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Air Pollution in Kenya: A review

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Abstract

Rapid urbanization, the corresponding increase in vehicle ownership, and the continued use of solid fuels as an energy source has resulted in the deterioration of air quality in Kenya. Despite this, there is no publicly available official source of data on air pollution in the country. This paper provides an overview of published studies that report the concentrations of widespread ambient pollutants, outline major themes, and identify data gaps. This review reveals that since the 1980's particulate matter (PM) concentrations in some Nairobi locations, such as the industrial area, have been at dangerously high levels. Almost all of the studies included show that PM concentrations in Nairobi violate the World Health Organization (WHO) guidelines. Moreover, Black Carbon (BC) concentrations in Nairobi are among the highest in the world, indicating the need for cleaner vehicles in the city. There has been much less work done measuring the levels of gaseous pollutant concentrations in Kenya. Based on these findings, policies policymakers can use to improve air pollution in Nairobi, and monitoring strategies to fill in existing gaps are presented.

Keywords: Ambient air quality; Kenya; measurements; criteria pollutants; review

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1 Introduction

According to The State of the Global Air 2019 report, in Kenya alone, air pollution is the eighth leading risk factor for premature death, accounting for nearly 19,000 deaths (5,000 due to ambient air pollution and the remaining due to indoor pollution) in 2017 (State of Global Air,

2019). The Report goes on to say that the entire Kenyan population lives in areas with $\text{PM}_{2.5}$ (fine particles with a diameter less than $2.5 \mu\text{m}$) greater than $10 \mu\text{g}/\text{m}^3$, which is the World Health Organization (WHO) Air Quality Guidelines for healthy air.

In 2014, the Minister of the Environment enacted the Environmental Management and Coordination (Air Quality) Regulations (EMCA), 2014 to control air pollution. The EMCA (2014) specifies national ambient air quality standards for residential and industrial areas and occupational air quality limits, to tackle air pollution. Kenya's air quality governance framework is structured around ensuring the standards are met. However, the deployment of air quality monitors and the creation of publicly available air quality data to enforce the standards has been slow.

Specifically, the Kenya Meteorological Department (KMD) owns and runs a mobile monitoring van that has high quality instruments to measure a wide variety of pollutants. None of the original data are public, so the extent of monitoring is unknown. KMD has published some academic papers using data collected mostly in Nairobi by this van. The findings from these papers will be discussed later. KMD also operates a monitoring station on Mount Kenya, which is part of the World Meteorological Organization's (WMO) Global Atmospheric Watch network. The station has instruments for measuring particulate matter/dust and surface ozone, among other air pollutants and its data is supposed to be public. However, only surface ozone data is currently being reported at this site. KMD has for several years also been collecting and publishing data on surface ozone and vertical ozone profiles in partnership with MeteoSwiss, the Swiss Office of Meteorology and Climatology, at their Nairobi headquarters. Surface ozone is very harmful to human health and such data is exceedingly useful for developing pollution management plans. Finally, Kenya's National Environment Management Authority (NEMA) requires industrial facilities to contract a set of authorized laboratories with high-quality equipment to report their stack emissions and to make provisions for continuous monitoring in accordance with the 2014 Air Quality Regulations. However, none of this data has been made public. Therefore, little official air quality data exists for Kenya (deSouza, 2018).

In countries such as the United States, a relatively dense official monitoring network has provided the infrastructure to track progress on air quality improvements, and to stretch the use of the network beyond enforcing the standards- to identify sources and trends of pollution (Lee et al., 2007; Zhang et al., 2014; among others), examine health effects (Dominici et al., 2006; Samet et al., 2000; among others) and evaluate the effectiveness of different policy interventions (Sullivan et al., 2018; among others). Without access to data from such a single, robust network in Kenya, there have been competing narratives about the state of air pollution in the country. A report produced by a renewable energy firm The Eco Experts, widely circulated in the press (Kisambe, 2018) identified Kenya as the least toxic country in the world accounting for air pollution, energy consumption and renewable energy, using data from the International Energy Agency and WHO and has been widely cited in the press. Other studies indicate that the city of Nairobi has severe air quality issues.

This paper reviews scientific studies that report air pollution concentration levels of widespread ambient pollutants: PM_{2.5}: (fine particles with diameters less than 2.5 µm), PM₁₀ (coarser particles with diameters up to 10 µm), Nitrogen Dioxide (NO_x), Sulfur Dioxide (SO₂), Tropospheric Ozone (O₃), for which standards exist in Kenya. Most such studies were conducted in the city of Nairobi. Most were limited to short-duration measurements with different monitoring devices in different locations. However, taken as a whole, there is remarkable consistency in the major sources of ambient air pollution identified. This paper also uses the published literature to review which pollutant concentrations exceed the current standards in Nairobi, and where these exceedances occur. This information can thus provide policy makers with the information needed to take steps to reduce air pollution in Nairobi.

2 Methodology

Studies that report widespread ambient pollutant concentrations in Kenya were identified by using the search phrase: (Nairobi OR Kenya) AND (air pollution OR air quality OR particulate* OR nitrog* OR ozone), in the PubMed, Web of Science and SCOPUS databases on June 01, 2020.

Although most air pollution studies were conducted since the early 2000's, there are some studies that go back as far as the early 1990's. Some of the earlier studies reference results from ground-based pollution measurement campaigns that had been carried out in the early 1980s. The results from these early campaigns were published in student dissertations and could not be found in the peer-reviewed literature. However, such measurements are critical to providing an understanding of how air pollution in Nairobi has changed over time and are thus included in this review. In order to document studies published in dissertations, local journals and conference proceedings, searches of the afore-mentioned databases were supplemented with thesis searches, Google searches, and a careful perusal of references in the early studies to identify gaps that the author may have missed. The inclusion of these measurements and the focus on multiple widespread pollutants distinguishes this review from others conducted previously (Petkova et al., 2013; Nairobi Air Quality Action Plan 2019-2023).

While many studies have been conducted on household air pollution from cookstoves in Kenya, the current review is limited to studies of outdoor pollutant concentrations. I also excluded studies that reported concentrations of pollutants other than criteria pollutants: particulate matter (PM), NO_x, SO₂, O₃, such as volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), H₂S. Section S1 in Supplementary Information contains a short note about these studies. I choose to limit this review to outdoor criteria pollutants because as mentioned in the Introduction Kenya has standards for certain criteria or widespread outdoor air pollutants and there is a growing understanding of the large global burden of disease caused by criteria pollutants like PM_{2.5} and O₃ (Anenberg et al. 2010).

