Research article
Analysis of air quality issues and air quality management status in five major African cities

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Received: 15 March 2023 - **Reviewed:** 5 June 2023 - **Accepted:** 12 July 2023
https://doi.org/10.17159/caj/2023/33/2.15605

Abstract
Poor air quality is one of the main dysfunctions of the rapid urbanisation process in Africa. Although the information is fragmented, the limited evidence available points out that air quality is a leading health risk in Africa, especially affecting the poorest, most vulnerable communities. In this study, we look into five cities in Africa to understand the nature of urban air quality issues and to delve into the initial responses. We report on the status of the main air quality management dimensions, including air quality standards and monitoring strategy/capabilities, emission inventories and air quality modelling, health impact assessment studies, communication practices, development and implementation of clean air action plans (in connection with other relevant strategies, i.e. climate change policies) and governance issues. We find that all cities have limited monitoring capabilities although communication strategies may differ substantially. While indoor pollution sources are declining in more developed economies, traffic is a growing concern in all five cities. In most cases, air quality issues are mostly related to $PM_{2.5}$ and natural contributions worsen air pollution from road transport, biomass and open waste burning. While nationally-driven strategies, often based on large-scale engineering projects and financial schemes, may report substantial gains in early stages, multi-level governance and planning is likely to maximize benefits and provide a useful framework for the complex problem of air quality management in the long run. The integration of air quality plans in overarching strategies to tackle persistent poverty and social inequity is urgently needed.

Keywords
urban air quality, air quality standards and monitoring, emissions inventories and modelling, communication, clean air action plans, governance

Introduction
Urbanisation has historically been accompanied by industrialisation, economic growth and better living standards for citizens. However, demographic growth requires public policies to steer the urbanization process and to help ensure a more equitable distribution of wealth (UN Habitat, 2010), especially in the context of rapid population movements towards urban areas. While Africa currently is the least urbanised of the settled continents, it is experiencing the fastest rate of urbanisation in the world, with an average annual growth rate of 2.55% in the period 2000 – 2015. Such trends are expected to cause the urban population of the continent to rise from 1.3 billion today to a projected 2.5 billion by 2050 (UN, 2019). Many parts of Africa seem to be experiencing urbanisation without significant productivity increases or adequate service provision, infrastructure and regulation, leading to the “urbanisation of poverty”. At present in sub-Saharan Africa, 59% of the urban population live in slums (UN Habitat, 2016), while only 45% have access to basic sanitation facilities. Many cities have evolved as a collection of fragmented neighbourhoods not connected by efficient transportation or other networked infrastructure; this results in congestion and other dysfunctions such as poor air quality (Stanaway et al., 2018) and high population exposure in urban areas where both emissions from unplanned and unregulated activities occur.

While the major cities on the continent do not experience the same levels of chronic air pollution as some cities in Asia do (Lelieveld et al., 2015), available data suggests that African cities are bearing a considerable share of the global burden of air pollution-related disease. The limited literature on air pollution in Africa identifies particulate matter (PM) as the single most relevant pollutant from a public health perspective (Burnett et al., 2018), even when PM chemical composition is usually not characterized. The review of PM source apportionment analyses carried out by Karagulian et al. (2015) identified eleven such studies for Africa (out of 419 for the entire world). On average, the largest contributor to $PM_{2.5}$ ambient concentration is household fuel burning, responsible for 34% of total concentration –the largest relative concentration on the planet. Natural sources (desert dust and sea salt) were the second source in importance, accounting for 22% of $PM_{2.5}$. (For comparison, natural sources represent the largest share of ambient concentrations in Middle-eastern countries, as much as 52%). Traffic was identified as the third largest contributor to $PM_{2.5}$ levels in Africa, with a 17% share. This sector was, however, the main cause of PM_{10} levels, contributing around 34% of the total ambient concentration of this pollutant on the continent. Other studies have identified open-field burning activities as a major source of this pollutant in Africa (Naidja et al., 2018). According to the continental DACCIWA inventory (Keita et al., 2018), PM emissions from the residential sector, mostly related to household solid fuel combustion, represent more than 70% of total combustion sources on the continent. As a consequence, African cities need to deal with both indoor and outdoor air pollution, in contrast with OECD country cities, where indoor air quality is driven by outdoor concentration levels (Tang et al., 2018).

Traffic is a relevant polluting sector in nearly all African cities, and its relative importance is expected to grow substantially in the near future (Liousse et al., 2014). Use of old cars, the poor quality of fuel or diesel fuel, underdeveloped infrastructures, and unorganized public transport (Assamoi & Liousse, 2010) are common challenges in African cities, contributing to worsening air pollution (Mbow-Diokhane, 2019). It should be noted that exhaust emissions are not the only source of PM from mobile sources – abrasion (road, brake and tyre wear) and dust re-suspension can be even larger contributors to PM emissions. Non-exhaust emissions are particularly relevant in Africa where unpaved roads make up the majority of the road network (Naidja et al., 2018).

