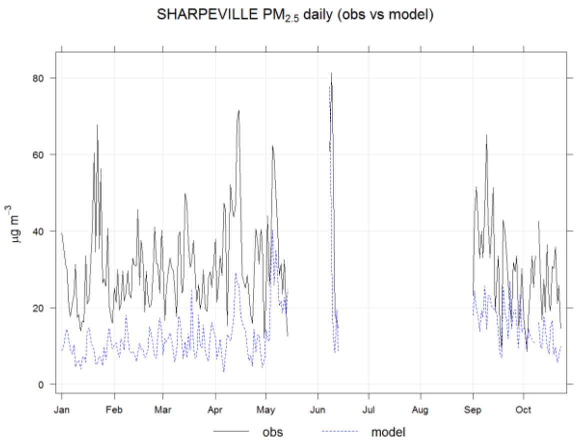

RANDWATER PM$_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM$_{2.5}$ (µg m^{-3})
0
12
24
36
48
60
hour
obs_PM$_{2.5}$
camx_PM$_{2.5}$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

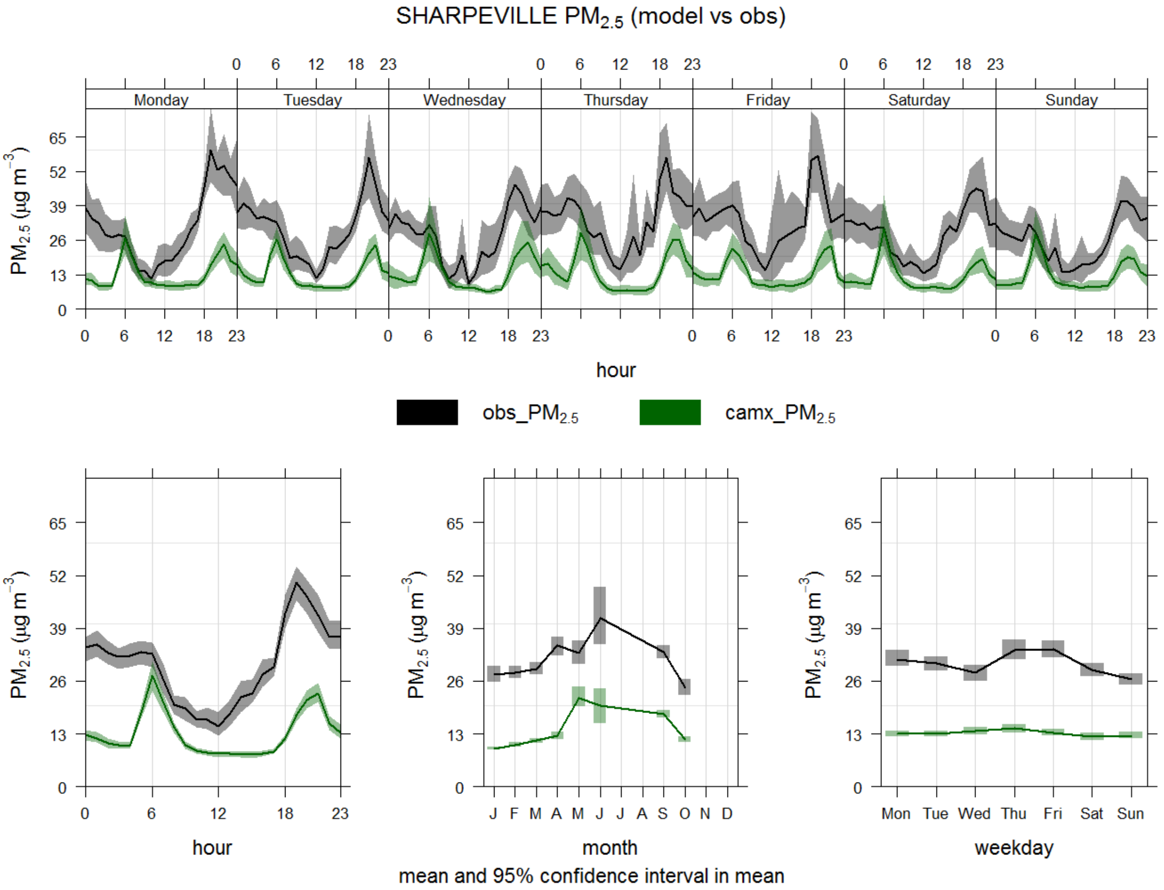

SEBOKENG PM$_{2.5}$ observations
µg m^{-3}
0
100
200
300
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

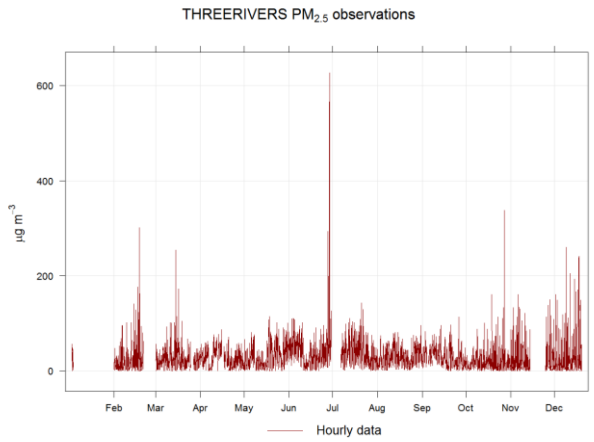

SEBOKENG PM$_{2.5}$ daily (obs vs model)
µg m^{-3}
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

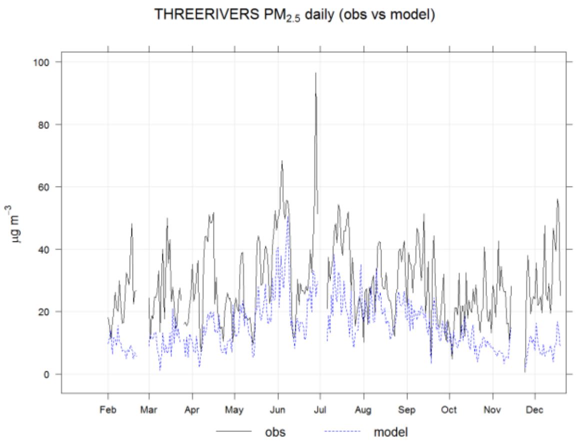

SEBOKENG PM$_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM$_{2.5}$ (µg m^{-3})
0
14
28
42
56
70
hour
obs_PM$_{2.5}$
camx_PM$_{2.5}$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

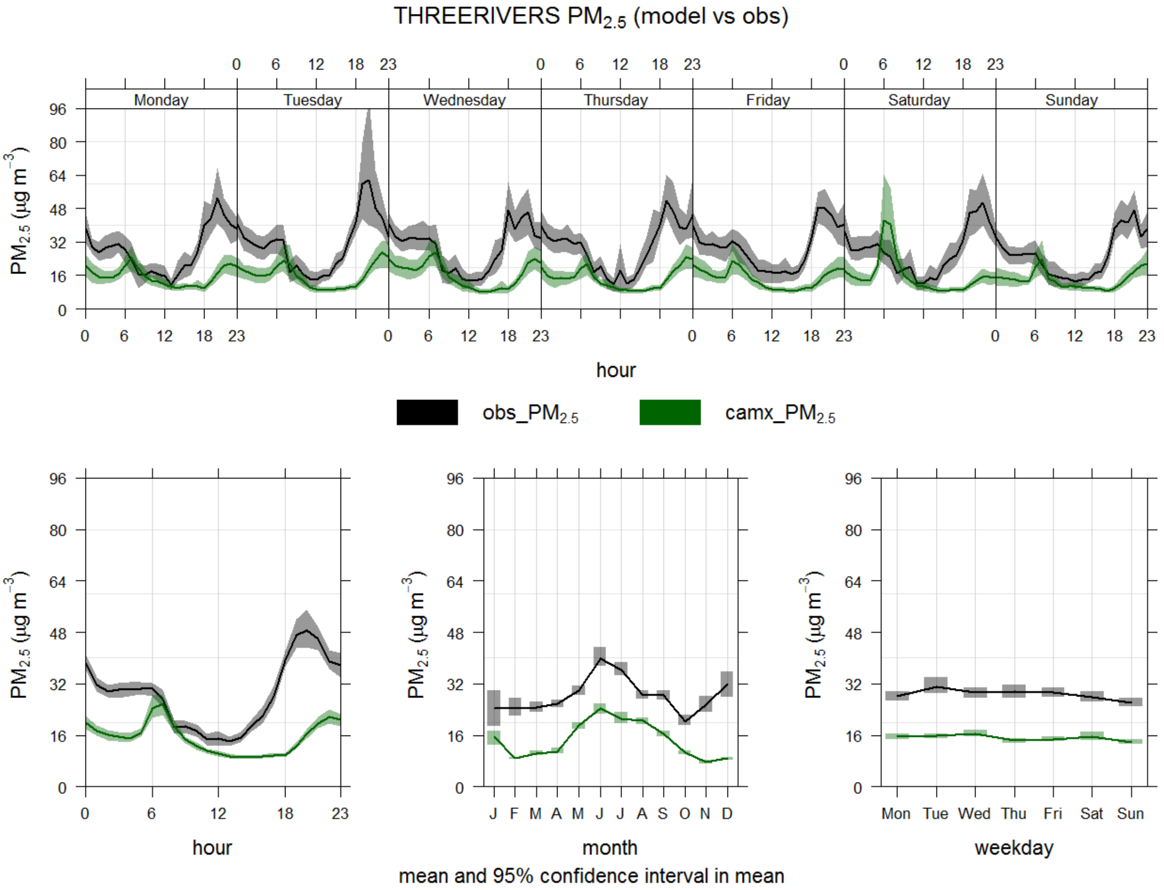

SHARPEVILLE $PM_{2.5}$ observations
µg m^{-3}
0
50
100
150
200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Hourly data

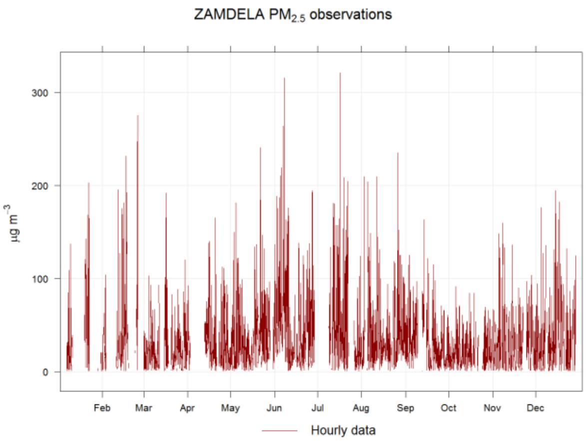

SHARPEVILLE $PM_{2.5}$ daily (obs vs model)
µg m^{-3}
0
20
40
60
80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
obs
model

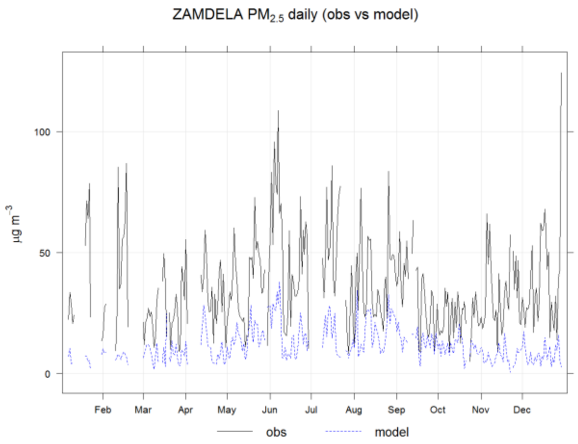

SHARPEVILLE $PM_{2.5}$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
$PM_{2.5}$ (µg m^{-3})
0
13
26
39
52
65
hour
obs_$PM_{2.5}$
camx_$PM_{2.5}$
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

