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Contents

NACA Courses 2018

5-Day Air Quality Management Courses

Centurion, Gauteng
19 to 23 February 2018

Who should attend:
Current or aspirant air quality practitioners in the public and private sector, specifically persons responsible for implementing aspects of the NEM: Air Quality Act. Intending participants should have knowledge of the basics of air quality with a bachelor's degree, a national diploma or several years of relevant experience

Cape Town, Western Cape
13 to 17 August 2018

Certification:
A certificate of attendance and satisfactory completion will be issued by NACA.

Course fee: R10,500.00 (Excl. 14% VAT)
Fee includes participation in the course, a full set of printed notes and CD disk and certificate. Morning and afternoon tea, and daily lunches will be provided.

3-Day Introduction to Air Dispersion Modeling

Centurion, Gauteng
11 - 13 June 2018

Who should attend:
South Africa has legislated air dispersion modeling as an accepted tool for managing components of air quality. Applications include; understanding current source receptor relationships, explaining ambient air quality standards exceedances, predicting impacts from existing and planned emissions sources and siting ambient air quality monitoring stations. This course will teach participants a basic understanding of the theory of dispersion modeling as well as providing hands on training with AERMOD Dispersion model.

Certification:
A certificate of attendance and satisfactory completion will be issued by NACA.

Course fee: R10,500.00 (Excl. 14% VAT)
Fee includes participation in the course, a full set of printed notes and CD disk and certificate. Morning and afternoon tea, and daily lunches will be provided.

4-Day CALPUFF and AERMOD Modeling Course

Centurion, Gauteng
16 - 19 July 2018

Who should attend:
Current or aspirant air quality practitioners in the public and private sector, specifically persons responsible for performing or evaluating applications for Air Emissions Licences, based on dispersion modelling. Intending participants should have at the minimum knowledge of the basics of meteorology and air quality management.

Lecturers and Course Content:
Two course-days are dedicated to the CALPUFF Module and two days to AERMOD Modeling. The course is presented by a senior lecturer from the Canadian company, Lakes Environmental.

Certification:
A certificate of attendance and satisfactory completion will be issued by NACA.

Course fees:
For more information on course fees, special discounts and group rates, please visit the NACA website.

Visit the NACA website at www.naca.org.za for more information on course content and registration forms.

Message
Message from the NACA President

http://dx.doi.org/10.17159/2410-972X/2017/v27n2a1

The Clean Air Journal is a product of the National Association for Clean Air (NACA) that the organisation is immensely proud of. This is the 83rd edition of the journal, which was first published in 1971. The success of the journal is unquestionable and attributable to the hard work of many individuals that make valuable, selfless contributions and notably the co-editors, Dr. Gregor Feig, Dr. Rebecca Garland and Dr. Caradee Wright. I would hence like to take this opportunity of expressing my heartfelt gratitude to the co-editors for volunteering their time and expertise towards ensuring that the journal grows from strength to strength. The success of the journal was recently rewarded by being accepted for inclusion in Scopus, the world's largest abstract and citation database of peer-reviewed research literature. This is certain to result in increased international visibility of the journal, and increased opportunity for articles being cited and improved contribution to the wider scholarly community within the subject field.

The year 2017 has been an eventful one for NACA. Council welcomed three new members, namely, Ms Gabi Mkhatshwa, Dr Herman van der Walt and Mrs Nicolette von Reiche. Council members unanimously voted Prof Stuart Picketh in as NACA Vice President. The work of Council kicked off early, following the formation of several sub-committees to assist with the organisation of the various NACA events and activities.

A successful 2017 Air Quality Week was hosted in collaboration with the Department of Environmental Affairs at the Cedarwoods of Sandton. A total of 161 delegates attended the conference, significantly up from the previous year, and a total of 25 scientific papers were presented. The conference is the premier event in the South African air quality calendar and the most important meeting place for the air quality family of industry, government, consultants, academics and civil society.

A total of six branch seminars were hosted this year. A total of four training courses were presented in Gauteng and KwaZulu on the "Introduction to Air Quality Management" and the "Introduction to Dispersion Modelling". Several training courses have also been scheduled for next year with the "Advanced Dispersion Modelling" course likely to be the highlight. For this, we will be graced with the presence of Jessie Thé of Lakes Environmental.

A special thank you also to Ms Beverly Terry for arranging sponsorships for the Journal through advertising and in turn to the many advertisers for their generous contributions.

Benton Pillay
NACA President

News
Leadership in Air Quality award

Willie Kok (Chair NACA Awards Committee)

http://dx.doi.org/10.17159/2410-972X/2017/v27n2a2

The NACA awards are used to recognize and reward special efforts towards achieving NACA's goal of obtaining clean air in South Africa. The awards are presented annually at the NACA Conference.

The award categories are as follows:
- Industrial/Mining Award
- Leadership in Air Quality
- Golden Award

A member, branch or council member may make nominations for the awards. NACA membership of the nominee shall not be a factor in either the nomination or the award itself.

This year, the NACA Council & Awards Committee made a decision, based on the nominations received, only to present an award in the *Leadership in Air Quality* category.

The *Leadership in Air Quality* award was presented at this year's Annual NACA Conference to EnviroNgaka for the development of a manual for the Stack Testing Association of South Africa (STASA) which will serve as an exceptional guidance to industry to be accessible and technically correct. This dedication to develop a "tool" to industry to educate all practitioners responsible for stack emissions is something that has to be recognized. Congratulations to Jan Potgieter for his dedication and guidance for many years to industry.

Editorial
Clean Air Journal accepted for indexing in Scopus

Gregor T Feig, Rebecca M Garland, and Caradee Y Wright

http://dx.doi.org/10.17159/2410-972X/2017/v27n2a3

The editors are very excited to announce that the *Clean Air Journal* has recently been accepted for indexing in Scopus.

Scopus is the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings. Content for indexing in Scopus is conducted by an independent Content Selection and Advisory Board in order to evaluate and validate peer reviewed Journals against fair and transparent criteria. The criteria for indexing in Scopus consist of 5 main categories:

- The Journal Policies; such as the Editorial Policies, the peer review policies and sufficient geographic diversity within the editors and authors
- The contributions included in the Journal; relating to the academic contribution made by the Journal, the quality and readability of the abstracts and articles and conformity to the stated aims and scope of the Journal
- The Standing of the journal; relating to the number of citations of the articles and the standing of the editors
- Regularity of publishing; is the journal published when it should be?
- Online availability; where factors such as the online availability the quality of the home page are considered.

Being indexed in Scopus confers a number of advantages to the *Clean Air Journal*, such as increased international visibility, and increased opportunity for articles being cited and improved contribution to the wider scholarly community within the subject field. It also means that contributions to the *Clean Air Journal* must be of the highest quality, and the administrative duties of the Editors and reviewers must adhere to the strict standards of the Journal.

The current editors would like to thank the broader South African air quality community for the interest and support that has been shown to the *Clean Air Journal* since it was first published in 1971. Special thanks needs to go out to Prof Gerrit Kornelius, who edited the journal for over thirty years and is responsible for ensuring that an archive of South African air quality research is available to upcoming generations of South African researchers and those who strive to promote the cause of clean air in South Africa.

Recently, our geographical focus has expanded to cover the African continent and we hope that we will continue to meet the needs of the air quality community across the continent, to share knowledge and experience and foster collaboration.

Research brief
Increasing mercury trend observed at Cape Point Global Atmosphere Watch (GAW) Station from 2007 – 2015

Lynwill G. Martin[1*], Casper Labuschagne[1], Thumeka Mkololo[1], Franz Slemr[2] and Ernst Brunke[1]
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Gaseous elemental mercury (Hg^0) is the dominant form of natural and anthropogenic Hg emissions and is transported globally through the atmosphere. Mercury, released into the environment by natural and anthropogenic activities, cycles between the atmosphere, water, and land reservoirs. Because of fast mixing processes in the atmosphere, monitoring of tropospheric mercury concentrations and of its deposition will thus be the most straightforward way to verify the decrease of mercury emissions expected from the implementation of the Minamata Convention. According to Zhang et al. (2016) worldwide anthropogenic emissions decreased from 2890 tonne Hg yr^{-1} in 1990 to 2160 tonne yr^{-1} in 2000 and increased slightly to 2280 tonne yr^{-1} in 2010. However, there is indeed some recent evidence that the downward trend in the Northern Hemisphere is slowing or even turning upwards (Weigelt et al., 2015). Here we report on the atmospheric mercury trend observed at the Cape Point (CPT) Global Atmosphere Watch (GAW) station from March 2007 till June 2015.

In a recent study by (Martin et al., 2017) - briefly summarized here the long-term dataset collected at CPT was analyzed using The Mann-Kendal test for trend detection. Figure 1 shows the monthly average GEM concentrations calculated from all data from March 2007 until June 2015, and in the lower panel monthly average GEM concentrations were calculated from baseline data, i.e., GEM concentrations measured at ^{222}Rn concentration ≤250 mBq m^{-3}, which is considered to represent essentially marine air. The slope of the least-squares fit of all data (0.0222 ±0.0032 ng m^{-3} $year^{-1}$) is not significantly different from the slope calculated from the baseline data only (0.02190 ±0.032 ng m^{-3} $year^{-1}$). Sen's slope and trend significance were found to be 0.0210 ng m^{-3} yr^{-1} for all data and 0.0208 ng m^{-3} yr^{-1} for background data respectively. Sen's slopes tend to be somewhat lower than the slopes from the least-squares fits, but they are in agreement within the 95% uncertainty range. All trends are highly significant, i.e., at a level ≥99:9 %. The results are essentially the same whether monthly median or monthly average concentrations are used. This shows that the trend is robust and not influenced by occasional pollution or depletion events. This is the first analysis that suggests an increase in atmospheric mercury concentrations. During the 2007–2015 period the highest upward trend was found in austral spring. Hg emissions from biomass burning in South America and Southern Africa both peak in August and September. Biennial variation of the GEM concentrations at Cape Point, (not shown here) suggest that climatological changes of transport patterns can also play a role in seasonally different trends.

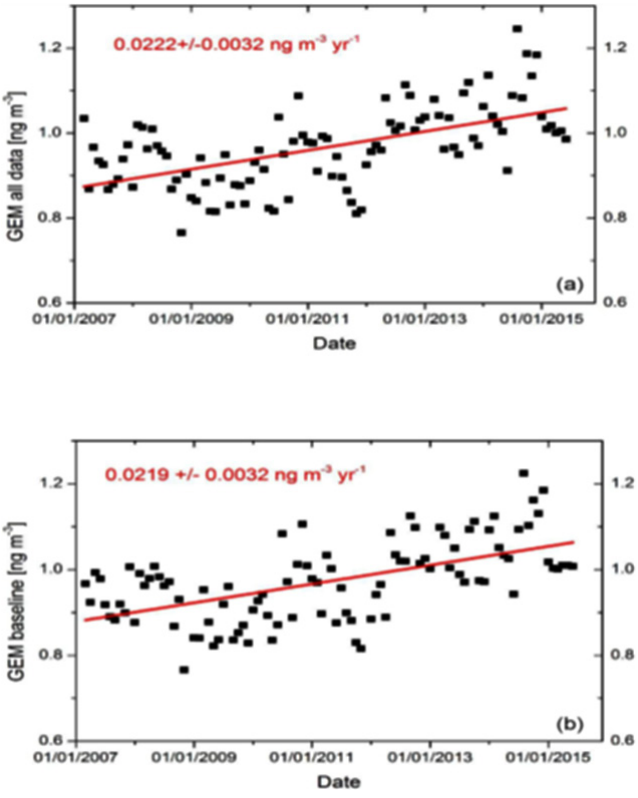

Figure 1: *Monthly average GEM concentrations and their least-squares fit: upper panel – all data; lower panel – baseline data (i.e., only GEM concentrations at ^{222}Rn concentrations ≤250 mBq m^{-3} [taken from Martin et al. 2017]*

We report here an upward trend for mercury concentrations at CPT for the period 2007–2015. We show that the observed

trends of GEM concentrations at CPT result from the trend of worldwide mercury emissions and are modulated by regional influences. Combining all this evidence, we conclude that the worldwide mercury emissions are now increasing, after a decade or two of decreasing emissions. This finding is consistent with the temporal development of mercury emissions in the most recent mercury inventory.

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Company Profile

an EOH company

Originally formed in 1976, SI Analytics provides air monitoring solutions to industry, government and research organisations. Our analytical instrumentation offers continuous measurement of both surrounding air pollution and chimney emissions.

We design, manufacture, supply, install, commission, train and provide after sales service for either individual monitors, or integrated systems in southern Africa.

SI Analytics is currently a B-BBEE level 2 contributor.

Being a founding member of Europa Environmental gives us the expertise to supply and support advanced environmental monitoring technology.

Our aim is to bring you the world's best instrumentation, spare parts, service, technical support and training - at the most affordable pricing - to meet your environmental monitoring needs.

Services

Due to government regulatory requirements, our clients are under increasing pressure to collect emissions data. This is not part of their core business - their expertise lies in manufacturing the products they sell. Our expertise lies in assisting them to manage their data and compliance issues.

We offer a wide range of services such as ambient air quality and continuous emissions monitoring which include:

- Environmental monitoring
- Certified USEPA, European EN and UK MCerts equipment sales
- Data management and reporting
- Service and maintenance contracts
- Equipment rentals
- Indoor air quality assessments
- Short courses (e.g. Operator monitoring assessment training).

Products

Stand alone products, integrated systems, spare parts, local factory repair, and on-site maintenance are all part of what SI Analytics has to offer, thus providing tailor-made solutions to client applications.

Instrumentation from the most popular products includes:

Ecotech:	manufactures a range of ambient air quality instruments.
Grimm:	mobile and stationary ambient dust monitors.
Ecochem:	extractive high sensitivity gas analyser systems.
Procal Analytics:	in-situ continuous stack gas analysers.
Chromatotec:	chlorine, hydrocarbon and sulphur speciation analysers.

Clients

an EOH company

SI Analytics has successfully installed and maintained various analysers and systems for a variety of clients such as:

We also provide data management and monthly reporting services for clients throughout South Africa, Botswana, Mozambique, Nigeria, Zambia and Zimbabwe, amongst others.

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Research brief

Summary of research paper published in Atmospheric Chemistry and Physics titled: Spatial, temporal and source contribution assessments of black carbon over the northern interior of South Africa

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According to the latest assessment report of the Intergovernmental Panel on Climate (IPCC), aerosol black carbon (BC) is considered the second most important contributor to global warming after carbon dioxide (CO2). Since BC is part of the atmospheric particulate fraction that have a relatively short atmospheric lifetime, the climatic influence of BC is particularly relevant on a regional scale. This paper presents equivalent black carbon (eBC) (derived from an optical absorption method) data collected from three sites in the interior of South Africa, where continuous measurements were conducted, i.e. Elandsfontein, Welgegund and Marikana, as well elemental carbon (EC) (determined by evolved carbon method) at five sites where samples were collected once a month on a filter and analysed off-line, i.e. Louis Trichardt, Skukuza, Vaal Triangle, Amersfoort and Botsalano.

Analyses of eBC and EC spatial concentration patterns across the eight sites indicate that the mass concentrations in the South African interior are in general higher than what has been reported for the developed world and that different sources are likely to influence different sites. The mean eBC or EC mass concentrations for the background sites (Welgegund, Louis Trichardt, Skukuza, Botsalano) and sites influenced by industrial activities and/or nearby settlements (Elandsfontein, Marikana, Vaal Triangle and Amersfoort) ranged between 0.7 and 1.1, and 1.3 and 1.4 µg/m3, respectively.

Similar seasonal patterns were observed at all three sites where continuous measurement data were collected (Elandsfontein, Marikana and Welgegund), with the highest eBC mass concentrations measured during June to October, indicating contributions from household combustion in the cold winter months (June-August), as well as savannah and grassland fires during the dry season (May to mid-October). Diurnal patterns of eBC at Elandsfontein, Marikana and Welgegund indicated maximum concentrations in the early mornings and late evenings, and minima during daytime. From the patterns it could be deduced that for Marikana and Welgegund, household combustion, and savannah and grassland fires were the most significant sources, respectively.

Possible contributing sources were explored in greater detail for Elandsfontein. Five main sources, i.e. coal-fired power stations, pyrometallurgical smelters, traffic, household combustion, as well as savannah and grassland fires, were identified and the source strengths quantified. A comparison of these source strengths indicated that household combustion, and savannah and grassland fires were the most significant sources of eBC, particularly during winter and spring months, while coal-fired power stations, pyro-metallurgical smelters and traffic contribute to eBC concentrations year round. Concentration ratios, which can be used as emission factors for the afore-mentioned sources were also presented.

Research article

A Nairobi experiment in using low cost air quality monitors

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Abstract

Many African cities have growing air quality problems, but few have air quality monitoring systems in place. Low cost air quality sensors have the potential to bridge this data gap. This study describes the experimental deployment of six low cost air quality monitors consisting of an optical particle counter Alphasense OPC-N2 for measuring PM_1, $PM_{2.5}$ and PM_{10}, and Alphasense A-series electrochemical (amperometric) gas sensors: NO2-A43F, SO2-A4, NO-A4 for measuring NO_2, NO and SO_2 in four schools, the United Nations Environment Program (UNEP) headquarters and a community center in Nairobi. The monitors were deployed on May 1 2016 and are still logging data. This paper analyses the data from May 1 2016 to Jan 11 2017. By examining the data produced by these sensors, we illustrate the strengths, as well as the technical limitations of using low cost sensors for monitoring air quality. We show that despite technical limitations, sensors can provide indicative measurements of air quality that are valuable to local communities. It was also found that such a sensor network can play an important role in engaging citizens by raising awareness about the importance of addressing poor air quality. We conclude that these sensors are clearly a potentially important complement but not a substitute for high quality and reliable air quality monitoring systems as problems of calibration, certification, quality control and reporting remain to be solved

Keywords

outdoor air quality, low cost sensors, Nairobi, citizen science, African cities

Introduction

Poor air quality is the world's single largest environmental health risk. Exposure to air pollution in 2012 was responsible for an estimated seven million premature deaths and this problem is growing (World Health Organisation 2014). Given the large public health costs of air pollution, many countries are putting in place more measures to improve air quality, including laws, regulations, monitoring systems and public awareness campaigns (http://web.unep.org/airquality/). As further impetus for these efforts, the new Sustainable Development Goals includes as global targets, reducing annual mean levels of urban fine particulate matter (PM_{10} and $PM_{2.5}$) and the mortality rate attributed to household and ambient air pollution.

These efforts at monitoring and research are uneven across the globe. In sub-Saharan Africa, air quality data often do not exist, and regulations and laws are often not in place to curb air pollution; or if in place, are not implemented, even though existing research shows that the annual mean fine particulate matter in these cities often exceeds World Health Organisation standards (Njee et al., 2016; Petkova et al., 2013). Few African cities operate air monitoring systems, and most cities lack any air quality monitoring capabilities (Schwela, 2012a, Njee et. al 2016). Currently, only Ghana and South Africa operate comprehensive and well organized air quality monitoring programs (Amegah and Agyei-Mensah, 2016). In addition, the air quality data that does exist is not always made public and/or communicated effectively, which limits public awareness and effective policy (Petkova et al., 2013).

Although systematic, long term monitoring is missing in most African cities, existing studies show a serious and growing problem in urban air quality due to rapid urbanization coupled with industrialization, increasing motorization and the continued use of biomass fuel as the household energy source

(UNEP, 2016; Lindén et al., 2012; Fiore et al., 2012; Schwela, 2012b). The worst urban air pollution may actually be in sub-Saharan African countries (Schwela, 2012a). There is thus an urgent need to monitor urban air quality in this region so that the health effects of pollutants can be better understood and quantified, leading to cost-effective abatement strategies and greater public awareness and pressure.

For many African cities, cost is one barrier to investing in air quality monitoring (Amegah and Agyei-Mensah, 2016 ; Schwela, 2012a). The cost of reference air quality monitoring systems (AQMS) is high (costing between US $5000 and US $200,000 for each AQM), and training and AQMS maintenance, as well as managing and analysing the data can also be expensive (Kumar et al., 2015; Mead et al., 2013). This means that even in those countries that have air quality standards and laws, there are often no monitoring systems to measure compliance.

Within this context, low-cost sensors (costing between US $100 and US $3000 for each node) appear to have the potential to help us move from a paradigm of high cost, highly accurate, sparsely located reference air quality monitors, to a dense, low cost, reasonably accurate air quality monitoring network that can also involve citizen science. However, currently no standards or certification criteria exist for such sensors, and there are concerns about the quality of the data (Lewis and Edwards, 2016). Further, the flood of low cost sensors onto the market makes it difficult to determine the reliability of each model. Complicating the challenge of certification, cheap sensors from the same manufacturer often have variable performance.

A US Environmental Protection Agency study of low cost sensors on the market found that either 'no lower cost sensors currently meet [the EPA's] strict requirements or have not been formally submitted to the EPA' (Williams et al., 2014). The US EPA in their study tested these sensors in a clean environment in North Carolina, but how these sensors will perform in the polluted, hot, humid environments frequently found in the developing world is unknown. This is because temperature and humidity can affect the sensitivity of some of these sensors-especially low cost electrochemical gas sensors. Therefore, more work is needed to quantify the accuracy of these sensors under different conditions. Overall, more research is needed on the performance of low cost air quality networks in the field to address the need for monitoring in many of the world's cities (Kumar et al., 2015, Lewis and Edwards 2016).

This paper presents the results and lessons learned from an experiment in using a low cost air quality monitoring network in Nairobi, Kenya. The main aim of this work is to contribute to the growing and important conversation about the role of low cost sensors in air quality monitoring efforts in cities (Kumar et al., 2015; Lewis and Edwards 2016, Kotsev et al. 2016, Piedrahita et al., 2014; Popoola 2012). We were interested in exploring the feasibility of deploying such networks in African cities as a means of gathering some basic data in a quick and efficient way that also involves citizens.

A collaboration between UNEP, the company Alphasense, the University of Cambridge, NASA-GLOBE, the Wajukuu Arts Collective and the Kibera Girls Soccer Academy, resulted in the deployment of a pilot, six node air quality network in four schools, UNEP and one community center in the city of Nairobi, Kenya. The collaboration also aimed to share the experience of air quality monitoring with interested citizens. The sensors include an optical particle counter (Alphasense OPC-N2) that measures PM_1, $PM_{2.5}$ and PM_{10}, Alphasense A-series electrochemical gas sensors (NO2-A43F, NO-A4, SO2-A4) for measuring NO_2, NO and SO_2, temperature and humidity sensors, and a SIM card to transmit data in near real time via the GSM network.

These pollutants were chosen to be measured because particles with aerodynamic diameters less than 10 μm, when inhaled, become embedded in soft tissue and have major health effects. Particulate matter in the environment can have hundreds of different sources. NO and NO_2 are the two oxides of nitrogen that majorly affect human health. NO typically rapidly oxidizes to NO_2. However, the direct emission of NO from vehicles can result in high levels of NO close to roads. SO_2 also negatively affects health. It also reacts with other compounds in the atmosphere to form fine particulates. SO_2 is typically emitted from power plants, industrial facilities, and from the burning of diesel with high sulphur content.

This network started running on May 1, 2016 and is still in operation at the time of writing this paper. After a brief review of air pollution in Nairobi, where no continuous monitoring system yet exists, we present our methods and analyse data collected from this network. Drawing on this experimental deployment, we discuss lessons learned for the potential of low cost air quality networks to support air quality monitoring in African cities.

Background to the Nairobi Case Study

The capital of Kenya, Nairobi is a rapidly growing metropolitan area with an estimated 4 million people living or working within its city boundaries. By 2030, this population may grow to as much as 6 million (World Bank 2016). Air pollution has accompanied this urban growth. Sources include vehicles, open air burning of solid waste, industrial activity and domestic cooking using biomass (Gatari 2009, Kinney et al. 2011, Muindi et al. 2016). Despite growing air quality regulations, such as in the Environmental Management and Coordination Act (Air Quality) Regulations 2014, Nairobi, like most Africa cities, does not have an institutionalized air quality monitoring system.

Scientists at the University of Nairobi, African Population and Health Research Center and their international collaborators (Gaita et al., 2014; Gatari et al., 2009; Gatari and Boman, 2003; Kinney et al., 2011; Muindi et al., 2014; Ngo et al., 2015; Vliet and Kinney, 2007) have taken a number of measurements in Nairobi. These are, however, short-term observations at limited points around the city (background, industrial, roadways, and households in informal settlements) and limited numbers of pollutants, mostly $PM_{2.5.}$ In many cases, levels of $PM_{2.5}$ appeared well above the World Health Organization (WHO) 24-h average guideline of 25 mg/m^3 and an annual average guideline of 10 μg/m^3. However, some measurements were not always comparable with these guidelines, as continuous monitoring was not taking place (Kinney et al., 2011; Ngo et al., 2015).

Methods

Air quality monitors were bought from the company: Atmospheric Sensors Ltd. in the UK (The product catalogue is found here: http://atmosphericsensors.com/products/product-brochures/remote-air-quality-monitor/view). The monitors comprised of an optical particle counter (Alphasense OPC-N2) and Alphasense A-series electrochemical gas sensors, temperature and humidity sensors, and a SIM card to transmit data in near real time via the GSM network. The OPC-N2 (costing USD 450 each) measures particle counts in 16 bins ranging from 0.38 µm to 17.5 µm. It does this by illuminating one particle at a time using focused light from a laser, and measuring the intensity of light scattered from aerosol particles. The amount of scattering from a particle is a function of particle size and composition, which can be calibrated using mono-disperse particles (Sousan et al., 2016). The number of particles per volume for each of these bins can be obtained by dividing the particulate counts of each bin by flow rate and sample time. Alphasense provides a partially proprietary algorithm that makes assumptions about the particle density to calculate PM_1, $PM_{2.5}$ and PM_{10} data from the particle count data. The OPCs in this deployment turn on and run for 20s every 60s; there is 15s of warm up then 5s of actual measurement. The sampling flow rate (SFR) is typically 3.7 mL/s, but varies with temperature. The accuracy of these monitors depends on the size distribution of particulates present, environmental factors such as humidity and the hygroscopicity of the particulates present (Sousan et al., 2016). Without this detailed information, the uncertainty in measurements of the OPC-N2 cannot be quantified.

The Alphasense A-series electrochemical (amperometric) gas sensors (NO2-A43F, SO2-A4, NO-A4): 4-electrode, 20 mm diameter aperture sensors (USD 50-75 each), measure NO_2, NO, SO_2. The electronics of the node used to convert the current of the electrochemical gas sensors to volts and the analogue-to-digital conversion of this voltage signal is proprietary to Atmospheric Sensors. The gas sensors log data every minute at the same time as the OPC. The monitors were coupled to a UPS in order to maintain instrument sensitivity during short power failures. Electrochemical gas sensors exhibit cross-interferences with other pollutants. For example, the NO sensor is sensitive to NO2 (Data sheet: http://www.alphasense.com/WEB1213/wp-content/uploads/2016/03/NO-A4.pdf). The NO_2 sensor is extremely sensitive to O_3 (Data sheet: http://www.alphasense.com/WEB1213/wp-content/uploads/2016/04/NO2-A43F.pdf). The SO_2 sensor is most sensitive to H_2S and NO_2 (Data sheet: http://www.alphasense.com/WEB1213/wp-content/uploads/2013/12/SO2A4.pdf).

Changes in ambient temperature and humidity also affect the sensitivity and sensor gain. The sensors were pre-calibrated at the Alphasense laboratory in the UK, and calibration curves were provided for the gas sensors in order to convert the signals into gas concentrations, expressed as parts per billion by volume (ppb). Alphasense also provided the temperature correction factors for the gas sensors. Research has shown though, that although the sensor manufacturer's correction is effective for sensitivity-dependent temperature correction, it is not effective for temperature-dependent baseline change. Research has also shown that this baseline effect is more pronounced for the NO sensor than for the NO_2 sensor (Popoola et al., 2016). This shall be discussed further when the results are presented.

Data was pulled from the Alphasense server via a file transfer protocol.

One of the biggest drawbacks of our network is that co-location of the low cost monitors with a reference air quality monitor was not conducted. Thus, we have no way to test the accuracy of data from our monitors. We also did not calibrate the electrochemical gas sensors in the ambient environment. We tried to conduct a qualitative appraisal of the data we gathered by going to each site and talking to the people there about what they observed. However, we acknowledge that co-locating at least one of our monitors with a reference air quality monitor would have significantly enhanced our results. We present our analysis and data in this context.

This is the first time air quality was monitored in schools in Nairobi. We specifically engaged with three schools that were part of the NASA GLOBE community (https://www.globe.gov/), which is an international program that allows students the opportunity to participate in data collection. We did this to leverage the existing citizen science program in the schools. We also hoped that we could use our collaboration with NASA GLOBE to expand our deployment in other GLOBE schools in the future.

We selected our sites in a variety of locations. We deployed air quality monitors in low-income schools in the informal settlements: a) Kibera Girls Soccer Academy situated in the informal settlement: Kibera near the railway tracks and b) Viwandani community center in an informal settlement in the industrial area of Nairobi. We also deployed monitors at c) St Scholastica, situated 20 meters away from the notoriously congested Thika Highway in order to capture pollutants from vehicular emissions, d) at UNEP located in Gigiri, which is a relatively green, low density residential, and wealthy part of the city. At e) All Saints Cathedral School which is close to a major road, Mbagathi road, as well as several small shops and industries. Finally, we deployed a monitor at the elite national school, f) Alliance Girls School, located in Kikuyu, a small town to the North of Nairobi as an urban background site. By deploying our monitors in this range of sites, we hoped to capture the signature of different sources in the city as well as get a sense of the differing conditions between very poor and wealthier neighbourhoods. Figure 1 shows the geographic locations of the sites in the city.

The monitors were deployed on walls 1.5-2 meters above the ground so that they would be at close to adult breathing height, but out of reach of the casual passer-by. Note that as the monitors were mounted on walls instead of poles, the sensors only measure pollutants from air masses for a swath of 180 degrees. A plastic shield provided by Alphasense was used to protect the monitor from rain as seen on the upper right-hand side of Figure 1. As of January 11, 2017, the OPCs at all the sites, except for that at Viwandani, which experienced power outages for a few days in May and June and an extended power outage past July 2016, are logging data. The monitor at Alliance Girls School experienced a power outage for most of the month of September 2016, and the one at Kibera Girls School Academy experienced a few hours of power shortage on 19 August 2016, but otherwise have been logging data.

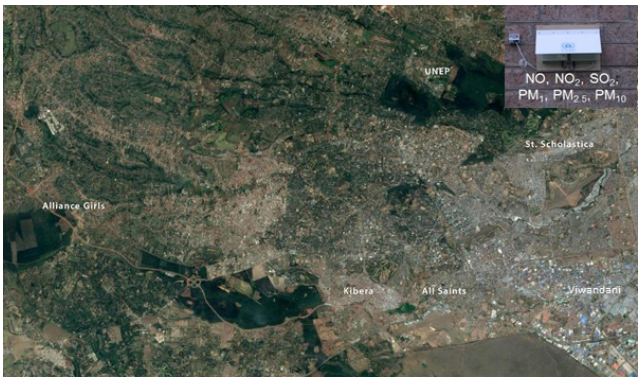


Figure 1: *This shows a map of the six deployment sites with a photograph of what each site looks like. The upper right figure is a photograph of the monitor deployed at each site.*

We hoped that by engaging with schools and community centers, we would be able to involve the public in air quality monitoring. Participation by residents in the monitoring is an important way to communicate the science of air pollution to citizens (Ngo et al. 2015a). Studies show that Nairobi residents from poor neighbourhoods appear to have a wide variety of often-inaccurate perceptions about air pollution, in part because they have very little information about it (Egondi et al., 2013; Muindi et al., 2014; Ngo et al., 2017, 2015). Nevertheless, a 2015 telephone survey of a representative sample of Nairobi residents, revealed that a majority of Nairobi's adult citizens perceive the air in the city as bad or very bad (69%) and among those who consider the air bad, 93% believed it had an impact on their health. This makes the idea of involving people in monitoring, especially through learning institutions, a viable and potentially important approach that we wanted to test

Finally, we presented preliminary data analysed using the 'OpenAir' package in R version 3.3.2 (Carslaw and Ropkins, 2012) to school children at each deployment site in order to raise awareness about air pollution as well as to brainstorm potential pollution management strategies for the community. We sourced large-scale wind data (that is not local, canyon-influenced wind data) averaged over a period of two minutes, half hourly for this analysis from the Wyoming Weather Website (http://weather.uwyo.edu/surface/meteorogram/), for the Jomo Kenyatta airport site to the south of the city at an elevation of 1624 meters.

Results

Figure 2 shows the hourly averaged PM data obtained from monitors at each of the six sites from May 5 2016 to Jan 11 2017. The monitors started running at different times on May 1 so for consistency, we ignore the data for the first 5 days of measurement. Raw minute wise PM data has been plotted in Fig 1A in the Appendix. The raw PM data showed peaks that were as high as a few 1000 µg/m^3. It is extremely unlikely for PM readings to reach such high values in a natural environment. However, without co-location with a reference instrument, it is impossible to distinguish the signal from the noise.

From Figure 2, we see that the PM readings at the informal settlements Kibera and Viwandani are routinely very high. A summary of the average minute wise PM readings for each site are provided in Table 1. We note that the difference in $PM_{2.5}$ in up-scale schools such as St Scholastica and Alliance Girls School, and the $PM_{2.5}$ recorded by the monitors at the sites in the informal settlements: Kibera and Viwandani are not very high. We also observe that particulate matter pollution recorded by our monitors at UNEP and All Saints are lower than at the other sites.