While deaths attributable to other risk factors such as unsafe water, unsafe sanitation, and childhood malnutrition have decreased markedly since 1990, air pollution-related deaths have risen in Africa (Roy, 2016) and remain a major public health issue. Heft-Neal et al. (2018) suggest that modest reductions in the levels of fine particulate matter ($PM_{2.5}$) in the air in African cities may have larger health benefits to infants than most known health interventions. There is a clear economic case to deal with air pollution in Africa as well. The World Bank estimates that, in 2013, air pollution costs in Sub-Saharan Africa totalled 3.8 percent of GDP (WB, 2016). This means that the loss in economic output due to air pollution-related morbidity and mortality may be as high as USD 1.63 billion in countries like Ghana (Fisher et al. 2021). In addition, since the emissions of air pollutants often coincide with the release of greenhouse gases, worsening air quality is intimately related to global warming. The impacts of climate change have been identified as an additional, growing health threat in Africa, especially for the more vulnerable layers of society (Chersich et al., 2018).

This underpins the importance of prioritizing air quality interventions in the political agenda of African major cities. To contribute to that goal this study analyses the current air pollution issues as well as air quality management and initial responses in five illustrative cities in the continent. Comprehensive studies regarding air quality management status in Africa are very limited (Schwela, 2012) and there are no studies comparing approaches in specific urban areas that may illustrate effective options to improve air quality in the continent. This research is done in the framework of an initiative of UN Habitat to raise awareness about the issue of urban air quality in Africa (UN Habitat, 2023) and ultimately, aims at extracting general conclusions and identifying effective approaches to improve urban air quality in the whole African region. The specific scientific goals are to understand urban air quality issues (current ambient concentration levels of any pollutant relevant to air quality, sources, and impacts related to them) and analyse whether interventions from national, regional, or local administrations as well as any other initiatives driven by international institutions, donors, companies or the civil society are adequately targeted to those issues and draw conclusions and recommendations that may improve air quality management in Africa and curb harmful emissions in an efficient way considering limitations and constraints of real cities.

Methodology

Case studies

The case studies selected to investigate air quality issues and policies in African cities correspond to five large (capital) cities that cover a variety of geographical locations (Figure 1) and socio-economic development stages (Table 1) (in alphabetical order): Accra (Ghana), Cairo (Egypt), Cape Town (South Africa), Dakar (Senegal) and Nairobi (Kenya). While all of them face similar challenges related to rapid urbanization, social inequalities and population growth, each presents specific air quality issues and has different constraints and prospects and thus, they may contribute to building a more comprehensive picture and help identify policy approaches toward air quality issues in other urban areas in the continent. The selection criteria included the availability of information as well as previous cooperation track with UN-Habitat and an on-the-ground presence to assure the accuracy and relevance of the analysis. Further details on socio-economic and geophysical conditions and specific emission sources in each city can be found in UN Habitat (2023).

According to Stanaway et al. (2018) total premature deaths per annum from outdoor (ambient) air pollution are on the rise in the case study countries (Figure 2). In all of them, premature deaths from air pollution per annum outstrip deaths from unsafe water, sanitation, and underweight childhood (Roy, 2016). Since about 2005, the five countries under review have collectively had some success in curbing premature deaths from