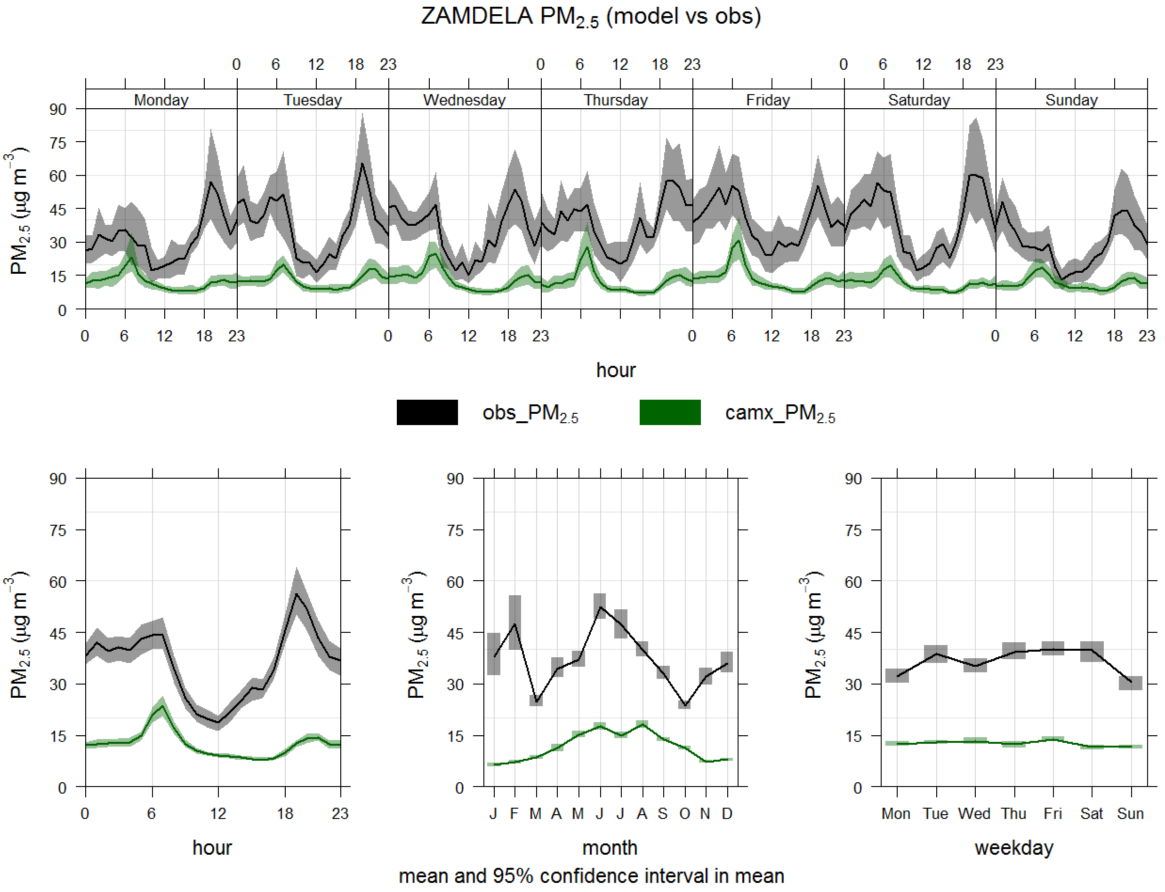

THREERIVERS PM2.5 observations
µg m-3
600
400
200
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

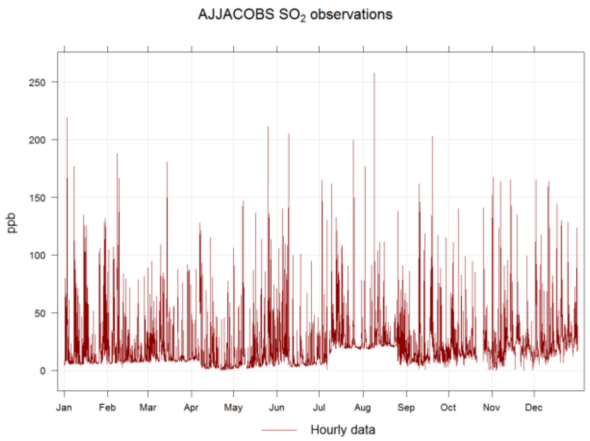

THREERIVERS PM2.5 daily (obs vs model)
µg m-3
100
80
60
40
20
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model


THREERIVERS PM2.5 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
PM2.5 (µg m-3)
96
80
64
48
32
16
0
0
6
12
18
23
hour
obs_PM2.5
camx_PM2.5
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean

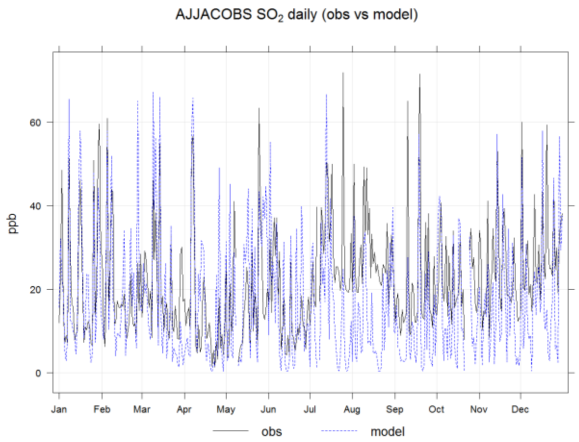

ZAMDELA PM2.5 observations
µg m⁻³
300
200
100
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data


ZAMDELA PM2.5 daily (obs vs model)
µg m⁻³
100
50
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

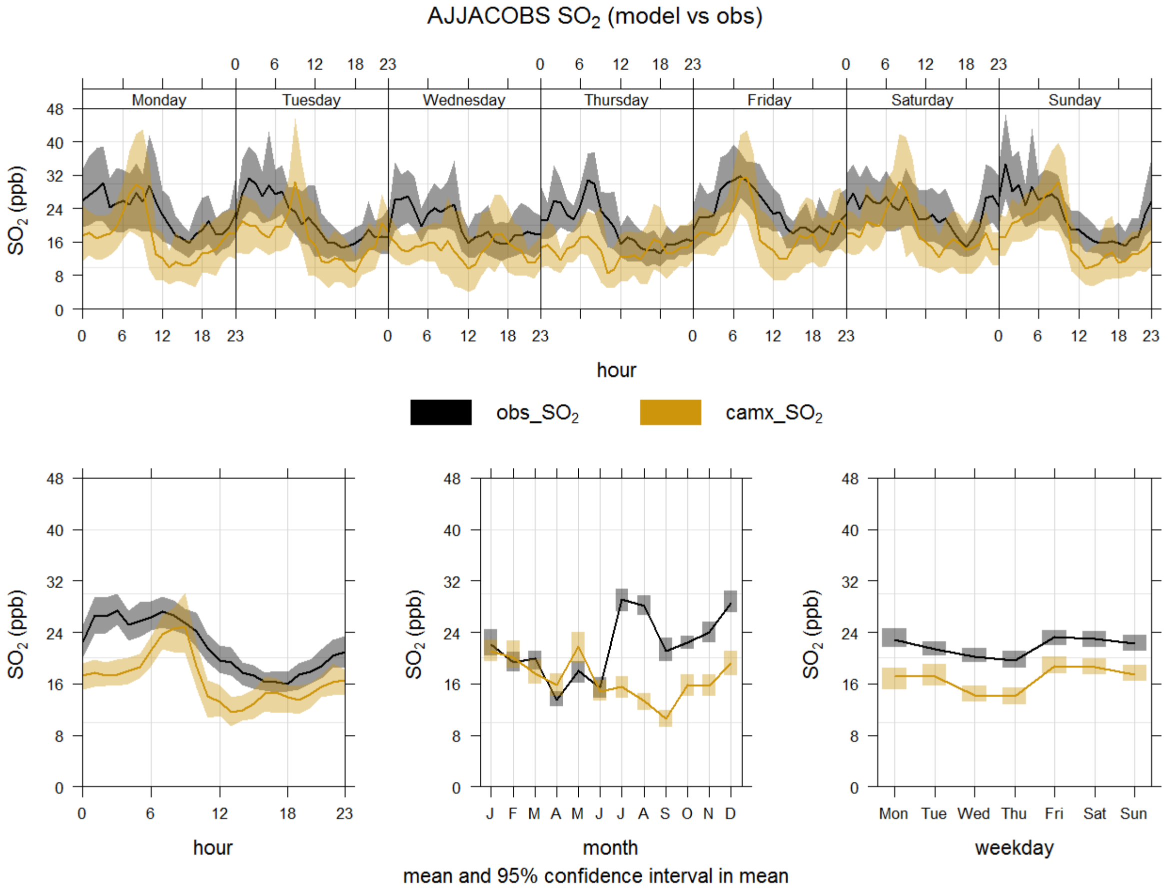

ZAMDELA PM2.5 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
PM2.5 (µg m⁻³)
90
75
60
45
30
15
0
hour
obs_PM2.5
camx_PM2.5
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean



AJJACOBS SO_2 observations

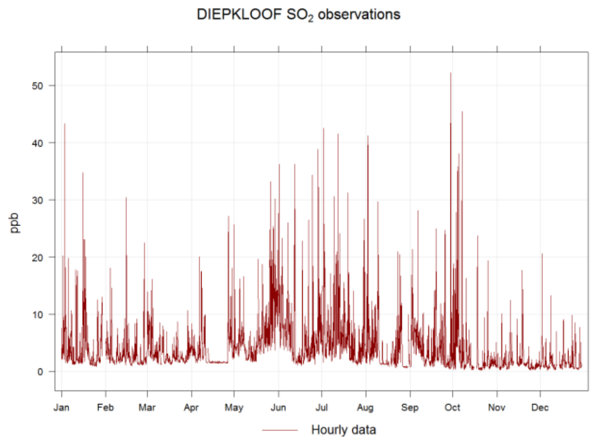


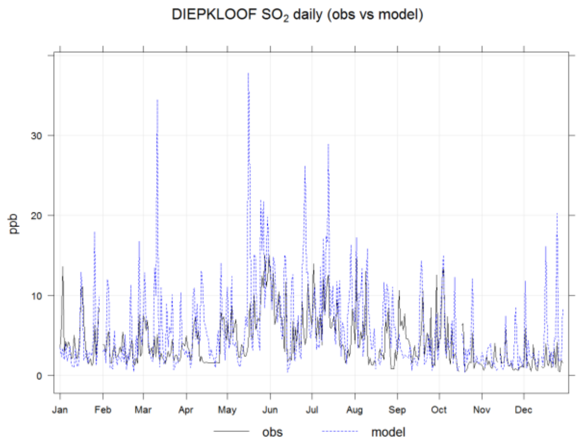
AJJACOBS SO_2 daily (obs vs model)



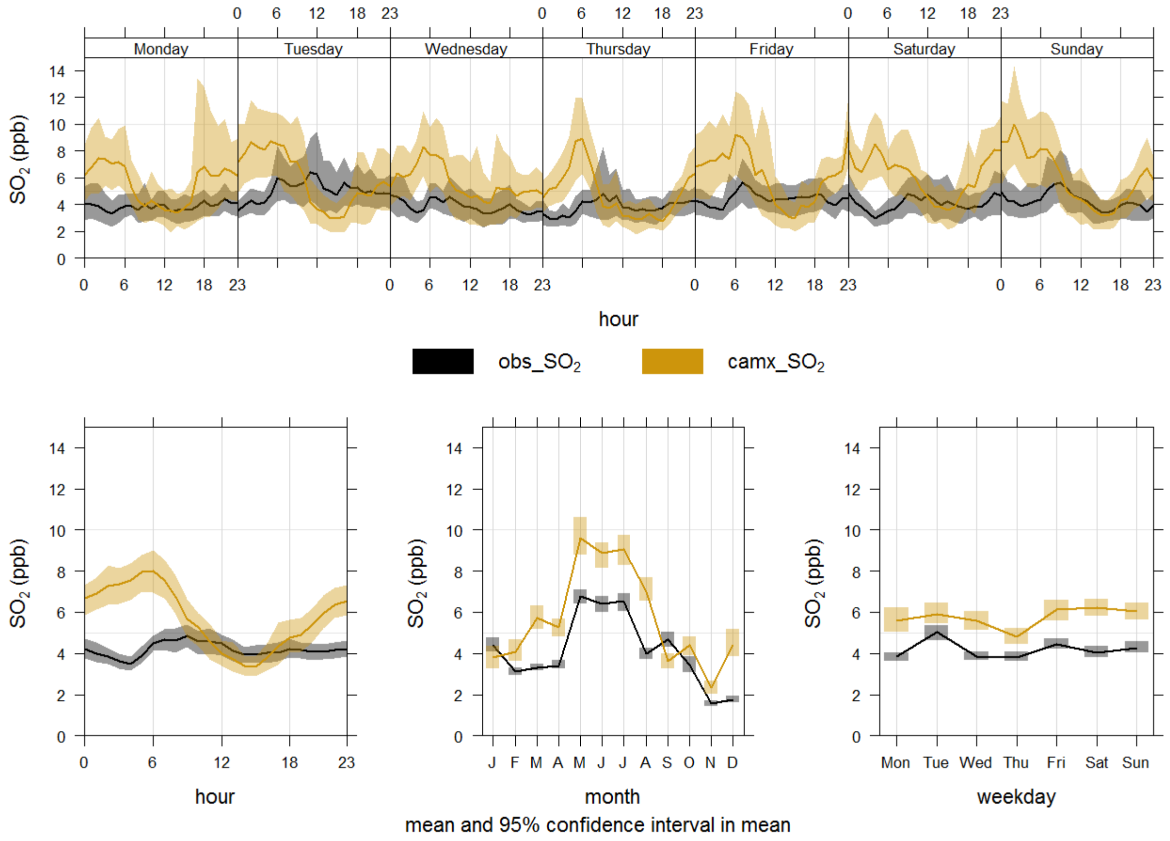
AJJACOBS SO_2 (model vs obs)