The hourly averaged periodic spikes in PM_{10} at the Alliance site are observed to reach a few 1000 µg/m^3. As mentioned previously, it is unlikely that PM_{10} reaches such high values in the natural environment. These peaks in pollution could indicate a source of pollution very close to the sensor. On going to the site, we found that the school did indeed burn wood very close to the site. This 'ground-truthing' shall be discussed further. It is interesting to note that peaks of the same magnitude as seen in the PM_{10} data were not seen in the finer particulate observations. More information on the kind of burning is required to speculate why this is the case.

We analysed the temperature corrected gaseous pollutant data using the Alphasense calibration and temperature correction at each site. Figure 3 shows temperature-corrected hourly-averaged NO_2, SO_2 and NO data at each site. Raw minute wise gaseous pollutant data for each site can be found in Figure 2A in the Appendix.

We see from Figure 3 that a significant number of gaseous pollutant observations were < 0. Table 1 shows how much of the gaseous data recorded was < 0. This appears to be an issue of instrument calibration and also perhaps consistency between instruments, which we will discuss in more detail in later sections.

The raw data in Figure 2A in the Appendix also shows that for each site some NO observations go to a few -100 ppb. This seems to correspond to the value of NA for the NO sensor. We have applied a filter and eliminated NO values less than -100 ppb from our analysis from here onwards.

As mentioned before, no ambient calibration was carried out for the electrochemical gas sensors and therefore the gaseous pollutant values have to be viewed with skepticism. We present them here to see if any useful signal can be gleaned from the pollutant data.

Table 1 provides a summary of the pollutant data at each site. A multi-pollutant approach of analysing air quality in Nairobi can be useful in identifying common-sources across the city, as well as in identifying possible health effects that could arise from exposure to multiple pollutants, and not just a single pollutant. (Dominici et al., 2010).

From Figure 3 we note that SO_2 is measured to be highest at Viwandani. This seems reasonable. Our site is located in the industrial area of Nairobi. Community members informed us that several factories existed in the vicinity of the site ranging from a paint factory, a factory that manufactured electrical connections and a factory that produced the raw materials for tear gas. Given this background, the high SO_2 values that we saw were not unexpected. We were, however, surprised to see the peak in SO_2 levels at St Scholastica. More work is required to verify this peak, and to identify a potential source. We posit that

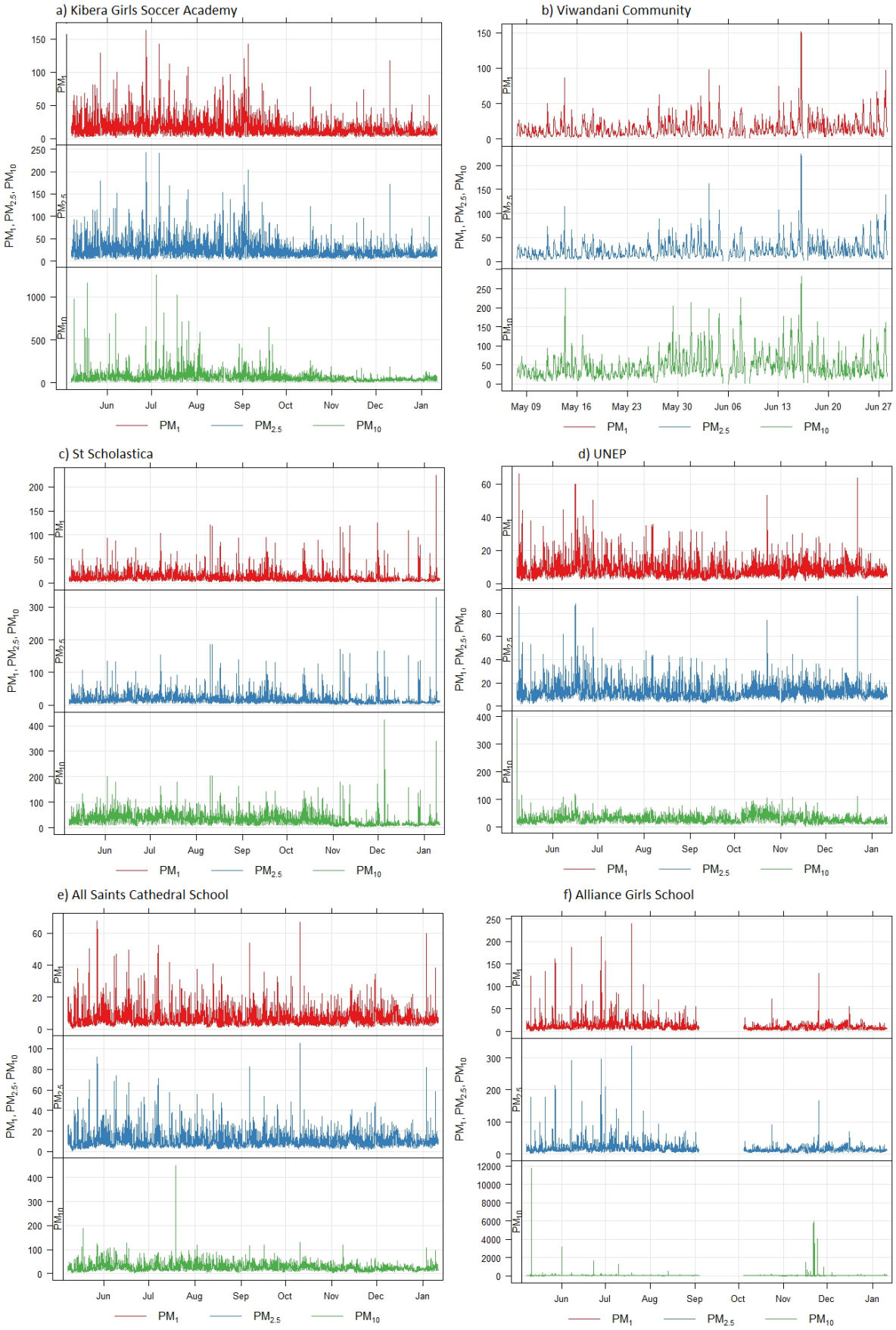


Figure 2: *Hourly averaged PM_1 (red), $PM_{2.5}$ (blue) and PM_{10} (green) time series plots for each site in units of µg/m³ a) Kibera Girls Soccer Academy, b) Viwandani Community Center, c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5 2016 to January 11 2017.*

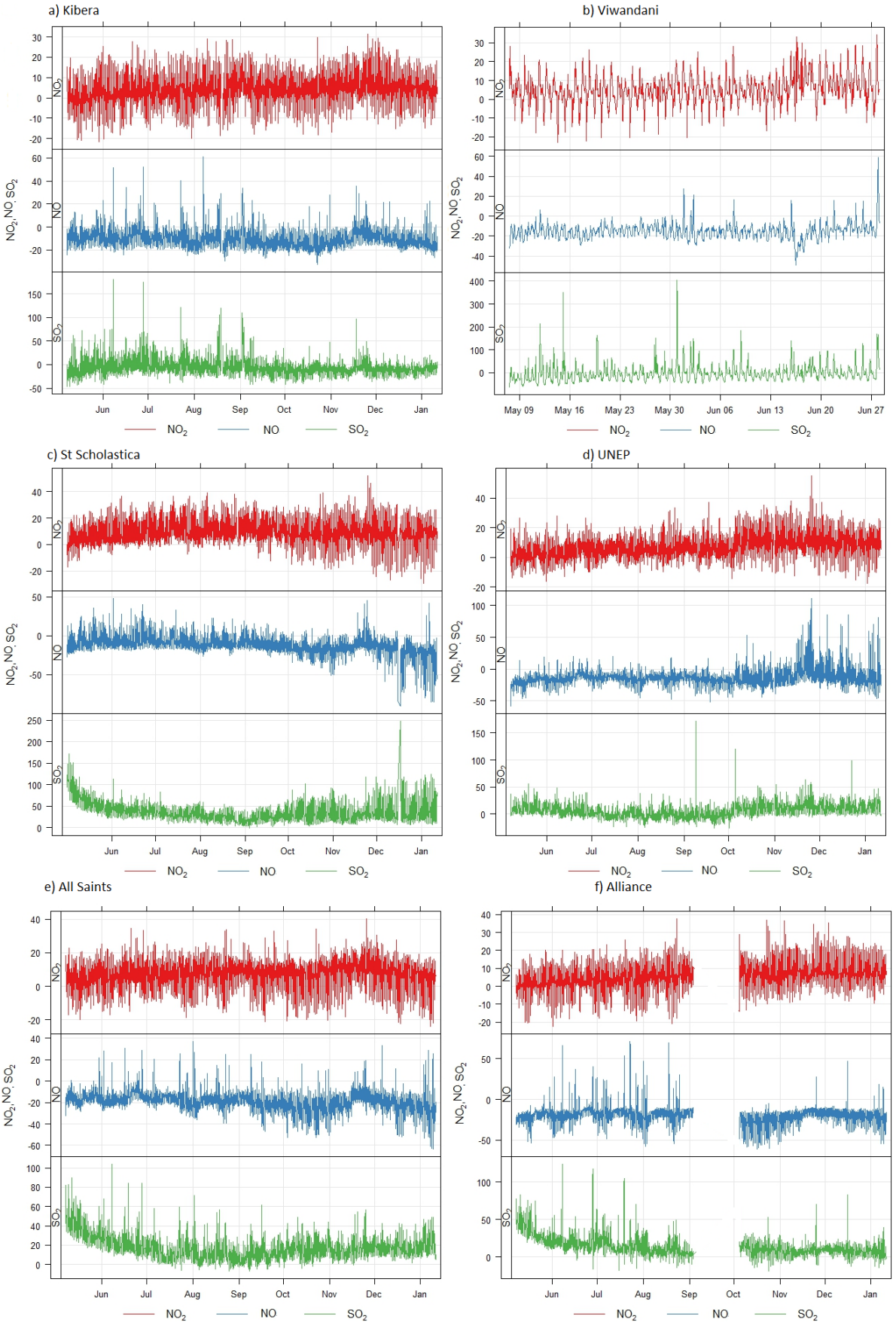


Figure 3: *Hourly averaged NO_2 (red), NO (blue) SO_2 (green) time series plots for each site in units of ppb for the sites a) Kibera Girls Soccer Academy, b) Viwandani Community Center, c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5 2016 to January 11 2017.*

Table 1: *Summary of air quality statistics at each of the six sites. We have rounded pollutant values to the nearest whole number to avoid reporting insignificant figures. Note that for calculating correlations (R) involving the gaseous pollutants we used raw values. We only applied a filter to remove NO values that were < -100 ppb at all sites.*

	Kibera	Viwandani	St Scholastica	UNEP	All Saints	Alliance
Total #	355274	72950	352926	355662	357168	312844
Mean PM_1 µg/m^3	15	14	11	8	7	12
Mean $PM_{2.5}$ µg/m^3	23	21	17	12	11	17
Mean PM_{10} µg/m^3	59	44	30	28	26	43
# NO_2>0	255692	54958	308370	288084	276668	248772
# SO_2>0	66192	21687	352638	220297	339850	283234
#NO>0	20782	1885	35812	27324	6202	5826
Mean NO_2 in ppb for values >0	8	9	12	10	10	8
Mean SO_2 in ppb for values >0	19	40	35	13	18	16
Mean NO in ppb for values >0	11	10	10	19	13	21
Correlation of temperature with humidity	-0.83	-0.86	-0.86	-0.89	-0.86	-0.86
Correlation of PM_1 with temperature	-0.11	-0.2	-0.13	-0.21	-0.19	-0.18
Correlation of $PM_{2.5}$ with temperature	-0.08	-0.18	-0.12	-0.18	-0.17	-0.17
Correlation of PM_{10} with temperature	0.039	-0.017	-0.054	0.12	0.05	-0.025
Correlation of NO_2 with temperature	-0.2	-0.33	-0.11	0.059	-0.51	0.015
Correlation of SO_2 with temperature	-0.38	-0.33	0.66	0.28	0.28	-0.0021
Correlation of NO with temperature	-0.39	-0.51	-0.69	-0.43	-0.74	-0.82
Correlation of PM_1 with humidity	0.09	0.16	0.09	0.25	0.2	0.17
Correlation of $PM_{2.5}$ with humidity	0.047	0.13	0.07	0.2	0.17	0.15
Correlation of PM_{10} with humidity	-0.06	-0.05	-0.045	-0.15	-0.12	0.05
Correlation of NO_2 with humidity	0.09	0.26	-0.05	-0.09	0.45	-0.079
Correlation of SO_2 with humidity	0.28	0.25	-0.5	-0.19	-0.12	0.069
Correlation of NO with humidity	0.40	0.44	0.44	0.41	0.74	0.72
Mean $PM_{2.5}/PM_1$	1.6	1.6	1.53	1.53	1.63	1.45
Standard Deviation $PM_{2.5}/PM_1$	0.29	0.2	0.15	0.15	0.18	0.26
Correlation between $PM_{2.5}$ and PM_{10}	0.43	0.71	0.87	0.64	0.62	0.12
Correlation between PM_1 and $PM_{2.5}$	0.96	0.99	0.99	0.99	0.99	0.99

as St Scholastica is situated next to the notoriously congested Thika Highway, fumes from the burning of diesel with high sulphur contents could have resulted in such high values of SO_2 being observed.

NO_2 values don't vary greatly across sites. The lowest NO_2 values were observed at Viwandani and Alliance. This could be because our monitors were located far away from the main roads at both sites. The highest NO_2 values recorded were at St Scholastica, and we again posit that this could be because of the proximity of this site to Thika Highway.

We were also surprised to see the high NO values at UNEP and Alliance.

More work is required to identify how many of the values we see were signal as opposed to noise. More work is also required to identify contributing sources.

Dependence of measurements on temperature / humidity

PM

Pearson correlation coefficients (R) of the pollutants with temperature and humidity were calculated at each site. These values are also summarized in Table 1. Note that we applied a filter to the NO data and eliminated records that were < -100 ppb. Otherwise we used the raw data to calculate correlations involving gaseous pollutants- including negative observations.

Table 1 shows that except for Kibera and St Scholastica, there is a small correlation between temperature/humidity and $PM_{2.5}$ and PM_{1}. When we plotted $PM_{2.5}$ versus temperature at each site in Figure 3A, it was not clear that peaks in $PM_{2.5}$ corresponded to low temperatures. More research is required to identify how this temperature dependence affects the measurements. One possible reason for this correlation is the lower the temperature, the higher the humidity (temperature and humidity are correlated strongly). If the particles at the site are hygroscopic, the particle size increases, and the OPC detects bigger particles and thus overestimates $PM_{2.5}$. We see that the correlation between temperature/humidity and PM_{10} is negligible.

Gaseous pollutants

As stated previously, temperature and humidity greatly impact the electrochemical gas sensors performance. We thus analyse the data from our sensors in relation to these parameters in order to identify temperature and humidity ranges in which the data is more likely to be less dependent on effects of these environmental factors.

We note that NO_2 and SO_2 and NO are strongly correlated with temperature at each site as can be seen from Table 1. The correlation of each pollutant with temperature varies widely across sites. In addition we note that the sign of the correlation also is not constant across sites for NO_2 and SO_2. We plotted the time series of NO_2, SO_2 and NO at each site with the temperature at each site determining the colour scale in Figures 4A to 7A in order to examine this correlation in more detail.

From Figure 4A and 6A, we clearly see that high temperatures (roughly > 20° Celsius) correspond to negative values of NO_2 and NO being recorded. As mentioned previously, we know that the Alphasense temperature correction does not adequately account for the baseline temperature correction of electrochemical sensors, especially for NO. We also know from the chemistry of electrochemical sensors that the effect of temperature is higher at higher temperatures (Popoola et al., 2016). We thus posit that this is the reason we observe negative gaseous values. Co-location with a reference instrument is required to test this hypothesis.

We note that the sign of the correlation between NO_2 and temperature is positive for the sites UNEP and Alliance in Table 1, because although all negative values of NO_2 recorded are at high temperatures, some high temperatures also correspond to positive NO_2 values, and there are fewer negative NO_2 values for these sites. (Note that in Figure 4A, we have applied a filter and removed NO values< -100 ppb. Figure 5A in the Appendix includes these values).

From Figure 7A, we see that negative values of SO_2 correspond to high temperature readings for the sites Kibera, Viwandani and Alliance. However, for St Scholastica, UNEP and All Saints we find that very few of the temperature corrected values are < 0 (refer to Table 1) and thus we do not see the same negative correlation. We are not sure why this is the case. It could be possible that the temperature correction factor for the SO_2 sensors for the latter three sites are better than for the former, which raises the question of potential consistency across these sensors; or it could mean that cross-interference with other pollutants are affecting the data at the sites at which they occur in significant quantities. To address questions of potential consistency between sensors, it would be helpful to test a number of these sensors at the same site.

Note, that in Table 1A, when only gaseous pollutant values > 0 were used, we see that the correlation obtained between the gaseous pollutants and temperature/humidity change dramatically, and this time, are the same sign across all sites. In addition, we find that the magnitude of correlation between the measurements that are > 0 and temperature/humidity is low indicating that the signal the sensors are picking up is more likely due to pollutants. We will thus work with these gaseous pollutant values for the rest of this analysis.

Table 1 and 1A also shows correlations between all observations of pollutants. Table 1 shows that PM1 and $PM_{2.5}$ are strongly correlated at each site. From Table 1A, we see a significant correlation between SO_2 and $PM_{2.5}$, NO and $PM_{2.5}$ (except at St Scholastica and UNEP), and NO_2 and $PM_{2.5}$ (except at Alliance), NO_2 and SO_2 (except at Alliance).

Intra Urban Variation of Pollution

We next examined the intra-urban variability in each pollutant across out sites. We note from the correlation between $PM_{2.5}$ for each site-pair in Table 2, that most site-pairs correlate with one other to a not-insignificant manner.

The correlation of $PM_{2.5}$ at each site-pair is not based on distance between sites. The sites at UNEP, St Scholastica, All Saints and Kibera are < 10 km away from each other. The site at Alliance Girls School is ~15 km away from all the sites. However, we note that correlations between Alliance, and UNEP and All Saints are relatively high, in spite of Alliance being far from these sites.

In order to understand if this correlation is due to wind, we produce continuous bivariate plots of normalized $PM_{2.5}$ for each site as a function of wind speed and wind direction using the package OpenAir as seen in Figure 3. Note by using smoothing techniques (via the polarPlot function in the openair R package) to produce the bivariate plots, we are able to identify and group similar features to help identify sources. Wind speeds are zero at the origin and increase radially in each plot. The black arrow in each plot corresponds to the direction in which the monitor at each site is facing.

We note here that for Viwandani and Alliance, for example, there appears to be a source of pollution existing in the west, so that winds from that direction result in the OPC logging high values of PM. This could partially explain the correlation in $PM_{2.5}$ we see across sites. However, we do not see any correlation between $PM_{2.5}$ at Kibera and St Scholastica even though there appear to be a source in the south-east for both sites. This could be because we are not using site-specific wind data. Local canyon effects could profoundly affect our results. In the future, we recommend using site-specific wind data for this analysis.

It must also be noted here that as our monitors were wall-mounted, their swath as mentioned before is 180 degrees instead of 360 degrees. By indicating the direction which each monitor is pointing, we can also examine if there is a directionality bias for

Table 2: *Correlation (R) between PM_1, $PM_{2.5}$, PM_{10}, NO_2, SO_2, NO for each pair of sites. Gas values > 0 are considered only.*

PM_1	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.13	0.09	0.18	0.19	0.15
Viwandani		1	0.11	0.25	0.29	0.14
Scholastica			1	0.18	0.09	0.11
UNEP				1	0.30	0.26
All Saints					1	0.22
Alliance						1
$PM_{2.5}$	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.13	0.08	0.16	0.18	0.13
Viwandani		1	0.10	0.24	0.28	0.14
Scholastica			1	0.16	0.09	0.10
UNEP				1	0.28	0.23
All Saints					1	0.21
Alliance						1
PM_{10}	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.04	0.07	0.06	0.08	0
Viwandani		1	0.15	0.15	0.28	0.01
Scholastica			1	0.24	0.2	0
UNEP				1	0.25	0.02
All Saints					1	0.01
Alliance						1
NO_2	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.53	0.49	0.53	0.67	0.51
Viwandani		1	0.32	0.46	0.62	0.38
Scholastica			1	0.53	0.32	0.45
UNEP				1	0.41	0.58
All Saints					1	0.35
Alliance						1
SO_2	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.29	0.11	0.12	0.18	0.22
Viwandani		1	0.044	0.09	0.17	0.12
Scholastica			1	0.17	0.56	0.14
UNEP				1	0.15	0.018
All Saints					1	0.21
Alliance						1
NO	**Kibera**	**Viwandani**	**Scholastica**	**UNEP**	**All Saints**	**Alliance**
Kibera	1	0.23	0.03	0	0.17	0.32
Viwandani		1	0.18	0.18	0.11	0.33
Scholastica			1	0.099	0	-0.06
UNEP				1	0.09	-0.13
All Saints					1	0.10
Alliance						1

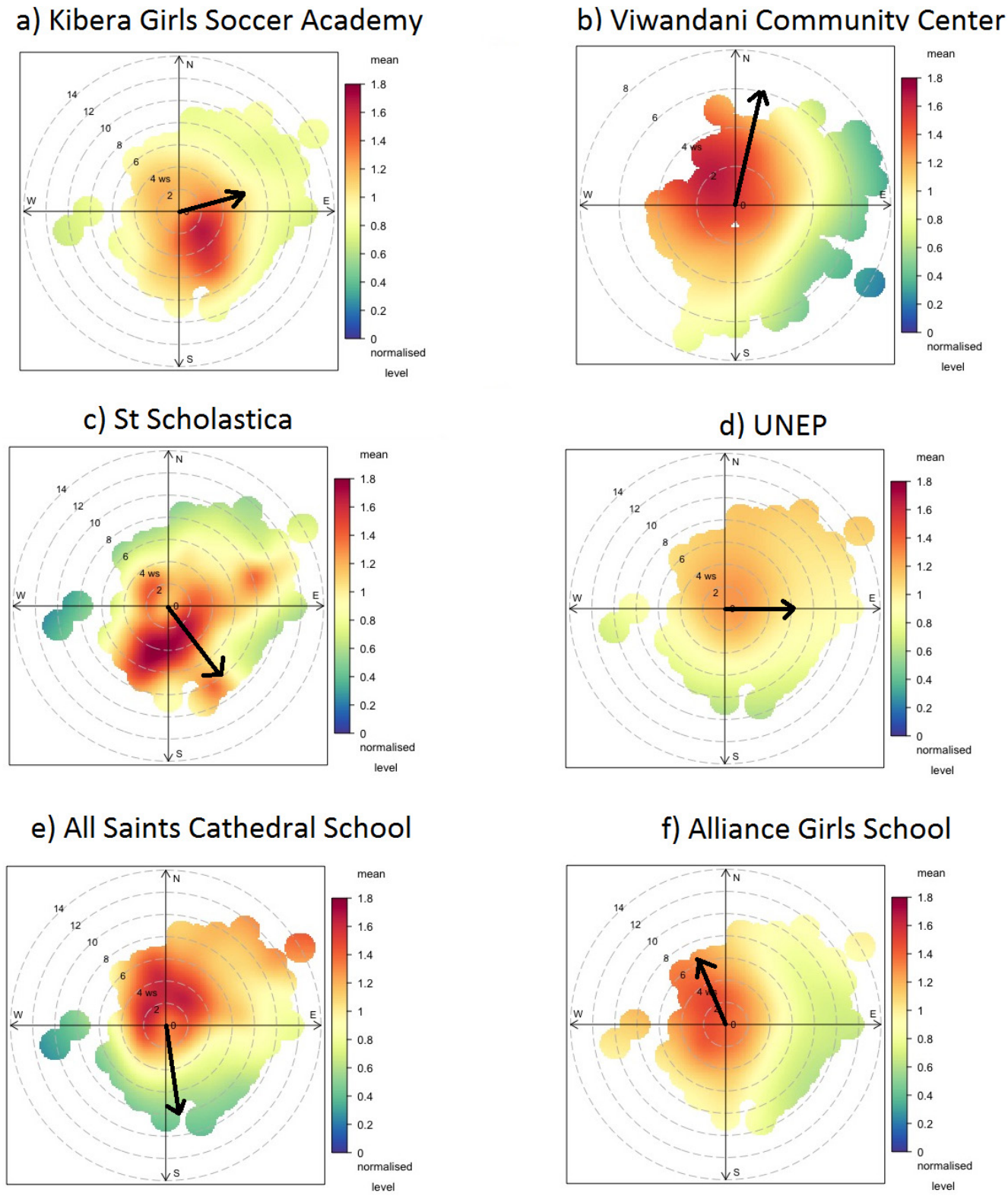


Figure 4: *Bivariate plot of $PM_{2.5}$ normalised by dividing by their mean value from 5 May 2016 to 11 January 2017 plotted against wind speed and wind direction for the sites a) Kibera Girls Soccer Academy, b) Viwandani Community Center, c) St Scholastica, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School. Wind speed is zero at the origin and increases radially. The color scale indicates the $PM_{2.5}$ concentration. The black arrow in each plot points in the direction each monitor is facing.*

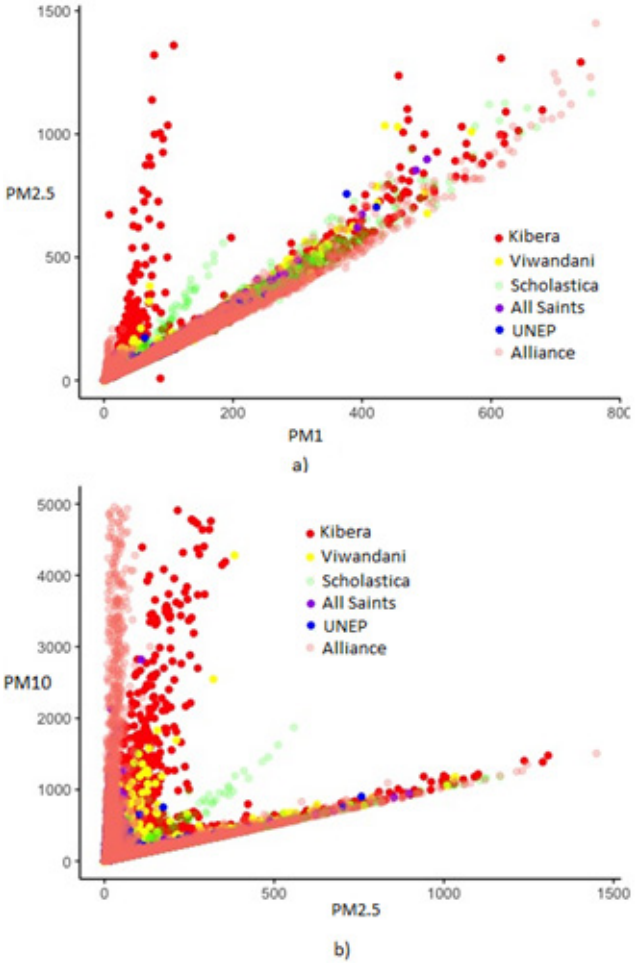


Figure 5: *Scatter plots of $PM_{2.5}$ versus PM_1 and PM_{10} for each site. Units are in µg/m³*

each monitor. It appears that the monitors record pollution in the direction in which they are facing, indicating that the limited swath of our monitors could also affect our results.

Analyzing the chemical composition of $PM_{2.5}$ at each site to conduct a source apportionment could also provide further insights into the correlation of $PM_{2.5}$ between sites.

Figure 4 provides us with further insights in itself. We see that for our sites in Kibera and Viwandani, fine particulates impinge on the monitor from many directions, even at low wind speeds, with the greatest pollution coming from the south-east for the former and north-west for the latter.

From Figure 4 we also note that for St Scholastica, there is a major source of pollution to the south of the site for fairly high wind speeds. Thika Super Highway is to the south-east of the monitor, and it is possible that most of the fine particulates that the monitor has registered are from vehicular emissions coming from the highway.

We note from Table 2 that the correlation for NO_2 across all sites is high. The correlation for NO across all sites is low on the other hand. NO is a chemical that persists in the atmosphere for a very short time before being oxidized to NO_2. This could explain the low correlation between NO across all sites. However, NO_2 persists longer and is mainly emitted from vehicles. Traffic patterns in Nairobi are roughly the same across the city at all sites and this could explain the high correlation in NO_2 across all sites.

We next look at the minute-wise $PM_{2.5}/PM_1$ and $PM_{10}/PM_{2.5}$ at each site as shown in Figure 5. These values are summarized in Table 1. We see that PM_1 and $PM_{2.5}$ correlate strongly. Figure 5 shows that observations from all sites can be viewed in 2 clusters. The bulk of the observations have a $PM_{2.5}/PM_1$ ratio between 1.4 and 1.7. A small cluster of observations have a much higher $PM_{2.5}/PM_1$ ratio ~ 5. St Scholastica, is unique in that the monitor at this site records some observations that have a $PM_{2.5}/PM_1$ of ~2.5.

This could indicate a unique source at this site. A visit to each site is required to test this hypothesis. Table 1 is a summary table that provides the mean $PM_{2.5}/PM_1$ at each site and the standard deviation of each ratio. We also note the clusters of data seen in the plot of $PM_{10}/PM_{2.5}$.

In order to understand the latter more closely we look at the variation in the ratio of $PM_{10}/PM_{2.5}$ with respect to wind speed and wind direction. This will allow us to look at the signature of different sources of pollution, located in different directions and different distances from each site.

We thus plotted PM_{10} versus $P_{M2.5}$ for each site versus wind speed and wind direction as seen in Figure 6. We see that the ratio of $PM_{10}/PM_{2.5}$ is somewhat dependent on wind speed and wind direction.

We repeat the same analysis for the gaseous pollutants and have plotted observations of NO_2, NO and SO_2 that are > 0 versus $PM_{2.5}$ for each site as seen in Figure 7. We see that the SO2-$PM_{2.5}$ ratio is correlated more strongly than any of the other pollutant combinations in Figure 7.

We will now examine the pollutants at each site in detail.

Site Analysis

Kibera Girls Soccer Academy

Figure 8 shows the raw PM concentration variations averaged over a week and over a single day, for the measurement timeframe: May 5, 2016 to January 11, 2017 at the Kibera Girls Soccer Academy site in the informal settlement of Kibera. We see pollution peaks in the morning shortly before 6 am and in the afternoon on weekdays. However, on Saturday, we see another sharp peak at noon. Pollution appears to reduce on Sundays.

The pollution at this school is far worse than at the other sites. PM_{10} goes up to 100 µg/m³ frequently and exceeds this value during peak hours. Kibera was the only site where on certain days, the 24-hour limit value for PM_{10} (100 µg/m³) set out in Kenya's EMCA (Air Quality) Regulations (2014) was exceeded. This limit was exceeded for 17 days for the time-period of measurement.

The high concentration of particulates could indicate the presence of a significant local source of pollutants. The practise

of burning waste due to inadequate waste collection is common here and could be the cause of the high values of pollutants recorded. $PM_{2.5}$ is above the WHO standard, an average of 20 µg/m^3 over the course of a day. These results are similar to the high PM2.5 levels measured in the poor neighbourhood of Mathare (Ngo et. al 2015a).

PM counts decrease at night, indicating that most of the PM pollution is due to daytime human activity.

In order to examine the various sources for this site in more detail, we again used bivariate plots using the OpenAir package (Carslaw and Beevers, 2013), and mapped all the pollutants with respect to wind speed and wind direction to identify common sources. Figure 9 shows continuous bivariate plots produced of each pollutant recorded with respect to wind speed and wind direction at the site. Although we are aware that the gas pollutant data in particular is suspect, we believe that by plotting bivariate plots of each pollutants and common sources are identified, that could give us some indication if we are observing any signal in the gaseous pollutant data and thus allow us to vet this data crudely. It is with this perspective that we examined the data. As mentioned earlier, smoothing techniques is used in producing these plots to identify similar groups of pollutants. We used a smoothing parameter of 100 (low smoothing) for producing plots for particulate matter and NO_2, while we used a smoothing parameter of < 50 (high smoothing) for NO and SO_2 as we did not have enough data to produce smooth continuous surfaces for higher cluster sizes.

It can be seen from Figure 9 that there appears to be a major source of particulate matter, some NO and some NO_2 in the south-east. When we visited the site, we learnt that a significant amount of burning was happening to the south of our site near the railway track and this could be a potential source of the particulates. There is a source of SO_2 and NO_2 pollution from the north-west for high wind speeds. The main road is to the west of the site, and this could be a source of these pollutants.

It is not clear if, given that the monitor faces the north-east, there is a bias in the directionality of particulates the monitor registers. Further studies will be needed to determine this.

Viwandani Community Center

Unfortunately, the OPC at this site stopped recording values in early July. However, for the months of May and June, we repeated the above analysis and obtained Figure 10.

We see that here, as at Kibera, PM_{10} levels are higher than at other sites. The monitor here is situated in an informal settlement in the industrial area of Nairobi that is highly polluted, which explains the high values of pollutants recorded. We see that particulate pollution peaks in the morning before 6 am, and in the evening around 6 pm. Pollution reduces on average on Sundays but peaks on Saturdays. Given that the pollution here too reduces in the night, we can conclude that pollution is driven by human activities. Thus, the time variation of the pollution provides us an idea of the time at which activities (cars on the street, burning of waste) take place at this site.

We also see that here, unlike in Kibera, $PM_{2.5}$ and PM_1 track PM_{10} more closely (the correlation between $PM_{2.5}$ and PM_{10} as shown in Table 2 is 0.71 as opposed to 0.43 for Kibera). An examination of the different sources in this area needs to be conducted to determine why this is the case.

Here too we plot bivariate plots for each pollutant at the site to identify common sources in Figure 11. We see that there appears to be a common source of fine and coarse particles as well as SO_2, NO_2 from the north of the site. We note that there appear to be multiple clusters of pollutants indicating the presence of multiple sources of pollution close to the site. Here, as in Kibera, we used a smoothing parameter of < 50 for SO_2 (note we did not have enough data to plot NO), while for the other pollutants we used a smoothing parameter of 100.