In addition, multiple studies analyze data from the station deployed on Mount Kenya as part of the World Meteorological Organization Global Atmospheric Watch (GAW) program and operated by the Kenya Meteorological Department. This station is situated far from local

pollution sources to measure regional pollution/background pollution levels. The current review highlights work that reports pollutant concentrations from this GAW station. However, I do not include studies that only discuss the setup of this monitoring station (for example, (Henne et al. 2008a), or the comparison of the data from the GAW station on Mount Kenya with GAW stations with other regions of the world (e.g., Klausen et al. 2009).

I also excluded studies that relied on air pollution models rather than ambient measurements. I have retained studies that report concentrations of components of PM- even if they don't report PM_{2.5} concentrations, as they provide important information about PM sources in Kenya. Such studies could thus provide important insights to policy makers about how to lower PM concentrations in Nairobi most effectively.

Finally, as such a review relies on studies already published, it does not capture burgeoning citizen science efforts to measure air pollution in Nairobi. Of these efforts, the work by Code for Africa (Data available at: <https://open.africa/dataset/sensorsafrica-airquality-archive-nairobi>, Last Accessed June 9, 2020) is notable, and has been widely shared on social media.

3 Results and Discussion

*Overall, a total of 33 studies matched the review criteria and are summarized in **Table S1** in Supplementary Information, which provides information about the pollutant measured, the kind of instrument, time period and duration of the study, as well as key results.*

The timeframes of the studies vary, with most measurement campaigns running for a few weeks to several years. Different instruments, with different detection limits and levels of precision were used among the studies, making direct comparisons across studies difficult. Four studies (Shilenje and Ongoma 2014; Shilenje et al. 2015, 2016; Apondo et al., 2018) were conducted with funding from the Kenyan Meteorological Department and are indicated in bold in **Table S1**.

All but nine of the studies focus on measurements in Nairobi alone. Of the nine, four (Gatari et al. 2001, 2005, 2009b; Henne et al. 2008b) report measurement results in Nanyuki only. The GAW site is on Mt Kenya in Nanyuki. Two report concentrations in Nanyuki in addition to Nairobi (Gatari and Boman 2003; Pope et al. 2018). One study reported pollutant concentration in the Athi River township (Shilenje et al. 2015). One study reported pollutant concentrations in Nakuru in addition to Nairobi (Odhiambo et al. 2010), and one study was conducted in Kiirua in Meru county in rural Kenya (Teather et al. 2015).

Twenty studies report PM₁, PM_{2.5} or TSP concentrations (Ngang'a and Ngugi 1986; Karue et al. 1992; Gatebe et al. 2005; Vliet and Kinney 2007; Gatari et al. 2009a, b, 2019; Odhiambo et al. 2010; Kinney et al. 2011; Gaita et al. 2014, 2016; Ngo et al. 2015; Shilenje et al. 2015, 2016; deSouza et al. 2017; Mukaria et al. 2017; Maina et al. 2018; Pope et al. 2018; Egondi et al. 2018; West et al. 2020). One study included in this review also reports the number and kind of bacteria in aerosol samples in Nairobi (Yin et al. 2018). As each of the 20 studies gives pollutant concentrations using different time-averaging, presenting a coherent summary is difficult,

especially as all studies except for deSouza et al. (2017)¹ did not make the raw data publicly available.

Figure 1 displays estimates from sixteen studies of PM₁, PM_{2.5}, PM₁₀ and total suspended matter (TSP) in units of $\mu\text{g}/\text{m}^3$ averaged over the study period. Average PM concentrations over the study period shown in Figure 1 were those directly reported in the different studies. The two studies sponsored by KMD provide daily average PM_{2.5} and PM₁₀ concentrations and are displayed separately in Figure 2. The WHO daily air quality guideline is displayed, where applicable in both Figure 1 and 2 for comparison. It can be seen that many studies, including official monitoring efforts by KMD, report harmful concentrations of PM. I display the daily-averaged WHO value, $25 \mu\text{g}/\text{m}^3$, which offers a conservative standard for comparison. The WHO annual-averaged standard for PM_{2.5} is $10 \mu\text{g}/\text{m}^3$.

Almost every published study that measures particulate matter (PM) going back as far as 1983 in Nairobi indicates that levels of some air pollutants in certain parts of the city are unsafe vis a vis the World Health Organization (WHO) guidelines. For example, Ngugi, (1983) (The same results also to be found in Ngang'a and Ngugi, (1986)- I have thus combined the two studies in a single row in **Table S1**), reports that estimates of TSP reached levels exceeding $250 \mu\text{g}/\text{m}^3$ in the industrial area, where many poorer residents of Nairobi live. This estimate exceeds Kenya's 2014 TSP standard for residential areas, which is $200 \mu\text{g}/\text{m}^3$ for 24-hour averages and $140 \mu\text{g}/\text{m}^3$ for annual-averaged measurements. Fast-forwarding to 2015, West et al., (2020) find PM_{2.5} concentrations as high as $300 \mu\text{g}/\text{m}^3$ in Viwandani, a poor neighborhood in the industrial area. Average PM_{2.5} concentrations over about a month experienced by the residents followed in the study ranged between $22.4\text{--}39.6 \mu\text{g}/\text{m}^3$, which is almost equal to or higher than the WHO *daily* PM_{2.5} guideline of $25 \mu\text{g}/\text{m}^3$. Recent research that uses visibility measurements as a proxy for PM_{2.5} estimated that PM_{2.5} concentrations increased by ~ 180% between 1970 and 2018 in Nairobi (Singh et al. 2020).