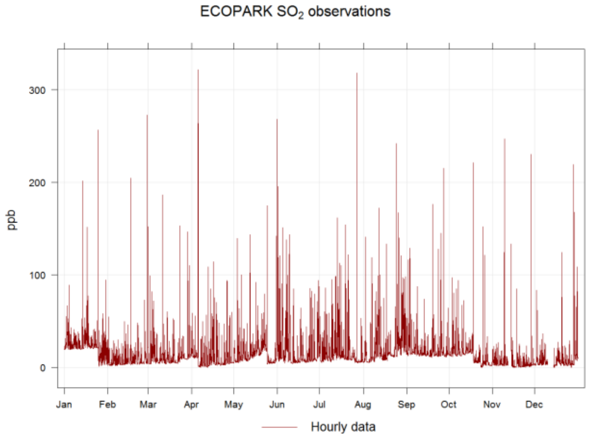
mean and 95% confidence interval in mean

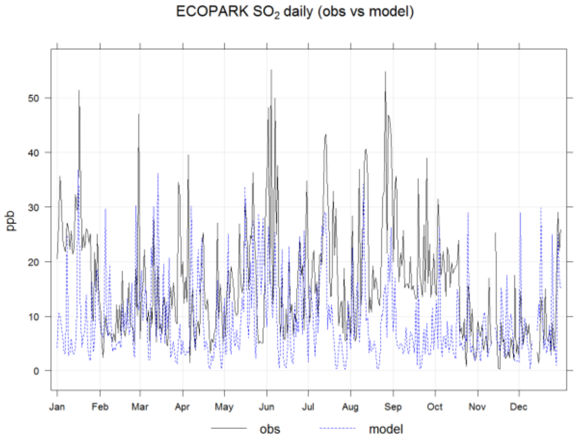


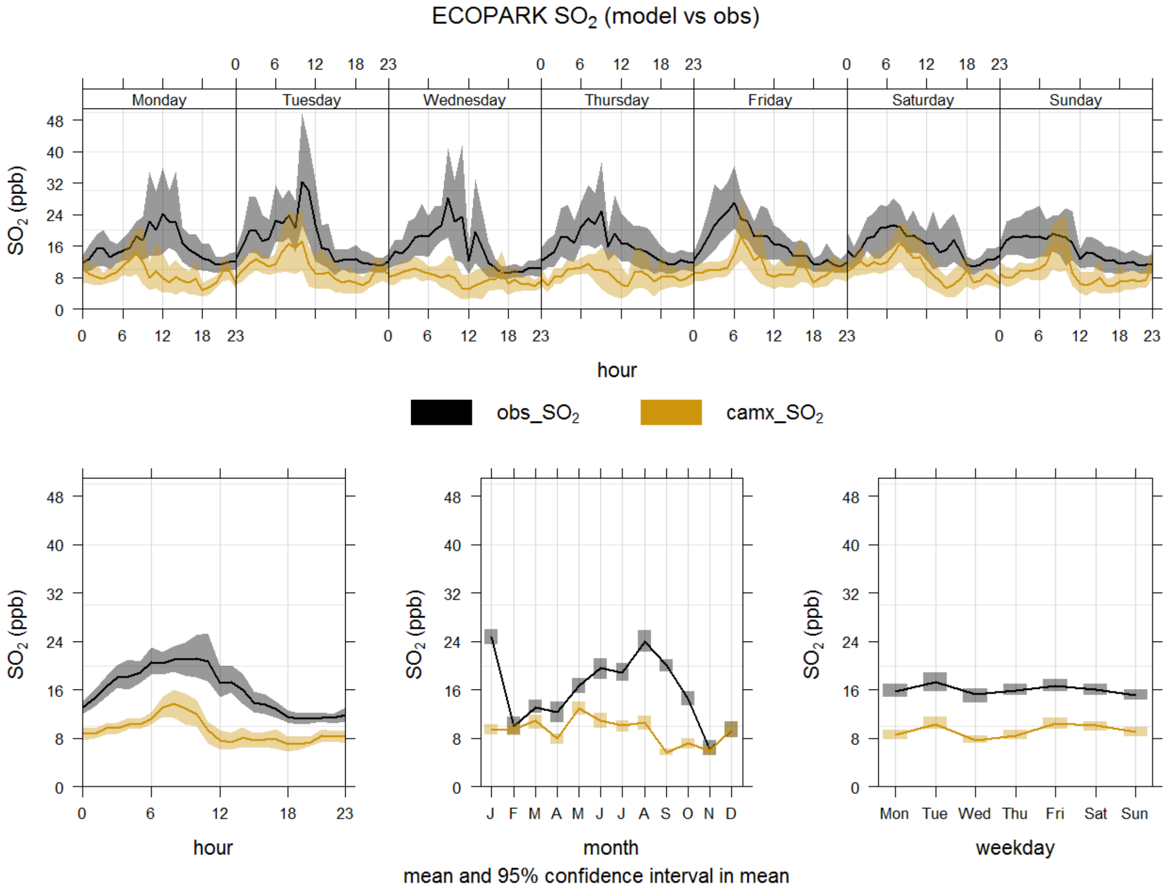


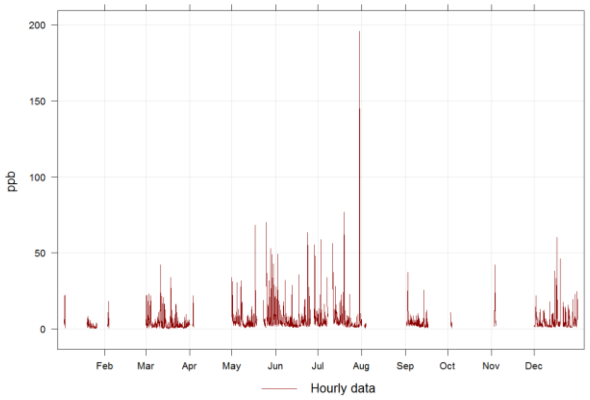
DIEPKLOOF SO_2 (model vs obs)

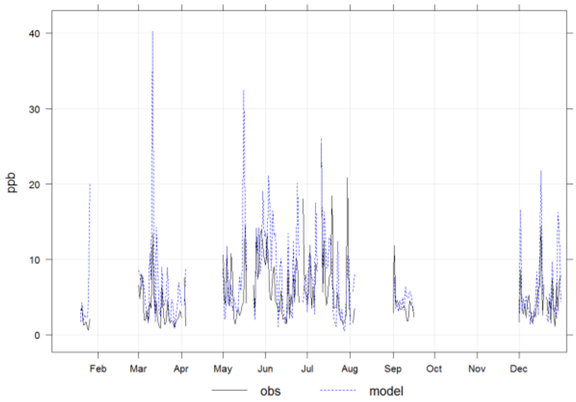


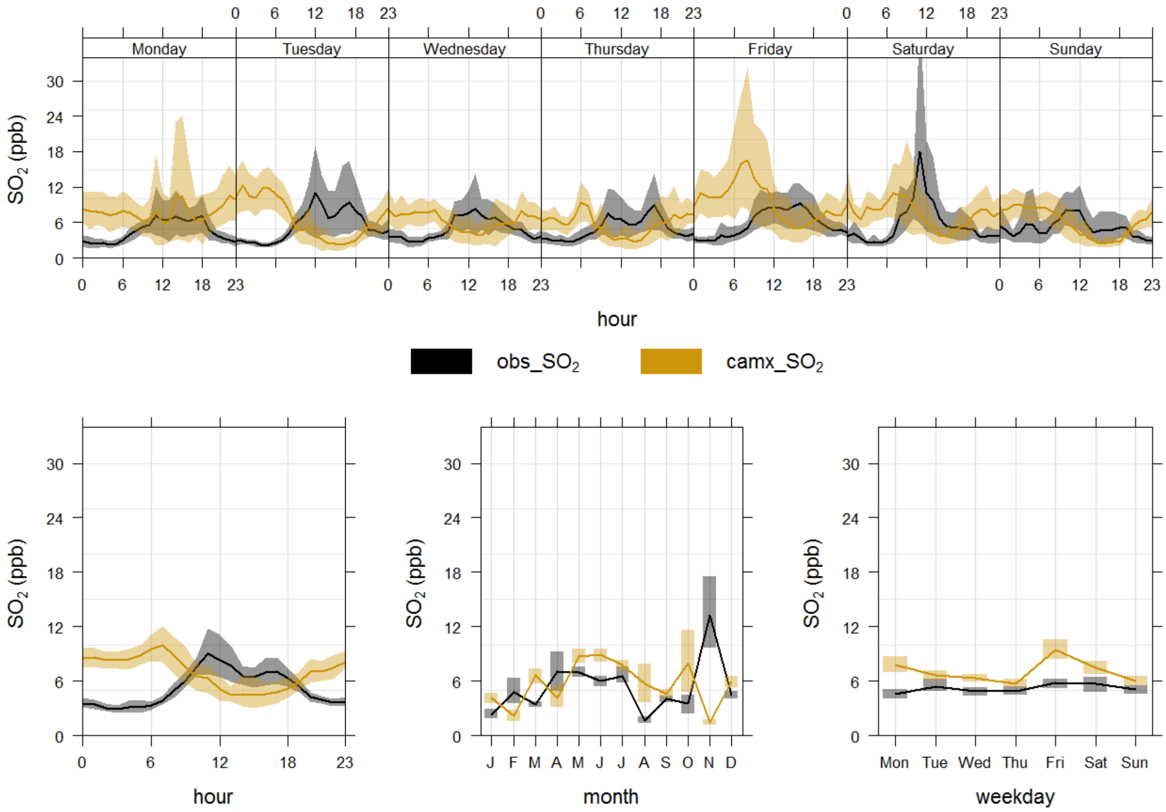

ECOPARK SO_2 observations
ppb
0
100
200
300
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Hourly data


ECOPARK SO_2 daily (obs vs model)
ppb
0
10
20
30
40
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
obs
model

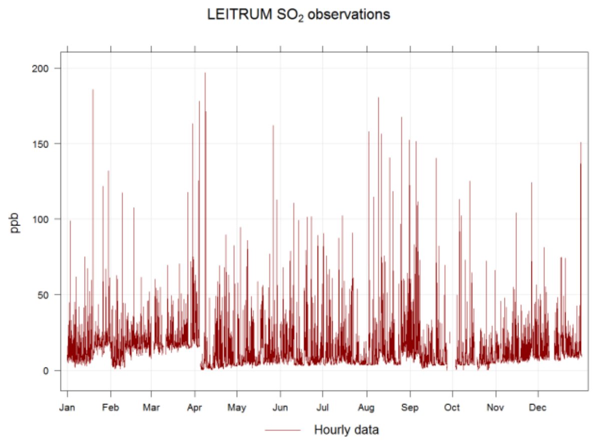

ECOPARK SO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0 6 12 18 23
SO_2 (ppb)
0
8
16
24
32
40
48
hour
obs_SO_2
camx_SO_2
hour
month
J F M A M J J A S O N D
weekday
Mon Tue Wed Thu Fri Sat Sun
mean and 95% confidence interval in mean