St Scholastica School

The time variation of PM_1, $PM_{2.5}$ and PM_{10} at St Scholastica School as shown in Figure 12. Here we see that PM peaks in the morning and in the evening. These peaks corresponds to the flow of traffic of people coming to work in the morning, and leaving in the evening, implying that emissions from vehicles is a major source of pollution at this site. The peaks in particulates are far more pronounced than at UNEP (Figure14) which is also next to a road. Indeed, $PM_{2.5}$ during the day is as much as 15 µg/m^3 higher than during the night. This could be because Thika Highway, a major highway closer to the school, accommodates far more traffic than UN Avenue where UNEP is located. Pollutant concentrations decrease on average on both Saturday and Sunday, and not just on Sunday as seen at UNEP. PM peaks in June as at UNEP.

Figure 13 shows bivariate plots of all pollutants. It can be seen that there is a source of particulate matter in the south. We see there appear to be multiple sources of SO_2 from different directions. There also appears to be a source of NO_2 and NO in the west for high wind speeds. Thika Highway running from the south-west to the north-east of the monitor could be a major source of pollutants.

UNEP

Figure 14 shows the variation of minute-wise particulate matter concentrations over a typical week and a typical day for our other urban background site at UNEP.

Note that typical $PM_{2.5}$ concentrations vary between 10-15 µg/m^3 for this site in keeping with the studies done earlier by (Gaita et al., 2014). Here, as at St Scholastica, particulate matter concentrations tend to peak in the morning and evening from Monday to Saturday, corresponding to the flow of traffic of people coming to work in the morning, and leaving in the evening, implying that emissions from vehicles is a major source of pollution at this site. The peak registered on Saturday evenings is surprisingly high, and we still have to account for its cause. We speculate that it is due to people visiting the nearby mall Village Market. Note that on Sunday, pollutant levels are low. We can also see that PM levels are also highest in June.

Figure 15 shows the bivariate plots of each pollutant with respect to wind speed and wind direction. Note to produce the plots we used a smoothing parameter of 100 for all pollutants except for NO, where we used a smoothing parameter of < 50. We see that there is a source of fine particulates close to the monitor. We see there is a major source of coarse particulates

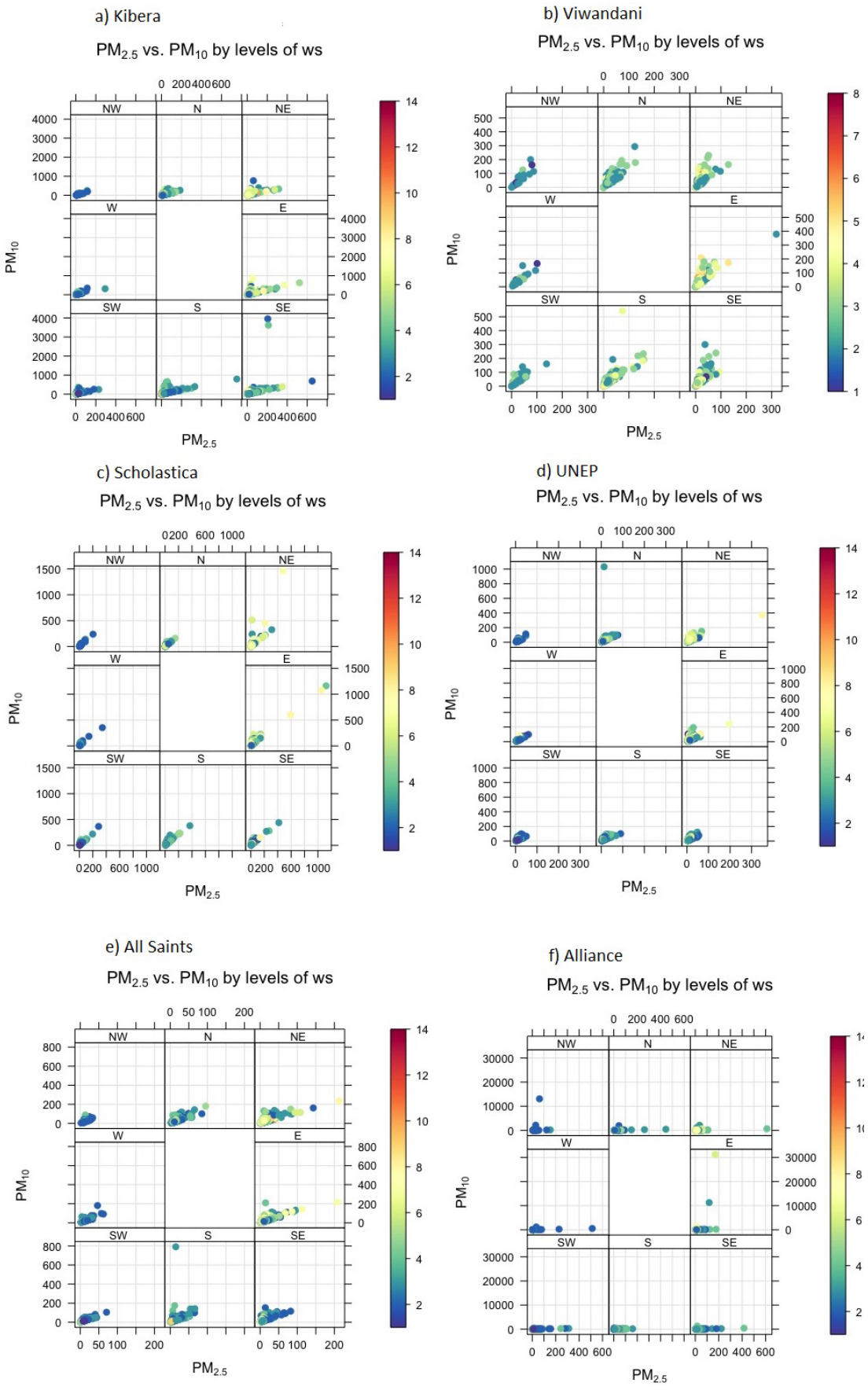


Figure 6: *Scatter plots of $PM_{2.5}$ versus PM_1 and PM_{10} for each site with the color scale indicating wind speed, broken up by wind direction. Units are in µg/m³.*

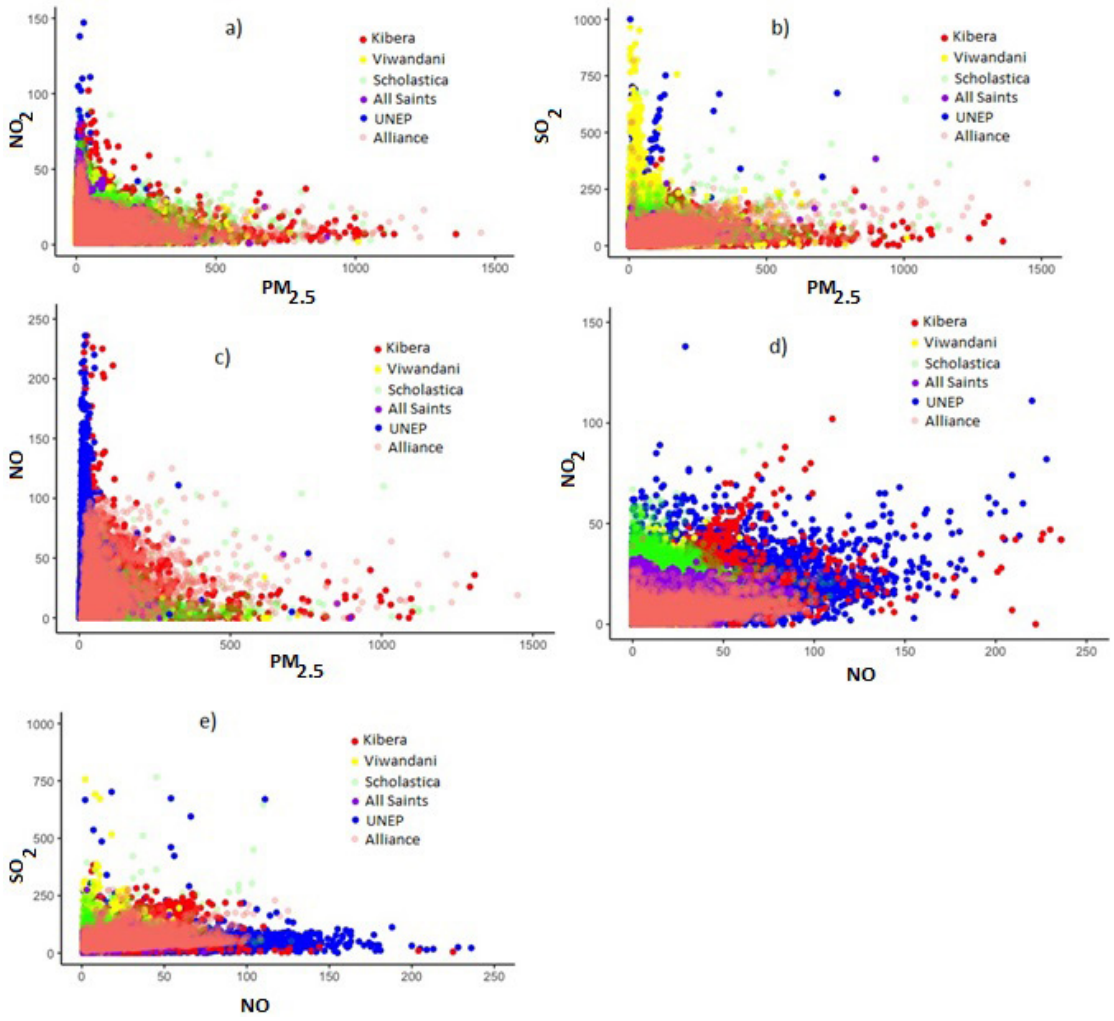


Figure 7: *Scatter plots of a) NO_2, b) SO_2 and c) NO (units in ppb) versus $PM_{2.5}$ (units are in µg/m³) for each site, d) NO_2 versus NO at each site, e) SO_2 versus NO at each site (all gases are reported in ppb).*

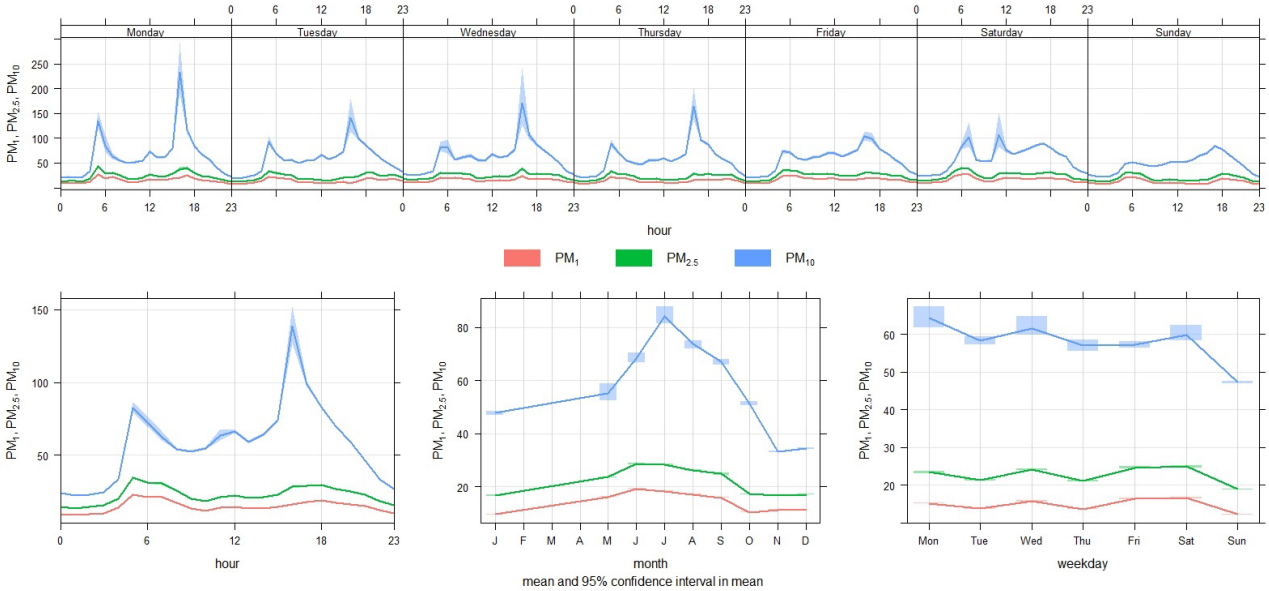
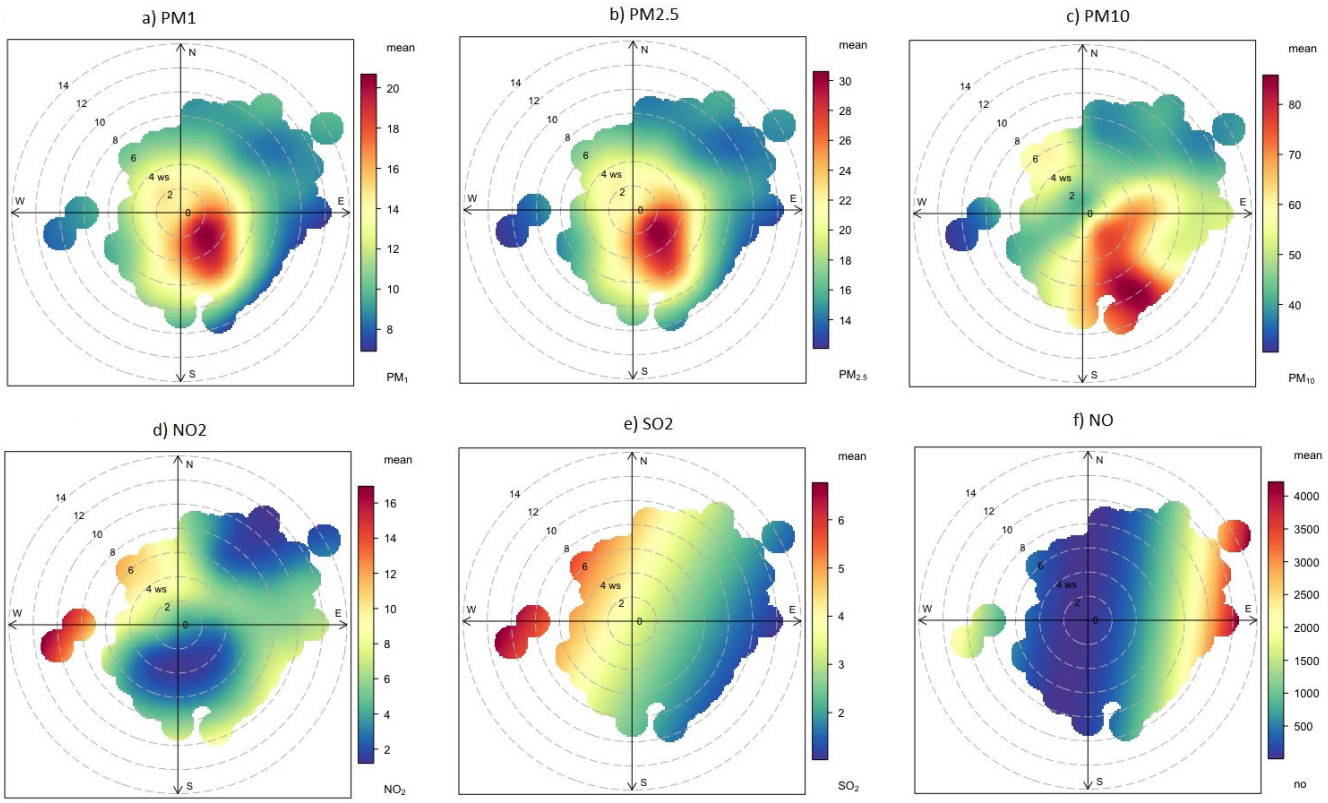


Figure 8: *Kibera Girls Soccer Academy. The top panel shows the variation of PM_1, $PM_{2.5}$ and PM_{10} over the course of an average week in units of µg/m³. The panel on the bottom left shows these concentrations varying over the course of an average day. The bottom middle figure shows the variation of PM over 8 months (May 5, 2016 to Jan11, 2017). The bottom right figure shows concentrations during an average week. The shadings in the plot indicate 95% confidence intervals.*



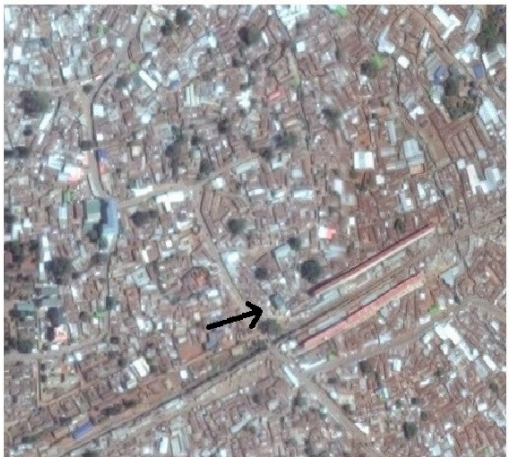


Figure 9: *Kibera Girls Soccer Academy. Bivariate plots of each pollutant (note even negative values of the gas pollutants were considered) with respect to wind speed and wind direction from May 5, 2016 to Jan11, 2017. The image at the bottom shows the site and the black arrow indicates the direction that the monitor.*

in the south east and north east for high wind speeds. There is a common source of SO_2 in the southeast. There are sources of NO in the north-north west and south-south-west of our site. There is a source of NO_2 and NO from the west. UN Avenue is located to the west of the monitor and is a potential source of vehicular pollution.

All Saint's Cathedral School

The particulate matter pollution at All Saint's Cathedral School is shown in Figure 16. Here as for the previous two sites, we see peaks of pollutants in the morning and in the evening corresponding to traffic patterns. Note that the values of PM registered at this site are in the same range as at UNEP. Here too, PM levels dip on Sunday but not on Saturday. This indicates that people come into the city on Saturdays but not Sunday .

From Figure 17, we see there is a common source of fine particulates in the north west for low wind speeds. We see that there is also a source of SO_2 in the north west. There is a common source of SO_2 and coarse particulates in the east. Note there are several small industries and shops in this area which are potential sources of pollution. We did not have enough data to produce a similar plot of NO.

Alliance Girls School

We examined the data further to see why pollution was so high at Alliance Girls School. Figure 18 indicates that on some mornings, between midnight and 6 am, there is an immense spike in PM_{10} registered by the OPCs. When we examine the total PM time series plot in Figure 2, we see periodic spikes in PM_{10} as well. On speaking to the schoolchildren, we were told that boilers were lit using firewood at a site located very close to the deployed air quality monitor. Our monitors were thus able to highlight an important finding.

Figure 19 indicates NO_2 comes mainly from the south and west of the site at rather high wind-speeds. The Southern Bypass a major highway is in this direction, and it is possible that vehicular fumes from this road are a major source of NO_2. Figure 18 also indicates that there is a major common source of PM_1, $PM_{2.5}$ and SO_2 from the west as well which could also be due to traffic on the Southern Bypass. Trucks typically use the Southern Bypass. They burn diesel with high levels of sulphur, which could be the source of the SO_2 seen. However, there is a major source of PM_{10} from the north-east as well. The burning of firewood takes place at the north of our site and thus it is highly likely that it is this that is the major source of the coarse particulates picked up by the monitor. Note we do not have enough data to plot NO for this site.

Discussion and Policy Implications

Even with technical limitations in both the study and the sensors, we were nevertheless able to glean a number of insights from the data. At a local level, the data we gathered led to new discussions about air pollution within the schools, which up to this point have not been sites for air quality measurements. The exception is the monitoring station at the University of Nairobi, which is primarily used for teaching and research on campus. This suggests that further experimenting with sensors through citizen science efforts can be a valuable way of spreading awareness and having public discussions, as long as the potential uncertainties in the data are also part of the conversation (Impressing on the communities the working of the optical particle counter that we used to measure particulate matter allowed them to understand the limitations of the instrument).

For example, identifying the peak in PM_{10} at Alliance Girls School on Wednesday mornings was an important discovery- especially as the monitor was deployed on the wall of a dormitory. Conversations with the school led us to discover the burning of firewood to heat water as a source of this pollution. This allowed us to engage with the school and discuss with students and staff the hazards of air pollution, as well as ways to mitigate their particular source by using cleaner fuels or burning firewood in a different location far away from the students. Identifying that the school was in control of this burning allowed us to work with them to think through various possible pollution management plans. Continued monitoring will reveal if the measures the schools adopts are effective.

Conversations with students at the Kibera Girls Soccer Academy were more complex because the school is located in a large slum and faces a multi-faceted air pollution source problem. Thus, mitigation became part of the conversation – for example, whether planting trees might block the influx of particulates into the school premises from the south-east. This type of conversation around air pollution mitigation also came up in the conversations in Mathare slum (Ngo et al 2015b). More accurate measurements of local, canyon-influenced wind speed and wind direction over different seasons will be crucial to improving the efficacy of any interventions aimed at addressing sources. Given the poor services in these slum areas, waste burning is likely to be one source that needs addressing. However, without alternatives such as better solid waste disposal, mitigation techniques like tree planting or finding ways to avoiding the worst sources where possible becomes important (Ngo et al. 2015b). Finally, our discussion with the community at the Viwandani Community Center led to the community leaders resolving to bring this issue up with the Nairobi City County, which is responsible for solid waste disposal, and also air quality along with the National Environmental Management Authority (NEMA).

It is important to note that the monitors were not stolen as many people had feared. Our discussions with the community led to them to appreciate the importance of our monitoring instruments. The Kibera Girls Soccer Academy even built a small gate to the alley on which our instrument was located, at their own cost to protect the instrument. However, the OPC at the Viwandani community center and at Alliance Girls School did lose power. Better understanding of the electric power situation and how it can be addressed at each location will be necessary for future deployments. This suggests overall, that more experiments with air quality sensors in collaboration with citizens are possible and provide a fruitful way to get some data and discussion on air quality in the absence of systematic air quality monitoring going on in the city. It is also a way to help citizens and entities like schools understand how they can play a role in improving air quality and ask more of their government.

Some broader conclusions can be drawn regarding air quality in the city of Nairobi. The pattern of peaks in data at most of our school sites indicates that vehicular emissions are a major source of pollution. Therefore, this implies that the city should prioritize a shift toward non-motorized transport, better fuel standards, and adopting cleaner vehicular technologies, as opposed to widening existing roads and building super highways. Another point of interest is that PM seems to peak in June over the roughly 8 months that the deployment took place. This needs to be examined in more detail. However, the policy implications could be that the Nairobi city council should focus especially on reducing vehicular traffic during this month. Another interesting observation is that the morning pollution peaks in the informal settlements occur earlier in the day than at the UNEP, St Scholastica and All Saints Cathedral sites. This is important to note, as it speaks to the way different groups of people use the city. Do people have to set off to work earlier in the informal settlements, as their workplaces are further, and transportation less convenient? This raises important questions around “spatial mismatch” in the city.

This study had many technical limitations. With sparse resources, we were not able to calibrate the gas sensors in the ambient conditions of Nairobi, which we know to be very important (Piedrahita et al. 2014). We therefore do not know how environmental factors and interference from other pollutants affected the gas sensors in the field. The interference from other pollutants could be large (Hasenfratz et al., 2012.; Popoola et al., 2012) . We also did not analyse the particle size distribution or the chemical composition of the particles sampled by the OPC, which could help determine the density of the particles sampled. In addition, the analysed data we obtained were noisy, and we were unable to determine which filter to apply to separate the signal from the noise without having access to any air quality measurements from a reference instrument.

We strongly recommend the calibration of low cost gas sensors

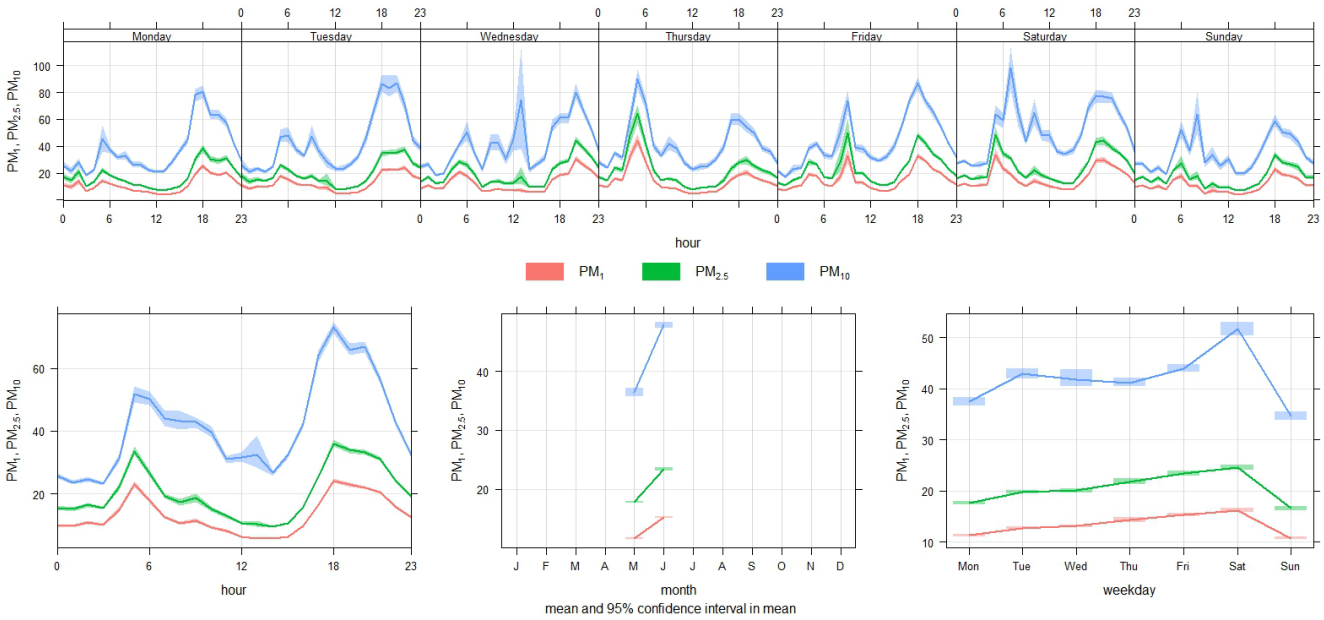


Figure 10: *Same as Figure 8 but for the Viwandani Community Center site for the period May 5, 2016-June 27, 2016.*

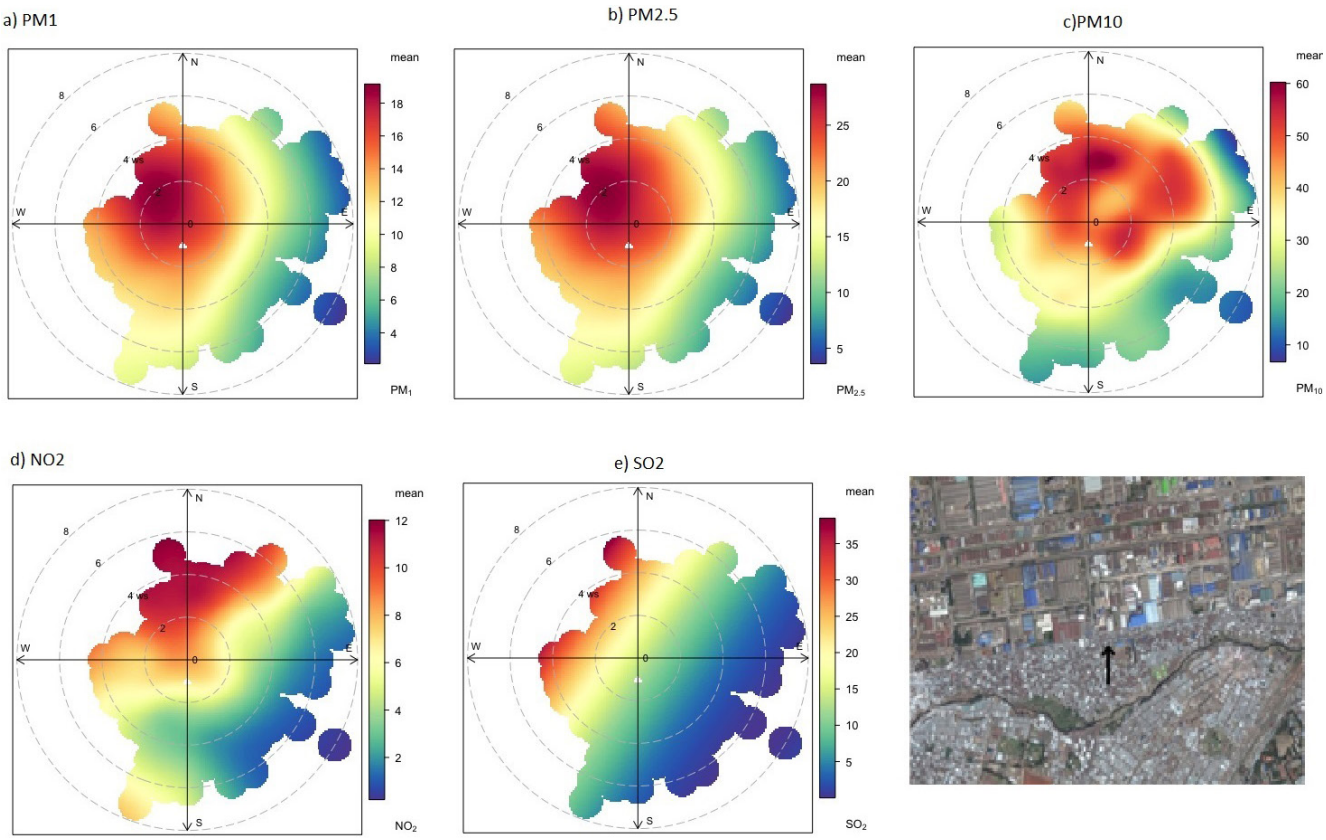


Figure 11: *Same as Figure 9 but for the Viwandani Community Center site for the period May 5, 2016-June 27, 2016. The image at the bottom shows the site and the black arrow indicates the direction that the monitor faces. The image has been taken such that the direction north in the image is towards the top of the page.*

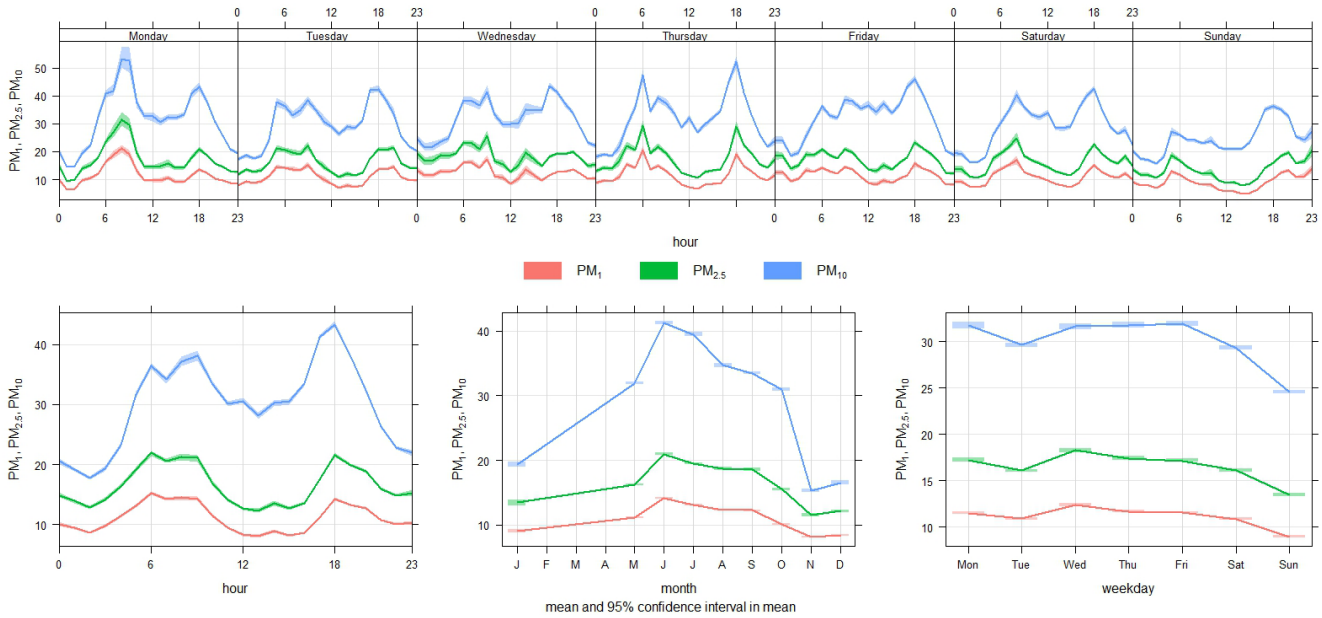


Figure 12: *Same as Figure 8, but for the St Scholastica site.*

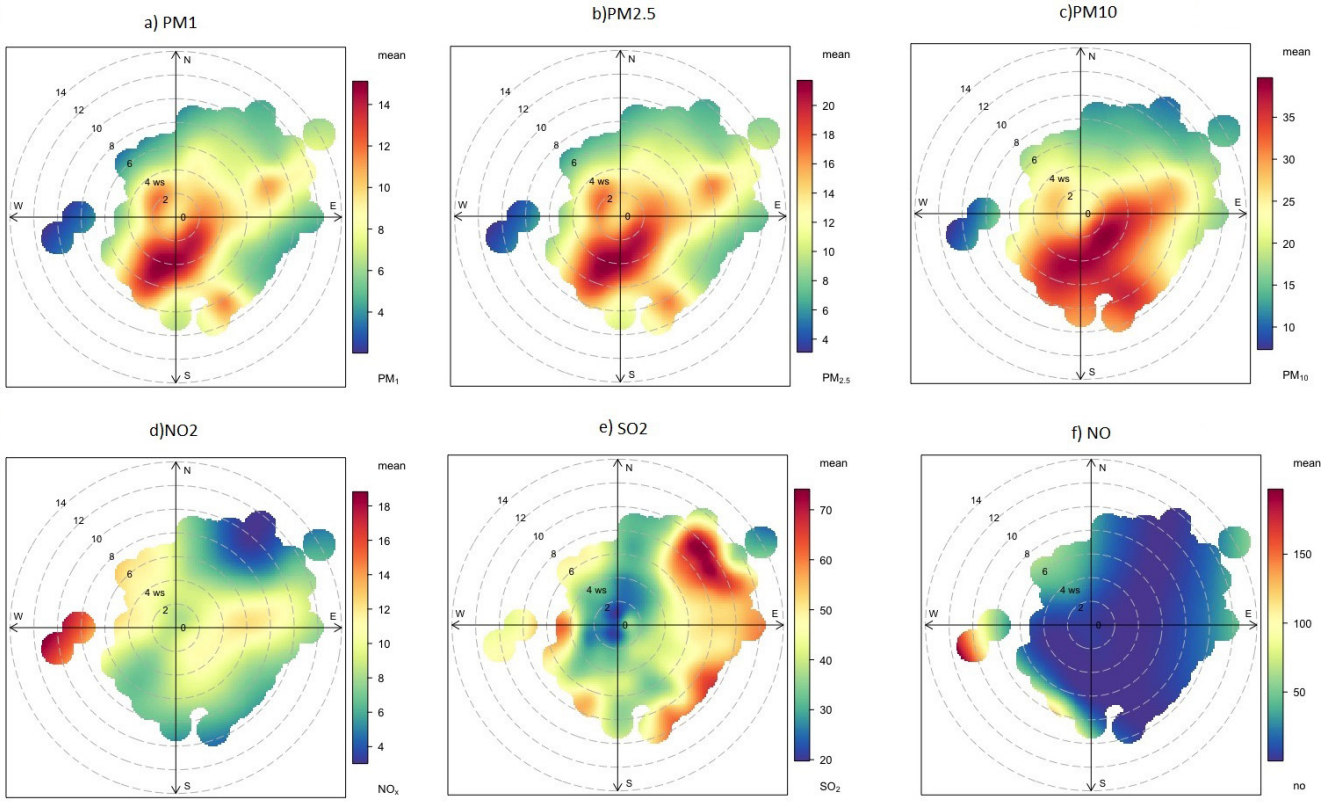


Figure 13: *Same as Figure 9 but for the St Scholastica site. The image at the bottom shows the site and the black arrow indicates the direction that the monitor faces. The image has been taken such that the direction north in the image is towards the top of the page.*