¹ Data is available from: <http://senseable.mit.edu/cleanair-nairobi/>

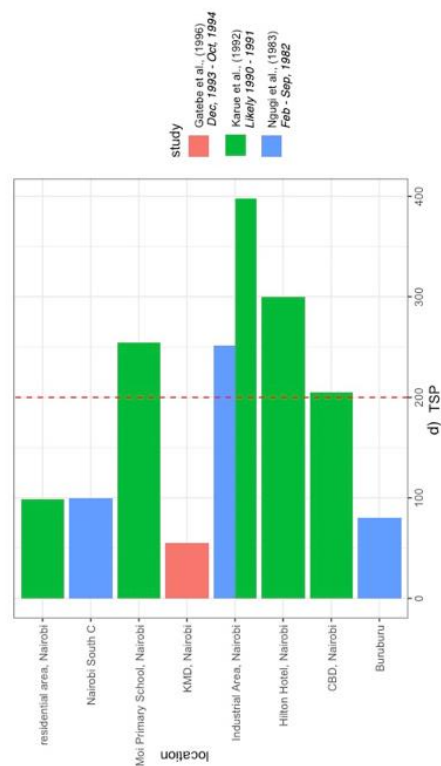
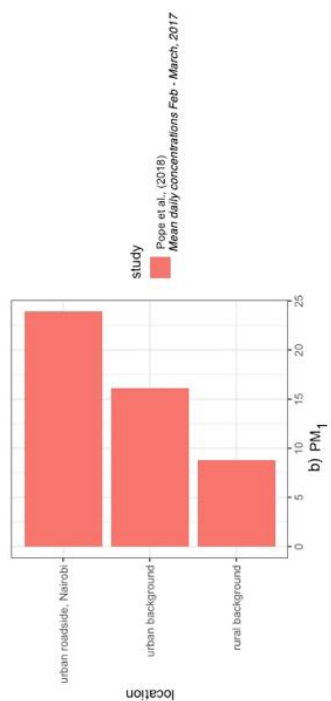
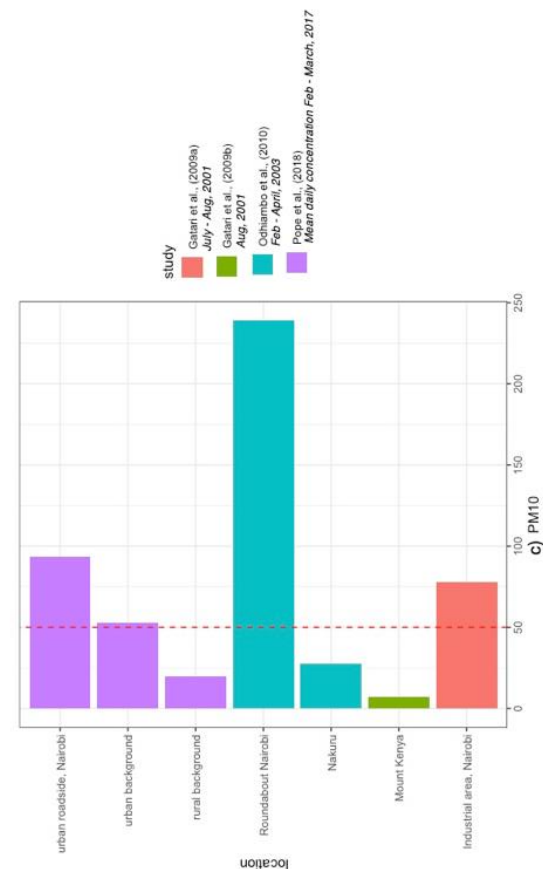
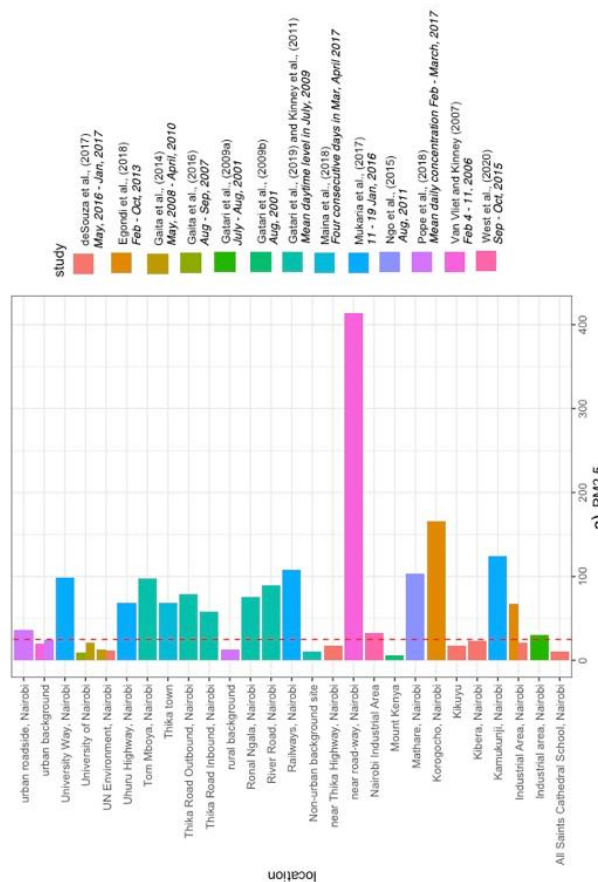


Figure 1: a) $PM_{2.5}$, b) PM_1 , c) PM_{10} and d) TSP in units of $\mu g/m^3$ for different studies averaged over the study-specific period. Study-specific periods are listed in the legend. The red dotted lines on panels a) and c) indicate the World Health Organization (WHO) daily guideline. As there is no WHO guideline for TSP, the red dotted line on panel d) indicates the Kenyan 2014 daily average standard for residential areas. There is no standard set for PM_1 .