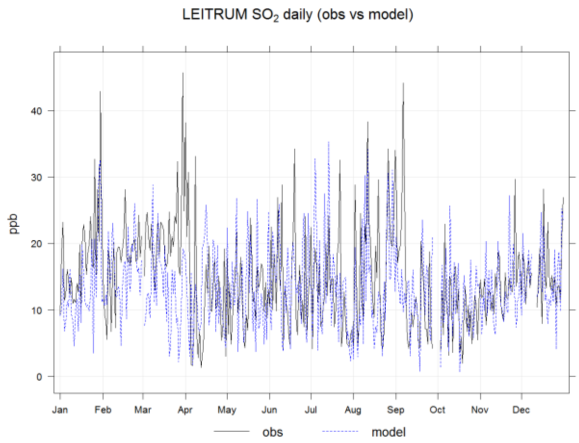

KLIPRIVIER SO_2 observations

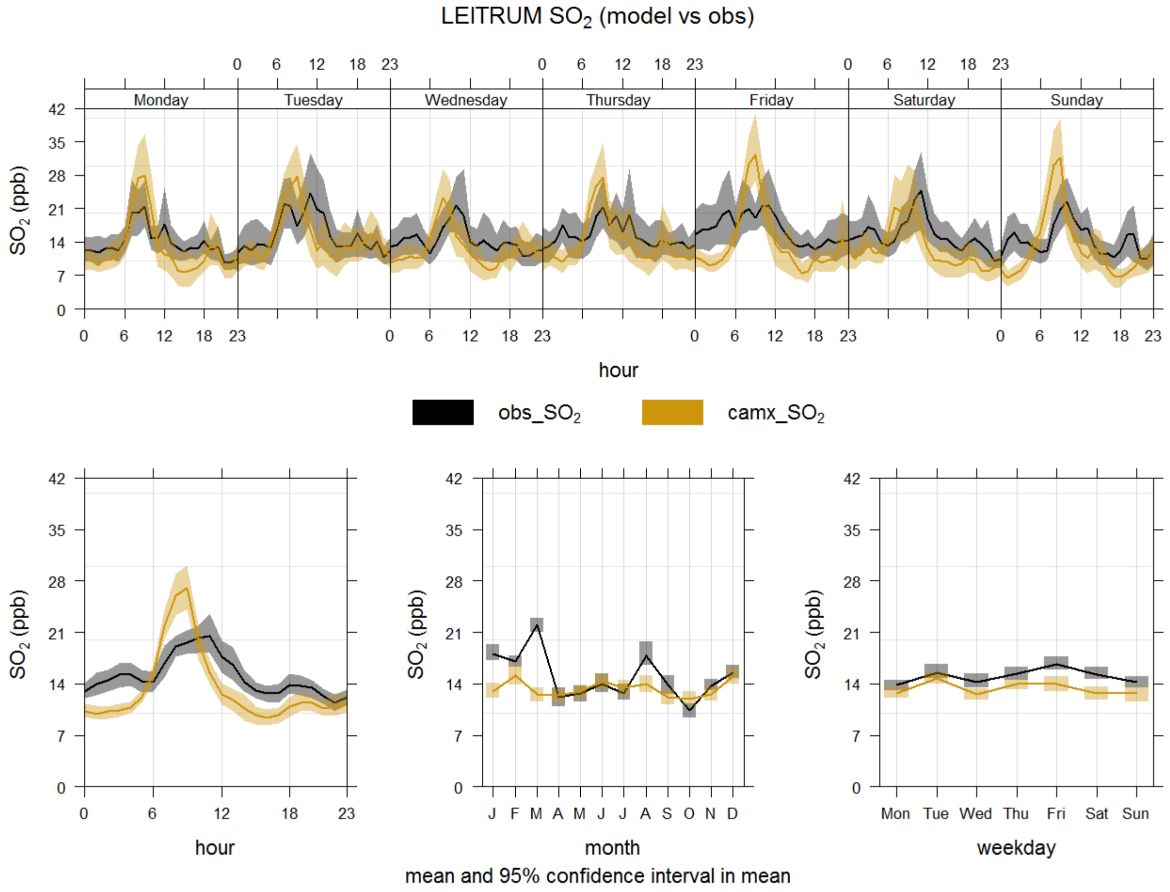

KLIPRIVIER SO_2 daily (obs vs model)

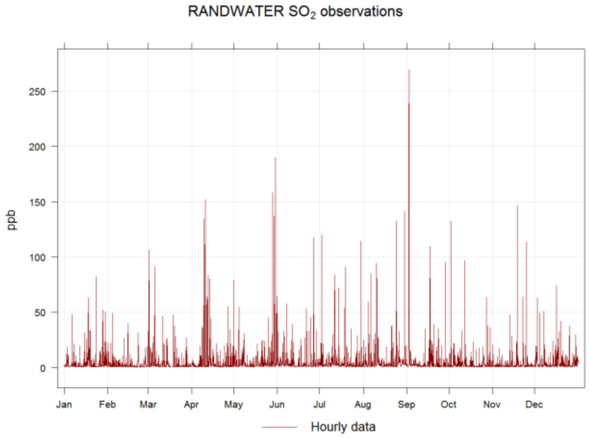

KLIPRIVIER SO_2 (model vs obs)

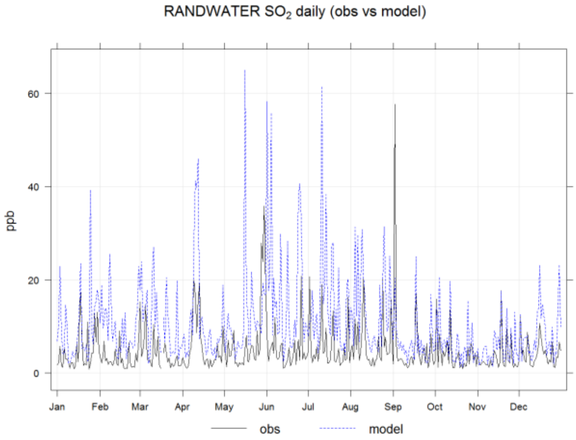
mean and 95% confidence interval in mean

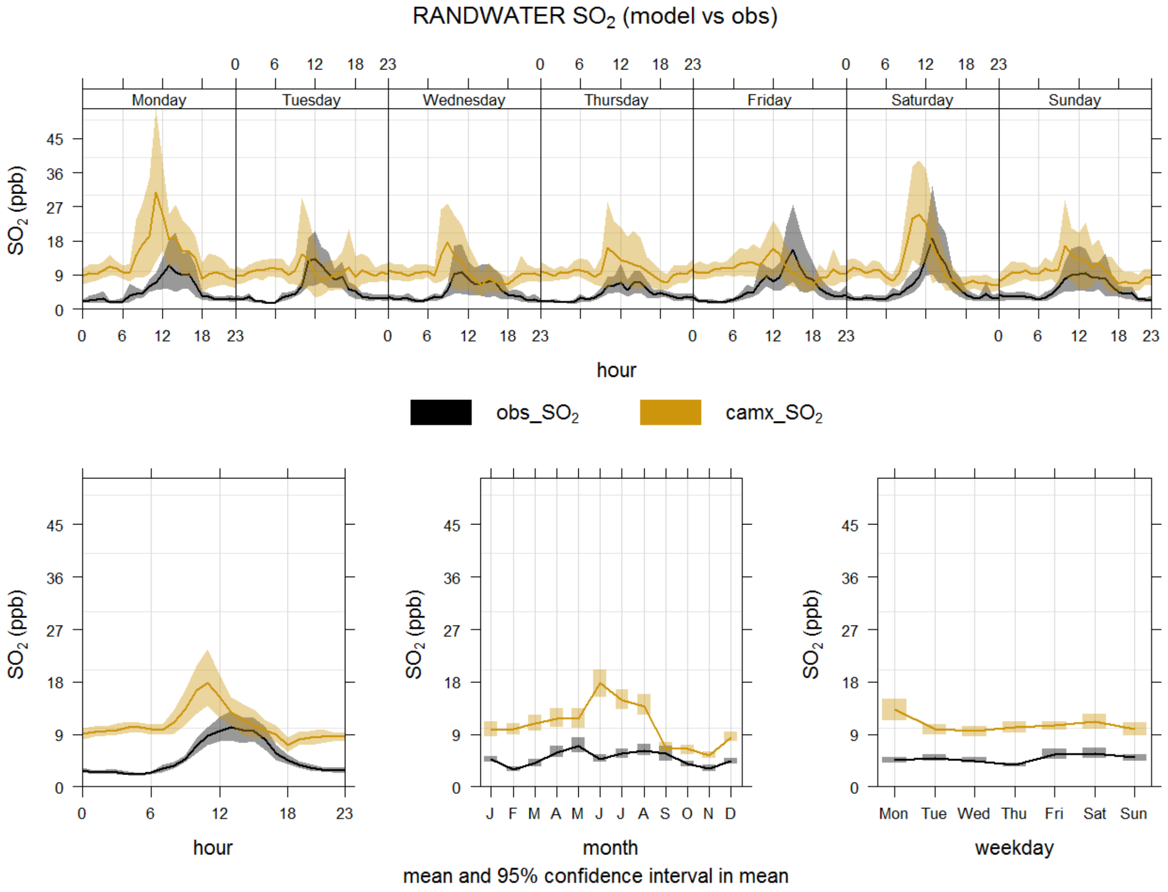

LEITRUM SO$_2$ observations
ppb
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

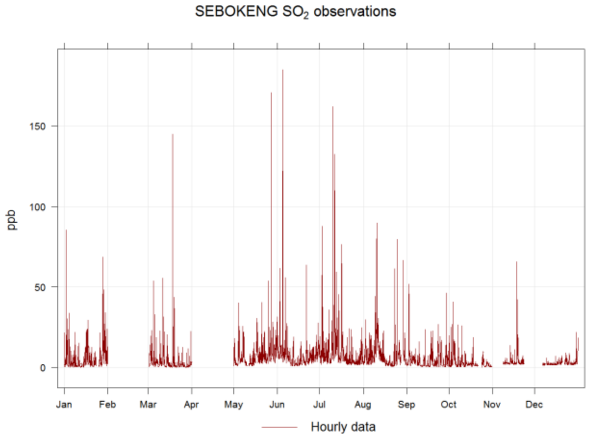

LEITRUM SO$_2$ daily (obs vs model)
ppb
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

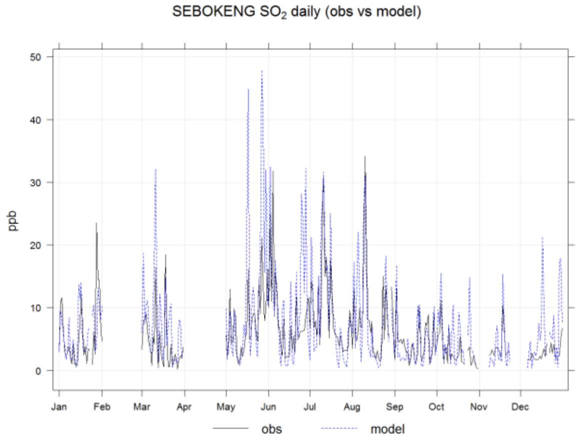

LEITRUM SO$_2$ (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
SO$_2$ (ppb)
42
35
28
21
14
7
0
0
6
12
18
23
hour
obs_SO$_2$
camx_SO$_2$
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

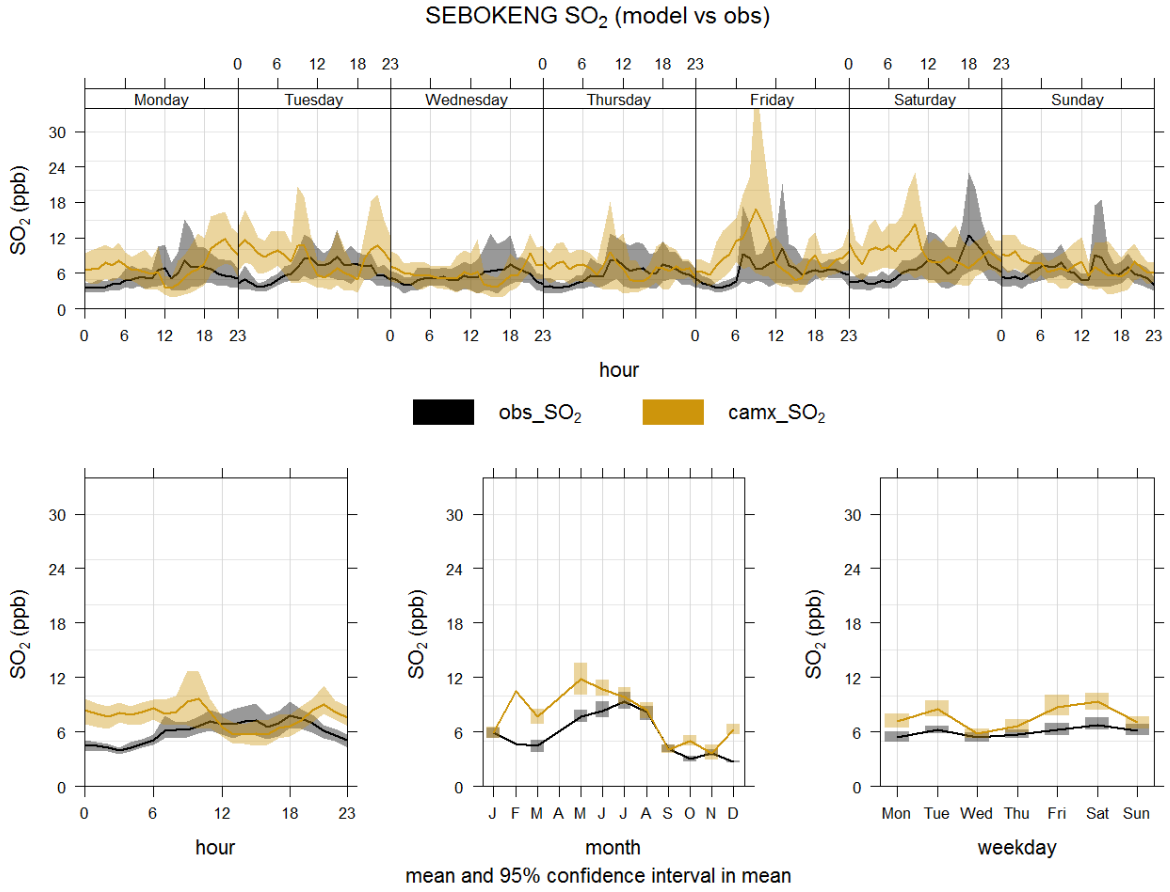

RANDWATER SO_2 observations

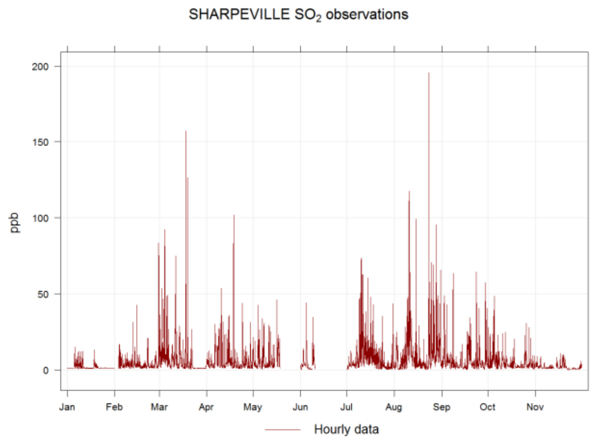

RANDWATER SO_2 daily (obs vs model)