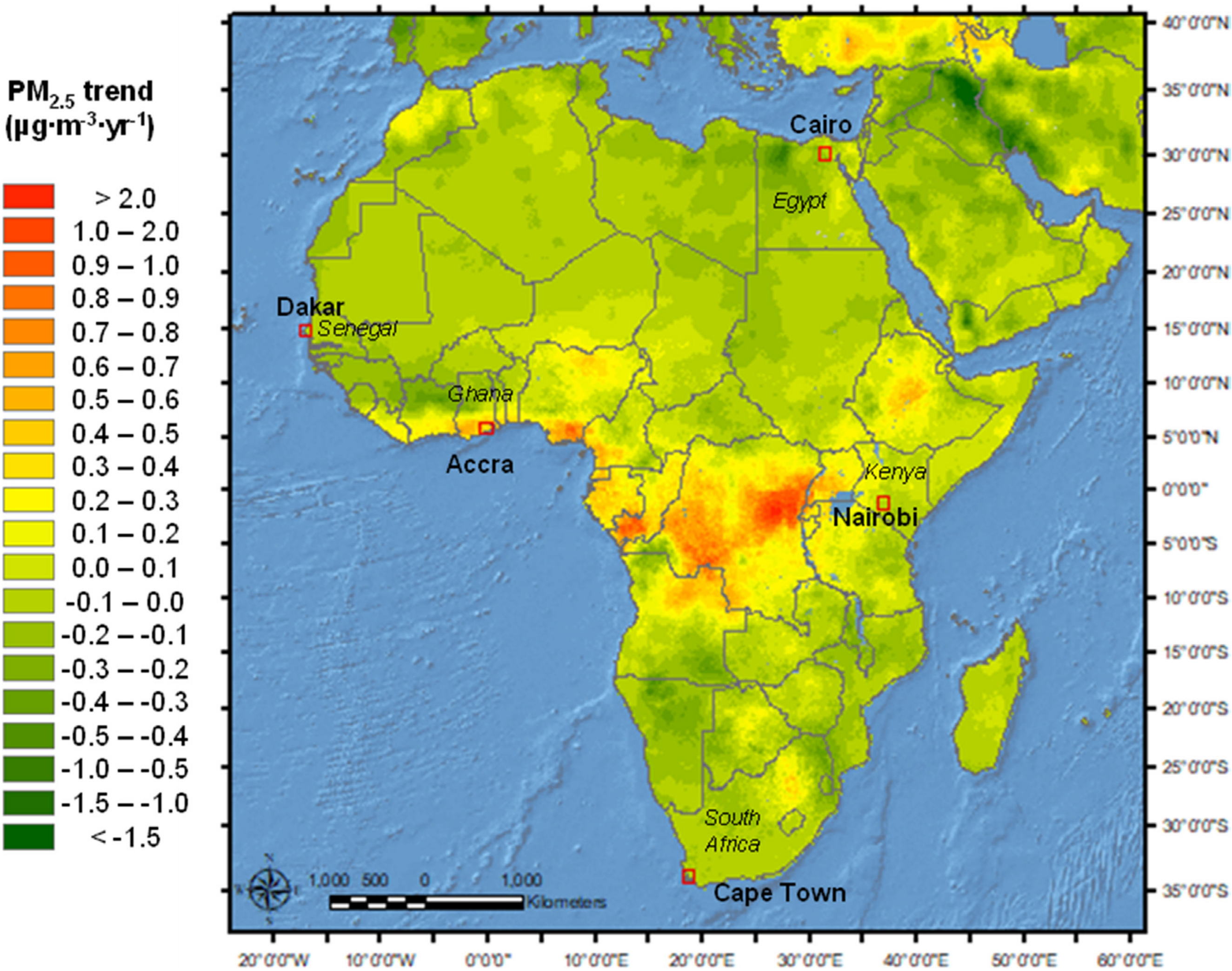

Figure 1: *Anthropogenic $PM_{2.5}$ ambient concentration trends in the 2000-2016 period and location of the five case studies (elaborated from van Donkelaar et al., 2018)*

Table 1: *Summary of socio-economic and demographic information of the five case studies*

City	Country, national GDP (USD)[1] and poverty headcount ratio (%)[2]	Population (million people)[3]	Recent annual growth rate (%) and future projections (%)[4]
Accra	Ghana, 4738 (56.9%)	2.3	2.1% / 2.2%
Cairo	Egypt, 12390 (61,9%)	18.8	2.2% / 2.0%
Cape Town	South Africa, 13730 (57.1%)	4.1	2.6% / 1.9%
Dakar	Senegal, 3776 (88.1%)	2.8	2.6% / 3.0%
Nairobi	Kenya, 3461 (86.5%)	3.9	3.8% / 3.9%

(1) GDP per capita, PPP (current international $) (WB, 2018)
(2) Poverty headcount ratio at $5.50 a day (2011 PPP) (% of population) (WB, 2018)
(3) 2018 population according to UN (population division) (UN, 2019)
(4) Average population growth rate (2000-2015) and growth rate projection (2015-2030) according to UN (population division) (UN, 2019)

indoor air pollution. More specifically, available data (Stanaway et al., 2018) suggest that household air pollution is generally a larger health concern in the lower income countries while high ambient air concentrations have greater relative importance in emerging economies. The trends in Egypt and South Africa clearly show that the burdens of disease have shifted towards outdoor (ambient) air quality over the last years while per capita GDP has grown; meanwhile, indoor air quality still dominates health impacts in Senegal, Kenya and Ghana (Figure 3).