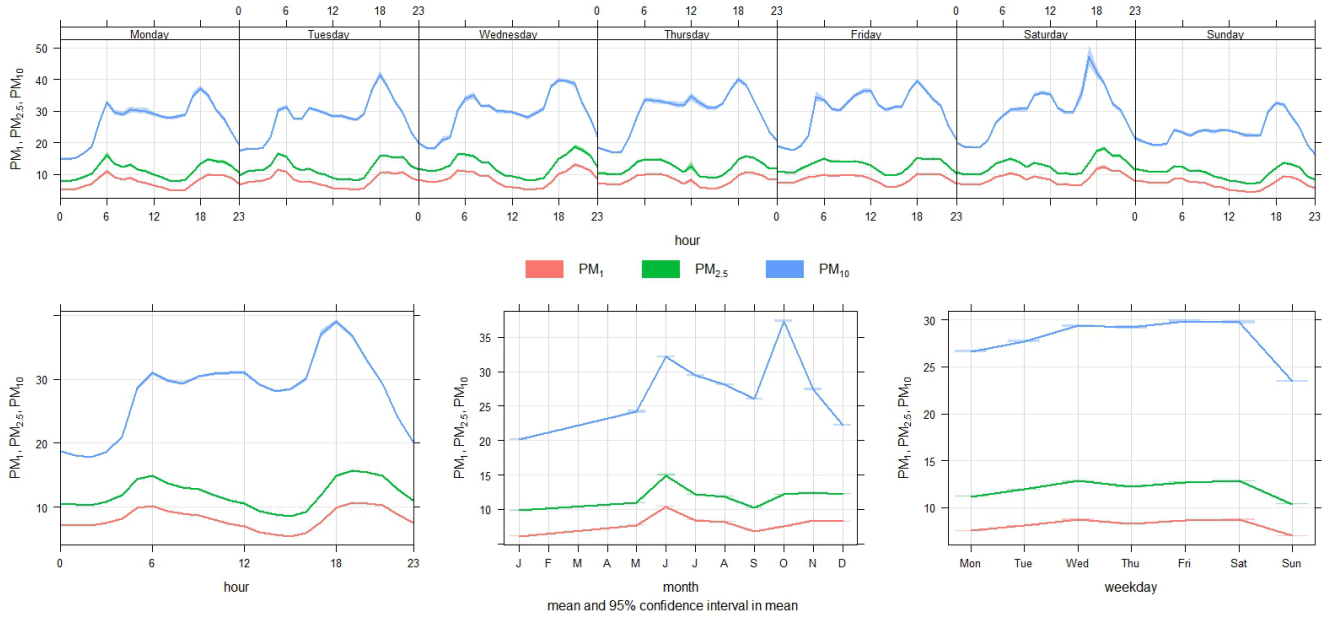


Figure 14: *Same as Figure 8, but for the UNEP site.*

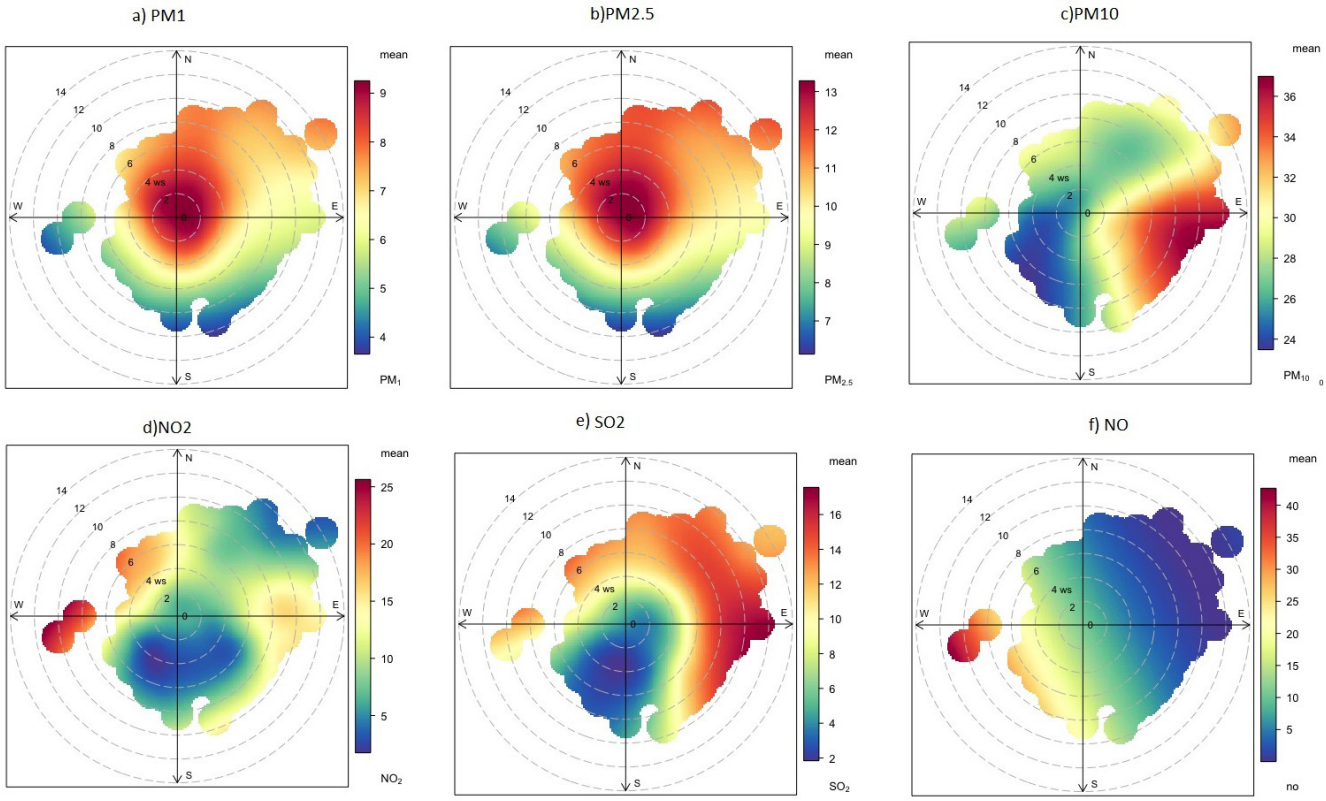


Figure 15: *Same as Figure 9 for the UNEP site. The image at the bottom shows the site and the black arrow indicates the direction that the monitor faces. The image has been taken such that the direction north in the image is towards the top of the page.*

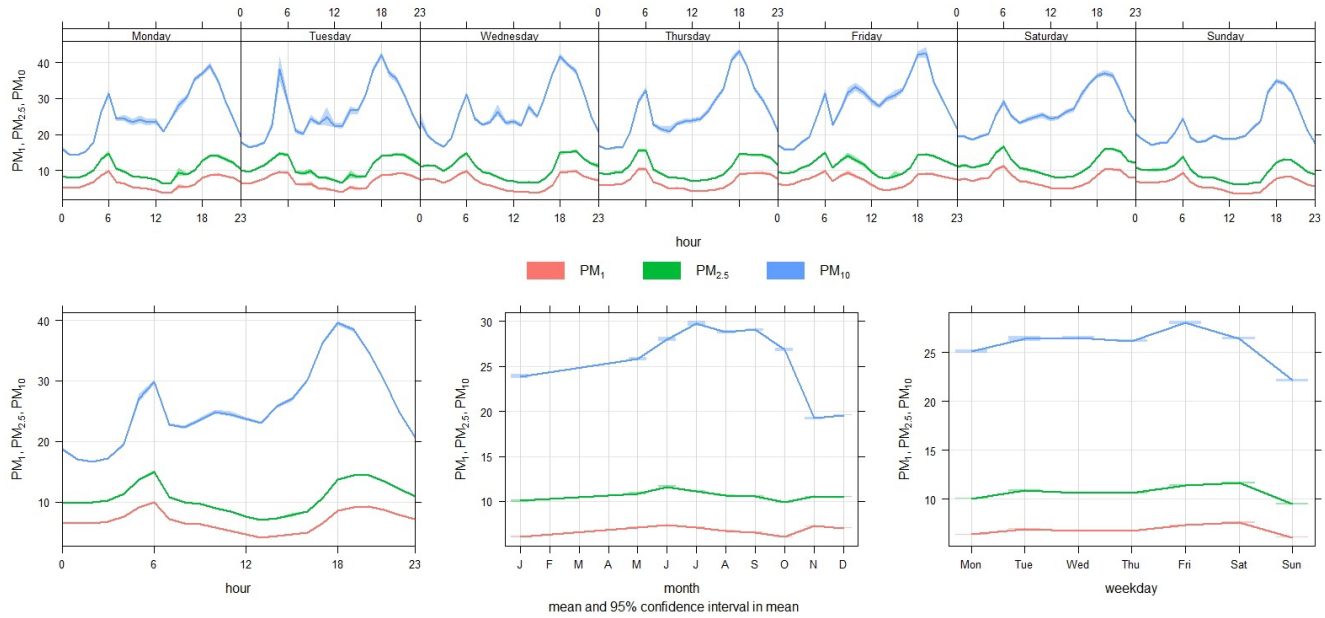


Figure 16: *Same as Figure 8 but for the All Saints.*

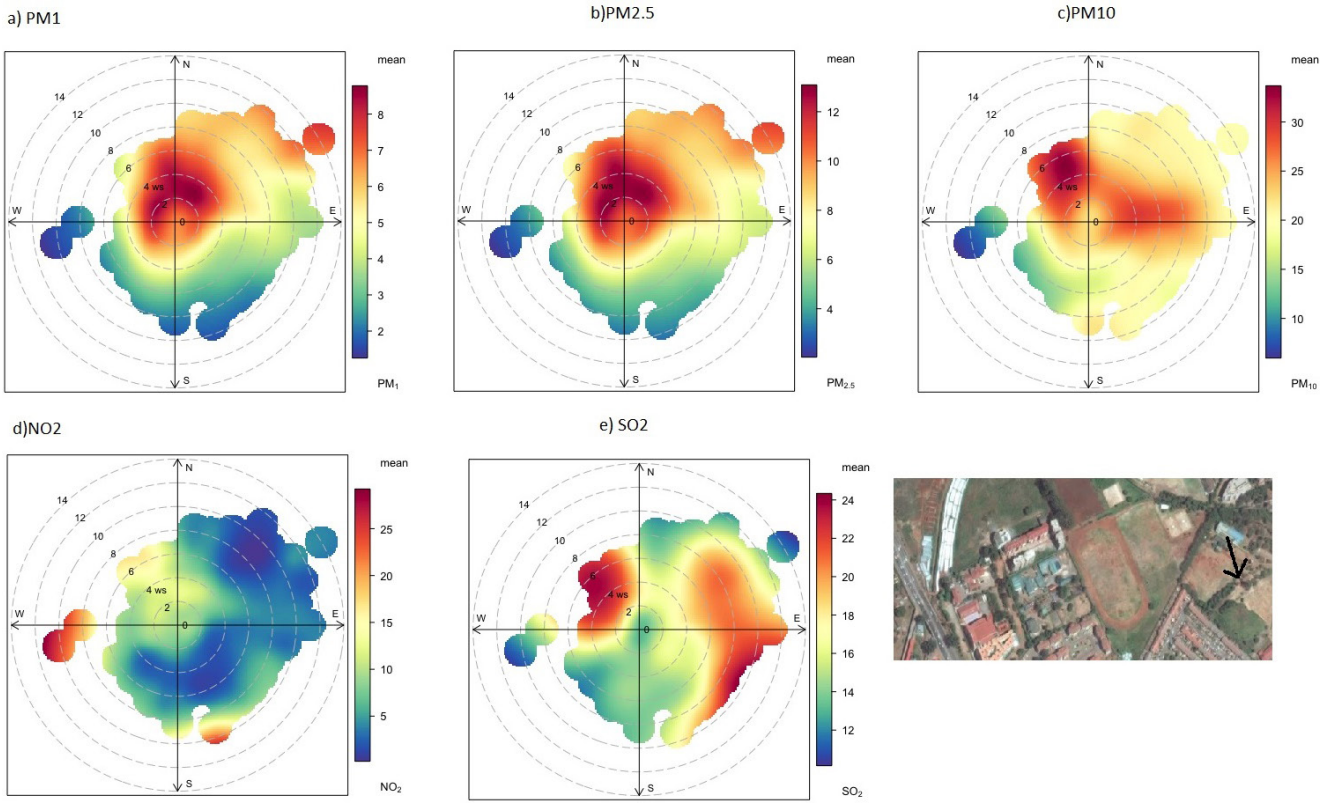


Figure 17: *Same as Figure 9 but for the All Saints Cathedral site. The image at the bottom shows the site and the black arrow indicates the direction that the monitor faces. The image has been taken such that the direction north in the image is towards the top of the page.*

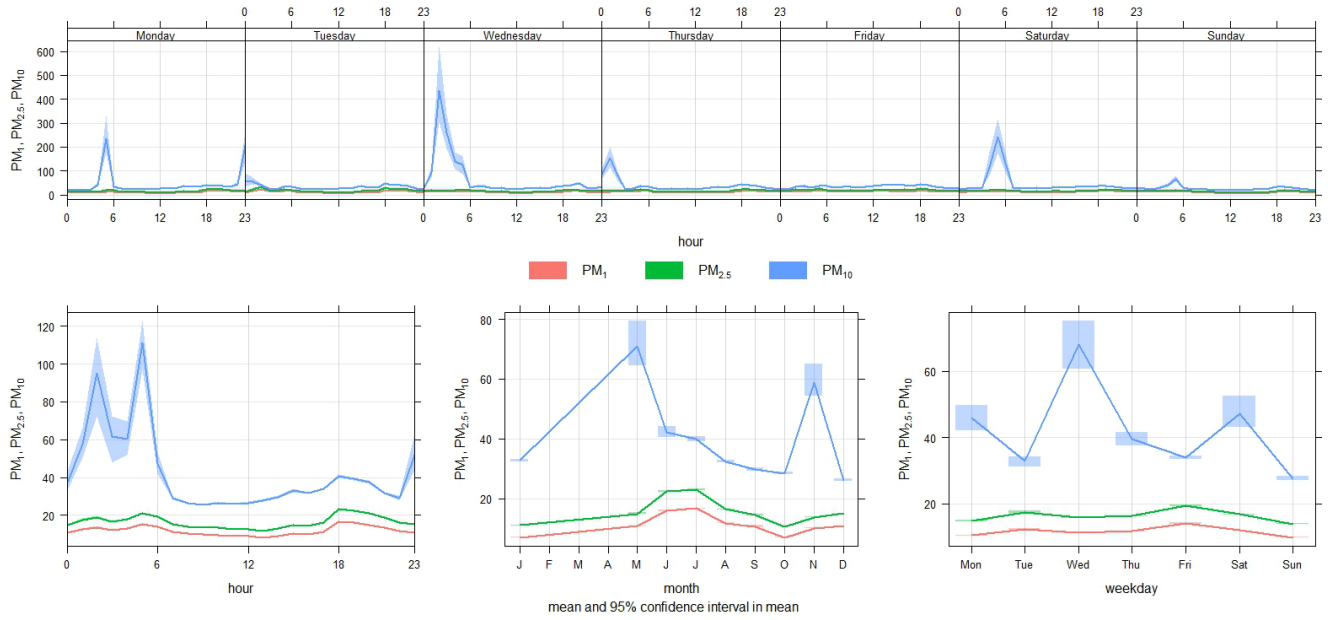


Figure 18: *Same as Figure 8 but for the Alliance Girls School site.*

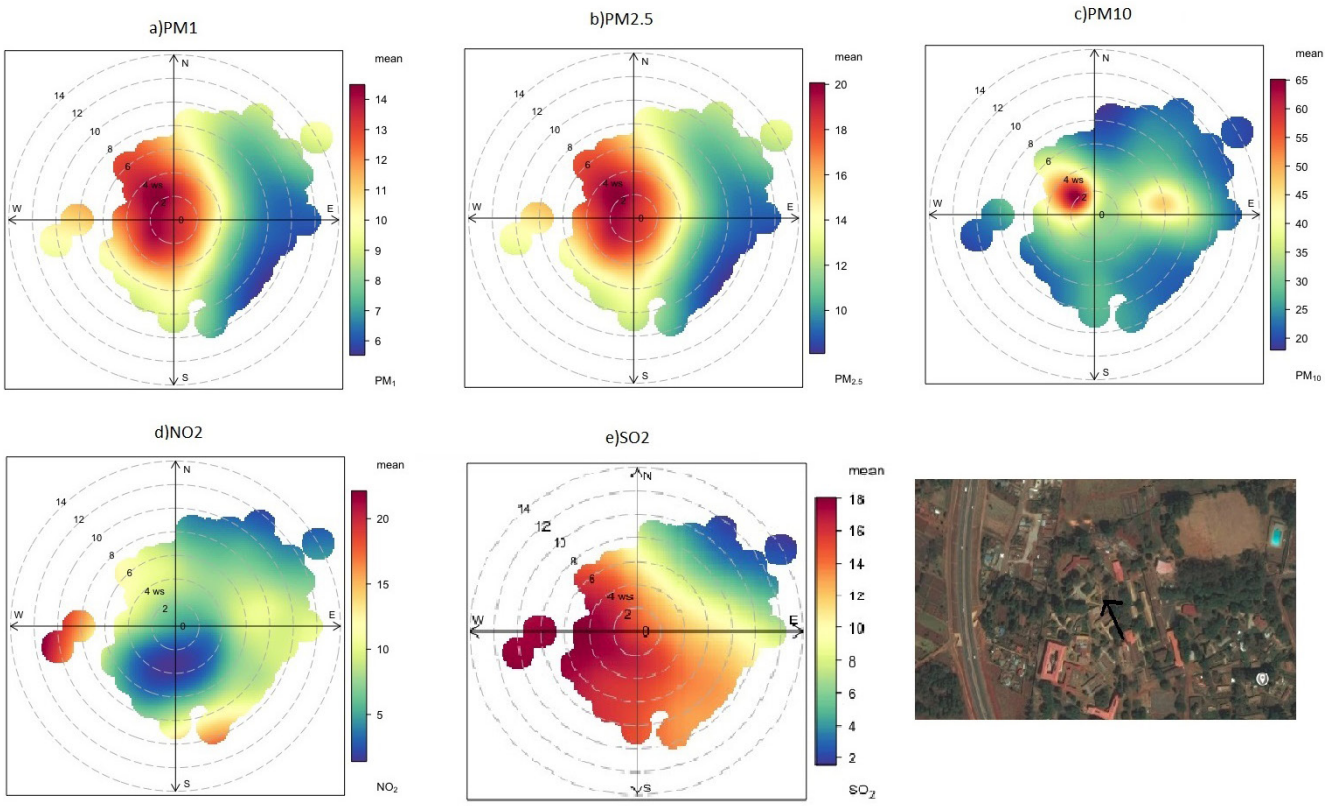


Figure 19: *Same as Figure 9 but for the Alliance Girls School site. The image at the bottom shows the site and the black arrow indicates the direction that the monitor faces. The image has been taken such that the direction north in the image is towards the top of the page.*

with reference air quality monitoring instruments in ambient conditions in order to determine the error in sensor readings due to interference effects of other pollutants and the effect of environmental conditions: specifically temperature and humidity. In addition, the rate of sensor drift depends on the season of the year so it is important to validate the network by regular calibrations of the sensors in each season. Work is underway on using machine learning algorithms to increase the accuracy of low cost sensors (Esposito et al., 2016), and we see this work as being very important for reducing calibration costs and improving data reliability.

We also strongly recommend obtaining a better understanding of the size distribution of particles collected by the OPC at each site over time. This is because the OPC does not function very well for counting particles of sizes < 380 nm. Thus, depending on the size distribution of particles (which varies over time), our measurements could have large errors, and understanding the extent of these errors is important for drawing inferences from the sources and type of particulate pollution. In addition, analysing the chemical composition of particulates at each site can help us develop a better understanding of sources of pollution, as well as help us in identifying correct value of density to use to convert the particle counts collected by the OPC to obtain particulate mass. This could also help us reduce the error in measurement.

Another limitation stemming from the proprietary nature of the technology is that we cannot report in detail on the performance of the electronics or the configuration of the device. These factors can affect results as well, and more research is required to identify standard configurations to facilitate comparisons of experiments. We believe that it is important to set a precedent for the reporting of the type of sensor used because, for example, it is unclear how the Alphasense A series gas sensors compare with the B series. No reports have been published examining this comparison. This makes comparing data from different low cost air quality sensor experiments difficult. In addition, components such as the analogue to digital converter (ADC) could add noise to the data, and thus reporting the kind of converter used could allow for a greater degree of comparison across networks. Over all, better reporting on the mechanics of low cost monitoring projects is needed moving forward.

Conclusions

Low cost sensors and apps that draw on their data to inform citizens about air pollution are becoming more and more prevalent. Given the magnitude of the data gaps in African cities, the growing availability of low cost sensors presents an important opportunity. This is especially the case as plans move forward to measure air pollutants for the Sustainable Development Goals and fight against climate change. However, much more research is needed on how well these new devices work under widely varied conditions, and whether the less accurate data these sensors generate is helpful or even harmful (Lewis and Edwards 2016, Kumar et al. 2015).

Our experiment using less expensive, lower-quality sensors in Nairobi schools contributes to this critical discussion. We did find significant technical limitations that need further work. However, we found that less accurate but carefully interpreted data created by sensors within a citizen science initiative was clearly better than no data. Both the process of getting the data and the data itself, once carefully interpreted, helped to generate broader public understanding and interest in monitoring air quality and addressing likely sources of ambient outdoor air pollution. We also gained some idea of the air pollution problems affecting schoolchildren across class divides with more challenges clearly facing low income children in the slums.

The deployment and analysis of our network also showed that the cost of the sensors is only a small fraction of the total cost of network deployment. This is because maintenance of the network, calibration of the sensors and the analysis of the data is time consuming and therefore expensive. It is also abundantly clear that “low cost” sensors cannot obviate the need for stronger investment in high quality monitoring and related local scientific research around air quality in African cities. While low cost sensors can allow for more measurements and more civic engagement, this is ideally conducted in collaboration with local scientists who are well-equipped to ensure data are collected and interpreted accurately for the public. Lewis and Edwards (2016) suggest “well designed sensor experiments, that acknowledge the limitations of the technologies as well as the strengths, have the potential to simultaneously advance basic science, monitor air pollution — and bring the public along”. We believe we have shown this to be the case for African cities like Nairobi that currently do not have an air quality monitoring system but do have a substantial air quality problem.

Acknowledgements

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Appendix

Figures 1A and 2A show the raw 1-minute data recorded of particulate pollutants and the gaseous pollutants, respectively.

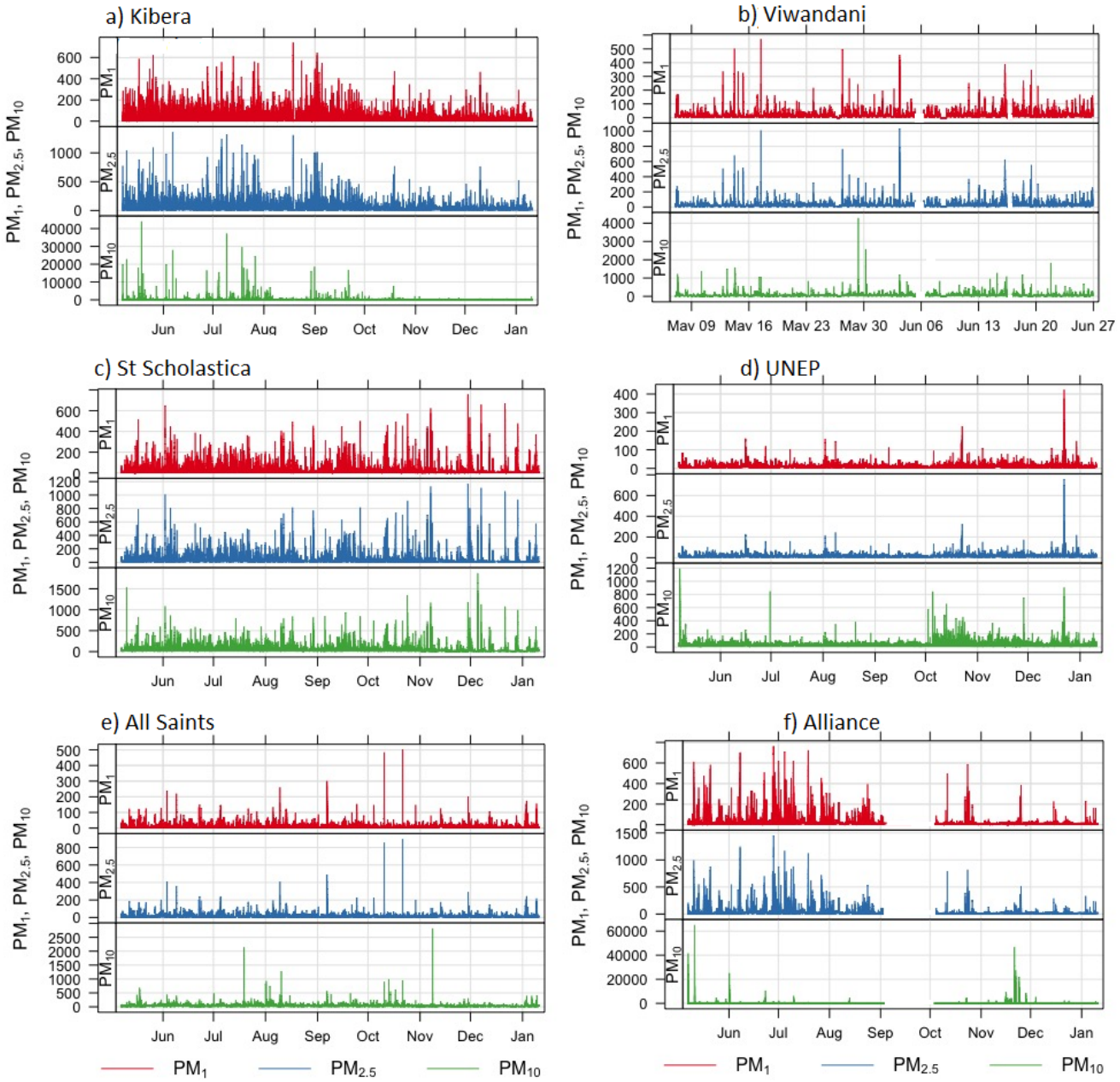

Figure 1A: *1-minute PM_1 (red), $PM_{2.5}$ (blue) and PM_{10} (green) mass concentration (µg/m³) time series plots for each site; a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 1, 2016 to January 11, 2017.*

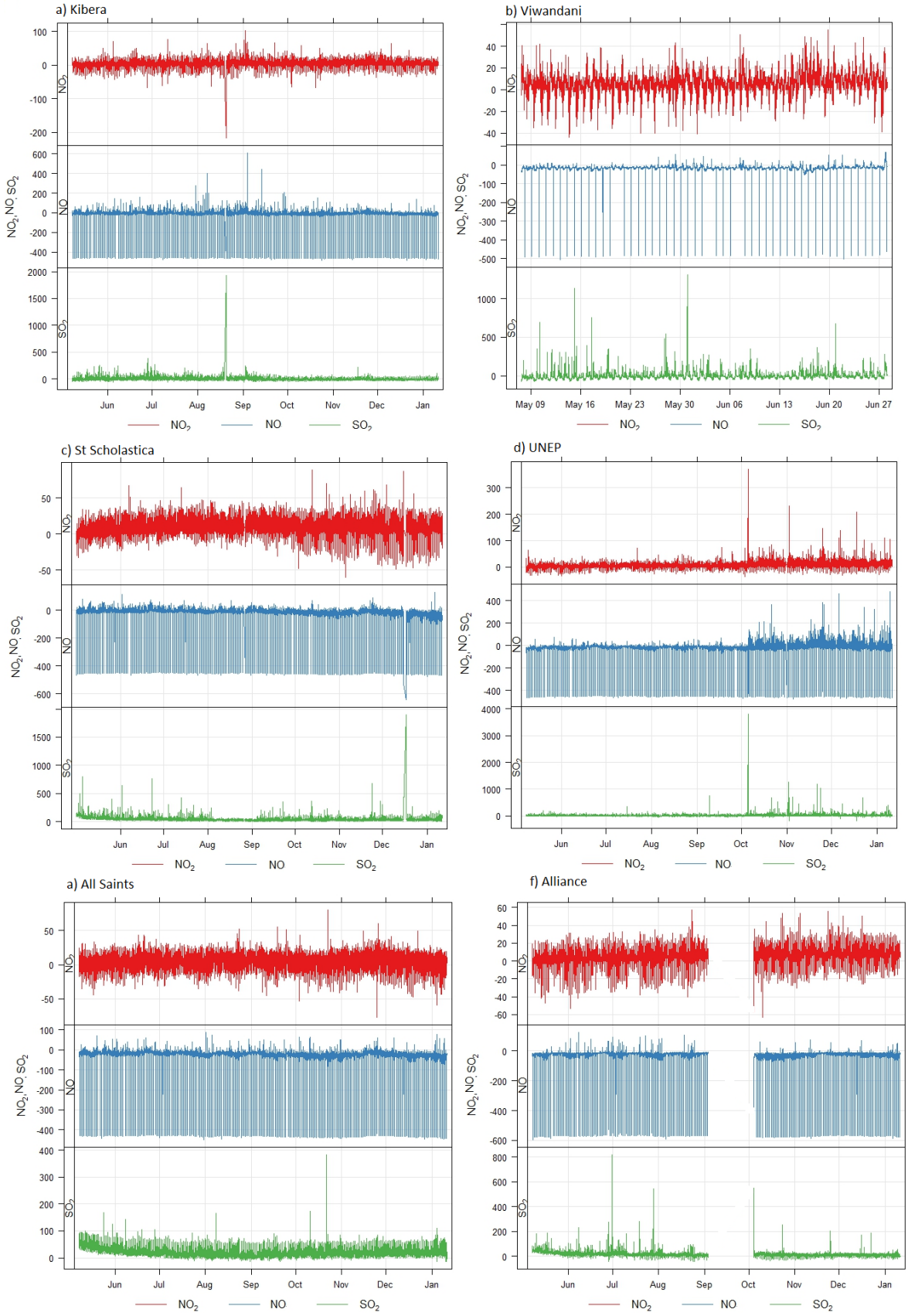

Figure 2A: *: 1-minute NO_2 (red), NO (blue) and SO_2 (green) concentration (ppb) time series plots for each site a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 1, 2016 to January 11, 2017.*

Table 1A shows the correlation between gaseous pollutant values > 0 and temperature/humidity and the other pollutants measured at each site. This table shows that for gaseous pollutants with values > 0, the correlation between temperature and humidity is low, and has the same sign across sites. This indicates that the signal registered is more likely to only be due to the pollutants and is not affected by environmental factors.