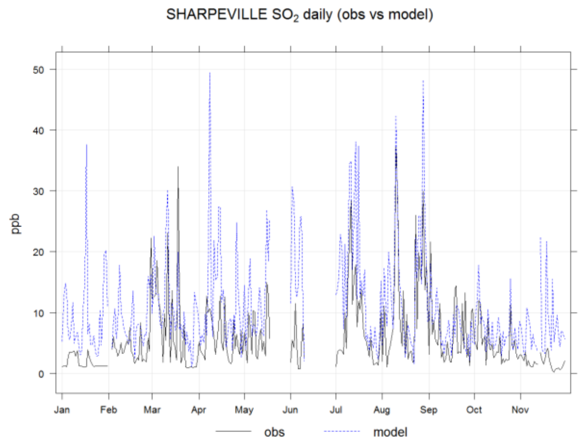

RANDWATER SO_2 (model vs obs)

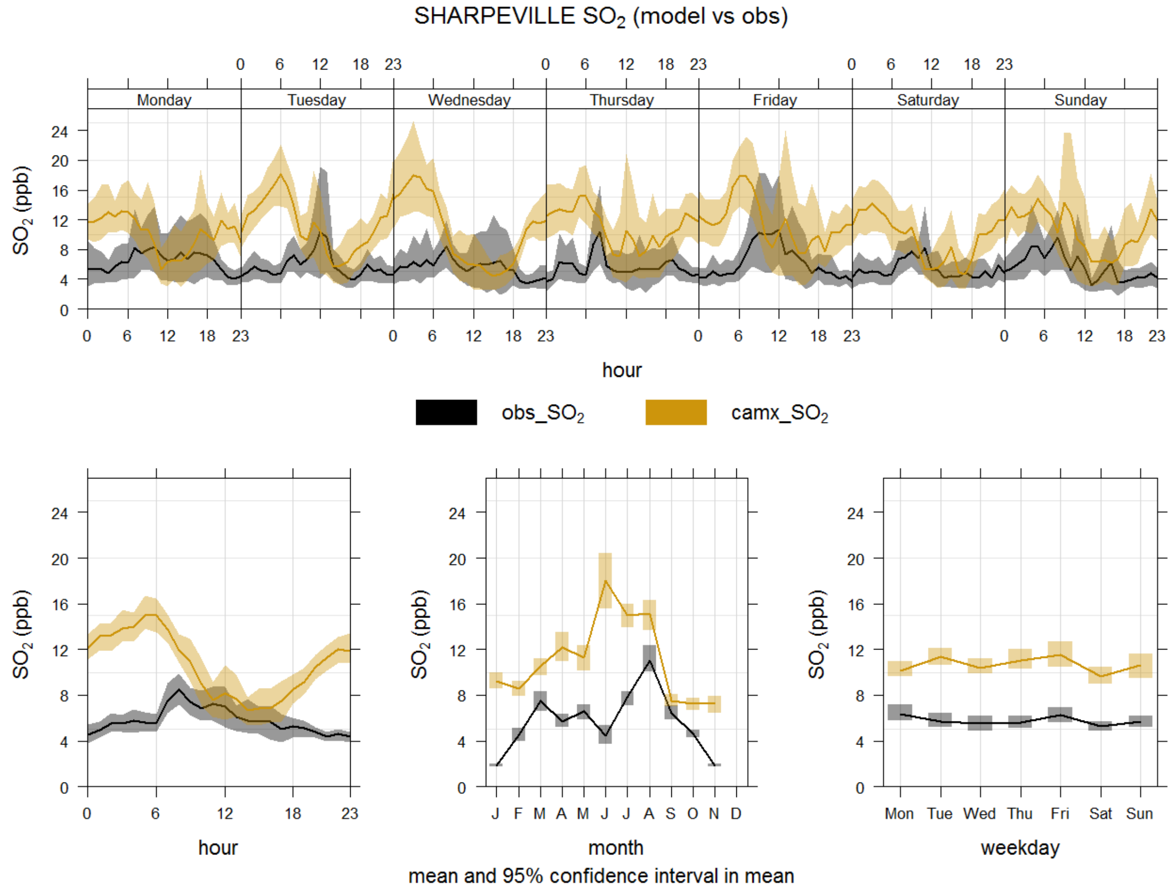

SEBOKENG SO_2 observations
ppb
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

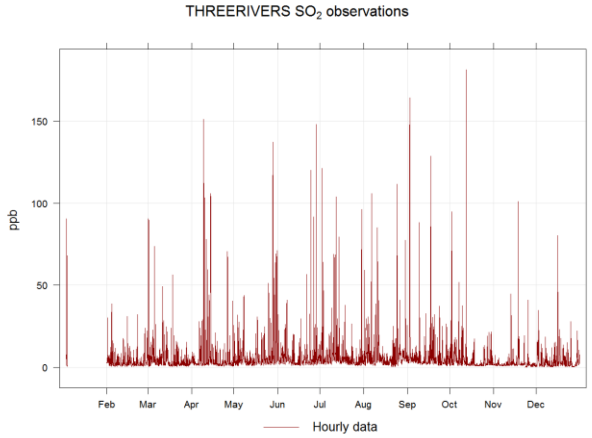

SEBOKENG SO_2 daily (obs vs model)
ppb
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model


SEBOKENG SO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
SO_2 (ppb)
0
6
12
18
24
30
0
6
12
18
23
hour
obs_SO_2
camx_SO_2
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

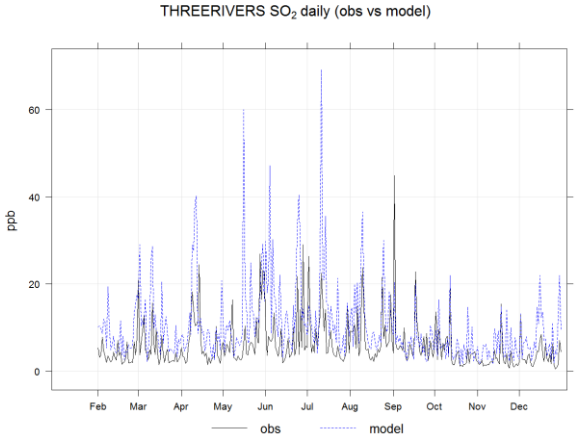

SHARPEVILLE SO_2 observations
ppb
0
50
100
150
200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Hourly data


SHARPEVILLE SO_2 daily (obs vs model)
ppb
0
10
20
30
40
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
obs
model

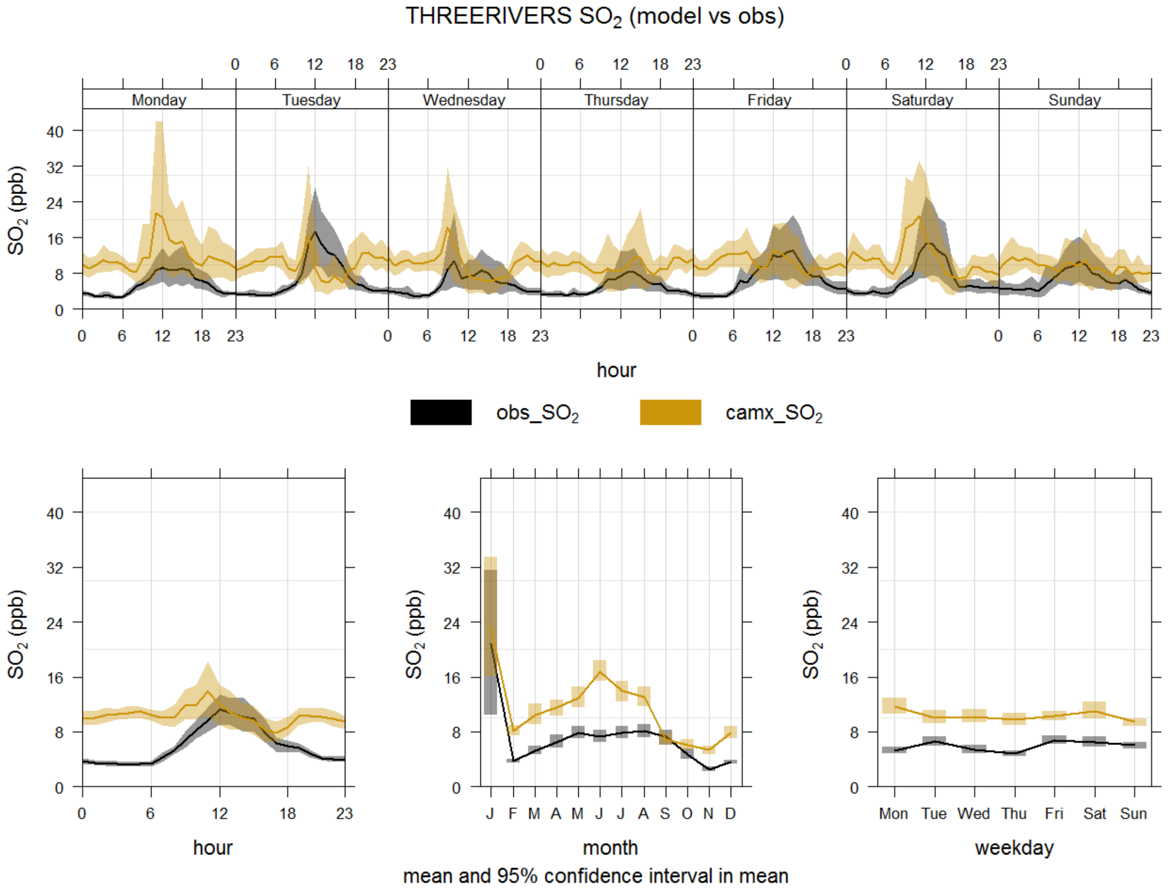

SHARPEVILLE SO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
SO_2 (ppb)
0
4
8
12
16
20
24
hour
obs_SO_2
camx_SO_2
hour
J
F
M
A
M
J
J
A
S
O
N
D
month
Mon
Tue
Wed
Thu
Fri
Sat
Sun
weekday
mean and 95% confidence interval in mean



THREERIVERS SO_2 observations

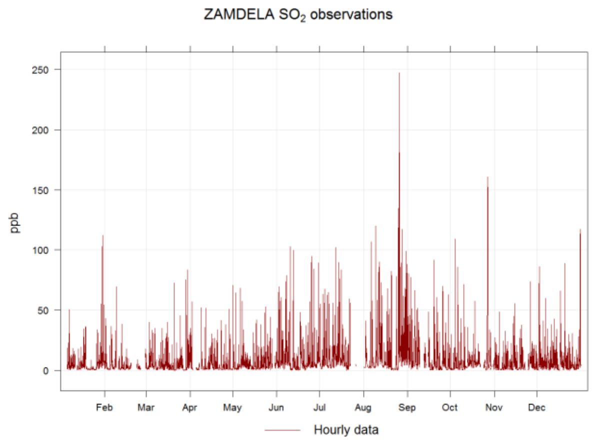


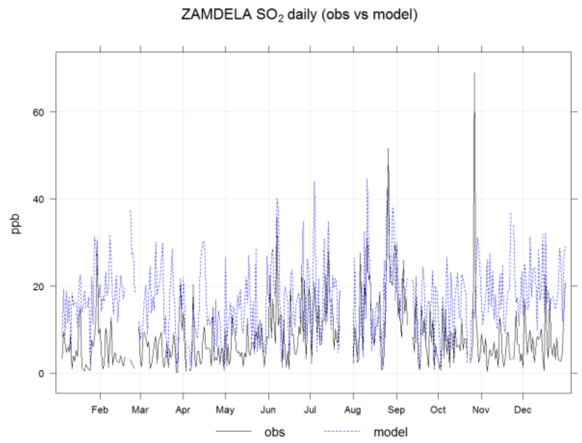
THREERIVERS SO_2 daily (obs vs model)