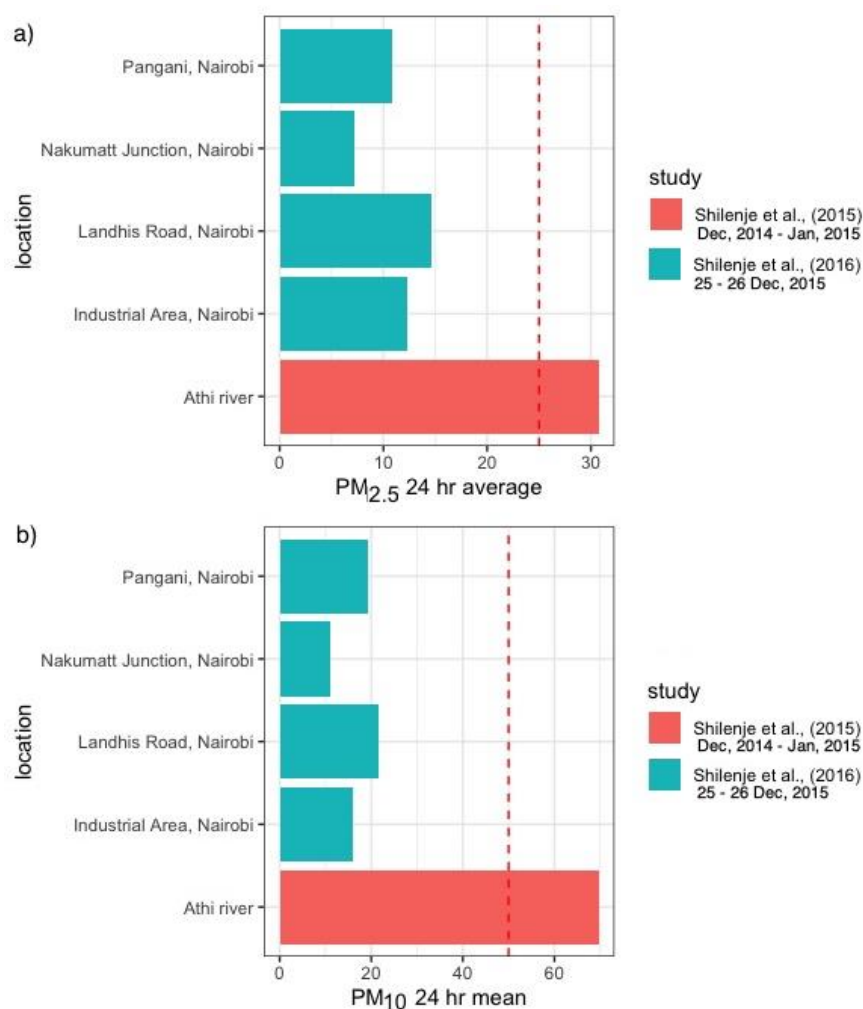


Figure 2: Daily averaged a) $PM_{2.5}$ and b) PM_{10} reported by scientists at the Kenya Meteorological Department (KMD) using an official mobile air quality monitor owned by KMD. The red dotted lines indicate the WHO PM_{25} daily averaged guideline.

Many of the studies also indicate likely air pollution sources based on different techniques such as: (i) deciphering the diurnal and seasonal measurement trends (deSouza et al., 2017 among others), (ii) extracting source signatures from the aerosol elemental composition (Ngo et al., 2015 among others), and (iii) examining the correlation between pollutant concentration and activities such as traffic patterns (Odhiambo et al. 2010; Mukaria et al. 2017). Regardless of the technique, all the studies reviewed show a remarkable consistency in the dominant sources identified.

Specifically, all studies demonstrate that vehicular emissions are a highly important pollution source in Nairobi. Roadside pollution concentrations were much higher than in residential/background areas. Levels of air pollution along major roadways can be dangerously high, in almost all cases exceeding the WHO daily guideline as shown in Figures 1 and 2. One study that examined air pollution exposure among bus drivers and mechanics that worked on or close to roads found extremely high exposure rates (Ngo et al., 2015).

Nine of the 33 studies also report Black Carbon (BC) (Gatari and Boman 2003; Vliet and Kinney 2007; Gatari et al. 2009b, a, 2019; Gaita et al. 2014; Ngo et al. 2015; Shilenje et al. 2015, 2016): a component of PM produced from the incomplete combustion of fuel (typically produced by older vehicles) that causes many adverse health effects (Jansen et al., 2005; Janssen et al., 2011). A key finding from this review is that BC forms a large percentage of the PM in Nairobi, with levels among the highest reported in the world. Mbandi et al. (2019) provides estimates of the fuel economy of road-vehicles in Nairobi. They find that the fuel economy of different vehicles is 2–3 times worse than in the countries from which these vehicles were imported: Japan, Europe and India and China. Specifically, this paper notes that Kenyan passenger vehicles would require a 4-fold improvement to achieve the Japanese fuel economy standard of 5.95 L/100 km.

Multiple studies showed that the informal neighborhoods, especially ones in the industrial area, suffer from particularly high levels of pollution. This can also be seen in Figure 1, where the neighborhoods in the Industrial area, Korogocho, and Kibera exhibit fine particle levels of several $100 \mu\text{g}/\text{m}^3$. Code for Africa has partnered with journalists, providing them with low-cost air quality monitors so that they can monitor specific factories that residents have long complained about. This work resulted in the temporary closure of an asphalt factory in the neighborhood of Syokimau in Nairobi (Serwanjja 2019). This initiative points to the value of scientists partnering with communities to achieve common goals.

Nearly one third of the studies also report concentrations of other trace elements such as lead (Pb), bromine (Br), zinc (Zn), manganese (Mn), which were used to identify pollution sources. Invariably most studies performed over time find that resuspended road dust, the wear and tear of brake linings, biomass burning and emissions from industrial sources are other major sources of PM in Nairobi. Several studies going as far back as the early 1990's reported much higher levels of Pb in Nairobi. For example, Karue et al. (1992) reported Pb levels in Nairobi that were as much as 5x higher than in European countries at that time. Gatebe et al. (1996) demonstrated that vehicle emissions were major sources of Pb and Br. Gatari et al. (2005) reported high levels of Pb near open-air vehicle garages. Odhiambo et al. (2010) also found levels of Pb and Mn (an additive to petroleum fuels) at a busy roundabout in Nairobi to be much higher than levels in the US or Europe. Gatari et al. (2009) found that Mn levels in Nairobi exceeded the WHO guideline of $150 \text{ ng}/\text{m}^3$. All the aforementioned studies were conducted before 2006, the year when leaded gasoline was phased out. However, even after 2006, Maina et al. (2018) found high concentrations of Cd, Pb and Zn at locations along Thika highway, indicating moderate to high contamination. Gaita et al. (2014) from their examination of the ratio

of Br/Pb in Nairobi, concluded that tire abrasion, likely made worse due to the heavy use of second-hand tires, was a major source of aerosol in Nairobi. More work is required to investigate the sources of the heavy metal concentrations in aerosols in Nairobi and elsewhere in Kenya.