Table 1A: *Summary of the Pearson correlation coefficient (R) at each of the six sites for all gaseous pollutant observations greater than zero.*

	Kibera	Viwandani	St Scholastica	UNEP	All Saints	Alliance
Correlation of NO_2 with temperature	0.13	0.02	0.17	0.32	-0.045	0.38
Correlation of SO_2 with temperature	0.027	0.01	0.18	0.18	0.25	0.04
Correlation of NO with temperature	0.028	-0.12	-0.17	-0.04	-0.28	-0.12
Correlation of NO_2 with humidity	-0.13	-0.032	-0.27	-0.31	0.099	-0.39
Correlation of SO_2 with humidity	-0.056	-0.018	-0.16	-0.16	-0.11	0.013
Correlation of NO with humidity	-0.15	-0.09	0.26	0.06	0.058	-0.06
Correlation of NO with NO_2	0.32	0.11	0.098	0.26	-0.097	0.27
Correlation of NO with SO_2	0.55	0.24	0.31	0.33	0.47	0.36
Correlation of NO with PM_{10}	0.13	0.16	0.12	0.12	0.37	0.19
Correlation of NO with $PM_{2.5}$	0.16	0.13	0.09	0.06	0.27	0.16
Correlation of NO with PM_1	0.16	0.12	0.09	0.03	0.27	0.17
Correlation of NO_2 with SO_2	0.16	0.14	0.21	0.28	0.18	0.066
Correlation of NO_2 with $PM_{2.5}$	0.13	0.29	0.1	0.16	0.28	0.02
Correlation of NO_2 with PM_{10}	0.058	0.32	0.24	0.31	0.26	0
Correlation of NO_2 with PM_1	0.12	0.3	0.089	0.12	0.27	0.014
Correlation of SO_2 with $PM_{2.5}$	0.25	0.13	0.12	0.18	0.25	0.12
Correlation of SO_2 with PM_{10}	0.086	0.12	0.19	0.22	0.25	0.01
Correlation of SO_2 with PM_1	0.26	0.13	0.12	0.16	0.23	0.12

Figures 3A to 7A clearly show the variation of the gaseous pollutants with temperature. It is clear from these figures that for high temperatures (roughly > 200 C), negative values of pollutants ae registered. Co-location with a reference monitor is required in order to truly identify the ranges in which the values are correct. However, plotting these graphs is a rough way to identify temperature ranges in which the sensors clearly make incorrect measurements.

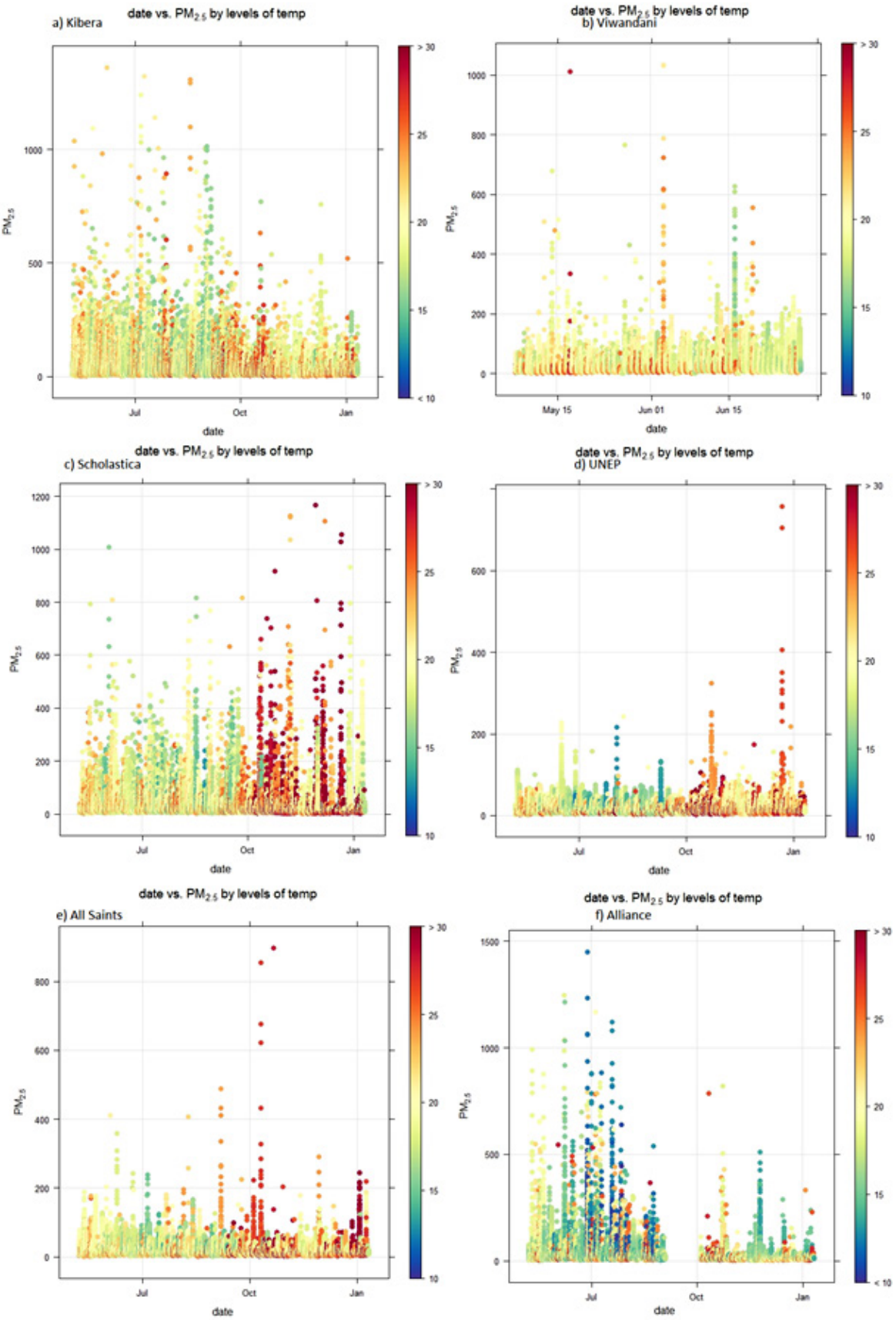

Figure 3A: *Time series of $PM_{2.5}$ in units of µg/m³ with the color scale corresponding to temperature for the sites: a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5, 2016 to January 11, 2017.*

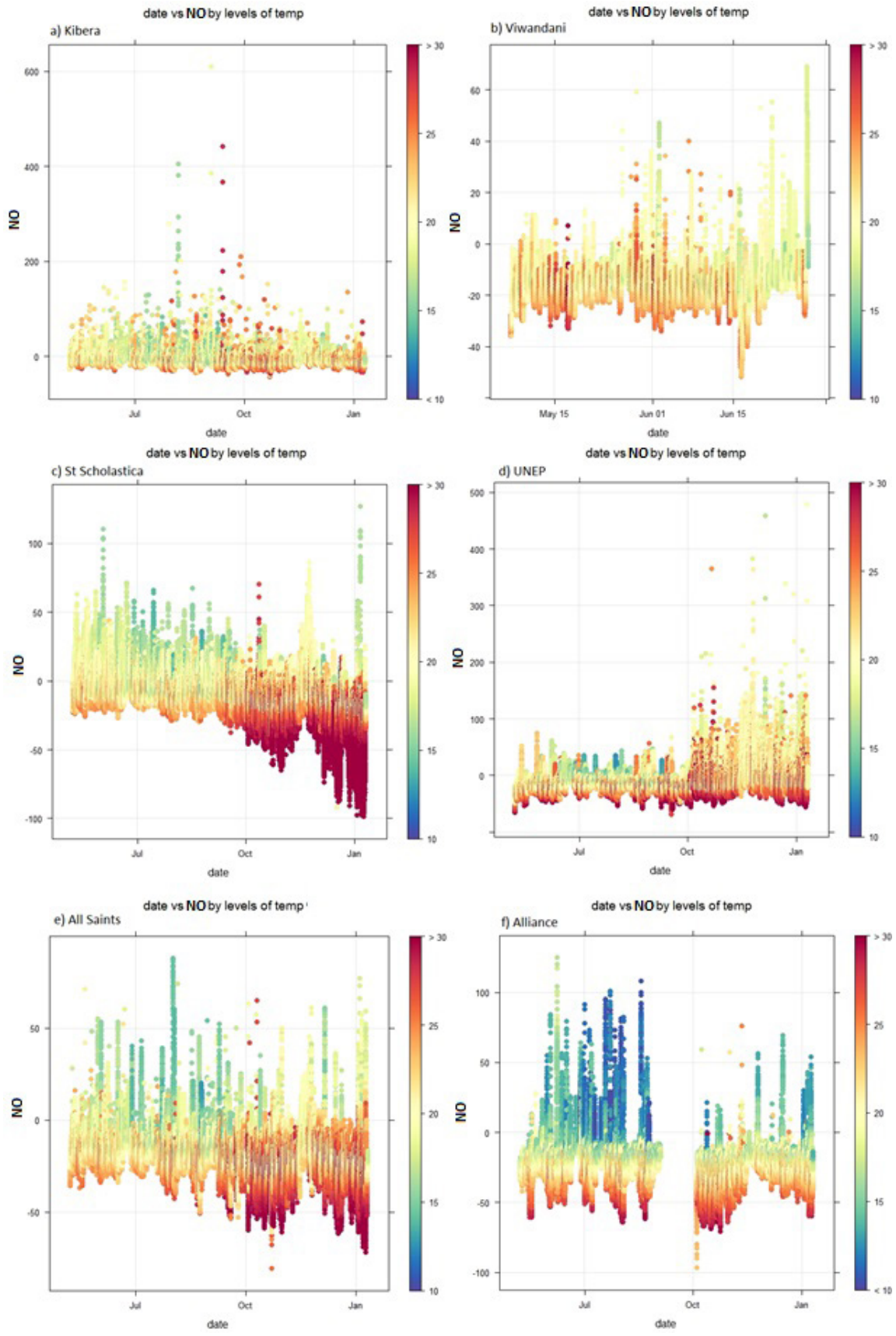

Figure 4A: *Time series of NO for recordings >-100ppb in units of ppb with the color scale corresponding to temperature for the sites: a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5, 2016 to January 11, 2017.*

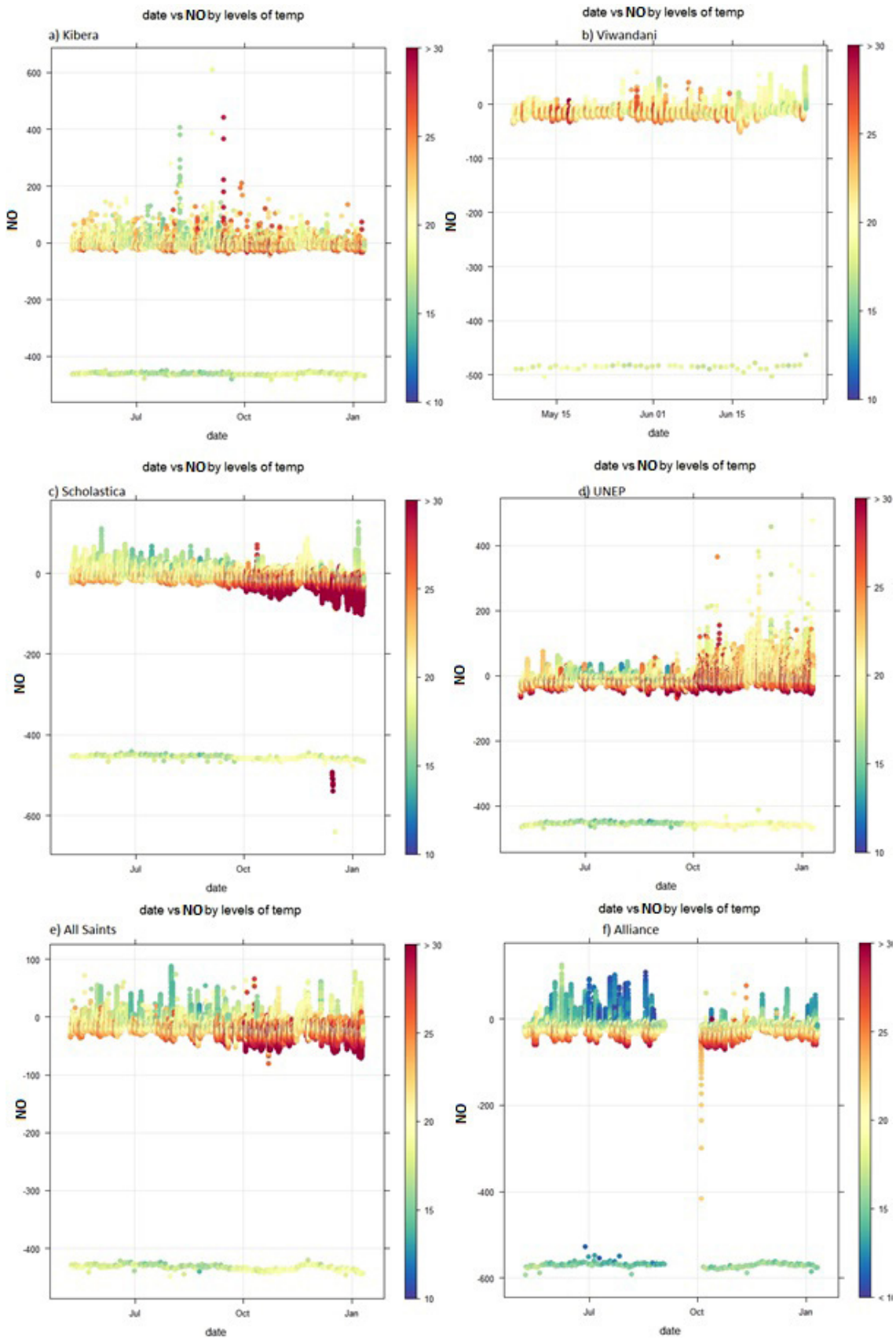

Figure 5A: *Time series of NO in units of ppb with the color scale corresponding to temperature for the sites. No filter was applied to the NO data: a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5, 2016 to January 11, 2017.*

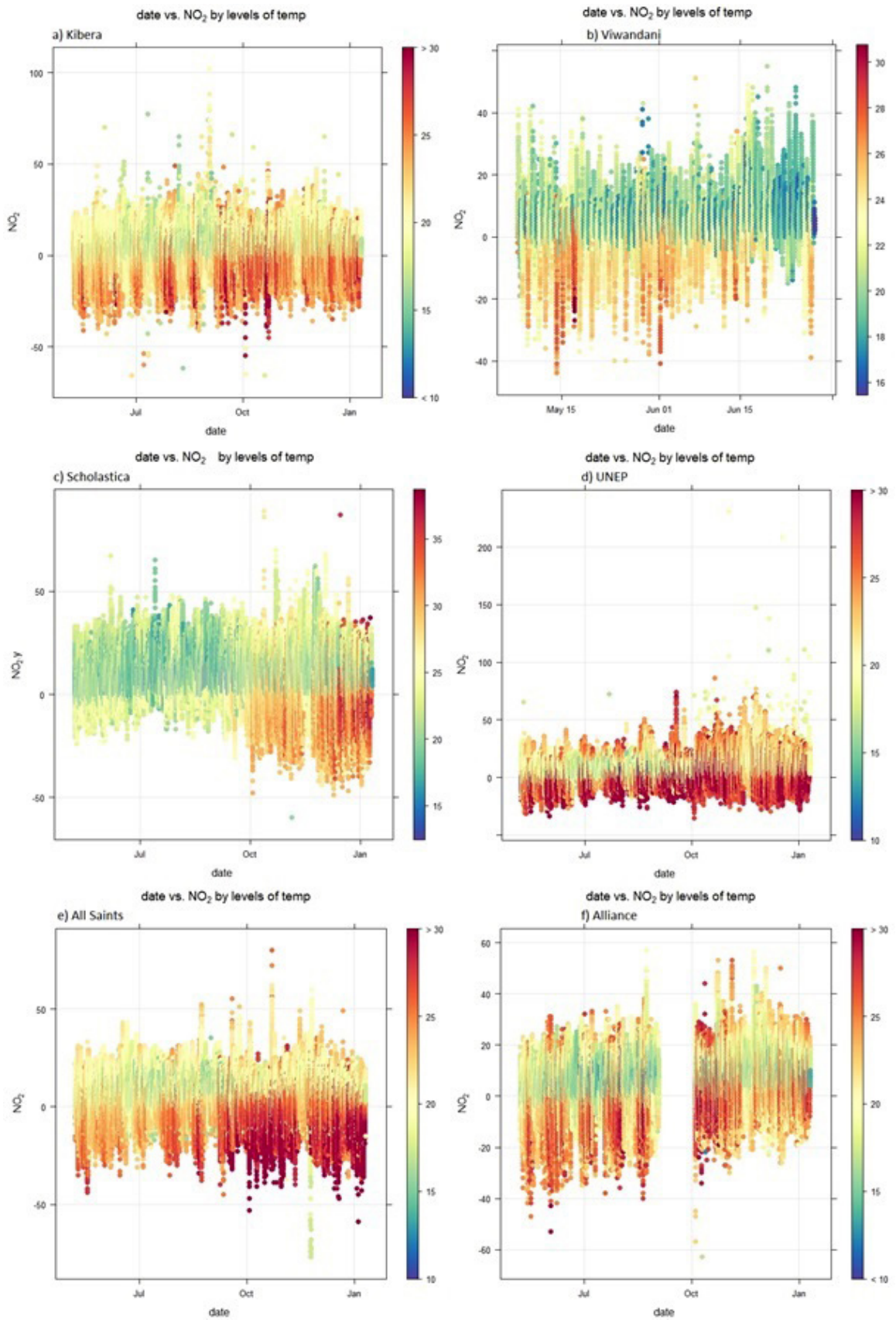

Figure 6A: *Time series of NO_2 in units of ppb with the color scale corresponding to temperature for the sites: a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5, 2016 to January 11, 2017.*

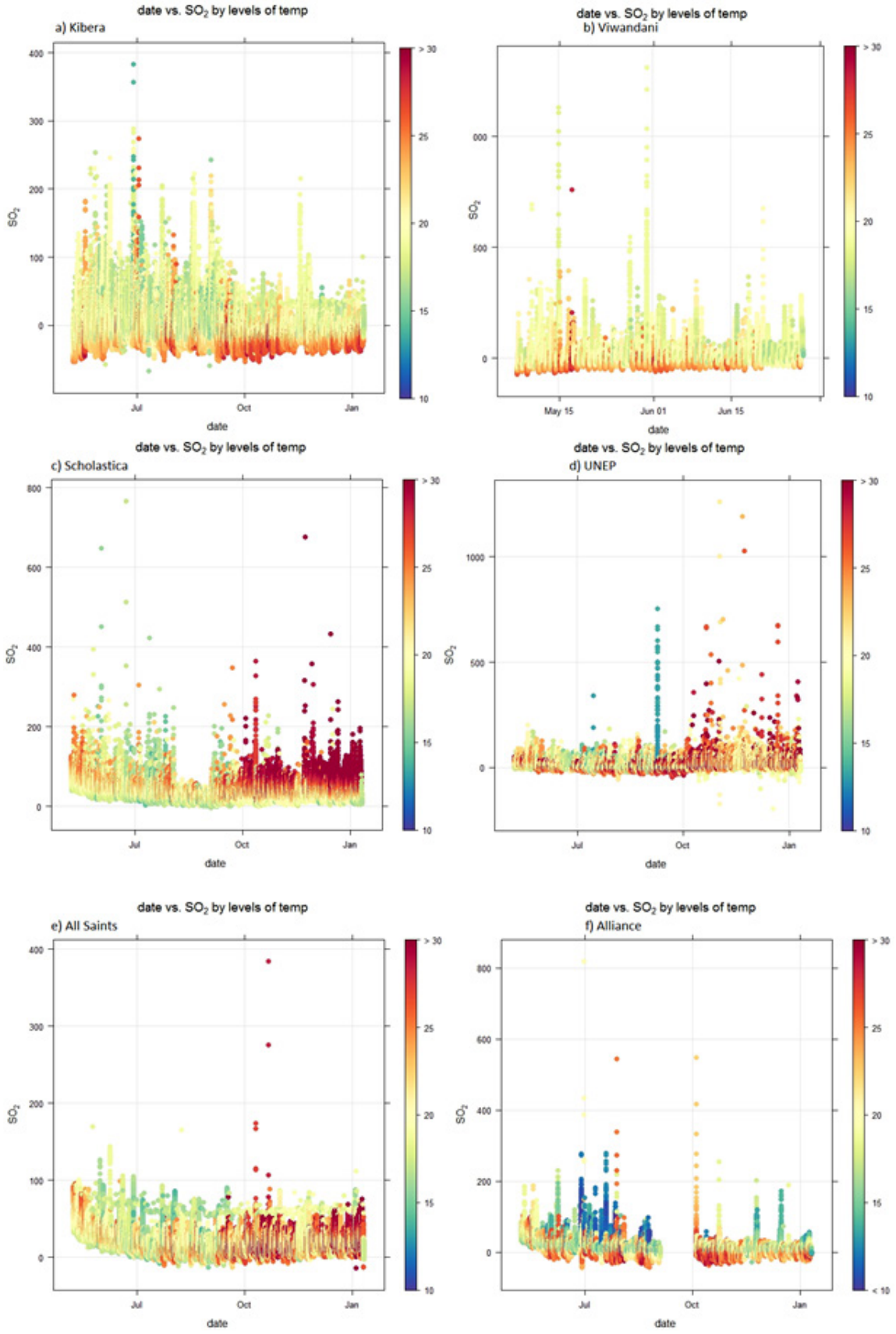

Figure 7A: *Time series of SO_2 in units of ppb with the color scale corresponding to temperature for the sites: a) Kibera Girls Soccer Academy, b) Viwandani Community Center (note that due to an extended power outage this monitor stopped logging data after June 27, 2016), c) St Scholastics, d) UNEP, e) All Saints Cathedral School, f) Alliance Girls School from May 5, 2016 to January 11, 2017.*

Research article

A National Greenhouse Gas Inventory Management System for South Africa

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Abstract

South Africa has committed to reducing its contribution to the global GHG budget. It ratified the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. The UNFCCC stipulates that Non-Annex 1 countries are required to submit inventory reports every two years as part of their Biennial Update Reports (BURs) or National Communications (NCs). To assist with this increased reporting a National GHG Inventory Management System (NGHGIS), with new internal procedures and capacities, is being developed. The NGHGIS has been designed to ensure transparency, consistency, comparability, completeness and accuracy of the GHG inventory. It ensures the quality of the inventory through planning, preparation and management of inventory activities. The NGHGIS has been set up in a web-based, collaborative platform that allows for document management, sharing and storage. The main components of the NGHGIS are the (a) organisational structure; (b) inventory preparation work plan where responsibilities are assigned; (c) data supplier and stakeholder lists; (d) input datasets (linked to the stakeholder list) providing information on required data, MOU's, and data due dates; (e) quality assurance and quality control (QA/QC) objectives, checks, logs and tools; (f) emission calculation method statements; (g) GHG inventory outputs which include estimation files, a trend viewer and a public website; and (h) improvement plans. In addition to the web-based system, new institutional arrangements and data flows have been proposed, the legal landscape has been mapped, draft MOUs for data suppliers have been drawn up and a detailed QA/QC plan has been developed. The final stage of the NGHGIS is the development of the data collection plan and technical guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) and Waste sectors. The centralised NGHGIS will reduce the loss of information, improve continuity between inventories and assist in the timely completion of inventory updates.

Keywords

National system, GHG inventory, institutional arrangements, stakeholders, datasets, quality control

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) stipulates that signatory parties (ratified by South Africa on 29/08/1997) are required to submit inventory reports that account the nations GHG sources and sinks. As part of the Conference of the Parties 17 (COP17) outputs, Non-Annex I parties, such as South Africa, are now required to submit inventories every two years as part of their Biennial Update Reports (BURs) and National Communications (NC). This regular reporting becomes challenging if countries do not have well established systematic approaches in place for developing their inventories. With well-developed and robust inventory systems this regular reporting becomes more manageable and the quality of inventories can be more easily improved upon (Damassa and Elsayed, 2013).

Furthermore, following the Paris Agreement (UNFCCC, 2015) which South Africa ratified on 11/01/2016, and with enhanced action in mind, all signatories need to be well informed of their mitigation and adaptation options. Countries need to understand the positive and negative co-impacts of climate action in order to make the right decisions on climate action. The Greenhouse Gas (GHG) inventories provide historical trends in emissions and removals from different activities in South Africa. This information is needed to provide timely decision making information to government, business and the public to capitalise opportunities and to avoid costly problems later on. This information also feeds into analysis of projections in GHG emissions and removals, and in the quantification of GHG savings from possible future action.

The core roles of the National GHG Inventory Management System (NGHGIS) are, therefore, to aid in the biennial compilation of the GHG inventories and contribute to South Africa's nationally determined contributions (NDCs) on adaptation, mitigation and investment requirements. As South Africa moves towards 2030, the system will also play a supporting role for actives such as Mitigation Potential Analyses, National Emission Trajectories, Desired Emission Reduction Outcomes, Carbon Budgets, Policies and Measures Assessments, Carbon Offset Scheme, Low-Emission Development Strategies and compliance reviews.

The aims of the NGHGIS are to:

- Establish robust institutional memory
- Enhance and maintain domestic capacity
- Identify institutional arrangements with roles and responsibilities
- Implement and maintain sustainable data management
- Support the co-ordination of all MRV activities
- Engage with the domestic and international community
- Produce timely and high quality outputs and
- Drive continual improvement

The aim of this paper is to introduce and describe the NGHGIS for South Africa and to increase transparency of the system.

Development of the NGHGIS

South Africa's National GHG Inventory Management System (NGHGIS) has been designed to ensure transparency, consistency, comparability, completeness and accuracy of inventories as defined in the *Good Practice Guidelines* (GPG) for preparation of inventories. It also contributes towards the enhanced transparency requirements defined in Article 13 of the Paris Agreement (UN, 2015). In accordance with Article 5 of the Kyoto Protocol (KP) (Kyoto Protocol, 1997) it ensures the quality of the inventory through planning, preparation and management of inventory activities. The system defines and allocates specific responsibilities in the inventory development process, including those related to choice of methods, data collection, processing and archiving, and quality assurance and quality control (QA/QC). The NGHGIS has been developed in SharePoint, which is a secure, web-based, collaborative platform that allows for document management, sharing and storage. Access to the system is password protected to ensure manageability, to minimize the number of people who can make alterations, corrections or updates to the system, and to protect confidential information. Different stakeholders can be given different levels of access. Components of the system, such as the public website, can be opened to the public. The Single National Entity (SNE) and inventory managers, compilers and reviewers to be involved in the inventory preparation process will be decided on and assigned with responsibilities during the initial GHG inventory preparation meeting. These contributors will then be logged onto the system for the duration of the process. At the start of each inventory preparation cycle the logins will be re-evaluated.

The NGHGIS consists of a number of components that support good practice activities and reinforce the institutional memory of South Africa's institutions. The key components are:

- Institutional arrangements and data flows
- Inventory preparation work plan
- Stakeholders
- Datasets
- Methods
- QA/QC
- Calculations
- Outputs and
- Improvements.

Institutional arrangements, data providers, data flows and quality control plans for other countries (both Annex 1 and non-Annex 1 countries) were reviewed and used as guidance for the development of these components. A description of each of the key components, along with comparisons to other countries, is provided below.

Institutional arrangements and organisational structure

The front page of the web-based national system provides the organisational structure and clearly lays out which organisations have which roles in the development and operation of the National System for GHG inventory production. It also presents the current and future data flows and system layout as discussed further in the section about stakeholders and data flows.

The Department of Environmental Affairs (DEA) is the central co-ordinating and policy-making authority with respect to environmental conservation. It is mandated by the National Environmental Management: Air Quality Act (Act 39 of 2004) to formulate, co-ordinate and monitor national environmental information, policies, programmes and legislation. The 1990, 1994 and 2000 inventories were compiled by the Council for Scientific and Industrial Research (CSIR), but since then South Africa has moved towards a more centralised system with DEA playing a more active role and taking over the management of the compilation process. This seems to be the general trend in other countries as well. In the majority of Non-Annex 1 countries reviewed the national entity is a research institute (Salas Cisneros, 2013; Gutierrez Arias et al., 2013; 2013a; Mauritius NIR2006), mainly because the expertise lie outside of the ministries, however, as climate change becomes more important and policies and acts are introduced at a national level then the ministries start to take over the role of the national entity (Bhattacharya, 2013). In the majority of the Annex 1 countries there is an appointed single national entity which is usually a ministry of environment or climate change (for example NZ NIR2014; German NIR2014; Norwegian NIR2014; UK NIR2014; Japan NIR2014).

Finances can also contribute to the ad hoc nature of institutional arrangements in non-Annex 1 countries as inventory development is often project based. As the inventory processes become more developed there is a general movement away from project based towards institutional base inventory systems (Kabuswe, 2014).

Currently DEA is responsible for collecting data and compiling the Energy, Industrial Processes and Product Uses (IPPU) and Waste sector inventories, while the compilation of the Agriculture, Forestry and Other Land Use sector (as well as the combining and compiling of the NIR) is out-sourced to consultants (Figure 1). This is not unusual as this is a complex sector that relates to a range of data and expertise (land management including forestry, farm management, Geographical Information Systems) not usually available and difficult to maintain within central government departments. Many countries successfully out-source these Agriculture, Forestry and Other Land Use services as well as other components of the inventory co-ordination and compilation without losing control of the overall GHG inventory outputs. The review indicates that Annex 1 countries generally have a hybrid approach which is described in the New Zealand inventory as centralised and distributed (NZ NIR2014). In this scenario the management and co-ordination of the inventory preparation and compilation are carried out in a centralised manner (i.e. one agency co-ordinates all processes), but sector specific work is designated to various agencies across the country. This is the approach which South Africa is starting to follow. Austria is the exception to this as it has a fully centralised approach, with all the work relating to the inventory being conducted within a single national entity, the *Umweltbundesamt* (Austrian NIR2014).

Several of the Non-Annex 1 countries (Miguez, 2012; Gutierrez Arias et al., 2013; 2013a; Salas Cisneros, 2013; Baffoe, 2014), make use of sectoral working groups to pool expertise. The adoption of sectoral coordinating institutions and/or working groups leverages a country's cross agency expertise and could additionally help spread the workload. By identifying in-country or existing staff and assigning them coordination responsibilities, there is an increased likelihood that technical and process knowledge will be retained, and a broader set of stakeholders will have ownership of the final product. This is an option which South Africa can consider in future, particularly for the larger Agriculture, Forestry and Other Land Use sector.

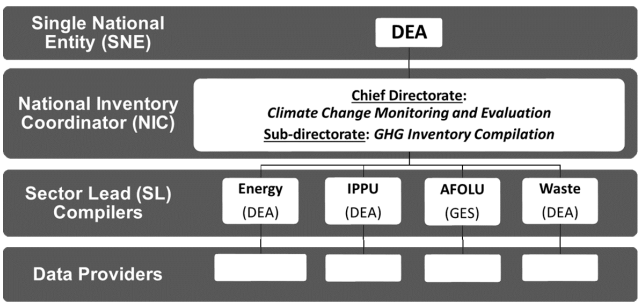

Figure 1: *Institutional arrangements for SA's GHG Inventory compilation.*

The review of other country institutional arrangements indicates that it is not essential for DEA to build in-capacity to compile all sectors of the inventory, as long as South Africa has sufficient resources available to manage external services and understands the key drivers and approaches for the GHG estimates. It is more important to make use of the wide range of existing expertise available from within and outside government.

In order to maintain continuity and build sustainability it would, however, be beneficial to seek and develop longer term (5-year) agreements with service providers for out-sourced expertise and experienced GHG inventory compilation and co-ordination support.

Inventory preparation work plan

To produce the inventory in a timeous manner it is essential for South Africa to develop a work plan and timeline. The work plan component of the national system provides a detailed plan of the inventory preparation process and this can be shared with stakeholders. It allows the co-ordinators to manage tasks and to engage sector experts and wider stakeholders in the planning and delivery of timely outputs. The work plan allows tasks to be assigned to stakeholders and progress on tasks to be tracked. Alerts can also be inserted into the system so that the inventory manager or compiler receives messages indicating when tasks are complete or overdue.

The work plan can take guidance from the recommended inventory preparation cycle that has been developed as part of the project. The cycle has 6 main steps (Figure 2), namely, plan, collect, compile, write, improve and finalise. It is recommended that South Africa focus its initial efforts on the following three phases:

- *Collect*: Data collection involves understanding what data is required, sourcing the data from various stakeholders, screening the data (for usefulness and appropriateness), selecting the appropriate data sets and quality checking the data (IPCC 2006 Guidelines). Once data is selected procedures need to be put in place so as to maintain a continuous supply of data. In order to ensure continuous inventory improvement, data gaps must be identified and measures taken to fill these gaps. Provision of guidelines on how new data should be collected or measured and what quality control procedures should be adhered to are recommended. The data collection procedures should also be reviewed periodically so as to maintain its integrity.

- *Compile*: Once data are selected and checked all information relating to the data needs to be recorded in the Inventory database. There is first the data input, which is followed by the completion of the uncertainty data sheets. Finally the metadata must be compiled. This involves documenting the names of the people responsible for incorporating the data, specific data calculation, data sources, uncertainty sources, recalculations undertaken and links to data or reference files.

- *Write*: The National GHG Inventory Report (NIR) is drafted based on the summary outputs from the inventory database. The report will also draw methodological and uncertainty information from the metadata and uncertainty files in the inventory database.

Throughout these phases the National System should consider the co-ordination and encouragement of quality control and quality assurance activities. Quality control and quality

assurance are an integral part of the inventory process. There are several quality control steps throughout the inventory improvement process which assess and maintain the quality of the inventory as it is being compiled and provides routine and consistent checks to ensure data integrity, correctness and completeness.