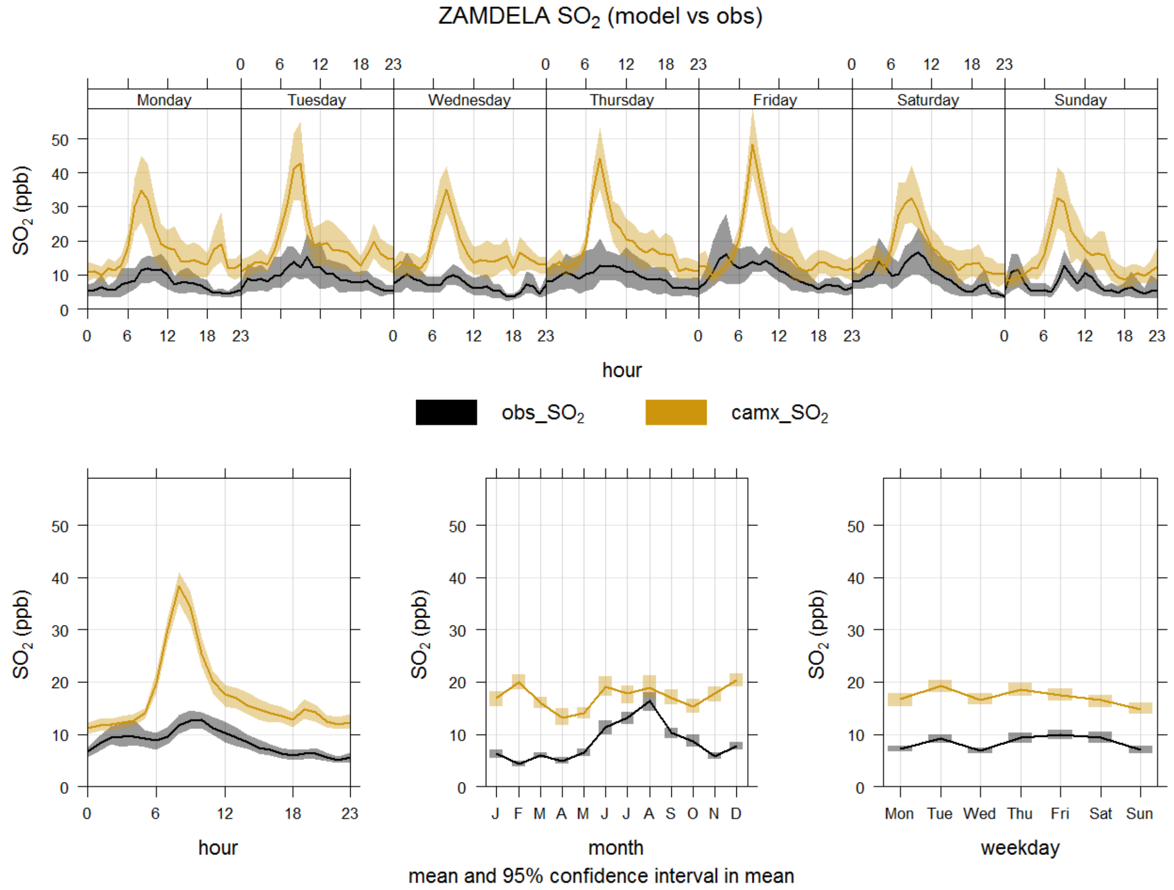


THREERIVERS SO_2 (model vs obs)

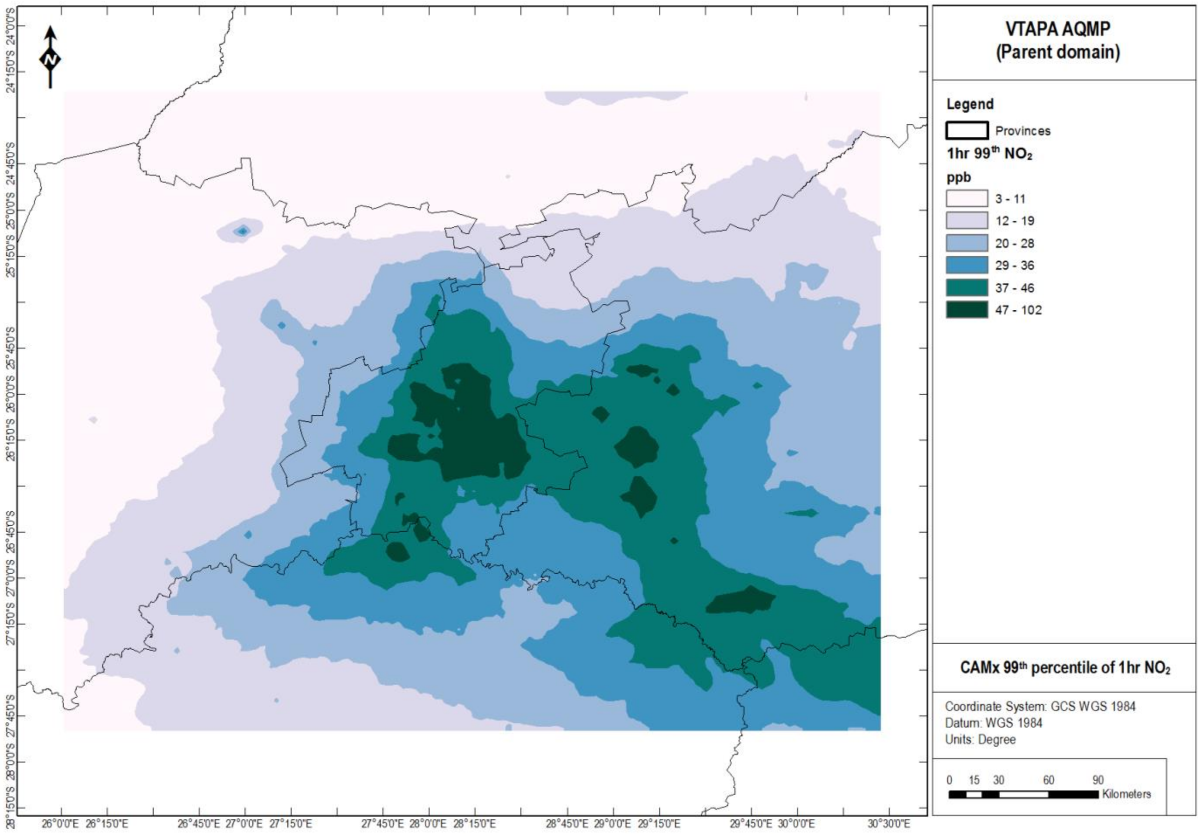
mean and 95% confidence interval in mean

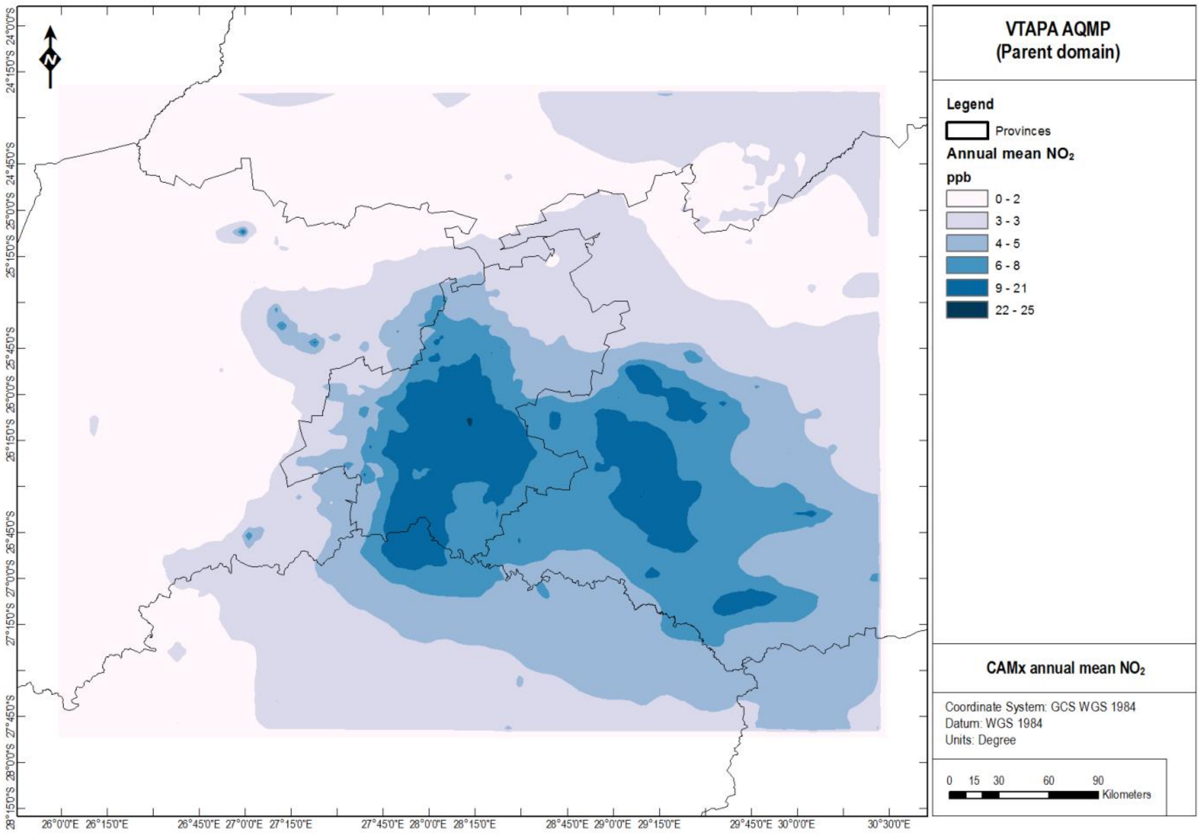

ZAMDELA SO_2 observations
ppb
250
200
150
100
50
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Hourly data

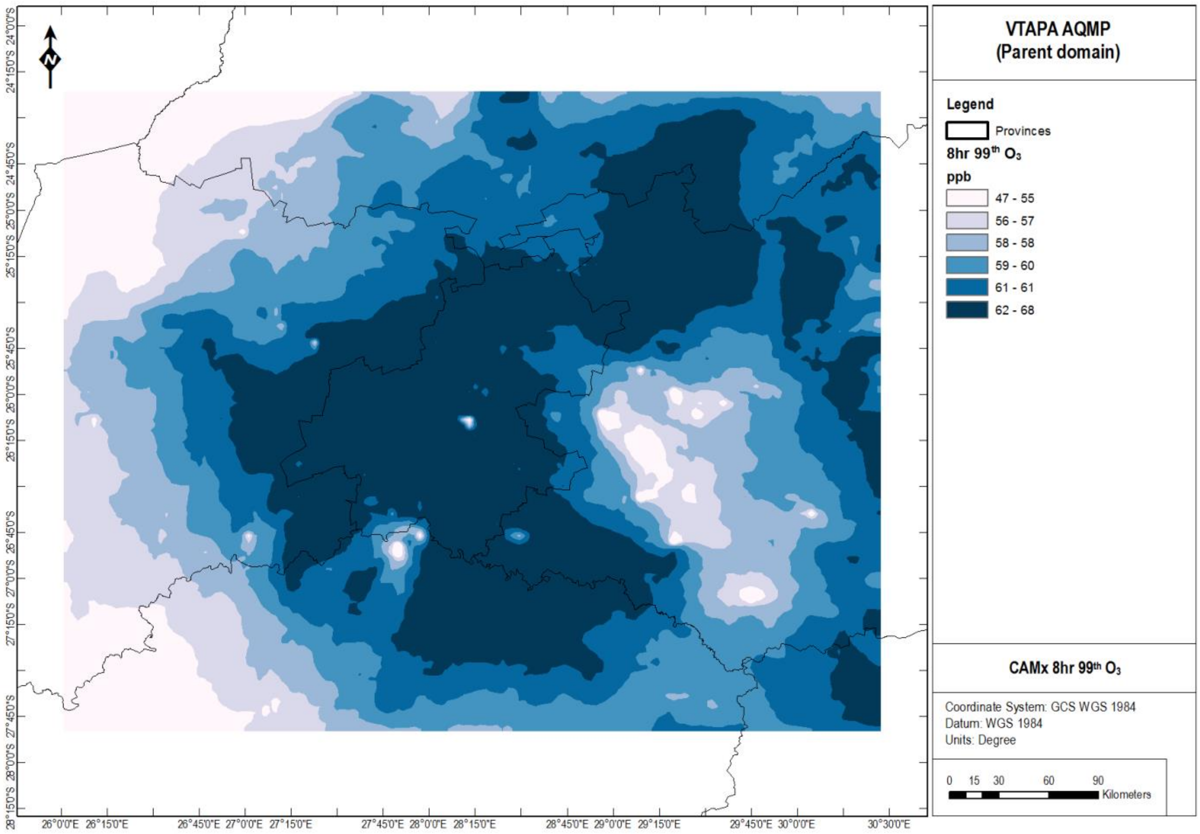

ZAMDELA SO_2 daily (obs vs model)
ppb
60
40
20
0
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
obs
model