The studies conducted so far were in a small number of locations within Nairobi and in a few other towns. In order to obtain country-wide estimates of pollution, annual-averaged population-weighted $PM_{2.5}$ estimates for Kenya derived from satellite data calculated using the method listed in van Donkelaar et al., (2016) (Publicly available from: http://fizz.phys.dal.ca/~atmos/martin/?page_id=140 , Last Accessed Feb 17, 2020) for the period 2000-2016 are displayed Figure 3, in conjunction with new vehicle registrations (<https://www.ceicdata.com/en/kenya/road-transport-number-of-motor-vehicles-registered/road-transport-no-of-motor-vehicles-registered>, Last Accessed Feb17, 2020). This extensive dataset allows us to see the long-term trend of increasing $PM_{2.5}$ as well as the correlation between satellite-derived $PM_{2.5}$ and vehicles registered. However, it must be noted that satellite estimates of $PM_{2.5}$ are error-prone, especially in areas without reference monitors. The dip in PM after 2006 is likely due to the fact that Kenya phased out leaded gasoline in 2006. More work is required to characterize the long-term effects of such policy interventions. The caveat with using this data is that Alvarado et al., (2019) found high errors in satellite-based estimates of daily $PM_{2.5}$ in cities in low-and middle-income countries. They highlight that satellite-derived data can never be a substitute for reference ground-monitors in such cities. However, trends derived from long-term satellite data records are much more robust than instantaneous values.

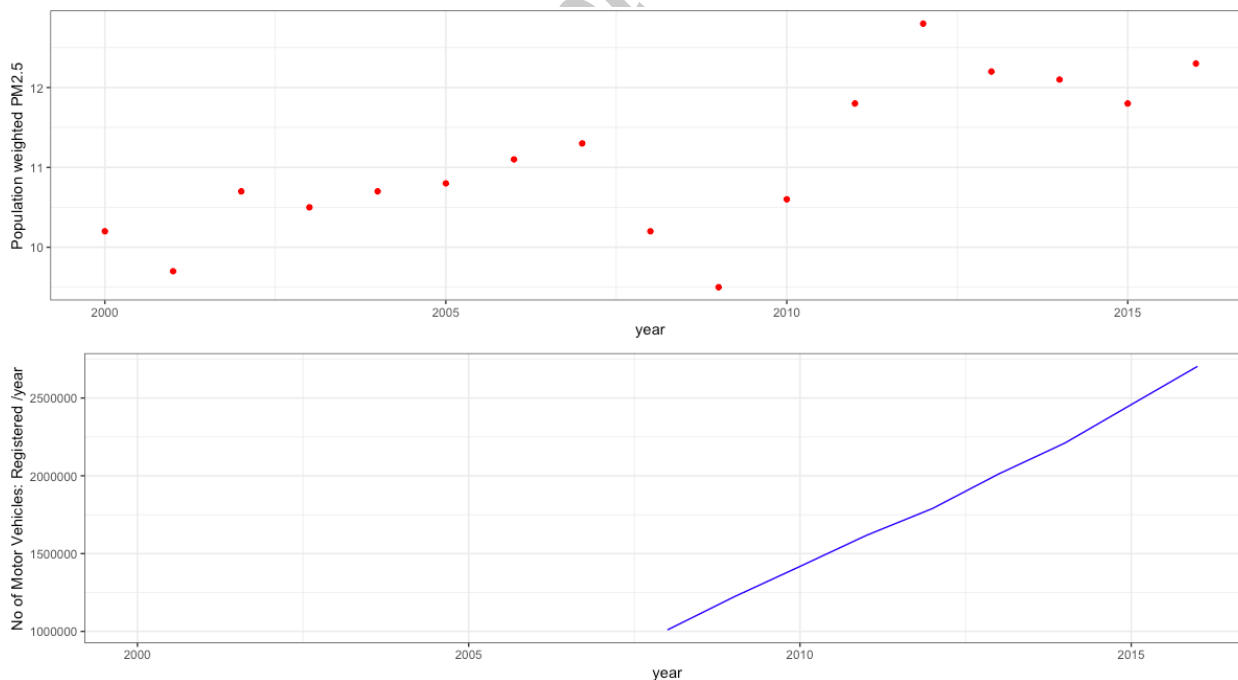


Figure 3: (a) Population-weighted annual- $PM_{2.5}$ levels in units of $\mu g/m^3$ in Kenya from 2000-2016, derived from satellite data, using the method described in van Donkelaar et al. (2016). Note these results produce significant uncertainties, but the qualitative trends are likely to be

robust, (b) number of new motor vehicles registered/year in Kenya from 2008-2017 from CEIC Global Economic Data, Indicators, Charts & Forecasts data

In contrast to PM, eight studies report concentrations of different gaseous pollutants (Henne et al. 2008b; Odhiambo et al. 2010; Shilenje and Ongoma 2014; Shilenje et al. 2015, 2016; deSouza et al. 2017; Kimayu et al. 2017; Okuku 2018). Each of these studies conducted so far find that gaseous concentrations fall within WHO guidelines. Across the different studies, researchers find that vehicles are a major source of NO and NO₂. NO₂ is likely an important source of tropospheric O₃. The formation of O₃ is strongly dependent on solar radiation and temperature. Apondo et al., (2018) however, found that concentrations of CO, likely formed from vehicular emissions exceeded WHO guidelines near major urban roads. More studies are needed to better characterize the dynamics of gaseous formation in Nairobi and to better understand the sources.

Each panel in Figure 4 shows the concentrations of gaseous pollutants for which multiple averages are reported at different locations for the same time-averaged intervals. For example, Henne et al., (2008b) is the only study that reports night-time concentrations of CO, Shilenje et al., (2014) is one of the few studies that report the annual average concentration of O₃, and have thus been excluded from graphical representation.