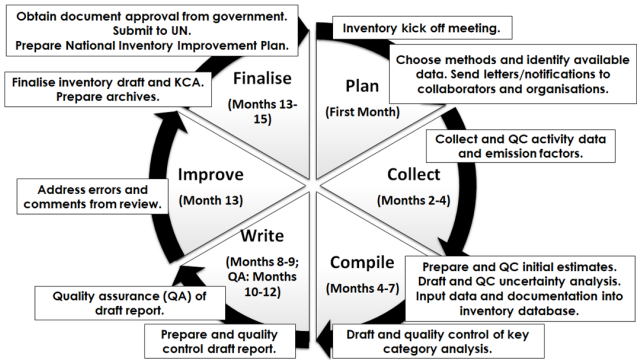

Figure 2: *Inventory preparation cycle with suggested timelines.*

Stakeholders and data flows

The national system provides a live list of all stakeholders engaged in the GHG inventory compilation. It identifies the stakeholder roles, logs details of their engagement with the GHG inventory activities and provides an essential reference point for co-ordination of future engagement activities. Connected to the list of stakeholders are templates for the elaboration of data supply agreements that can be set-up between the GHG inventory single national entity and the data providing stakeholder. Where appropriate, elaborated and agreed versions of these templates can be attached to the relevant stakeholder records so that agreed data supply is transparent and referenceable.

In South Africa data is sourced from many institutes, associations, companies and ministerial branches. At this stage there is a lack of legal and formal procedures for obtaining data and compiling the GHG emission inventory. This is common amongst Non-Annex 1 countries. The Industrial Processes and Product Use sector has, until now, had some formality in that DEA has requested data from industries through the umbrella organisation Business Unity South Africa (BUSA). Even so, this system has no legal obligation attached to. In all sectors input data is obtained on a voluntary system and relies on good relationships which have been built up over time. This system is however, no sustainable should relationships turn sour or if key compilers or contacts leave their organisations.

The draft GHG regulations (RSA GG, 2015) will bring some formality to the Industrial Processes and Product Uses sector, but formality needs to be developed in the other sectors as well. South Africa needs to move towards a formalized system, as is evident in Annex 1 countries where there are most often signed agreements between the leading institutions and the single national entity (for example Bulgarian NIR2014; German NIR2014; UK NIR2014). Germany not only has agreements between the SNE and the state secretaries, but also signed individual cooperation agreements with the relevant sector stakeholders (Roeser, 2015). In terms of the NGHGIS it is recommended that DEA develop legal instruments (e.g. MoUs) to regulate the Department's engagement with other institutions regarding: the formalisation of institutional and procedural arrangements; the alignment of government's inventory processes as well as to provide dispute resolution mechanisms and to protect confidential data and information. The legal instruments developed by DEA must accordingly regulate processes and activities in the department (e.g. in relation to confidentiality and ethical conduct); the relationship between the DEA and other line functionaries (e.g. the Department of Energy), municipalities and other organs of state (e.g. the National Energy Regulator (NERsa)); as well as the department's interaction with private institutions. As part of this project an intergovernmental and an industry/other non-state institution Memorandum of Understanding (MoU) have been drafted so as to address these issues in the future. These are both available on the NGHGIS.

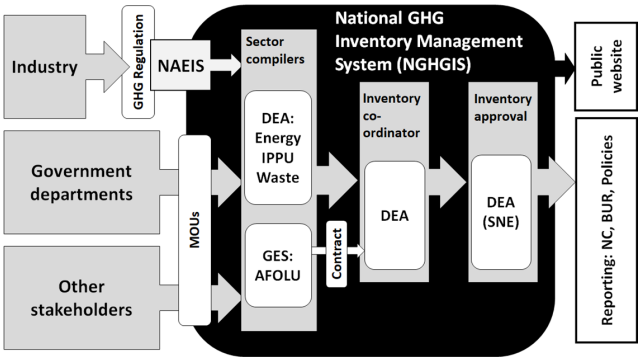

Figure 3: *Future organisational structure for SA's GHG Inventory compilation.*

In both Annex 1 and Non-Annex 1 countries national statistics are shown to play a prominent role in many inventories (Norwegian NIR2014; NZ NIR2014; Bulgarian NIR2014; Salas Cisneros, 2013; Mauritius NIR2006; Namibia SNC, 2011). In Norway, Statistics Norway (Statistisk Sentralbyrå (SSB)) is responsible for the official statistics on emissions to air and is one of three core institutes involved in inventory compilation. This is not the case in South Africa. DEA has had some discussions with Statistics SA and it is recommended that these discussions continue to determine whether their role as a data supplier for the inventory can be strengthened and whether Statistics SA can assist in steering new data collection processes.

The envisaged organisational structure and data flows for South Africa are shown in Figure 3. It is proposed that the GHG inventory data collection be integrated with the current National Atmospheric Emissions Inventory System (NAEIS) as is the case in most Annex 1 countries (e.g. Norwegian NIR2014; German NIR2014; UK NIR2014; Austrian NIR2016). Using the same structures for reporting both GHG's and air pollutants minimize duplication, reduce the reporting burden on data suppliers and makes use of the same resources for two tasks.

Datasets

The NGHGIS provides a list of datasets which allows the GHG inventory system co-ordinators, experts and other stakeholders to track the data used or needed for the GHG estimates. The datasets are linked to a stakeholder from the stakeholder list with associated elaborated data supply agreements (if relevant). This makes it clear for all stakeholders within the GHG inventory national system where datasets are sourced and the connection of organisations to data provision.

Method documentation

The methods and data source section of the NGHGIS allows the team and stakeholders to manage (create, share and store) the key documentation files describing the methods, data sources and assumptions. This is managed in a customised document library which includes metadata on the status and content of the method descriptions. The library also provides access to a templates with a pre-defined structure and embedded guidance and links to writing guidance that can be used when documenting GHG estimates.

The method statements, which are critical for continuity in the inventory, can apply to a single or group of category/subcategory/gas/fuels. A method statement can apply to a group of categories if the same method, assumptions and data sources are used. For example, where the same defaults and energy balance data are used for a number of categories and fuels. This will minimise repeated text and multiple references to data sources and assumptions. Method statements have a unique ID so that the methods can be linked to the appropriate sections of the inventory, as well as being linked to the required input data sets and quality control measures conducted on the data. The method statements contain information on the background of the emission source, data sources, datasets, method approach, assumptions, recalculations, improvements, QA/QC process, time series consistency, uncertainties and verification.

QA/QC procedures

South Africa does conduct QA/QC activities however there is no clear QA/QC process in place and roles and responsibilities are not clearly defined. A QA/QC plan is an important component of the inventory system. All Annex 1 countries have a QA/QC Plan or Quality Management Manual in place which generally follow the QA/QC guidance provided by the IPCC in terms of QA/QC plans. The majority of plans/manuals reviewed contained the following information:

- Definitions
- Quality objectives
- Roles and responsibilities
- General QC procedures
- Checklists for general QC checks
- Checklists for specific QC checks
- QA procedures

In some cases there are also details about the verification process (e.g. Denmark, Italy); QA/QC improvement plans (e.g. Iceland, Romania, Italy); reporting, documentation and archiving process (e.g. Iceland, Italy, Romania) and also qualitative uncertainty analysis (e.g. Italy, USA) (Nielsen et al., 2012; Hallsdottir and Guomundsson, 2007; Deaconu, 2013; Bernetti and Romano, 2006; EPA, 2002). The Tier 1 quality control checks outlined in 2006 IPCC Guidelines (IPCC, 2006; Chapter 6, Table 6.1) and the Good Practice Guidelines (IPCC, 2000; Chapter 8, Table 8.1) provide the basis for checks developed in all the countries. The various countries provide more detailed descriptions of their specific activities and procedures under each point.

QA activities in the reviewed countries take many forms, namely peer reviews, expert reviews, UNFCCC expert reviews, steering committee reviews, internal reviews, audits, bilateral reviews, public reviews stakeholder reviews, method and calculation validation exercises, in-depth sector and sub-sector reviews and working groups. All countries employ more than one of these activities, with peer reviews, expert reviews and the UNFCCC expert review being common to all countries. Some countries, such as Australia, Austria, Bulgaria, Finland and New Zealand, have their inventories audited. Audits can take the form of second and third party audits, accreditation audits, as well as data supplier audits.

Based on the review findings and as part of the NGHGIS a detailed QA/QC plan was developed for South Africa along with a recommended QA/QC cycle and timeframe (Figure 4). These documents are housed on the QA/QC plan component of the NGHGIS. The phases of the QA/QC process are:

- *QA/QC planning*: During the inventory planning meeting the review comments from the previous year's submission are considered and improvement plans are made for the upcoming submission. It is during this planning phase that the QA/QC plan is reviewed and improved. The planning stage includes the setting of quality objectives and elaboration of the QA/QC plan for the coming inventory preparation, compilation and reporting work and reviewing the quality control checks. The specific timeframes for the completion of each activity should be decided during this planning meeting;
- *Quality control*: All quality control activities are implemented during this phase;
- *Quality assurance*: All quality assurance procedures are completed during this phase;
- *QA/QC conclusions*: This phase is when all QA/QC activities are concluded and signed-off, and all documentation is finalised; and
- *QA/QC evaluation and improvement*: Results of the QA/QC process are evaluated and improvements are included in the planning phase of the following inventory cycle.

The QA/QC component of the NGHGIS includes:

- QA/QC objectives which provides a list of high level objectives along with a description of how the objectives will be met. These objectives are focused on ensuring all outputs from the GHG inventory system are fit for purpose with understood uncertainties/strengths and weaknesses. The objectives encompass the 2006 IPCC quality criteria (Transparency, Completeness, Comparability, Consistency

and Accuracy) and define objectives specific to South Africa's national circumstances. The quality objectives are reviewed when a new set of estimates or updates are planned and monitored;

- QA/QC checks which provides a library of all agreed and proposed QA/QC checks. This list identifies checks that should be implemented and where and when in the estimation and reporting processes. It provides an ID for each check so that the specific quality checks that are completed can be referred to in the calculation files or reports;
- QA/QC log which itemizes specific QA/QC activities undertaken by who and when. Evidence of the QA/QC (e.g. review reports) if needed or reference "emails" or filenames can be attached to the log for ease of access and transparency. It also provides a list of template checklist which need to be undertaken and the log will show which components are completed or which are overdue.

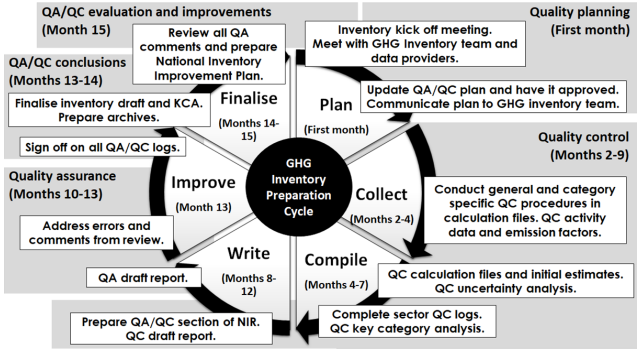

Figure 4: *Quality control procedures and timeframes for the GHG inventory.*

GHG emission inventory calculation files

The NGHGIS provides a library for sharing the calculations for the GHG estimates. It provides templates for the calculation files that facilitate efficient calculation and updates, support QA/QC activities, clear detailed documentation and aggregation of outputs for reporting. This also acts as an archive into which all of the relevant and essential calculation and background material for the GHG estimates can be preserved to safeguard against loss of institutional materials.

Calculation files were re-designed, based on international experiences, to make it easier to understand and follow the data in the calculation files, as well as incorporating aspects to make the QA/QC process easier. The following important improvements have been made to the calculation files:

- Incorporation of data for all years in the time series into one file to aid in the checking of time series consistency;
- Colour coding of all data in calculation files to assist in understanding where the data comes from or how it is derived;
- Addition of spark-lines (or trend lines) to the end of each row of data so that the compiler or review can do a quick visual check for inconsistencies in the data series;
- Incorporation of a standardised commenting system to enable information on methodology, or data queries, to be inserted directly into the calculation file. This assists reviewers and enables the QC process to occur alongside the inventory compilation; and
- Addition of the QA Analyst logging system to each sector file which pulls out all comments in the spreadsheets and creates a log of comments on the first page of the calculation file. This assists with tracking and transparency and enables the quality controller to see that all queries have been responded to.

Outputs

There are two components to the outputs on the NGHGIS. The first is the GHG emissions trend viewer. This can provide regular updates of the GHG inventory trends for national awareness raising and as input to progress tracking and analysis of future actions. This is possible once the data archive is working efficiently and the estimates can be aggregated into a transparent quality assured database.

The second component is the public website. A public presentation of the GHG inventory national system is being developed using summary data from the secure GHG inventory monitoring, reporting and verification (MRV) system. This public site could include interactive data on the GHG trends and associated indicators, summary lists of key stakeholders, datasets and improvements planned and implemented. It can also provide links to the detailed GHG estimates and to method descriptions for the GHG estimates. The site would provide a focal point for stakeholder engagement (e.g. for consultations) and to showcase the GHG inventory system to the international GHG mitigation community. A prototype has been developed to test out its usefulness.

Improvements

In this section of the NGHGIS a live list of improvement activities (proposed, planned and completed) are provided. The improvement plan is visible to all stakeholders with access to the MRV system. It acts as the focal point for logging and prioritising improvement suggestions, tracking live improvement activities and a resource for providing documentation of improvements and improvement needs in national reports (e.g. Nationally Determined Contributions, National Communications, and Biennial Update Reports).

Conclusions

The project to develop a sustainable GHG inventory national system for South Africa is expected to be concluded in December 2017. Through this project and other efforts to invest in expert capacity, South Africa is aiming to establish, in a functioning system, sustainable teams of experts managing transparent data in well-maintained tracking and planning (MRV) systems.

The NGHGIS is already functioning and evolving as South Africa continues to work on and deliver monitoring, reporting and verification activities for its Biennial Update Report and National Communications. The system helps South Africa to

manage a dynamic and changing spectrum of stakeholders. The structure (templates and lists) and accessibility (in a secure environment) of the system provides far greater transparency and improved continuity for the detailed work put into calculating GHG estimates. This facilitates the engagement of a wide range of stakeholders and contributors and offers the DEA added institutional memory, a place to collaborate and facilitate continuous improvement within a sustainable and secure framework. It also provides a backbone of structure and support for continuity and control.

The system is being tested with its ability to withstand the turnover of key staff and experts and the embedding of short term improvement projects over time.

Over the coming years South Africa's climate action reporters and decision makers will be supported with relevant and timely information by this system and its engaged teams for reporting, decision making and negotiation on climate action.

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Monitoring the contribution of desert dust intrusion to PM_{10} concentration in Northern Cyprus

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Abstract
Air quality in the Mediterranean basin has been affected by PM_{10} pollution induced by transported desert dust and local emission. The study used PM_{10} data from Nicosia, Kyrenia, Guzelyurt and Famagusta urban representatives, Kalecik rural background and Alevkayasi regional background. HYSPLIT model and satellite data were used to identify dust days and dust input was quantified using the method suggested by the European Commission. Anthropogenic background contribution of each site was then estimated by subtracting the regional background concentrations. A total of 35 dust days occurred on Cyprus island within the 3-years period; mostly during winter and spring. Daily PM_{10} concentration on dust days can reach up to 400 µg/m³. After removing dust background, annual PM_{10} concentrations were 48-58 µg/m³ in Nicosia, 42-47 µg/m³ in Famagusta, 40-50 µg/m³ in Kyrenia, 33-41 µg/m³ in Guzelyurt, 21-28 µg/m³ in Alevkayasi, and 32-38 µg/m³ in Kalecik. PM_{10} concentrations were higher during winters in the urban sites. Despite the high frequency of dust events, only a fraction of exceedances of the standard limit in the urban sites were attributable to dust. Anthropogenic background sources contributions were 12.3 µg/m³ in Guzelyurt, 18 µg/m³ in Kyrenia, 18.4 µg/m³ in Famagusta, 27.8 µg/m³ in Nicosia and 9.7 µg/m³ in Kalecik. Effects of other natural sources that the study did not assess, such as sea salt and local soil resuspension, could be the reason for exceedances.

Keywords
PM_{10}, Dust, HYSPLIT, Aerosol Optical Depth, Northern Cyprus

Introduction
Particulate Matter (PM), also known as aerosols, are complex mixture of tiny particles and liquid droplets that are composed of number of substances which include organic chemicals, acids, metals and dust and soil particles. The United States Environment Protection Agency (USEPA) (2015) listed particulate matter as one of the most common pollutants in the atmosphere. PM in the atmosphere may originate from various natural and anthropogenic sources. Natural sources of PM include crustal dust, sea salts, pollen and volcanic ashes. Human sources include burning fossil fuels in power plants, domestic heating, combustion engines of motor vehicles, resuspension of dust by road traffic, quarrying and agricultural activities. Dust is transported into the receptive atmosphere by lifting and advection of non-vegetative soil in the desert. Wind can lift dust at an atmospheric altitude ranging from 1500 m to as high as 8000 m above ground level into the receptive site which may persist for days to few weeks especially on cloud free days (Vautard et al. 2005).

The island of Cyprus experiences high PM concentration from anthropogenic sources such as vehicular emissions, burning of solid fuel, road side dust resuspension, local soil resuspension and emission from industrialized European countries (Kubilay et al. 2000, Querol et. al. 2009, Achilleos et al. 2014). Also due to its close proximity to the Sahara Desert and the Arabian Peninsula, PM_{10} concentration over the island has been heavily impacted by desert dust storm (Achilleos et al. 2014). Epidemiological investigations have linked increased cardiovascular, respiratory diseases and mortality to the exposure of people to high PM_{10} concentration during dust episodes in the region (Middleton et al. 2008, Neophytou et al. 2013). This is evident in the Turkish Republic of Northern Cyprus (TRNC) as there is an increasing number of mortality resulting from PM_{10} related diseases such as asthma and cardiovascular disease (State Planning Organization Statistics and Research Department (SPOSRD), 2015).

Yearly, Saharan dust contributes 5-10 µg/m³ to the annual mean PM_{10} concentration over the Mediterranean, which is higher than the 0-3 µg/m³ it contributes to Northern Europe (Vautard et al. 2005). Desert dust intrusion may result in extreme PM_{10} concentration in the island which may persist for few days (Middleton et al. 2008, Querol et al. 2009, Achilleos et al. 2014). Even among the Mediterranean countries, Cyprus is characterised as an epitome area where Saharan dust episodes cause high PM_{10} concentration. Average PM_{10} concentrations on dust days, as measured in Southern Cyprus regional background, could reach up to of 1000 µg/m³ (European Environment Agency

(EEA), 2012). Previous studies investigating PM_{10} concentration over the island and the contribution of local and foreign sources found that concentration of PM_{10} in the regional, rural and urban background exceed that of most Mediterranean sites of equal background characterization (Querol et al. 2009, Achilleos et al. 2014).

Research on air quality across Europe often do not consider investigating remote locations such as Cyprus (Karagoulian et al, 2015, Priemus and Postma, 2009). The few previous investigations done in the region; were mainly carried out to cover the southern part of the island (Querol et al. 2009, Mazouridez et al. 2015, Achilleos et al. 2014, Neophytou et al. 2013, Middleton et al, 2008). Mouzourides et al. (2015) investigated the role of trans-boundary sources of PM_{10} in South Cyprus as a representative of South Eastern Mediterranean using Dust Regional Atmospheric Model from Barcelona Super Computing Centre (BSC/DREAM) and meteorological parameters. Their findings revealed that PM_{10} concentration, in 19% of the days that they examined, exceeded the critical value of 50 $\mu g/m^3$ and were highly related to westerly dust from Sahara desert. The simulations they used identified sources, mode of dispersion and intrusion of the dust into the island. Despite that, the study made no attempt to quantify the amount of the dust or the contribution of dust to the concentration of particulates. Achilleos et al. (2014) used a combination of satellite imageries, Aerosol Optical Depth (AOD) and Hybrid Single Particle Integrated Trajectory (HYSPLIT) to identify dust days, and regression analysis to estimate the contribution of dust in an urban site and a regional background in South Cyprus. Their computations revealed that the overall concentrations and exceedances were higher than most European sites.

However, all these investigations were restricted to the southern part of the island. Conclusions derived from these studies could not necessarily reflect PM_{10} situation in the northern part of the region as meteorological conditions, building characteristic, land use pattern; economic activity and other anthropogenic factors vary between the north and south. These variations influence air flow and hence a spatial variation in PM_{10} concentrations (Pandis et al. 2005, Neophytou et al. 2013). Clear differences in climatic condition can be observed between cities in the region as distances and elevation from sea, which are significant factors that reflect differences in relative humidity and temperature, are not uniform over the island. Similar investigations are therefore required for the TRNC.

A preliminary assessment of the ambient air quality in the TRNC conducted in 2002-2003, under the Air Quality Framework Directive, revealed that the level of PM_{10} concentration exceeded the EU air quality objective and are affected significantly by urban sources, traffic and desert dust (Environmental Protection Department (EPD), 2015). Presently Air Quality in the TRNC is measured and maintained using strictly data from ground based monitoring stations, making it nearly impossible to estimate the contributions of the various sources.

Globally, measurements and models have been the main methods used (often in combination) for assessing air quality and determining sources of pollution (Priemus and Postma, 2009). However, due to mechanical failures experienced in ground based monitoring stations, at EU level; air quality standards should be assessed more in combination with models and satellite observations (Priemus and Postma, 2009, European Commission (EC), 2011). Atmospheric model calculations are mathematical computer simulations of the sources and dispersion of substances in the atmosphere.

HYSPLIT (Draxler and Rolph, 2015) is considered to be one of the most reliable atmospheric models at this stage. The model is a complete system for simulating simple air parcel trajectories to complex dispersion and deposition. It computes the advection and pathways of pollutant particle hence its effectiveness in tracking dusty wind sources. Several investigators have used HYSPLIT to accurately identify desert dust intrusions and track their source area, for example Ashrafi et al. (2014) simulated dust event over Iran using HYSPLIT, Escudero et al. (2011) apportioned dust outbreak in the Mediterranean via HYSPLIT application and Escudero et al. (2006) determined the contribution of Saharan dust source to PM_{10} concentration in the central Iberian Peninsula using HYSPLIT.

To identify and estimate dust contribution, satellite measurements and observations such as AOD and Angstrom Exponent Value (α) from Moderate Resolution Imaging and Spectra Radiometer (MODIS) are used alongside HYSPLIT. AOD is a quantitative measurement of the extinction of solar beam by haze or dust between the observation point and the top of the atmosphere. It is a dimensionless number that defines the quantity of particulates in the vertical column of the atmosphere over a particular location during observation. AOD is the easiest, most precise and unique parameter used with ground based measurement to determine PM load (Holben et al. 2001). Angstrom Exponent Value on the other hand is a qualitative indicator of the sizes of aerosols. The value has been used to characterize aerosols from biomass burning in South America and Africa (Eck et al. 2001, Reid et al. 1999), urban emission (Eck et al. 2001, Kaskaoutis and Kambezidis, 2006), desert-dust aerosol in Africa and Asia (Masmoudi et al. 2003). Ground based measurement, AOD and α are used in combination to study desert dust contribution (Achilleos et al. 2014, Mazouridez et al. 2015, Barnaba and Gobbi, 2004).

To address the air quality monitoring problems related with PM_{10} concentration in TRNC, as mentioned earlier, this study used a combination of HYSPLIT model, satellite imagery, MODIS products (AOD and α), ground based measurements and an EC proposed method based on Escudero et al. (2007) to monitor the level of concentration of PM_{10} in the ambient air and measure the contribution of dust and background emission to the PM_{10} concentration in the country. Based on the available literature, nearly no attempt has been made to assess the contemporary PM_{10} situation and quantify the contribution of natural and anthropogenic sources in the country.

The study aims at ascertaining the level of PM_{10} pollution in the ambient air for the period of 2012-2014 and the contribution of desert dust to this pollution. The following objectives were set

for the study:

- Identifying dust storm days and quantifying the amount of dust deposited in the ambient air over the study area.
- Evaluating the PM_{10} concentration attributable to land use characteristic.
- Assess the level of compliance to EU PM_{10} concentration limit and to determine whether cases of exceedances were caused by desert dust intrusion.

The significance of this study is mainly to provide complementary data to the existing ground based measurements for a comprehensive air quality management. The study will also provide a framework for checking whether the EU PM_{10} concentration limit in the ambient air has been exceeded. Exceedances of PM_{10} concentration limit can only be determined after the removal of the amount contributed by natural sources. The result of such estimation is important for formulating policies and designing strategies on the amount and place where emission needs to be cut off.

Quantifying PM_{10} contribution by natural sources provides information required in estimating population exposure to PM_{10} pollution necessary for health impact assessment. It worthy of notice that this study did not consider estimating the contribution of other natural sources of PM_{10} such as sea salt, pollen and volcanoes. Therefore, the effect of desert dust investigated here should not be generalised as the effect of all natural sources.

Methodology

Description of the Study Area

TRNC is the northern part of the island of Cyprus which is located in the Eastern Mediterranean. The island covers an area of 9,251 km^2 and is located off the south coast of Turkey, west coast of Syria, west of Lebanon, northwest of Israel, north of Egypt and east of Greece. Figure 1 is a satellite image showing the location of the island in the Mediterranean.

Figure 1: *Relative Location of Cyprus in the Mediterranean (Source: Google Earth 2017).*

Cyprus has a subtropical climate which is characterized as semi-arid with warm rainy winters around November to late March (average temperature of 17-18ºC during the day and 8-10ºC at night and average precipitation of 100 mm) and hot dry summers around June to late September (average temperature is around 33ºC during the days and 23ºC during the nights and average precipitation is around 4 mm). During winter, temperatures are higher over the inland than at coastal areas and vice versa in the summer. Spring season covers the period of April and May. Autumn is a short transition period to winter.

During winter westerly and south westerly surface winds prevail over the Eastern Mediterranean, while northerly and north-westerly winds prevail during summer periods. Variability in strength and direction in the wind blowing over Cyprus is influenced by the eastward moving cyclones crossing over the Mediterranean sea, sea and land breezes temperature differences, the continental anticyclone that stretch over Eurasia, the low pressure belt of North Africa, the monsoon low in summer, orographic factors and causes (Achilleos et al. 2014).

Description of the Monitoring Stations

This study used PM_{10} data obtained from the monitoring sites in TRNC which are monitored by the Air Quality Monitoring Network, Environmental Protection Department, Ministry of Environment and Culture, TRNC. A total of six monitoring stations which reflect some of the land uses in the region were selected. The positioning and characterization of these stations are within the EU framework legislation given in section C Annex III of CAFE-Directives 2008/50/EC on ambient air quality and cleaner air for Europe. Figure 2 shows the locations of the monitoring sites while Table 1 provides a summary of the characteristics of the monitoring sites.

Table 1: *Sampling sites and their characteristics*

Site	Type of site	Coordinates	Above Sea Level
Nicosia	Urban	35.20 N 33.35 E	108 m
Famagusta	Urban	35.13 N, 33.93 E	3 m
Kyrenia	Urban	35.33 N, 33.31 E	8 m
Guzelyurt	Urban	35.20 N, 33.00 E	51 m
Kalecik	Rural-Industrial	35.34 N, 34.00 E	10 m
Alevkayasi	Rural	35.30 N, 33.53 E	608 m

Method of Data Collection

24 hours PM_{10} concentrations were measured in the air quality monitoring stations and the average taken. These daily average PM_{10} data was collected from the EPD of TRNC. The data collected cover the three year study period (January 1st, 2012 through December 31st 2014) for all the monitoring sites. It was observed that within the period there were days with missing data coverage which were due to power failure or mechanical faults.

Figure 2: *Spatial arrangements of PM_{10} monitoring sites in TRNC (Google Earth 2017).*

Desert Dust Storm Identification

Identification of dust events influencing particulate matter concentration is a multi-task which may demand the use of various tools such as ground PM concentration data, aerosol maps, receptor and dispersion modelling and back trajectory analysis. To identify dust event days in this study, the methods described by the 2011 Commission Staff Working Paper of the Council of EU with the reference "Establishing guideline for demonstration and subtraction of exceedances attributable to natural sources" under the Directive 2008/50/EC on ambient air quality and cleaner air for Europe was referred to. Combination of other methodologies used in previous researches was also employed. The procedures will be discussed in further detail in the following sections:

High PM_{10} level identification

The occurrence of a dust storm was assumed to wholly affect the concentration of PM_{10} in the region and cause high PM_{10} level. High PM_{10} level was defined as days with concentration above the 95th percentile value. Presence of possible dust episode was recognized by high PM_{10} levels occurring in the same day at the sampled sites, especially a sudden high increase in the regional background station.

Identification using MODIS Products

Mean daily measurement MODIS AOD 550 nm and α from Giovanni Satellite Based Earth Science Online Data System were used to identify the particulate type. The data system was developed and managed by the National Aeronautic and Space Administration (NASA), Goddard Earth Sciences Data and Information Service Centre. The data are acquired by the MODIS sensor on both aqua and terra satellites on a spatial resolution of 1° ×1°.

AOD value of 0.01 corresponds to an extremely crystal clear atmosphere with little amount of aerosols, and a value of 0.4 and above means a very dusty aerosol dense atmosphere. While α is a qualitative measure of the sizes of aerosols. The value is inversely related to the average size of the particles in the atmospheric aerosols; that is to say, the smaller the particle the higher α (NOOA, 2015).

Therefore, high AOD value reflects high total atmospheric concentration of particulates and a lower α indicates the particles are of coarser sizes. A combination of high AOD value of >0.3 and α <0.9 indicates the particulates are of desert dust origin. Barnaba and Gobbi (2004) recommended these indicator values for analysis of dust particles over the Mediterranean.

Identifying Dust using HYSPLIT Model

To verify a dust episode identified using the above method, a 5-day backward trajectories of air masses originating from the Sahara or Arabian Peninsula at three different altitudes of 750, 1500 and 2500 m above sea level were examined. HYSPLIT Model (Draxler and Rolph, 2015) which is provided by the National Oceanic and Atmospheric Administration (NOAA) Air Resource Laboratory (ARL), available at Real Time Environmental and Display System Website was used to compute the trajectories. Archive re-analysis meteorological data provided by the National Centre for Atmospheric Research (NCAR) was used as the composite data for this computation. HYSPLIT model is a computer based simulation model that is used to compute air parcel trajectories, dispersion and or deposition of atmospheric based pollutants (Draxler and Rolph, 2015). This model uses a combination of both Eulerian and Lagrangian approaches to track the source point of dust events using the u- and v-components of the wind, temperature, height and pressure at different level of the atmosphere and the resulting backward trajectory contains information about the origin and pathways of the dust transport (Banacos and Ekster, 2010). Air parcel trajectories that originate from the desert indicate possible presence of dust.

The identification of the dust event days largely depends on the availability of data for the days in focus. Dust events days include the days where the dusty wind from desert arrived the region and the subsequent days where significant amount of dust persists in the atmosphere. HYSPLIT model identified the arrival of the dust while the presence of dust in the atmosphere were basically identified using the combination of the PM_{10} concentration data, AOD and α in accordance with the criteria mentioned in the methodology for determining possible dust in the atmosphere.

Lastly some days have missing AOD or α, or in some cases; both are missing. There are also days where ground based PM_{10} concentration were not captured in some of the monitoring stations. Such missing data is expected to hinder the study from identifying some possible dust days and hence the calculated dust contribution may underestimate the actual contribution.

Identifying Dust Storm using Satellite Imageries

MODIS satellite images on air aqua and terra platform retrieved from NASA's website database were also used to support the identification.

Other methods that are recommended by the EU and applied by investigators to identify dust storm events include mineralogical analysis, and dispersion and receptor modelling. These methods were not applied in this study as the former requires PM samples and the later requires data on hourly concentrations which were not available for this investigation.

Quantifying Desert Dust

In order to measure the amount of PM_{10} concentration attributed to desert dust storm episodes, the Escudero et al. (2007) based conservative method suggested by EC, (2011) under the Directive 2008/50/EC was employed: A moving average of PM_{10} concentration of 15 days before and 15 days after the identified dust episode (excluding any dust day which may occur within the period) was calculated. The calculated value corresponds to a moving 50th percentile of 30 days. The calculated 30 days average is the supposed PM_{10} concentration assuming there was no dust intrusion. The net dust amount was calculated by subtracting the 30 days average value from the high PM_{10} concentration.

Escudero et al. (2007) based methods are scientifically validated (EC, 2011). The methods save time, cost and are simple to use. Unlike chemical analysis methods which may require long analysis time, expertise and laboratory costs. The methods were earlier applied by Querol et al. (2009) to the whole of the Mediterranean basin. The other Escudero et al. (2007) based method requires subtracting a monthly moving 40th percentile (excluding days with dust influence) from the bulk concentration of PM_{10} of the dust day in the regional background site, the returned value is the net dust PM_{10} concentration for the region; hence the net dust contribution for each site can be calculated by subtracting this net dust PM_{10} concentration. However, this method was not preferred here because the other sites (especially Kalecik) were found to reproduce a better PM_{10} concentration on some dust event days than the regional background site, thus making the method not applicable as the subtraction of net 40th percentile from these sites on such days would yield a negative PM_{10} concentration.

Estimating Background Sources Contribution

After removing the contribution of dust, the impact of local natural particulate sources such as soil and sea salt were assumed to be the same at all the sites. Then daily background concentration of each site was estimated as the difference between the daily concentration in the site and the daily concentration in the regional background. The new data base created became the "PM_{10} urban" or "industrial" contribution variables, depending on the dominant land-use in the site.