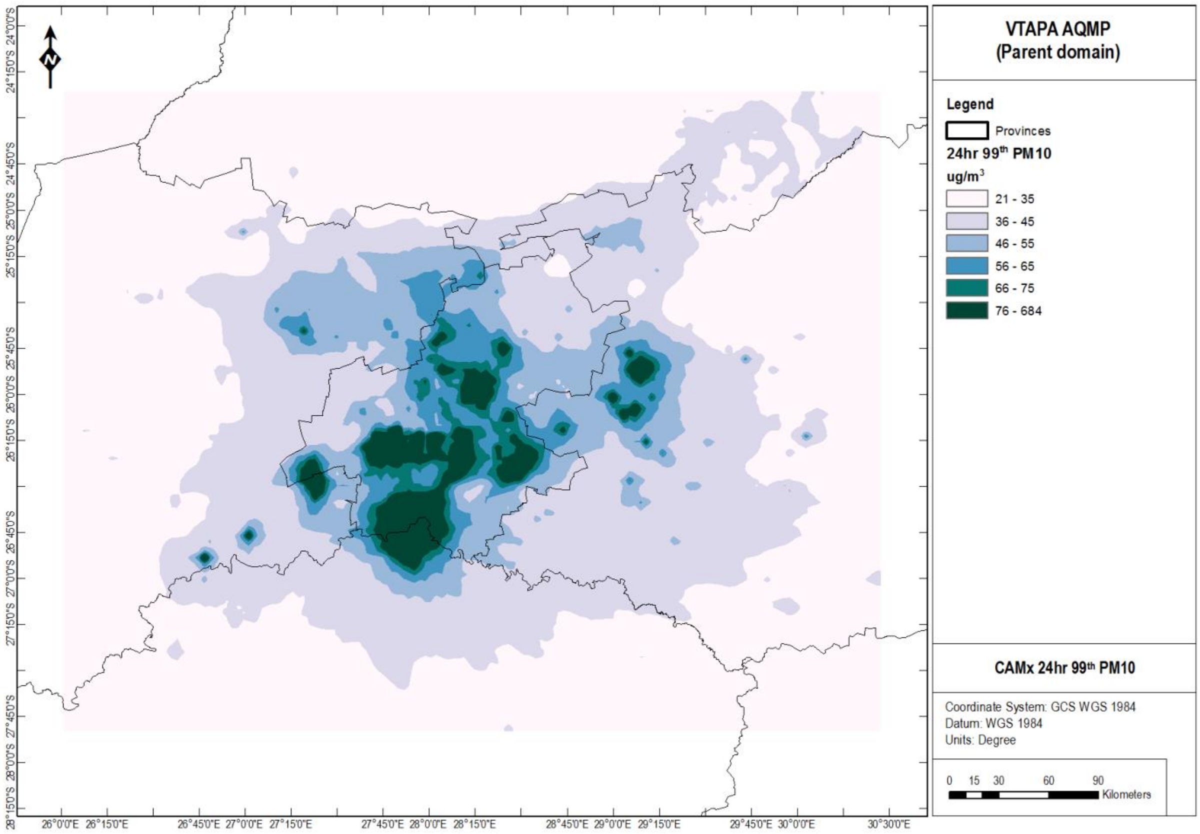

ZAMDELA SO_2 (model vs obs)
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
0
6
12
18
23
SO_2 (ppb)
50
40
30
20
10
0
hour
obs_SO_2
camx_SO_2
hour
J F M A M J J A S O N D
month
Mon Tue Wed Thu Fri Sat Sun
weekday
mean and 95% confidence interval in mean

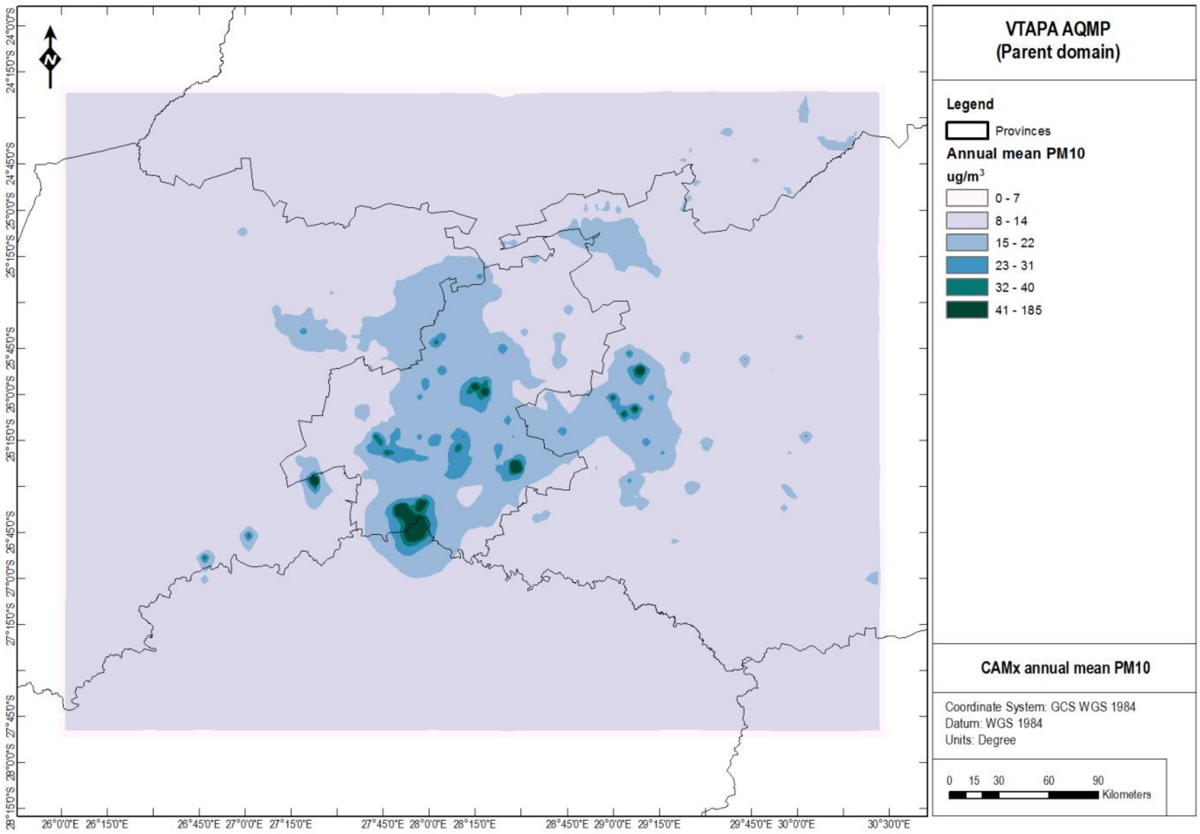
10 APPENDIX C – TIME AVERAGED CONCENTRATION MAPS FOR THE PARENT MODEL DOMAIN (I.E. 3KM RESOLUTION)