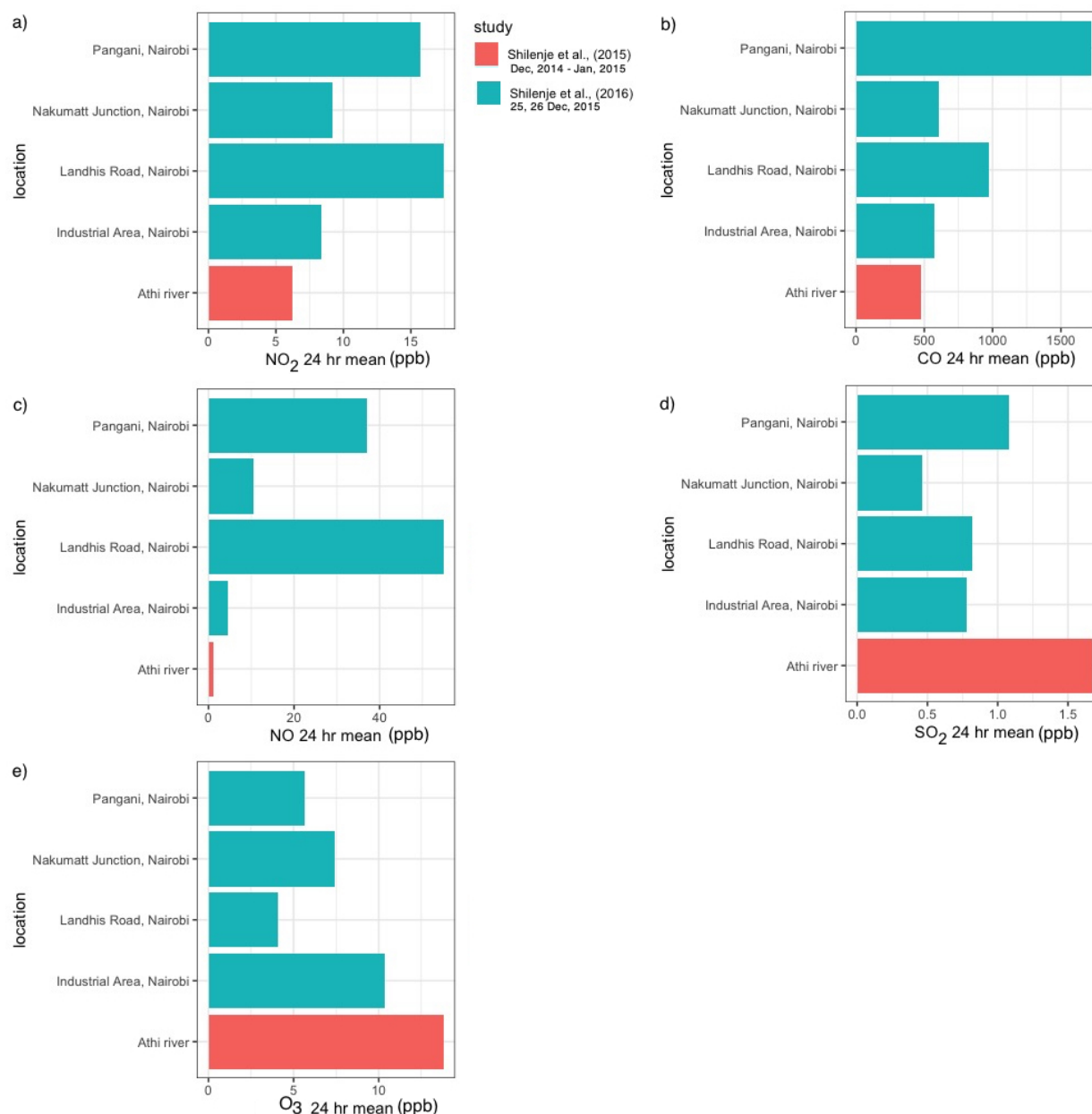


Figure 4: Daily, and annual-averaged CO, SO₂, NO₂, O₃ concentrations reported in different studies

4 Conclusions

Existing measurements of air quality in Nairobi indicate that for particulate matter (PM), the WHO guidelines have been exceeded in many parts of the city. Moreover, the guidelines have been violated for many years- going all the way back at least to the early 1980's. There is thus an urgent need for action to improve air quality in Nairobi.

Although the government of Kenya has not made the original data collected from official monitoring systems publicly available, the analysis of such data has been published in scientific journals. In Table S1, I highlight the studies that have been funded by the Kenyan Meteorological Department. These studies confirm that PM levels in Nairobi violate the WHO air quality standards. There is thus a need for transparency in official monitoring efforts and for the data to be made publicly available, for scientific as well as policy development purposes.

Another important finding from this review is that vehicles are a major source of pollution in Nairobi. This result can inspire concrete action by incorporating concerns about air pollution more fully into the environmental impact assessment (EIA) of new transportation-related projects in Nairobi. Air pollution concerns can also lead to a realization of the need for more projects that promote non-motorized transport (NMT), the improvement of public transportation infrastructure, and the need to enforce the ban on importing older vehicles into the country. The Kenyan government has taken first steps to impose restrictions on importing such vehicles (Miriri, 2019). It is important that such policies are enforced. Scrutiny of sources of heavy metal concentrations in Nairobi is also required to evaluate the need to speed up moving to a higher fuel standard.

A gap in the existing literature that this review highlights is that most of the studies conducted so far have been in Nairobi. More measurements in other urban areas in Kenya such as the busy Mombasa port need to be conducted. Satellite measurements can be used to help identify hotspots of pollution to guide the placement of more monitors. However, satellite measurements can never be a substitute for high quality reference monitors, as previous research has found that satellite-derived PM_{2.5} estimates for many cities in the global South can have larger errors (Alvarado et al., 2019). The errors are lowest in inland locations that are at low altitudes (Alvarado et al., 2019). deSouza et al. (2020) presents a new technique to constrain satellite estimates of PM_{2.5} using low-cost sensors that has the potential to produce more accurate estimates of PM from satellite data in Nairobi. There is thus a need to expand the ground-based air quality monitoring network in Kenya.

In addition, very little information exists about the trends of gaseous pollutants in Nairobi, and elsewhere in Kenya. This is another gap that needs to be filled. Most of the studies in this review were conducted for short periods of time. For example, one of the few studies that measures gaseous pollutants only comprises of measurements for Dec 25 and 26, 2015 (Shilenje et al., 2016). This finding highlights the need for long-term continuous measurements of air pollutants in Kenya to track air pollution trends in the city. Such a data source can also allow researchers to evaluate the impacts of different policies.

Even within Nairobi, more work is required to characterize the exposure of vulnerable populations in Nairobi, such as those that live in the informal areas, where studies so far have found high levels of pollution (Ngo et al. 2015; deSouza et al. 2017). The contribution of different sources to pollution levels in these areas must be assessed for urgent action to be taken to reduce concentration levels.