This method provides a good understanding of the level of emission from a background collectively where data for each emission sources is not available. Moreno et al. (2005) used this approach to assess the influence of urban sources in Spain. Achilleos et al. (2014) also used same method for similar investigation in South Cyprus.

Data Analysis

Microsoft Office Excel package was used to compute annual and monthly mean concentrations, percentages and frequency of exceedances of mean daily concentrations and dust contributions. Results were depicted using simple bar charts and tables.

To account for the loss of PM_{10} data capture during the estimation of exceedances of daily average concentration in calendar year, an adjustment was made to the available data. The adjustment assumes that the fraction of missing values that would have surpassed the EU limit is equivalent to the fraction of the available value that exceeded the limit. This approach was used on a quarterly basis, as EC (2013) suggested, and is computed as shown in equation 1:

$$Eq=\left(Vq \times \frac{Nq}{nq}\right) \quad \text{Equation 1.}$$

Eq in equation 1 refers to the estimated number of exceedances for the calendar quarter in question (qi). Vq refers to the observed number of exceedances for same calendar quarter. Nq is the number of days in the calendar quarter whereas nq is the number of days with valid daily values for the calendar quarter. q refers to the four calendar quarters in a year, that is to say; q= 1st, 2nd, 3rd, or 4th. The total number of exceedances (Ex) for the calendar year is then estimated as the summation of the estimated number of exceedances for all the calendar quarters of the years; as given in equation 2.

$$Ex=\sum_{q=1}^{4} eq \quad \text{Equation 2.}$$

Result and Discussion

The study identified dust storms, its frequency of occurrence and seasonal variability in the region. The study also estimated dust and local background contribution to PM_{10} concentration in the sampled sites.

Dust Storm Occurrences and Impact on Daily Concentrations

A total of 35 dust storm days were identified for the three years period in the region. The identified dust days and their daily PM_{10} average concentration are shown in Table 2 (see appendix), 4 dust days (less than 1% of the year) occurred in 2012, 8 dust days (2% days of the year) in 2012 and 24 dust days (7% days of the year) in 2013. These percentages correspond within the 1% (1993) - 9% (1998) dust days earlier estimated in the region (Achilleos et al. 2013). 75 percentile of the dust days in the urban areas fall within a mean daily concentration of ≥ 100 µg/m^3, 75 percentile of the dust days in Guzelyurt have a mean daily concentration of ≥ 70 µg/m^3, while in Alevkayasi and Kalecik; a 75 percentile of ≥50 µg/m^3 was estimated.

On the other hand, dust storms were more frequent in 2013. Concentrations of PM_{10} in the sites range from 40 µg/m^3 on

minor dust days to 280 µg/m³ on intense dust days. The frequency of dust storm occurrence in 2013 was also high in the Mediterranean city of Athens, Greece, however maximum daily average PM_{10} concentration on dust days were 125 µg/m³, less intense than those recorded in Cyprus (AIRUSE 2015). Frequent occurrence of dust in the Mediterranean is possibly as a result of drought and anthropogenic disturbances (such as clearing of vegetation cover) on the Saharan soil.

In 2014, daily average concentration of PM_{10} range from 45 to 400 µg/m³. Estimated dust contribution range from 10 (06 May, 2014) to 360 µg/m³ (03 Mar 2014).

Dust storms in the three years were found to intrude the island in each of the four seasons in a year. However, only 3 dust days were experienced in the summer throughout the study period and 75% of the dust episodes occurred during the winter months especially March and November. A 14 day long dust episode was found to occur in November 2013. Similarly to this investigation, dust storms occurrences in neighbouring Israel for that year were also found to be in winters and spring, and summers were dust free (Krasnov et al. 2014). While contrary to this, AIRUSE (2015) found that dust storm that year in Athens were more frequent and pronounced during spring and summers.

Amount of dust deposited on dust days depends to an extent on the distance from the source region. Intrusion originating from closer proximity such as Egypt, Morocco and the Arabian Peninsula are found to be more pronounced than intrusions from far sources such as Mali, Niger Republic or Mauritania. Some amount of the dust may probably have been deposited elsewhere as they travel towards the Mediterranean, as dust are often deposited along the travel path to their destination (Moreno et al. 2005). Therefore, less deposition is expected when dust originates from far distance as the loss along travel path is likely to be more.

Analysis of the computed trajectories showed that about 65% of the dust intrusions into the island were from the Saharan desert, specifically the western part of the Sahara. The remaining dust storms originated from the Arabian Peninsula. Dust intrusions in 2014 reached the island in a lower vertical height than dust storms in the previous years. Dust arriving at lower vertical height implies more deposition at the ground especially on cloud free days.

Figure 3 shows an example of computed backward trajectories arriving Cyprus. The dusty wind arrived Cyprus on 02 March, 2014 from western part of Sahara, Egypt and the Arabia. Figure 4, which is a satellite view of the dust event, shows the dust originating from Sahara desert and covering the Mediterranean, which was cloudless at the time of deposition. In examining satellite views, cloud cover were seen to be associated with cyclonic conditions on some dust days, therefore obstructing clear view to the dust. However, the dust event on 02 March, 2017 was a good example of deposition on cloud free day. Concentration of PM_{10} reached 280 µg/m³ in Kalecik and a shade above 200 µg/m³ in the other sites.

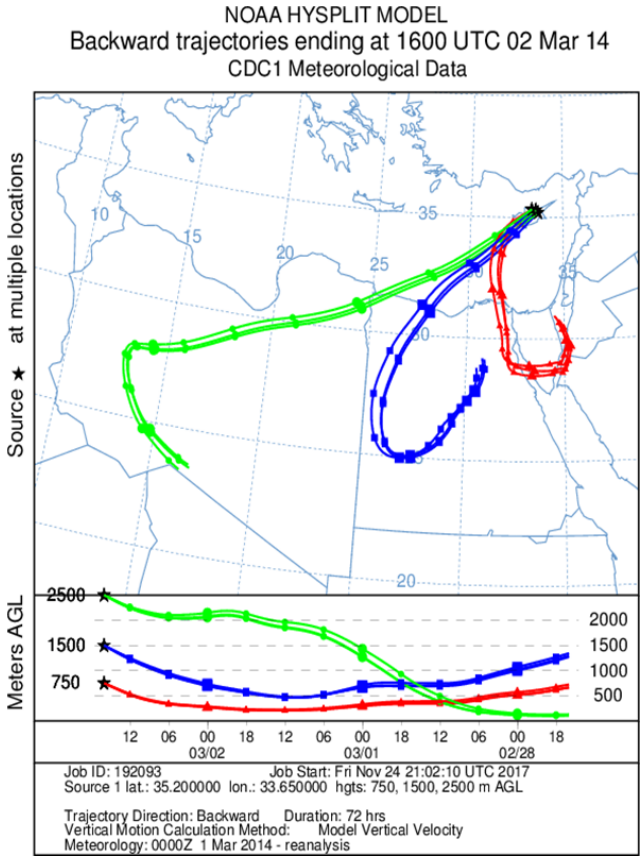

Figure 3: *Backward trajectories ending in Cyprus showing the arrival of dust on 02 March 2014.*

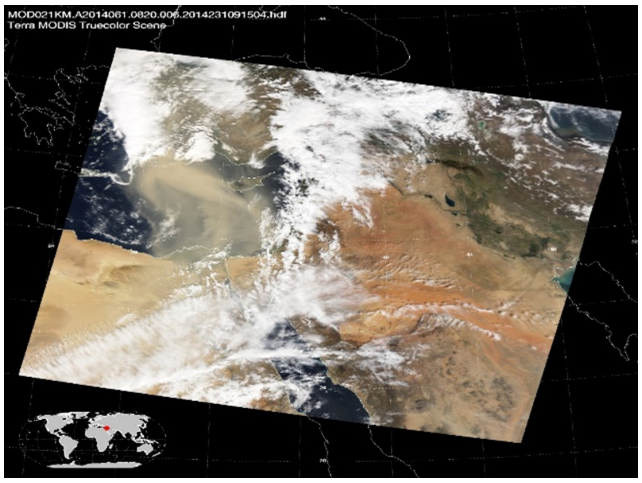

Figure 4: *MODIS satellite imagery over the Mediterranean on 02 Mar 2014.*

Contribution of Background Emission

Emission from urban background contribution was estimated for Nicosia, Kyrenia, Famagusta and Guzelyurt and industrial background contribution was estimated for Kalecik. As it can be seen in Figure 5, overall average urban background contribution for the three years period were 12.3 µg/m³ in Guzelyurt, 18 µg/m³ in Kyrenia, 18.4 µg/m³ in Famagusta and 27.8 µg/m³ in Nicosia. Industrial background contributed 9.7 µg/m³ to the overall average concentration of PM_{10} in Kalecik. Kalecik is

predominantly affected by emission from thermal station which after burning fossil fuel may give out high amount of coal fly-ash to the atmosphere.

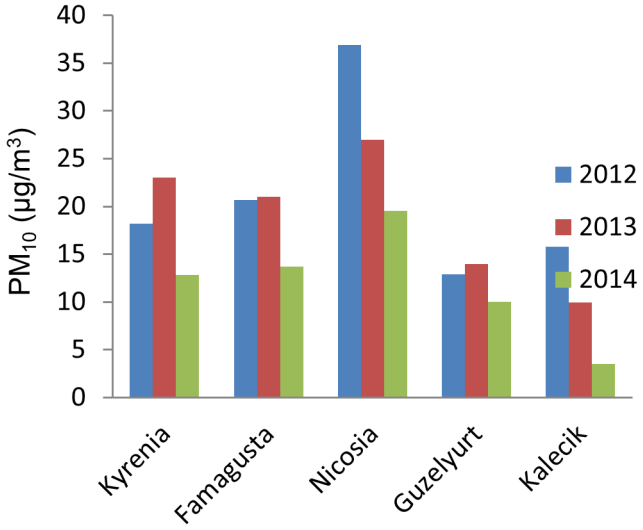

Figure 5: *Annual average contribution of background sources.*

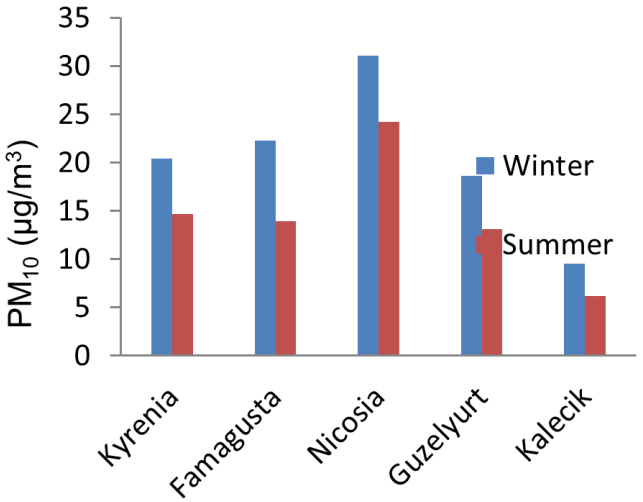

Figure 6: *Overall seasonal average contribution of local background emission.*

Effect of urban background to PM_{10} is spatially associated with traffic and population density. Nicosia among the urban sites, has the densest population and traffic hence the highest concentration while Guzelyurt has the lowest population and traffic density among the urban sites and hence the lowest concentration. Background sources of emission in the urban sites are majorly road dust resuspension and traffic emission, domestic heating and burning of solid fossil fuel, building construction and industries (especially in Nicosia). Shipping could contribute to the bulk of emission in Kyrenia and Famagusta. Current regulation regarding emission is not in compliance with the EU Directives. Field burning is still practiced in the country and these could be a major contributor of PM_{10} load in the affected sites (EPD 2015).

Figure 6 shows the average contribution of background emissions in relation to seasons. Overall background contribution to PM_{10} concentration is more during the colder months than the warmer season, except in Teknecik where the background contribution is seen to be more in the summer. Usually urban sites experience winter sanding of roads.

Daily Average Concentration and Exceedance of the Limit Standard

The EU directive sets a daily average threshold value of 50 µg/m³. This value is not permissible to be exceeded in 35 days (9.6% days) in a year. As summarized in Table 3, Nicosia, Kyrenia and Famagusta urban sites exceeded the daily average concentration of 50 µg/m³ in more than 35 days in all the years (with and without dust effect). Exceedances of daily average limit solely as a result of dust events range from 4.4 to 10% in Kyrenia, 4.2 to 13.8% in Kyrenia and 0 to 6.3% in Nicosia.

Guzelyurt was within the 35 days limit in 2012. However, the limit was exceeded in the two subsequent years. The limit was exceeded in 2013 in Kalecik. Both exceedances of the 35 days limit in Guzelyurt and Kalecik were not as a result of dust effect. In the regional background, daily average concentrations were below the 35 Days limit.

Table 3: *Percentage days with daily mean concentration above the EU 50 µg/m³ threshold value (A= with dust and B= without dust)*

Site	Year		
	2012	**2013**	**2014**
Kyrenia	A=18.6 B=17.7	A=37.5 B=34.2	A=16.4 B=14.7
Famagusta	A=20.4 B=18.6	A=32.2 B=26	A=18 B=15.3
Alevkayasi	A=1.6 B=0.5	A=6.8 B=2.2	A=7.3 B=5.7
Guzelyurt	A=22.7 B=7.4	A=16.9 B=13.6	A=11.7 B=11.2
Kalecik	A=51.1 B=22.2	A=16.7 B=10.1	A=8.5 B=1.9
Nicosia	A=51.1 B=51.1	A=45 B=43	A=35.1 B=43

Overall and Annual PM_{10} Concentrations

The overall average PM_{10} concentration was calculated as 54.7 µg/m³ with a Standard Error (±) of 0.9 µg/m³ for Nicosia and when the dust effect was removed the overall concentration decreased to 46.2 µg/m³. The overall average concentration for Kyrenia and Famagusta was 43.2 µg/m³ ±0.6 µg/m³ and 43.6 µg/m³ ±0.6 µg/m³ respectively and when the dust effect was removed the concentration reduced to 41.4 µg/m³ in Kyrenia and 41.8 µg/m³ respectively. Guzelyurt has an overall average of 37.5 µg/m³ ±0.58 µg/m³ with dust effect and 35.6 µg/m³ without the effect of dust. Kalecik has an overall concentration of 35.3 µg/m³ ±0.6 and 32 µg/m³ when the effect of dust intrusion

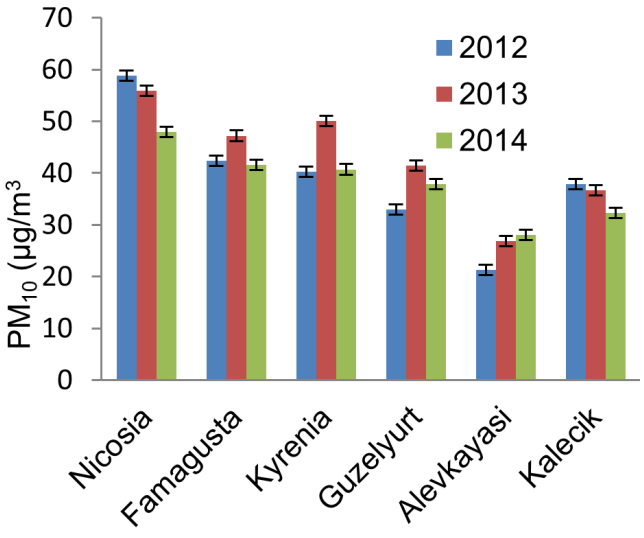

Figure 7: *Annual average concentration of PM_{10} with dust effect inclusive.*

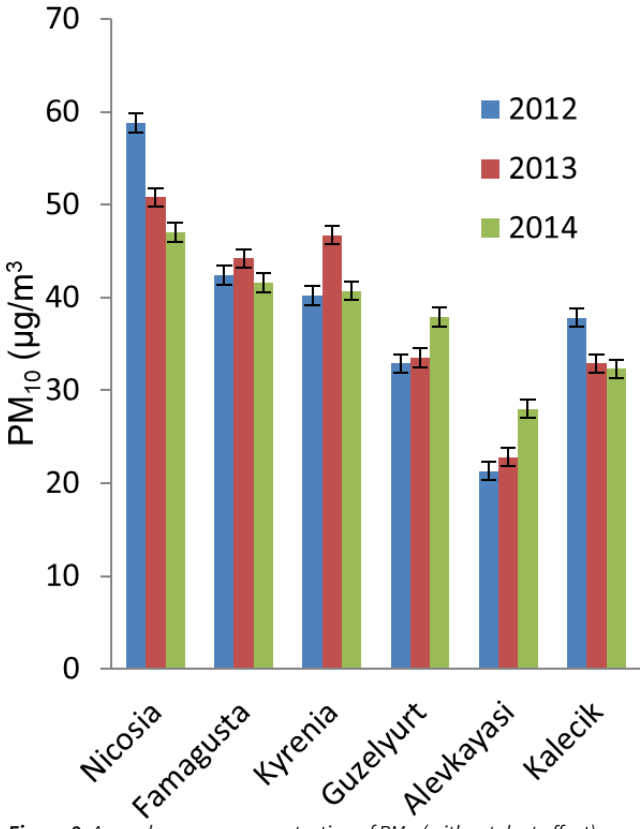

Figure 8: *Annual average concentration of PM_{10} (without dust effect).*

was removed. Alevkayasi regional background has an overall average of 25.4 µg/m³ ±0.6 µg/m³ and an overall average of 23.1 µg/m³ when dust effect was removed.

The annual average PM_{10} concentrations are shown in Figure 7 and 8. Annual average concentrations of PM_{10} (with dust and without dust effect) in Nicosia were above the EU 2006 limit of 40 µg/m³ for all the years. Annual average concentration ranged from 48 µg/m³ (2014) to 59 µg/m³ (2012) and it was found to exhibit a reducing trend after every year. After removing the effect of dust; concentrations only reduced by 1-5%.

PM_{10} Concentrations with dust effect were above the EU limit in all the years for Famagusta. Annual average concentrations were 42-47 µg/m³ with dust effect (Figure 7); however the limit was attained in 2014 after removing the effect of desert dust. Annual average concentration in Kyrenia were exceeded in 2013 and 2014, after removing dust effect the limit was achieved in 2014 (Figure 8). Annual average limit was exceeded in Guzelyurt in 2014 which after removing the effect of dust reduced to an acceptable value of 37 µg/m³.

Concentrations in the rural site and the rural industrial site were all within the EU annual mean limit. Concentrations were in the range 32-37.8 µg/m³ and 26-29 µg/m³ in Kalecik and Teknecik respectively. After removing dust effect, concentration reduced to 30-36 µg/m³ in Kalecik.

Annual average concentration in Alevkayasi ranges from 21-28 µg/m³ with dust effect. After removing effect of dust intrusion, it attained the EU 2010 target value of 20 µg/m³ in 2012. Annual concentrations exhibit an increasing trend Alevkayasi. Cristina et al. (2014) observed similar trend over the years in background sites among the EU sites.

Annual average PM_{10} concentrations (without dust) in Guzelyurt can be compared with 31 µg/m³ in central Mediterranean city of Lampedusa, Italy (Marconi, et al. 2014), 24-30 µg/m³ in Athens suburban site, 26-27 µg/m³ in Milan and Porto urban sites (AIRUSE, 2015). Annual average concentrations in Famagusta and Kyrenia can be compared with 37-43 µg/m³ in Athens urban sites (AIRUSE, 2015), 29-42 µg/m³ in Berlin urban background (Langener, et al. 2011) and 37-43 µg/m³ in Madrid Spain (Salvador et. al, 2015). Annual Average concentration in Nicosia can be compared with those estimated in other Eastern Mediterranean urban sites such as 56 µg/m³ in Nicosia, South Cyprus, (Achilleos et al. 2014), 43-77 µg/m³ in Beer-Sheva, Israel, (Krasnov et al. 2014), 51 µg/m³ in Heraklion, Greece, 57 µg/m³ in Tel-Aviv, Israel, 47 µg/m³ in Istanbul, Turkey (Gerasoupoulos et al. 2006, Karaca et al. 2005). Annual average concentration in Alevkayasi corresponds with other rural sites in the EU such as Berlin rural background 19-25 µg/m³ (Langener et al. 2013), 20-25 µg/m³ in Campisabolos, Spain (Salvador et al. 2015).

Overall average in the regional background and Kalecik were lower than the estimated 32.1 µg/m³ in Agia Marina regional background, southern part of Cyprus (Achilleos et al. 2014), Annual dust contribution in TRNC can be compared with the 5 µg/m³ in Italy (Salvador et al. 2013). Vautard et al. (2005) also reported 5-10 µg/m³ as the annual average in the Mediterranean.

Conclusion and Recommendation

In this study, inter annual and annual PM_{10} concentrations were analysed in Nicosia urban site, Famagusta urban site, Kyrenia urban site, Kalecik rural industrial background site and Alevkayasi rural background site. Dust episode and their contributions to daily, annual and seasonal PM_{10} concentrations were also estimated as well as the contribution of collective anthropogenic background.

A total of 35 dust days occurred in the island within the 3 years period. Dust intrusion contributed more to PM_{10} concentration during winter and spring, daily concentration could reach as high as 400 µg/m³. Contribution of desert dust to PM_{10} concentration in the study area was averagely; 102 µg/m³ and can range from 22 to 183 µg/m³. Average contribution of dust to the annual average concentration were 8.5 µg/m³ in Nicosia, 2.2 µg/m³ in Kyrenia, 1.8 µg/m³ in Famagusta, 2 µg/m³ in Guzelyurt, 3.3 µg/m³ in Kalecik and 2.3 µg/m³ in Alevkayasi. Overall average urban contribution to PM_{10} concentration was 12.3 µg/m³ in Guzelyurt, 18 µg/m³ in Kyrenia, 18.4 µg/m³ in Famagusta and 27.8 µg/m³ in Nicosia. Average industrial background contribution was 9.7 µg/m³.

The study found that despite the high occurrence of dust events, desert dust was only responsible for exceedance of the 2006 EU mean annual PM_{10} concentration of 40 µg/m³ in Famagusta and Kyrenia in 2014, and Guzelyurt in 2013. However, no exceedance of the 35 days permissible daily average limit of 50 µg/m³ was attributed to dust storms in any of the site analysed/

It's worth reminding that the study only investigated one natural source of PM_{10} (dust storms). Impact of other natural sources such as pollen, sea salt and local soil resuspension were not assessed in this investigation. There is the likelihood that if impact of other natural sources were subtracted, exceedances may not be recorded in the sites. Therefore an investigation is required to ascertain the influences of other natural source of PM_{10}. A source apportionment that will include chemical or mineralogical analysis is also needed to evaluate the impact of each anthropogenic source (such as shipping, traffic, domestic burning of fuel, agriculture etc.) to the backgrounds.

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Appendix

2012						
Date D/M	Nicosia (μg/m³)	Famagusta (μg/m)	Kyrenia (μg/m³)	Guzelyurt (μg/m³)	Alevkayasi (μg/m³)	Kalecik (μg/m³)
12/03	222.7	66.0	86.0	77.9	60.0	
13/03	167.1	81.5	107.6	103.2	62.4	
21/10	176.0	198.3	162.7			279.0
22/10	176.7	198.3	162.7			279.0
2013						
Date D/M	Nicosia (μg/m³)	Famagusta (μg/m)	Kyrenia (μg/m³)	Guzelyurt (μg/m³)	Alevkayasi (μg/m³)	Kalecik (μg/m³)
18/01	222.3		87.6	44.1	126.2	154.7
19/01	80.0			126.2	62.3	75.0
23/02	132.1	95.2		106.8	89.8	116.5
24/02	77.7	78.8		107.2	44.4	89.5
11/03	138.4	90.1		138.4	101.1	119.9
12/03	108.8	60.8		130.2	236	76.4
13/03	276.8	216.6		286.4	118.6	229.5
1/04	275.8	126.7	267.2	153.8	272.6	149.4
2/02	112.2	88.7	125.9	239.6	94.6	87.6
9/04	228.8	129.5	133.8	119.5	110.0	101.5
31/05	141.3	88.7	132.8	110.9	77.0	99.3
31/10	128.3	64.4	78.8	72.6	53.2	58.5
01/11	136.2	89.9	75.8	86.9	53.7	63.0
02/11	114.3	69.0	74.5	75.1	57.0	74.1
03/11	70.1	83.1	61.0	64.8	56.5	79.9
04/11	104.3	73.9	76.3	54.6	51.0	60.5
05/11	102.7	84.9		57.6	38.4	52.9
06/11	82.7	77.2	109.3	62.3	52.1	71.2
07/11	77.3	102.3	91.1	71.1	48.0	84.1
08/11	91.7	78.8	105	62.2	60.6	84.8
09/11	99.9	79.3	61.9	80.2	30.6	51.2
10/11	57.6	84.2	47.4	53.3	32.9	51.7
05/11	102.7	84.9		57.6	38.4	52.9
06/11	82.7	77.2	109.3	62.3	52.1	71.2
07/11	77.3	102.3	91.1	71.1	48.0	84.1
08/11	91.7	78.8	105	62.2	60.6	84.8
09/11	99.9	79.3	61.9	80.2	30.6	51.2
10/11	57.6	84.2	47.4	53.3	32.9	51.7
11/11	102.3	62.5	84.1	55.9	47.5	56.7
12/11	116.7	58.3	87.6	77.4	44.1	63.6
2014						
Date D/M	Nicosia (μg/m³)	Famagusta (μg/m)	Kyrenia (μg/m³)	Guzelyurt (μg/m³)	Alevkayasi (μg/m³)	Kalecik (μg/m³)
24/02	65.4	60.2	79.6	66.1	54.9	115.1
2/03	228.2	228.8	77.2	76.7	103.6	293.4
3/03	203	203.8	402.1	153.9	196.3	402.1
5/03		116.0	119.1	98.3	79.1	
6/06		97.3	108.5	95.0	89.3	
28/06	86.5	64.8	71.6	74.3	65.8	67.7

Understanding the atmospheric circulations that lead to high particulate matter concentrations on the west coast of Namibia

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Abstract

Atmospheric circulations play a significant role in determining the extent and impact of local and regional air pollution. The Erongo Region, located in the western part of Namibia, falls within the west coast arid zone of southern Africa, and is characterised by low rainfall, extreme temperatures and unique climatic factors influencing the natural environment and biodiversity. Episodic dust storms, associated with easterly wind conditions, are common during austral autumn and winter months. During these events, dust is transported westwards over long distances across the Namibian continent towards the Atlantic Ocean. During 2017, such easterly wind conditions appeared to occur earlier and more frequently than in previous years. Of interest is that high PM_{10} concentrations (particulate matter with aerodynamic diameters of less than or equal to 10 micron) measured at the coastal towns of Swakopmund and Walvis Bay in the Erongo Region during 2017 were found to also coincide with south-westerly to north-westerly winds from the ocean during prevailing easterly wind events. In this study, the easterly wind events that occurred on 19 March 2017 and 6 July 2017 were assessed to investigate how local-scale coastal atmospheric circulation changes could have developed from the easterly wind conditions, and how such development could have contributed to wind direction deviations and the high PM_{10} concentrations measured at Swakopmund and Walvis Bay. It was found that in addition to the westward transport of PM_{10} from inland sources during easterly wind events, higher coastal concentrations of PM_{10} can also develop as a result of north-easterly / south-westerly wind conversion lines and the cyclonic circulation enhancement associated with easterly wind induced coastal troughs and coastal lows.

Keywords

Namibia, Erongo Region, air quality, particulate matter, wind patterns

Introduction

The Erongo Region is located in the western part of Namibia and is bounded by the Atlantic Ocean to the west and the continental escarpment to the east (approximately 180 km inland). From a hydrological perspective, the Erongo Region is drained in the central part by the deeply-incised Swakop and Khan Rivers, with the Kuiseb River separating the stony desert from the Namib sand dunes in the south (Tyson and Seely, 1980).

The Erongo Region falls within the west coast arid zone of southern Africa, and is characterised by low rainfall with extreme temperature ranges and unique climatic factors influencing the natural environment and biodiversity (Goudie, 2009). Episodic dust storms, associated with strong easterly wind conditions, are common during austral autumn and winter months. Associated dust is derived primarily from intermittent natural sources, giving rise to dust emissions only under conditions of high wind speeds. Windblown dust from natural sources is estimated to account between 75% (Ginoux et al., 2012) and 89% (Satheesh & Moorthy, 2005) of the global aerosol load, of which 25% (Ginoux et al., 2012) to 50% (Tegen & Fung, 1995) is attributed to disturbed soil surfaces and the rest to natural soil surfaces. In Africa, approximately 54% of the dust is from desert and sparsely vegetated soils (Tegen & Fung, 1995). Anthropogenic sources account for 25% of global dust emissions (Ginoux et al., 2012). In the Erongo Region, anthropogenic sources of dust, such as unpaved roads, mining and exploration operations (primarily uranium prospecting), continuously contribute to atmospheric dust loads (Liebenberg-Enslin et al., 2010).

High concentrations of particulates in the air pose a risk to human health and welfare (Rashki et al., 2012; Rashki et al., 2013(a); Rashki et al., 2013(b)). Various studies have found a link between increased morbidity and mortality, especially amongst children and the elderly, and dust storm events (Ginoux et al., 2004; Karanasiou et al., 2012; De Longueville et al., 2013). In the Erongo region, radioactive dust associated with uranium mining and prospecting adds to the public concern (Liebenberg-Enslin et al., 2010).

Easterly wind events in the Erongo Region

During austral autumn and winter seasons, African continental anti-cyclonic circulation occasionally allows for easterly to north-easterly winds to descend along the downward slopes of the Namibian continent towards the Atlantic Ocean (Figure 1). This descend of air leads to a drop in air pressure as a result of vertical air column expansion, and the development of warm berg-wind conditions as a result of adiabatic heating. Although strong, hot and often uncomfortable for people, easterly wind conditions are usually relatively short lived[1].

During 2017, episodic dust storms associated with easterly wind events appeared to occur earlier and more frequently than in previous years. This heightened the public concern for high levels of radioactive dust from uranium prospecting and mining reaching the coastal towns of Swakopmund and Walvis Bay.

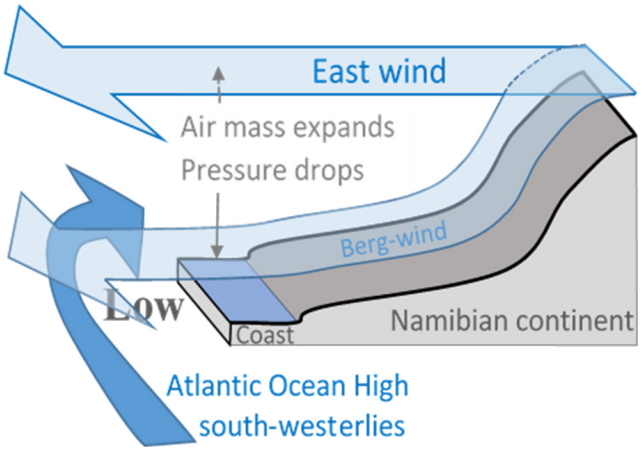

Figure 1: *Typical atmospheric flow characteristics during east wind conditions in Namibia. As berg-winds descends towards the coast, Mean Sea Level Pressures (MSLPs) drops to form either low pressure troughs or cut-off lows along the coastline. Because of the Coriolis force, such lows are associated with cyclonic (clockwise) circulation forcing.*

Although it is expected that fine particulates get lifted and carried across the interior of the Erongo Region towards the coast by easterly winds, easterly wind episodes that were monitored in 2017 indicated that high PM_{10} (Particulate Matter (PM) with an aerodynamic diameter of less or equal to 10 micron) concentrations recorded at Swakomund and Walvis Bay were also caused by PM_{10} that approached the towns from other directions than the prevailing easterly flow, which included onshore flow from south-westerly to north-westerly winds.

Of particular interest is that the high PM_{10} concentrations that were measured at the coastal towns of Swakopmund and Walvis Bay in the Erongo Region between 18 and 20 March 2017 were found to also coincided with south-westerly to north-westerly orientated winds during the prevailing easterly wind event, while wind direction deviations also occurred during the high PM_{10} concentration easterly wind event of 6 July 2017. While easterly wind conditions can explain the westward transport of PM_{10} from inland sources towards the Namibian coast, it is not clear why high PM_{10} concentrations were measured at the same time under conditions of local-scale south-westerly to north-westerly wind directions, indicative of onshore flow from the Atlantic Ocean.

The purpose of this paper is to investigate how the local-scale atmospheric circulation deviations (south-westerly to north-westerly winds, in contrast to the large-scale prevailing easterly winds) observed on 19 March 2017, as well as 6 July 2017, could have developed from easterly wind conditions, and how these could have contributed to the high PM_{10} concentrations measured at Swakopmund and Walvis Bay.

Ambient air quality monitoring in the Erongo Region

Monitoring stations and parameters recorded

As part of the Strategic Environmental Management Plan (SEMP) initiated by the Namibian Ministry of Mines and Energy, an ambient monitoring network was established in the Erongo Region at the end of 2016 with the objective to measure PM_{10}, $PM_{2.5}$ and Radon concentrations. In addition, meteorological variables such as wind direction and speed, temperature, Relative Humidity (RH), solar radiation, barometric pressure and rainfall are also recorded at selected stations (Table 1). Monitoring locations were chosen based on the most populated areas in the region (i.e. towns, except for Jakalswater which serves as a background station). The towns identified were Swakopmund, Walvis Bay, Arandis and Henties Bay (Figure 2).