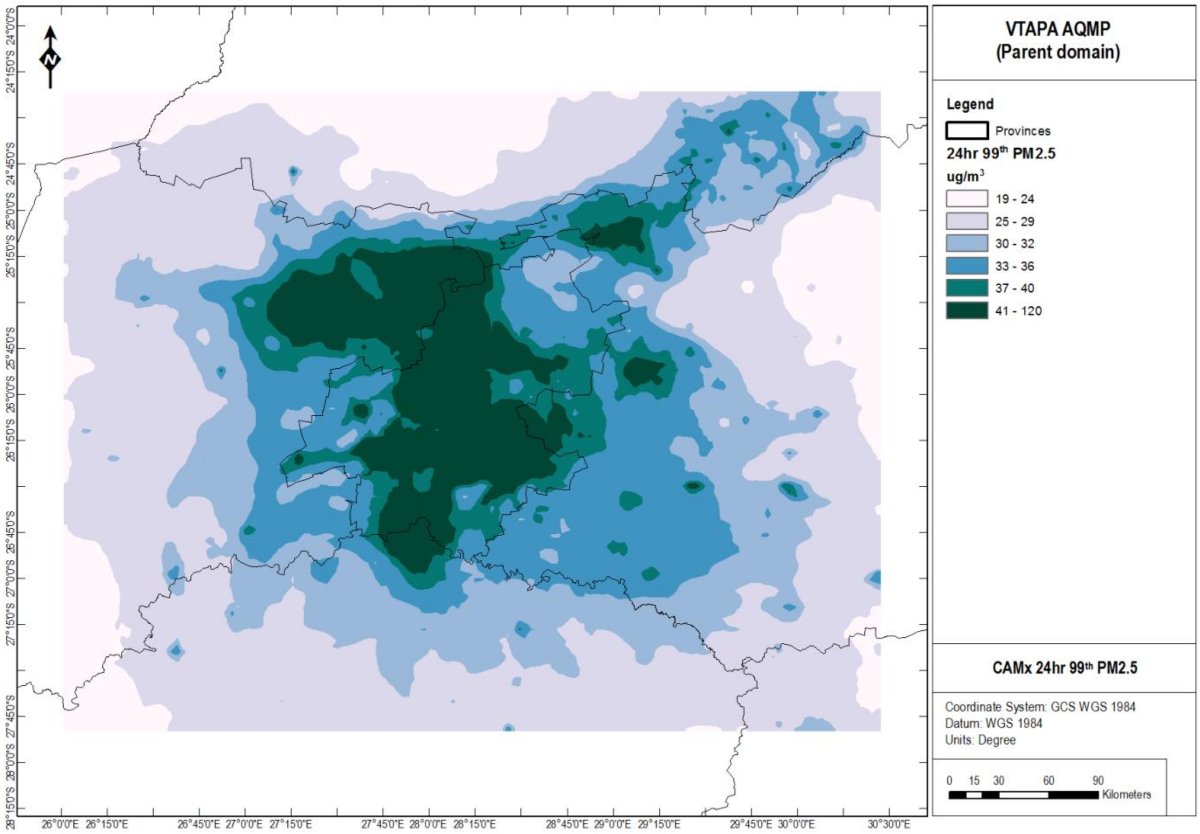


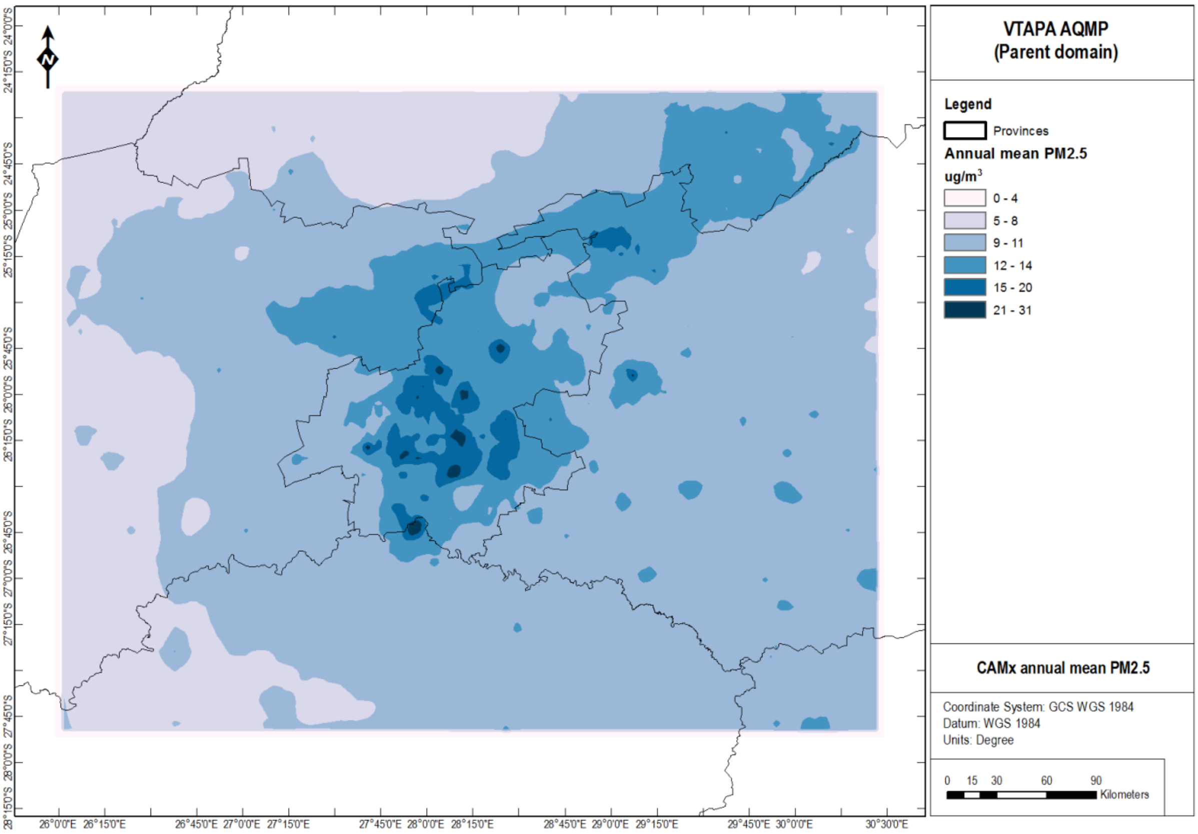


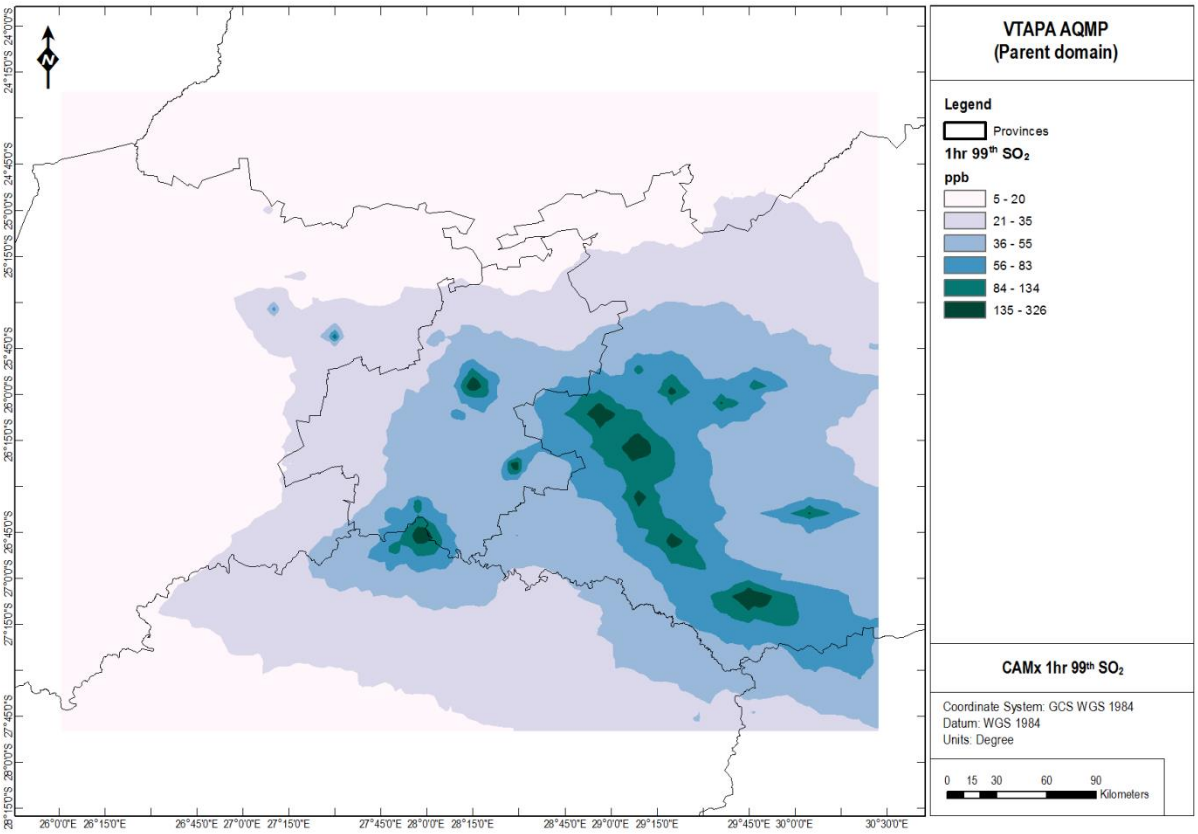

VTAPA AQMP
(Parent domain)
Legend
Provinces
8hr 99th O3
ppb
47 - 55
56 - 57
58 - 58
59 - 60
61 - 61
62 - 68
CAMx 8hr 99th O3
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90 Kilometers
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S

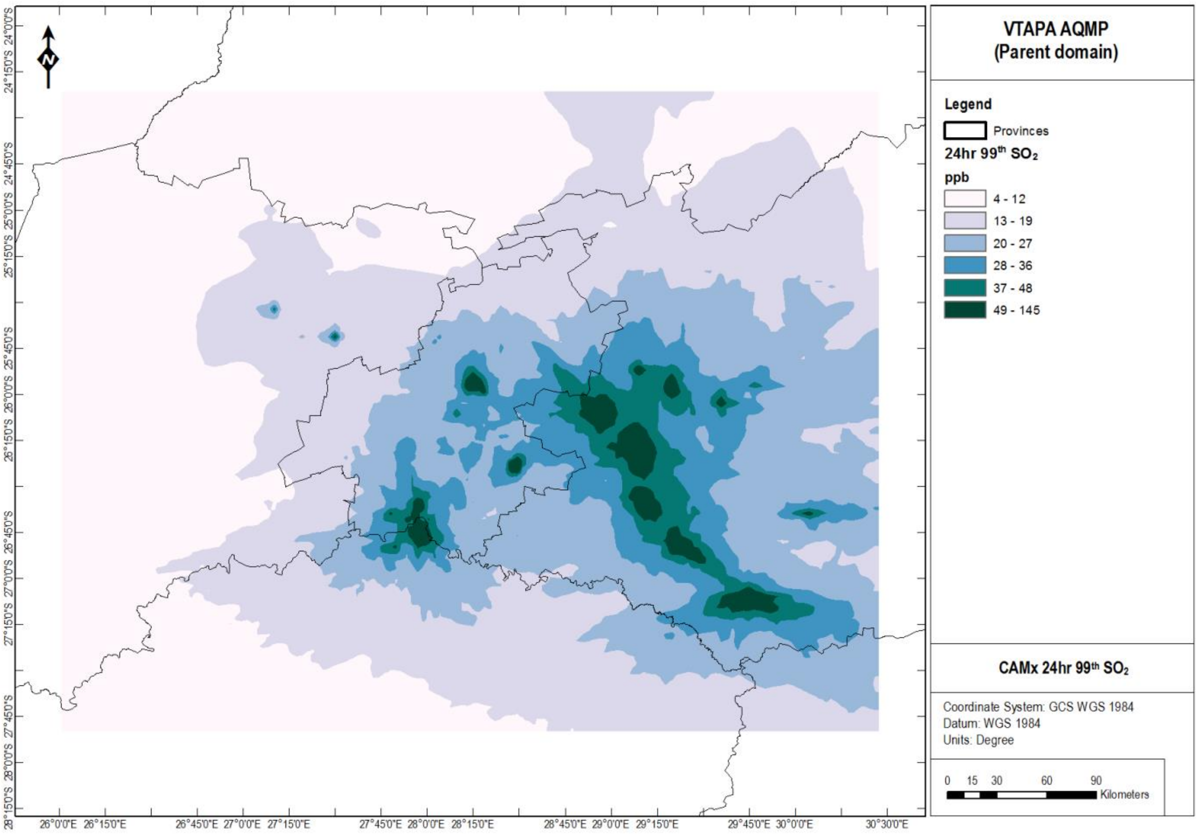

VTAPA AQMP
(Parent domain)
Legend
Provinces
24hr 99th PM10
ug/m3
21 - 35
36 - 45
46 - 55
56 - 65
66 - 75
76 - 684
CAMx 24hr 99th PM10
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90 Kilometers
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S

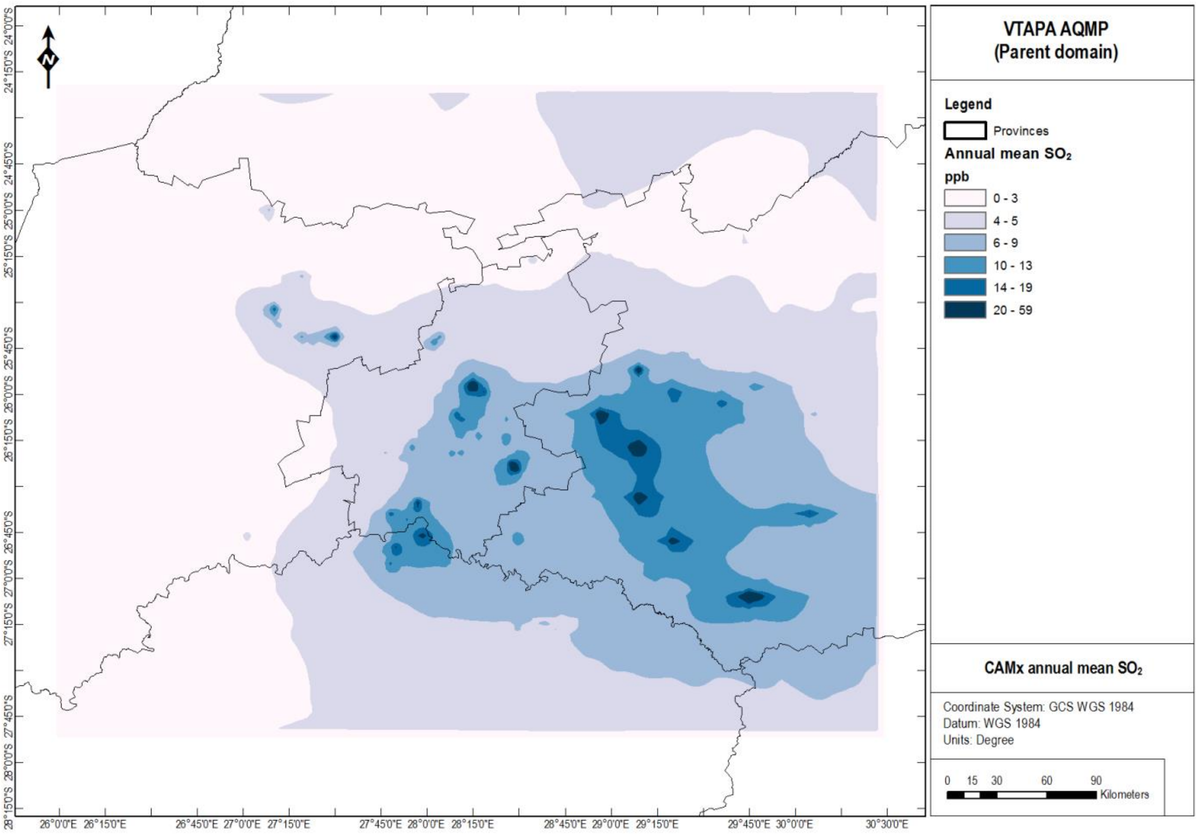

VTAPA AQMP
(Parent domain)
Legend
Provinces
Annual mean PM10
ug/m^3
0 - 7
8 - 14
15 - 22
23 - 31
32 - 40
41 - 185
CAMx annual mean PM10
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
24°0'0"S
24°15'0"S
24°45'0"S
25°0'0"S
25°15'0"S
25°45'0"S
26°0'0"S
26°15'0"S
26°45'0"S
27°0'0"S
27°15'0"S
27°45'0"S
28°0'0"S
28°15'0"S
26°0'0"E
26°15'0"E
26°45'0"E
27°0'0"E
27°15'0"E
27°45'0"E
28°0'0"E
28°15'0"E
28°45'0"E
29°0'0"E
29°15'0"E
29°45'0"E
30°0'0"E
30°30'0"E


VTAPA AQMP
(Parent domain)
Legend
Provinces
24hr 99th PM2.5
ug/m^3
19 - 24
25 - 29
30 - 32
33 - 36
37 - 40
41 - 120
CAMx 24hr 99th PM2.5
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
24°0'0"S
24°15'0"S
24°45'0"S
25°0'0"S
25°15'0"S
25°45'0"S
26°0'0"S
26°15'0"S
26°45'0"S
27°0'0"S
27°15'0"S
27°45'0"S
28°0'0"S
28°15'0"S
26°0'0"E
26°15'0"E
26°45'0"E
27°0'0"E
27°15'0"E
27°45'0"E
28°0'0"E
28°15'0"E
28°45'0"E
29°0'0"E
29°15'0"E
29°45'0"E
30°0'0"E
30°30'0"E


VTAPA AQMP
(Parent domain)
Legend
Provinces
Annual mean PM2.5
ug/m³
0 - 4
5 - 8
9 - 11
12 - 14
15 - 20
21 - 31
CAMx annual mean PM2.5
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S


VTAPA AQMP
(Parent domain)
Legend
Provinces
1hr 99th SO₂
ppb
5 - 20
21 - 35
36 - 55
56 - 83
84 - 134
135 - 326
CAMx 1hr 99th SO₂
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S


VTAPA AQMP
(Parent domain)
Legend
Provinces
24hr 99th SO₂
ppb
4 - 12
13 - 19
20 - 27
28 - 36
37 - 48
49 - 145
CAMx 24hr 99th SO₂
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S


VTAPA AQMP
(Parent domain)
Legend
Provinces
Annual mean SO₂
ppb
0 - 3
4 - 5
6 - 9
10 - 13
14 - 19
20 - 59
CAMx annual mean SO₂
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
0 15 30 60 90
Kilometers
N
26°0'0"E 26°15'0"E 26°45'0"E 27°0'0"E 27°15'0"E 27°45'0"E 28°0'0"E 28°15'0"E 28°45'0"E 29°0'0"E 29°15'0"E 29°45'0"E 30°0'0"E 30°30'0"E
24°0'0"S 24°15'0"S 24°45'0"S 25°0'0"S 25°15'0"S 25°45'0"S 26°0'0"S 26°15'0"S 26°45'0"S 27°0'0"S 27°15'0"S 27°45'0"S 28°0'0"S 28°15'0"S