References

- Alvarado MJ, McVey AE, Hegarty JD, et al (2019) Evaluating the use of satellite observations to supplement ground-level air quality data in selected cities in low- and middle-income countries. *Atmos Environ* 218:117016. <https://doi.org/10.1016/j.atmosenv.2019.117016>
- Anenberg S. C., Horowitz L. W., Tong D. Q., West J. J. (2010) An Estimate of the Global Burden of Anthropogenic Ozone and Fine Particulate Matter on Premature Human Mortality Using Atmospheric Modeling. *Environ Health Perspect* 118:1189–1195. <https://doi.org/10.1289/ehp.0901220>
- Apondo, W., Cherutoi, J., Shilenje, Z., Thiong'o, K., Okuku C (2018) Analysis of Surface Ozone and Its Precursors with Relevance to Urban Air Pollution in Nairobi, Kenya
- deSouza, P., Kahn, R.A., Limbacher, J.A., Marais, E.A., Duarte, F. and Ratti, C., (2020). Combining low-cost, surface-based aerosol monitors with size-resolved satellite data for air quality applications. *Atmospheric Measurement Techniques Discussions*, pp.1-30.
- deSouza P, Nthusi V, Klopp JM, et al (2017) A Nairobi experiment in using low cost air quality monitors. *Clean Air J Tydskr Vir Skoon Lug* 27:12–42
- deSouza P (2018) EVERY BREATH YOU TAKE: Who is monitoring air quality in Kenya? | The Elephant. <https://www.theelephant.info/features/2018/07/05/every-breath-you-take-who-is-monitoring-air-quality-in-kenya/>. Accessed 1 Aug 2020
- Dominici F, Peng RD, Bell ML, et al (2006) Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA* 295:1127–1134. <https://doi.org/10.1001/jama.295.10.1127>
- Egondi T, Ettarh R, Kyobutungi C, et al (2018) Exposure to Outdoor Particles (PM_{2.5}) and Associated Child Morbidity and Mortality in Socially Deprived Neighborhoods of Nairobi, Kenya. *Atmosphere* 9:351. <https://doi.org/10.3390/atmos9090351>
- Gaita SM, Boman J, Gatari MJ, et al (2014) Source apportionment and seasonal variation of PM_{2.5} in a Sub-Saharan African city: Nairobi, Kenya. *Atmospheric Chem Phys* 14:
- Gaita SM, Boman J, Gatari MJ, et al (2016) Characterization of Size-Fractionated Particulate Matter and Deposition Fractions in Human Respiratory System in a Typical African City: Nairobi, Kenya. *Aerosol Air Qual Res* 16:2378–2385. <https://doi.org/10.4209/aaqr.2016.01.0019>
- Gatari M, Boman J, Maina D (2005) Trace element categorization of pollution sources in the equator town of Nanyuki, Kenya. *X-Ray Spectrom* 34:118–123. <https://doi.org/10.1002/xrs.771>

Gatari MJ, Boman J (2003) Black carbon and total carbon measurements at urban and rural sites in Kenya, East Africa. *Atmos Environ* 37:1149–1154. [https://doi.org/10.1016/S1352-2310\(02\)01001-4](https://doi.org/10.1016/S1352-2310(02)01001-4)

Gatari MJ, Boman J, Maina DM (2001) Inorganic element concentrations in near surface aerosols sampled on the northwest slopes of Mount Kenya. *Atmos Environ* 35:6015–6019. [https://doi.org/10.1016/S1352-2310\(01\)00393-4](https://doi.org/10.1016/S1352-2310(01)00393-4)

Gatari MJ, Boman J, Wagner A (2009a) Characterization of aerosol particles at an industrial background site in Nairobi, Kenya. *X-Ray Spectrom* 38:37–44. <https://doi.org/10.1002/xrs.1097>

Gatari MJ, Kinney PL, Yan B, et al (2019) High airborne black carbon concentrations measured near roadways in Nairobi, Kenya. *Transp Res Part Transp Environ* 68:99–109. <https://doi.org/10.1016/j.trd.2017.10.002>

Gatari MJ, Pettersson JBC, Kimani W, Boman J (2009b) Inorganic and black carbon aerosol concentrations at a high altitude on Mt Kenya. *X-Ray Spectrom* 38:26–36. <https://doi.org/10.1002/xrs.1094>

Gatebe C, Kinyua A, Mangala M, et al (2005) Determination of suspended particulates matter of major significance to human health using nuclear techniques in Kenya. *J Radioanal Nucl Chem* 203:125–134. <https://doi.org/10.1007/bf02060387>

Gatebe C, Kinyua A, Mangala M, et al (1996) Determination of suspended particulates matter of major significance to human health using nuclear techniques in Kenya. *J Radioanal Nucl Chem* 203:125–134

Gitari WM, Kinyua AM, Kamau GN, Gatebe CK (2010) Elemental Composition of Suspended Particulate Matter Collected at Two Different Heights above the Ground in A Sub-Urban Site in Kenya. *Ethiop J Environ Stud Manag* 3:. <https://doi.org/10.4314/ejesm.v3i3.63961>

Henne S, Junkermann W, Kariuki JM, et al (2008a) Mount Kenya Global Atmosphere Watch Station (MKN): Installation and Meteorological Characterization. *J Appl Meteorol Climatol* 47:2946–2962. <https://doi.org/10.1175/2008JAMC1834.1>

Henne S, Klausen J, Junkermann W, et al (2008b) Representativeness and climatology of carbon monoxide and ozone at the global GAW station Mt. Kenya in equatorial Africa. *Atmospheric Chem Phys* 8:3119–3139. <https://doi.org/10.3929/ethz-b-000075725>

Jansen Karen L., Larson Timothy V., Koenig Jane Q., Mar Therese F., Fields Carrie, Stewart Jim, Lippmann Morton, 2005. Associations between Health Effects and Particulate Matter and Black Carbon in Subjects with Respiratory Disease. *Environ. Health Perspect.* 113, 1741–1746. <https://doi.org/10.1289/ehp.8153>

Janssen Nicole A.H., Hoek Gerard, Simic-Lawson Milena, Fischer Paul, van Bree Leendert, ten Brink Harry, Keuken Menno, Atkinson Richard W., Anderson H. Ross, Brunekreef Bert, Cassee Flemming R., 2011. Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM10 and PM2.5. *Environ. Health Perspect.* 119, 1691–1699. <https://doi.org/10.1289/ehp.1003369>

Karue J, Kinyua A, El-Busaidy A (1992) Measured components in total suspended particulate matter in a Kenyan urban area. *Atmospheric Environ Part B Urban Atmosphere* 26:505–511

Kimayu JM, Gikuma-Njuru P, Musembi DK (2017) Temporal and spatial variability of tropospheric ozone in Nairobi City, Kenya

Kinney PL, Gichuru MG, Volavka-Close N, et al (2011) Traffic impacts on PM2.5 air quality in Nairobi, Kenya. *Environ Sci Policy* 14:369–378. <https://doi.org/10.1016/j.envsci.2011.02.005>