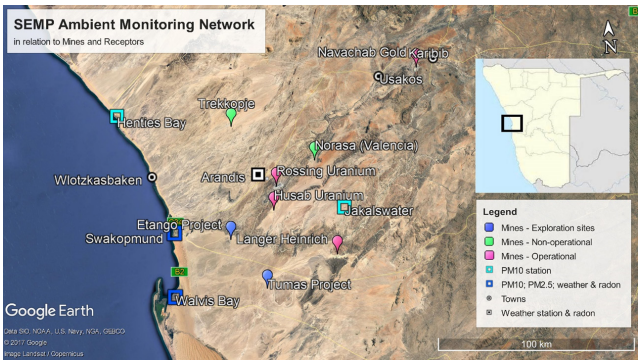

Figure 2: *Location of ambient air quality monitoring stations, meteorological stations and radon stations in relation to the mines and sensitive receptors.*

Ambient PM_{10} concentrations at Swakopmund and Walvis Bay are measured using Met One Instruments Model BAM 1020, designation for continuous PM monitoring. E-Samplers, a light-scatter Aerosol Monitor, are used to record PM_{10} concentrations at Henties Bay and Jakalswater and for $PM_{2.5}$ monitoring at Swakopmund and Walvis Bay. The E-Sampler at Jakalswater is fitted with a Met One Instrument measuring wind speed, wind direction and temperature. Met One weather stations at Swakopmund, Walvis Bay and Arandis are fitted with a wind speed sensor, wind direction vane, ambient air temperature

[1] http://www.raison.com.na

sensor, RH sensor, precipitation tipping bucket, as well as atmospheric pressure and solar radiation sensors. The Swakopmund and Walvis Bay stations are enclosed, while it should be noted that the Walvis Bay station is on top of the Walvis Bay Civic Centre (approximately 9 m above ground level), whereas the Swakopmund Station is on top of a 3m structure at the Swakopmund waste water works.

Table 1: *Monitoring stations and parameters recorded*

Monitoring Location	Pollutant/ Parameter Measured									
	PM_{10}	$PM_{2.5}$	Wind Speed	Wind Direction	Temperature	Relative Humidity	Solar Radiation	Barometric Pressure	Rainfall	Radon
Swakop-mund	X	X	X	X	X	X	X	X	X	X
Walvis Bay	X	X	X	X	X	X		X		X
Arandis			X	X	X	X	X	X	X	X
Henties Bay	X				X	X		X		
Jakalswa-ter	X		X	X	X	X		X		

Prevailing wind fields in the Erongo Region

The wind fields of the Erongo Region are influenced by a combination of synoptic and local scale circulations. Wind directions in the central-northern parts of the region are predominantly from the east, northeast and southwest, where the easterly and north-easterly winds (eastern wind conditions) are often being associated with high wind speeds. Along the coast, southerly to south-westerly wind directions are modulated by the Atlantic Ocean anti-cyclonic circulation as well as temperature and pressure gradients that are orientated parallel to the coastline between the upwelling Benguela ocean-current and the warm arid continent. During the period between November 2016 and April 2017, wind speeds in the region were found to be mostly between 0 $m.s^{-1}$ to 10 $m.s^{-1}$. Inland, at Arandis, prevailing west-south-westerly winds dominated, while at Jakalswater, the prevailing winds were east-north-easterly (Figure 2). Easterly winds, associated with berg-wind conditions, were recorded for 22% of the period between November 2016 and April 2017 at Jakalswater, 16% at Arandis, 9% at Swakopmund and 10% at Walvis Bay. Easterly wind conditions were most prevalent during the month of March 2017, occurring for 32% of the time at Arandis and 41% at Jakalswater. At the coast, easterly flow was recorded at 9% and 10% of the time at Swakopmund and Walvis Bay, respectively.

During east wind conditions, high wind speeds of up to 22 $m.s^{-1}$ were recorded at the Namibian coast. These strong winds are occasionally also being associated with south-westerly to north-westerly wind directions during east wind conditions at the towns of Swakopmund and Walvis Bay.

Case studies of easterly winds and high PM_{10} concentrations

Easterly wind event on 6 July 2017

Easterly berg-wind conditions prevailed across the Erongo Region on 6 July 2017. At Swakopmund wind directions were easterly from 00:00 to 09:00, from where it changed to north-easterly between 09:00 to 14:00 (Figure 4a). A significant change in wind direction appeared at 16:00 when a north-easterly wind developed. Shortly after this, the wind direction gradually returned to easterly winds in the later afternoon towards 24:00. On the same day, PM_{10} concentrations were mostly below 50 $\mu g.m^{-3}$. However, during the time interval when the winds turned to north-easterly (09:00-14:00), a significant increase in PM_{10} with a maximum of 312 $\mu g.m^{-3}$ at 10:00 developed, most probably from sources to the north-east of Swakopmund. It is interesting to note that the PM_{10} concentration peak of 312 µg.m 3 that occurred at Swakopmund is significantly higher than the six-month average (data for the period November 2016 to April 2017) which ranged between 30 $\mu g.m^{-3}$ (Swakopmund) and 35 $\mu g.m^{-3}$ (Walvis Bay).

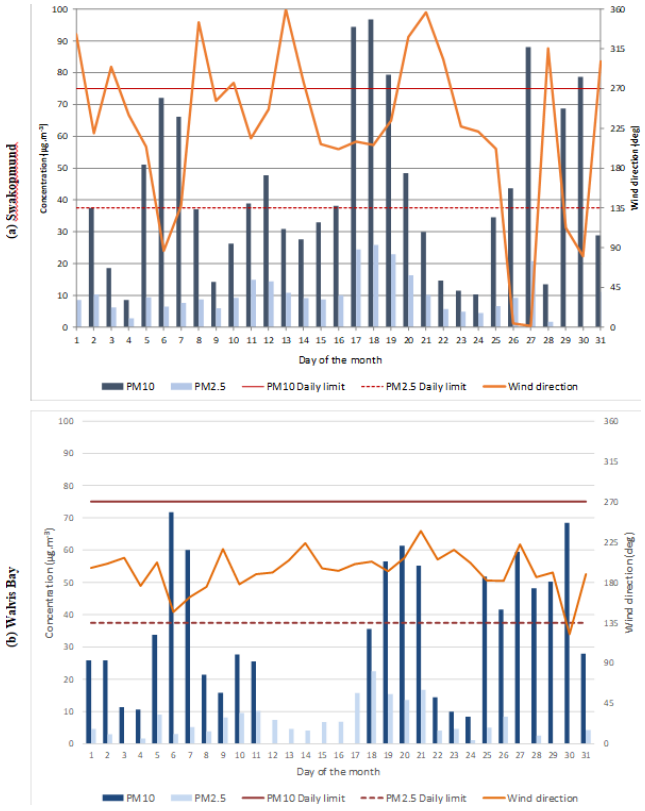

Figure 3: *Daily PM_{10} and $PM_{2.5}$ concentrations at (a) Swakopmund and (b) Walvis Bay with average daily wind directions indicated for the month of July 2017.*

At Walvis bay (Figure 4b), the wind direction pattern was very

similar to what was recorded at Swakopmund, where the significant wind direction change at 16:00 was also captured, while PM_{10} concentrations were mostly around 10 µg.m^{-3}, but also slightly increased to 132 µg.m^{-3} with the change in wind direction towards north-east when the concentration peak was recorded at Swakopmund.

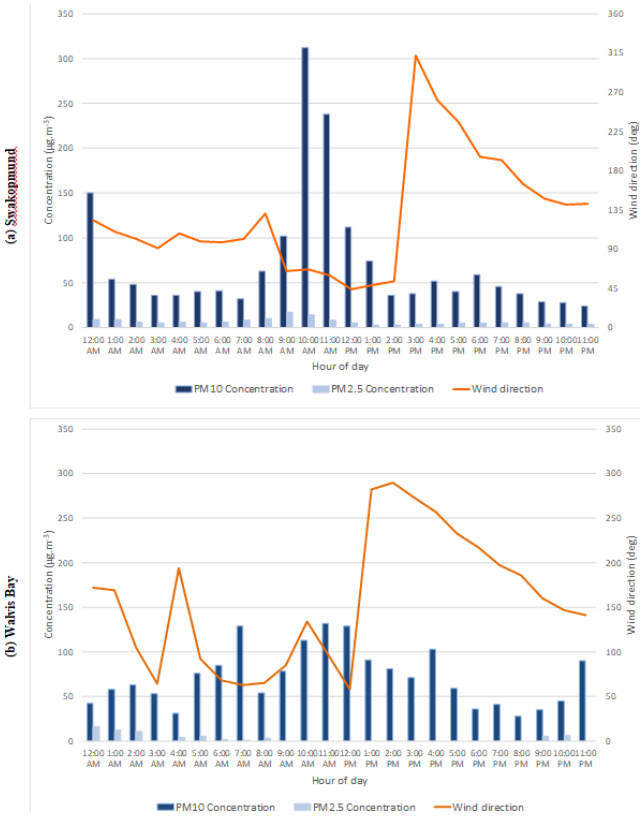

Figure 4: *Hourly PM_{10} and $PM_{2.5}$ concentrations at (a) Swakopmund and (b) Walvis Bay with average hourly wind directions indicated for 6 July 2017.*

Daily PM_{10} concentrations for the month July 2017 are presented as polar plots[2] in Figure 5. Polar plots represent the concentration in relation to the wind direction and wind speed from where it originated. At Swakopmund, high PM_{10} concentrations were recorded during higher wind speeds episodes (>8 m.s^{-1}) from the east-north-east, and during lower wind speeds (4-6 m.s^{-1}) from the east-south-east. Similarly, high PM_{10} concentrations at Walvis Bay occurred during strong east-north-easterly winds (>6 m.s^{-1}) with lower PM_{10} concentrations under higher wind speeds from the south and south-south-west. It therefore appears as if PM_{10} sources for Swakopmund are located to the north-west to south-south-west of the monitoring station, whereas for Walvis Bay sources might be located to the south-south-west to south-east of the station.

Polar plots for hourly PM_{10} concentrations on 6 July 2017 reflect the highest PM_{10} concentrations during strong east-north-easterly winds at both Swakopmund and Walvis Bay (Figure 6). Swakopmund recorded higher PM_{10} concentrations under these higher wind speeds than at Walvis Bay (highest hourly PM_{10} concentration of 312 µg.m^{-3} and maximum wind speed of 18.2 m.s^{-1} at Swakopmund compared to the highest PM_{10} concentration of 132 µg.m^{-3} and maximum wind speed of 7.6 m.s^{-1} at Walvis Bay). Lower PM_{10} contributions were associated with south and south-westerly winds at the Swakopmund station, and south-west to north-westerly winds at the Walvis Bay station.

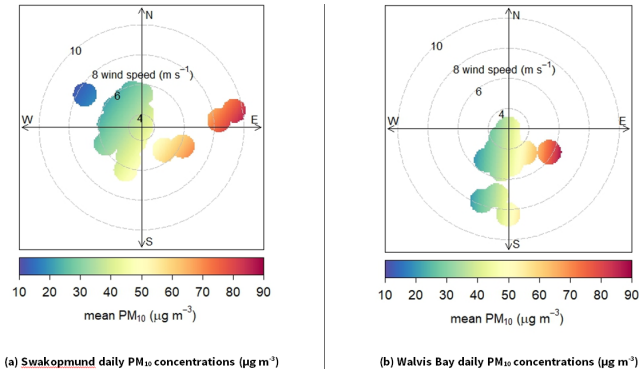

Figure 5: *Daily PM_{10} concentrations as polar plots for (a) Swakopmund and (b) Walvis Bay for the month of July 2017.*

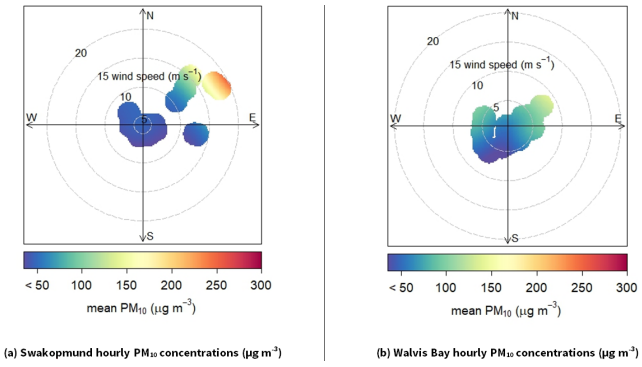

Figure 6: *Hourly PM_{10} concentrations as polar plots for (a) Swakopmund and (b) Walvis Bay for 6 July 2017.*

European Reanalysis Interim (ERA-Interim) data (Dee at al., 2011) were downloaded to produce wind and sea-level pressure maps for 00:00, 06:00, 12:00 and 18:00 Greenwich Mean Time (GMT) on 6 July 2017 (Figures 7a, 7b, 7c and 7d). According to these maps, north-easterly winds were observed between the Namibian escarpment and coastline, with the Botswana anti-cyclone well-established to the east of the country.

As the east wind descended from the Namibian interior towards the coast, the vertical air mass expanded and air pressures decreased to form higher pressures along the escarpment to lower pressures along the coast (illustrated in Figure 1 and observed in Figures 7a, 7b, 7c and 7d). As a result, a trough associated with lower pressures developed along the Namibian coast line.

In this trough, Mean Sea Level Pressure (MSLP) values at Swakopmund and Walvis Bay were in the order of 1019 hPa at

[2] R package for air quality data analysis (Carslaw & Ropkins, 2012) and the Openair version 0.8 0 (Carslaw, 2013).

00:00 GMT. Pressures increased towards 06:00 to values of 1020 hPa. I noticeable drop in MSLP to 1017 hPa occurred between 06:00 GMT and 12:00 GMT, from where MSLPs stabilised towards 18:00 GMT at 1017 hPa.

While north-easterly winds prevailed at the two towns at 00:00 GMT, 06:00 GMT and 18:00 GMT, the deepening of the trough reflected for 12:00 GMT (Figure 7c) resulted in cyclonic (clockwise) circulation enhancement (north-eastern to the east of the trough and south-western to the west of the trough), which could explain the noticeable change in wind direction towards a north-westerly direction at 16:00 – as reflected in the weather station data (Figures 4a and 4b). The cyclonic circulation enhancement that appeared on 6 July 2017, however, did not result in exceptionally high PM_{10} concentrations. The high concentrations that were observed earlier in the day may rather be attributed to an upwind source towards the northeast.

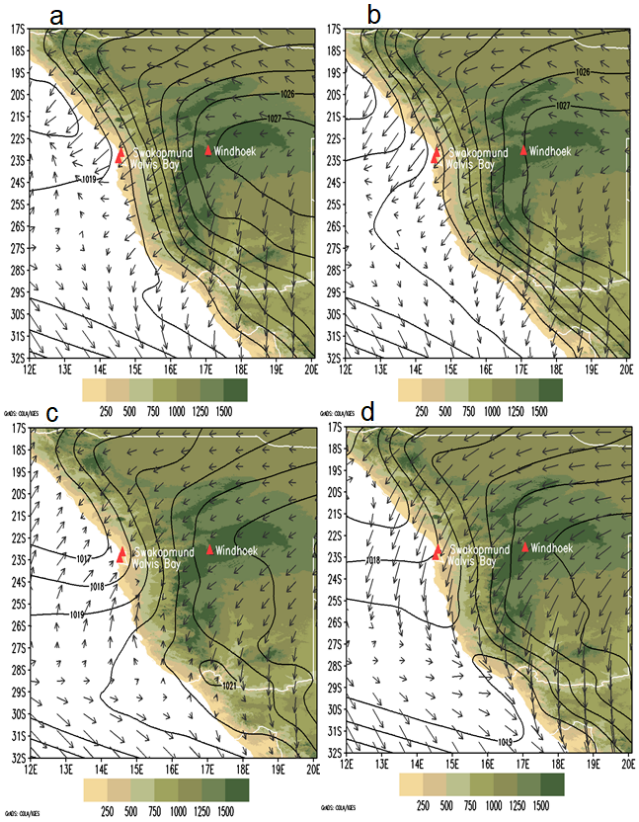

Figure 7: *Map of Mean Sea Level Pressure (MSLP) (contours) and 10m wind vectors at 00:00, 06:00, 12:00 and 18:00 Greenwich Mean Time: GMT (a, b, c, d, respectively) on 6 July 2017. Topography (meters above mean sea level) is shaded, while the positions of Windhoek, Swakopmund and Walvis Bay are indicated by red triangles.*

Easterly wind event on 19 March 2017

Easterly wind conditions were prevalent during March 2017, occurring for 32% of the time at inland stations of Arandis and 41% at Jakalswater. At the coast, easterly flow was recorded for 9% at Swakopmund and 10% at Walvis Bay. High PM_{10} concentrations were recorded on 18, 19, 20, 24, 25, 30 and 31 March 2017 at Swakopmund and Walvis Bay (Figure 8). On these days, easterly wind conditions prevailed inland at Jakalswater

Figure 8: *Daily PM_{10} and $PM_{2.5}$ concentrations for (a)Swakopmund and (b) Walvis Bay with average daily wind direction indicated for the month of March 2017.*

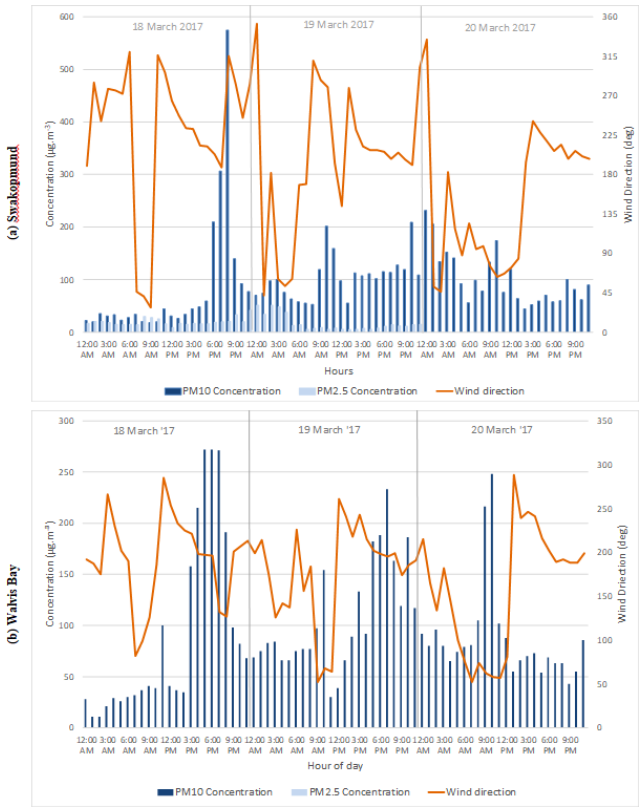

Figure 9: *Hourly PM_{10} and $PM_{2.5}$ concentrations for (a) Swakopmund and (b) Walvis Bay with average hourly wind direction indicated for 19 and 20 March 2017.*

and Arandis, but at Swakopmund and Walvis Bay high hourly PM_{10} concentrations recorded between the late hours of 18 March and the early hours of 20 March were mainly associated with southerly to south-westerly winds. The highest and third highest hourly PM_{10} concentrations recorded at Swakopmund of 575 µg.m^{-3} (20:00 on 18 March 2017) and 232 µg.m^{-3} (12:00 on 20 March 2017) were, however, recorded when the wind was from the north-west (Figure 9).

During the early hours of 19 March 2017 (the focus period for this study), wind directions at Swakopmund returned from north-west to easterly winds (Figure 9a). At 08:00 the wind direction turned to north-west in a very short time period, and maintained this direction until 13:00, from where south-westerly winds developed during most of the afternoon. Late at night, just before 12:00, the wind direction again changed to north-east over a relative short period. At Walvis Bay (Figure 9b), the changes in wind direction was not as extreme as observed at Swakopmund. Nevertheless, north-westerly winds with high PM_{10} concentrations developed from just before 12:00. What is interesting is that the north-westerly winds were all associated with higher PM_{10} concentrations at both Swakopmund and Walvis Bay.

Daily PM_{10} concentrations, presented as polar plots for the month of March 2017, indicate windblown dust under high wind speeds of 8 m.s^{-1} (Swakopmund) and 8 to 10 m.s^{-1} (Walvis Bay). At Swakopmund, these concentrations were recorded during east-south-easterly and south to south-south-westerly winds, and south-south-westerly winds at Walvis Bay (Figure 10). The highest hourly concentrations at Walvis Bay were mainly associated with south-south-westerly winds (Figure 10). On average, higher hourly PM_{10} concentrations and higher wind speeds were recorded at Swakopmund compared to Walvis Bay during 18 to 20 March 2017. From the highest PM_{10} concentration measurements were made during onshore south-west to north-west winds (from the Atlantic Ocean) at both Swakopmund and Walvis Bay.

Highest hourly PM_{10} concentrations for the period 18 to 20 March 2017, depicted as polar plots in Figure 11, show a combination of high PM_{10} concentrations associated with east-north-easterly to south-south-westerly winds at both Swakopmund and Walvis Bay. Although the expected easterly wind signature is present, higher PM_{10} concentrations resulted from winds from the Atlantic Ocean. The highest hourly PM_{10} concentration (575 µg.m^{-3}) recorded at Swakopmund over these three days was under moderate winds (5 m.s^{-1}) from the north-west. The second highest PM_{10} concentration (307 µg.m^{-3}) was during south-south-westerly winds at 6.4 m.s^{-1}. At Walvis Bay, the highest hourly PM_{10} concentration recorded was 272 µg.m^{-3} over two (2) hours when the wind was from the south-south-west blowing at moderate velocities (9.4 and 7.6 m.s^{-1}).

European Reanalysis Interim (ERA-Interim) data (Dee at al., 2011) were downloaded to produce wind and sea-level pressure maps for 00:00, 06:00, 12:00 and 18:00 Greenwich Mean Time (GMT) on 19 March 2017 (Figures 12a, 12b, 12c and 12d). As

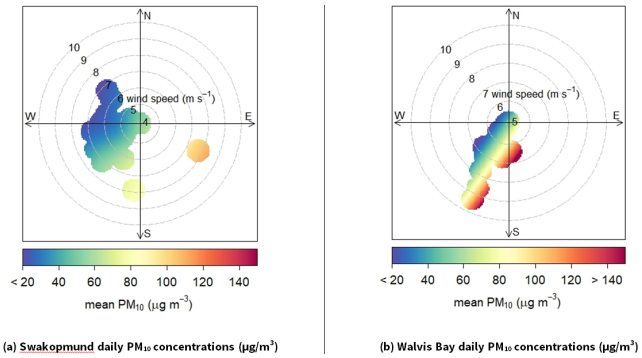

Figure 10: *Daily PM_{10} concentrations as polar plots for (a) Swakopmund and (b) Walvis Bay for the month of March 2017.*

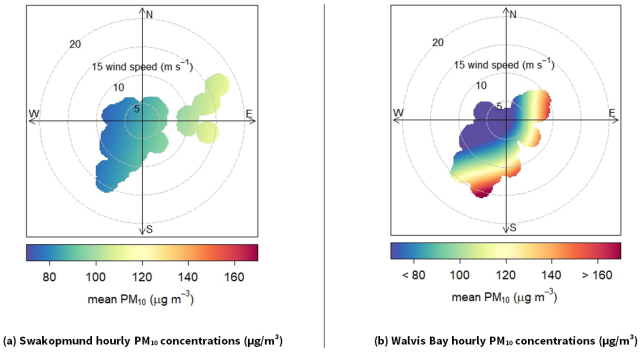

Figure 11: *Hourly PM_{10} concentrations as polar plots for (a) Swakopmund and (b) Walvis Bay for 18 to 20 March 2017.*

the easterlies blows towards the Namibian coastline from the higher escarpment, air pressures dropped, as indicated by isobars that are almost parallel to the coastline in the area west of the high escarpment, which had led to the development of a coastline trough. In general, north-easterly conditions were observed in the Swakopmund / Walvis Bay area at 00:00 GMT. With these north-easterlies, strong Atlantic Ocean anti-cyclonic south-westerly winds appeared to allow for a north-easterly / south-westerly wind conversion line to develop along the coast of Namibia. A coastal-low feature which is an extension of the coastal through is also visible at 00:00 GMT (Figure 12a). Signs of cyclonic circulation is visible around the coastal-low, which developed even further towards 06:00 GMT as MSLPs dropped from 1013 hPa to 1011 hPa (Figure 12b). Wind directions also changed from northeast to southwest between 00:00 GMT and 06:00 GMT, which is also indicative of cyclonic circulation enhancement, which form part of the north-easterly / south-westerly wind conversion line. At 12:00 GMT, north-westerly winds develop with a significant increase in PM_{10} concentrations, especially at Swakopmund (Figure 12c).

The change in wind direction from northeast to southwest to northwest can be interpreted as cyclonic circulation along the coast of Swakopmund and Walvis Bay, associated with the clockwise recirculation of PM_{10}. At the same time, the north-westerly / south-easterly wind conversion line would have prevented PM_{10} to be dispersed westwards towards the deeper Atlantic Ocean, which could also have contributed to the accumulation of PM_{10} along the coast that was recirculated

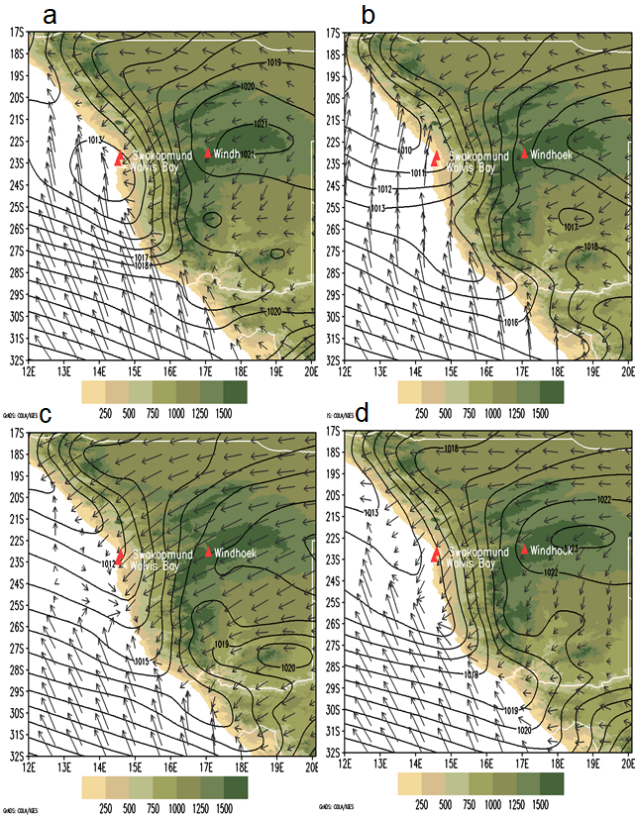

Figure 12: *Map of Mean Sea Level Pressure (MSLP) (contours) and 10m wind vectors at 00:00, 06:00, 12:00 and 18:00 Greenwich Mean Time: GMT (a, b, c, d, respectively) on 19 March 2017. Topography (meters above mean sea level) is shaded, while the positions of Windhoek, Swakopmund and Walvis Bay are indicated by red triangles.*

back towards the continent by north-westerly winds to generate conditions of exceptionally high PM_{10} concentrations, as indicated by the 12:00 GMT map (Figure 12c) as well as the high PM_{10} concentrations measured at Swakopmund (and Walvis Bay) (Figure 12a) between 08:00 and 13:00 on 19 March 2017.

Characterisation of likely dust sources

Filter tape from the PM_{10} BAM 1020 samplers at Swakopmund and Walvis Bay were analysed using Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) for elemental content (43 elements) in an attempt to differentiate between the main sources contributing of high hourly PM_{10} concentrations at Swakopmund and Walvis Bay. Both towns border the Atlantic Ocean to the west and the desert gravel plains to the east, with the Kuiseb River mount and Namib Desert to the south of Walvis Bay. The main anthropogenic sources within the gravel plains of the Erongo Region are unpaved roads and mining and exploration activities (mainly uranium prospecting). Particulate matter from these areas reaching the coastal towns are wind dependent (windblown dust) whereas wind independent sources closer to the monitoring stations are likely to the associated with vehicle emissions, small boilers and hospital incinerators, and harbour activities at Walvis Bay.

ICP analysis was done for 43 elements on samples representing hours with high PM_{10} concentrations during the two case studies – 6 July 2017 and 18 to 20 March 2017. Specific hours were selected reflecting the predominant wind direction during each case study as to eliminate dust from other directions during these periods.

For the 6th of July 2017 case study, 22 hours were selected from the Swakopmund station reflecting winds from the east-north-east to south-east (01:00 to 14:00 on 6 July and 04:00 to 11:00 on 7 July 2017). The main elements are presented in Table 2 and Figure 13. No filter tape was available from Walvis Bay for this period.

Table 2: *Elemental composition as percentages of the various samples*

Sample ID	Swakopmund		Swakopmund		Walvis Bay	
	06 July 2017		18-20 March 2018		18-20 March 2018	
Element	(mg/ sample)	(%)	(mg/ sample)	(%)	(mg/ sample)	(%)
Arsenic, As	0.0007	1%	0.0010	1%	0.0000	0%
Iron, Fe	0.0122	26%	0.0122	16%	0.0177	38%
Magnesium, Mg	0.0012	3%	0.0074	10%	0.0083	18%
Manganese, Mn	0.0002	0%	0.0002	0%	0.0006	1%
Phosphorus, P	0.0010	2%	0.0019	3%	0.0000	0%
Selenium, Se	0.0001	0%	0.0004	1%	0.0002	0%
Sulphur, S	0.0165	35%	0.0524	69%	0.0195	41%
Titanium, Ti	0.0004	1%	0.0007	1%	0.0009	2%
Vanadium, V	0.0000	0%	0.0001	0%	0.0000	0%
	0.0322		0.0765		0.0471	

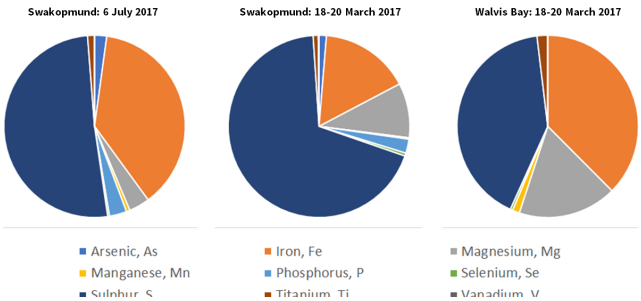

Figure 13: *Elemental composition of the samples from the case studies.*

Samples covering 25-hours from the Swakopmund station (06:00 to 23:00 on 18 March; 09:00 to 23:00 on 19 March and 00:00 to 04:00 on 20 March 2017) were analysed reflecting predominantly south-south-westerly to north-westerly winds during the period 18 to 20 March 2017. At Walvis Bay 15 hours (15:00 to 20:00 on 18 March and 15:00 to 23:00 on 19 March 2017) were selected reflecting similar wind directions. The main elements are presented in Table 2 and Figure 13.

The main elements from all three sample batches were arsenic (As), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P), selenium (Se), sulphur (S), titanium (Ti) and vanadium (V). During the July east winds, sulphur (51%) and iron (38%) were more pronounced in the samples from Swakopmund, with lower fractions of 4% Mg and 3% P, respectively. For the two sites during the March case study, S and Fe remained the main elements (69% S from Swakopmund and 41% from Walvis Bay, and 16% Fe from Swakopmund and 38% from Walvis Bay). The Mg fraction was higher during these predominantly south-south-westerly to north-westerly winds (10% at Swakopmund and 18% at Walvis Bay). Elements associated with sea water are predominantly sodium (Na) and chloride (Cl), followed by Mg, V, S, calcium (Ca) and potassium (K) (https://en.wikipedia.org/wiki/Seawater). Elements associated with desert dust are mainly Ca, silica (Si), aluminium (Al), and some traces of Na and Mg (Rashki et al., 2012).

No clear distinction could be made in the chemical composition of the three sample batches from the two case studies where high PM_{10} concentrations were recorded. The expectation would have been that under predominant easterly winds (6th of July 2017 case study), the elements mostly associated with desert dust would dominate; whilst under prevailing south-westerly to north-westerly winds (between 18 and 20 March 2017), elements associated with the ocean would alternatively have dominated. Instead, the similar elemental composition of the PM_{10} samples indicates sources of possibly similar origin. All three samples show strong sea water signatures with some traces of desert dust. This is supported by the cyclonic circulation along the coast of Swakopmund and Walvis Bay, associated with the clockwise recirculation of PM_{10} back towards the continent by north-westerly winds.

Conclusions and recommendations

Two case studies, one between 18 and 20 March 2017 and the other on 6 July 2017, were considered to assess the atmospheric circulation patterns associated with the easterly wind conditions resulting in high PM_{10} concentrations at Swakopmund and Walvis Bay along west coast of Namibia. It was found that although easterly wind conditions prevailed over the Namibian continent, extensive temporal wind direction changes were observed at the Swakopmund and Walvis Bay coastline. Through further investigation it was concluded that in addition to the westward transport of PM_{10} from inland sources during easterly wind events, higher coastal concentrations of PM_{10} can also develop as a result north-easterly / south-westerly wind conversion lines as well as cyclonic circulation or cyclonic circulation enhancement, with the recirculation of PM_{10}, associated with coastal troughs and coastal lows. The study found a relationship between the (1) coastward decrease in continental air pressures due to easterly wind conditions, (2) the resultant development of coastal troughs (and sometimes coastal-lows), (3) the consequent development of conversion lines, (4) extensive changes in wind speed and direction, and (5) the high concentrations of PM_{10} concentrations (both as a result wind conversion line blocking and cyclonic recirculation) at Swakopmund and Walvis Bay. This is further confirmed by the similarity in elemental content of dust sources under various prevailing wind conditions.

However, these findings need further investigation, especially on the meso-scale, which will not only provide lead to an improved understanding of local wind behaviour, but also local PM_{10} variation characteristics along the coastline of Namibia and the main contributing sources.

Acknowledgements

The authors would like to acknowledge the Ministry of Mines and Energy, Geological Survey of Namibia and the Federal Institute for Geosciences and Natural Resources for making the data available for use in this study. The contribution of the South African Weather Service (SAWS) in providing advice on the ERA-Interim synoptic maps.

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