[Kisambe S \(2017\) Kenya named World's Least Toxic country. In: CGTN Afr. https://africa.cgtn.com/2017/02/03/kenya-named-worlds-least-toxic-country/. Accessed 18 Jun 2020](https://africa.cgtn.com/2017/02/03/kenya-named-worlds-least-toxic-country/)

Klausen J, Henne S, Zellweger C, et al (2009) Surface Ozone and Carbon Monoxide Variability and Trends at the Global GAW Stations Assekrem (Algeria), Bukit Koto Tabang (Indonesia) and Mt. Kenya (Kenya). 11:8409

Lee S, Russell AG, Baumann K (2007) Source Apportionment of Fine Particulate Matter in the Southeastern United States. *J Air Waste Manag Assoc* 57:1123–1135. <https://doi.org/10.3155/1047-3289.57.9.1123>

Maina EG, Gachanja AN, Gatari MJ, Price H (2018) Demonstrating PM2.5 and road-side dust pollution by heavy metals along Thika superhighway in Kenya, sub-Saharan Africa. *Environ Monit Assess* 190:251. <https://doi.org/10.1007/s10661-018-6629-z>

Mbandi, A.M., Böhnke, J.R., Schwela, D., Vallack, H., Ashmore, M.R., Emberson, L., 2019. Estimating On-Road Vehicle Fuel Economy in Africa: A Case Study Based on an Urban Transport Survey in Nairobi, Kenya. *Energies* 12, 1177. <https://doi.org/10.3390/en12061177>

Miriri D. (2019) Kenya to restrict second-hand imports to boost domestic car sector. Reuters. <https://www.reuters.com/article/kenya-autos/kenya-to-restrict-second-hand-imports-to-boost-domestic-car-sector-idUSL8N1ZN3Z2> Last accessed Aug 1, 2020.

Mukaria SM, Wahome RG, Gatari M, et al (2017) Particulate Matter from Motor Vehicles in Nairobi Road Junctions Kenya. *J Atmospheric Pollut* 5:62–68

Nairobi Air Quality Action Plan 2019-2023. https://www.eci-africa.org/wp-content/uploads/2019/05/Nairobi-Air-Quality-Action-Plan_Final_ECI_31.12.2018.pdf . Last accessed Aug 1, 2020

Ngang'a JK, Ngugi GK (1986) Some features of aitken nuclei in Nairobi. *Atmospheric Environ* 1967 20:793–796. [https://doi.org/10.1016/0004-6981\(86\)90196-4](https://doi.org/10.1016/0004-6981(86)90196-4)

Ngo NS, Gatari M, Yan B, et al (2015) Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: A pilot study in Nairobi, Kenya. *Atmos Environ* 111:179–184. <https://doi.org/10.1016/j.atmosenv.2015.04.008>

Odhiambo GO, Kinyua AM, Gatebe CK, Awange J (2010) Motor Vehicles Air Pollution in Nairobi, Kenya. *Research Journal of Environmental and Earth Sciences*, 2(4), pp.178-187.

[Petkova EP, Jack DW, Volavka-Close NH, Kinney PL \(2013\) Particulate matter pollution in African cities. *Air Qual Atmosphere Health* 6:603–614. <https://doi.org/10.1007/s11869-013-0199-6>](#)

Pope FD, Gatari M, Ng'ang'a D, et al (2018) Airborne particulate matter monitoring in Kenya using calibrated low cost sensors [discussion paper]. *Atmospheric Chem Phys Discuss*

Samet JM, Zeger S, Dominici F, et al (2000) The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. *Res Rep*

Serwanjja S. (2019) Kenya pollution: How air sensors are helping people fight pollution. BBC News. <https://www.bbc.com/news/world-africa-50647465> Last accessed Aug 1, 2020.

Shilenje Z, Thiong'o KT, Ondimu KI, et al (2015) Ambient air quality monitoring and audit over Athi River Township, Kenya. *Int J Sci Res Environ Sci* 3:291–301

Shilenje ZW, Ongoma V (2014) Observed surface ozone trend in the year 2012 over Nairobi, Kenya. *Atmósfera* 27:377–384

Shilenje ZW, Thiong'o K, Ongoma V, et al (2016) Roadside air pollutants along elected roads in Nairobi City, Kenya. *J Geol Geophys* 5:1–10

Singh A, Avis WR, Pope FD (2020) Visibility as a proxy for air quality in East Africa. *Environ Res Lett* 15:084002. <https://doi.org/10.1088/1748-9326/ab8b12>

[State of Global Air. <https://www.stateofglobalair.org/>. Accessed 18 Jun 2020](#)

[Sullivan TJ, Driscoll CT, Beier CM, et al \(2018\) Air pollution success stories in the United States: The value of long-term observations. *Environ Sci Policy* 84:69–73. <https://doi.org/10.1016/j.envsci.2018.02.016>](#)

Teather K, Critchley K, Ross E, et al (2015) Air quality and children's health in rural Kenya. *WIT Trans Ecol Environ Air Pollut XXIII* 198:217–226

Vliet EDS van, Kinney PL (2007) Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. *Environ Res Lett* 2:045028. <https://doi.org/10.1088/1748-9326/2/4/045028>

West SE, Büker P, Ashmore M, et al (2020) Particulate matter pollution in an informal settlement in Nairobi: Using citizen science to make the invisible visible. *Appl Geogr* 114:102133. <https://doi.org/10.1016/j.apgeog.2019.102133>

Yamamoto, K., Kitanishi-Shirai, E., Inoue, Y., Hasegawa, M., Wandera, E., Ichinose, Y., Kanba, S. and Kondo, T., (2015). Use of metal mesh sensors with periodic microstructures to sense and separate aerosol particles in Kenya. *IEEE SENSORS* (pp. 1-4). IEEE.

Yin X, Yamamoto K, Wandera EA, et al (2018) Separation, Sensing, and Metagenomic Analysis of Aerosol Particles Using MMD Sensors. In: 2018 IEEE SENSORS. pp 1–4

Zhang H, Hu J, Kleeman M, Ying Q (2014) Source apportionment of sulfate and nitrate particulate matter in the Eastern United States and effectiveness of emission control programs. *Sci Total Environ* 490:171–181. <https://doi.org/10.1016/j.scitotenv.2014.04.064>