Mortality rates attributed to the joint effects of household and ambient air pollution vary considerably among countries,

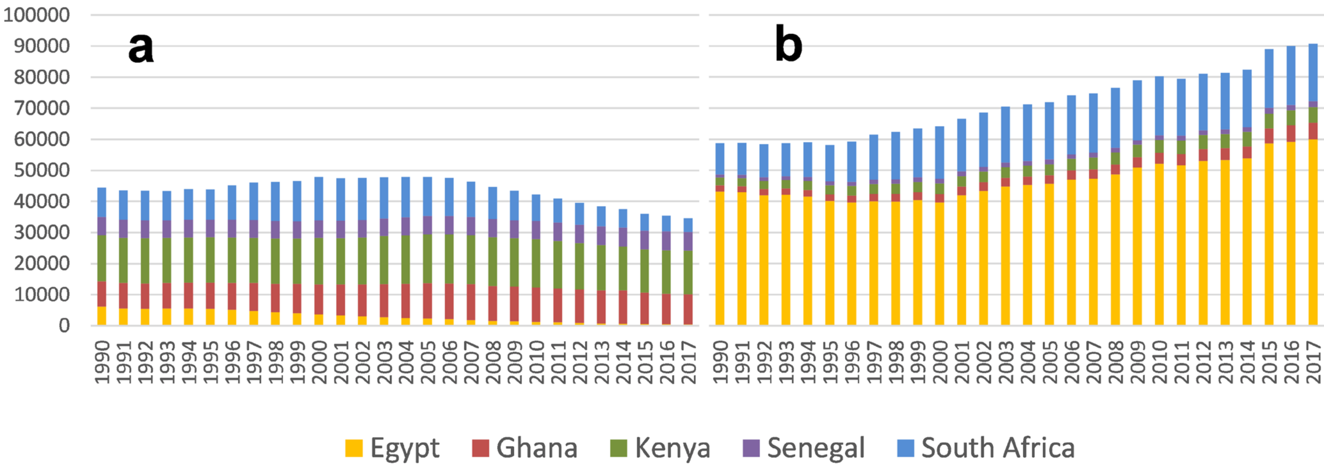

Figure 2: *Total deaths associated with air pollution in the countries where the five case study cities are located, according to the global burden of disease 2017, a) indoor, b) outdoor (elaborated from Stanaway et al., 2018)*

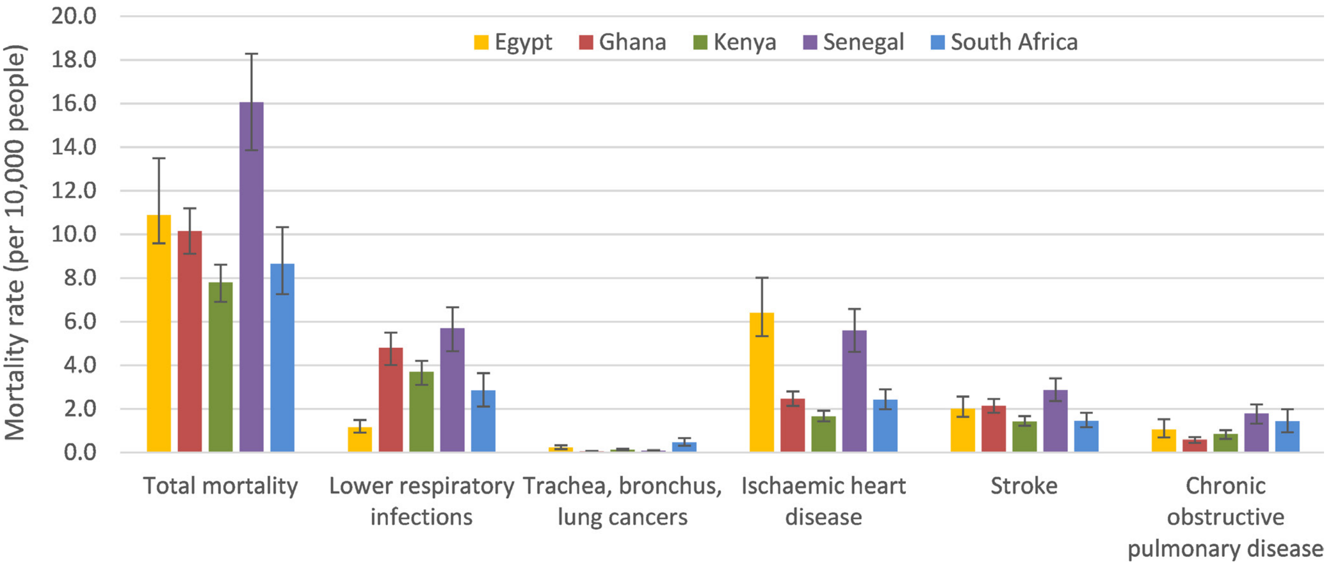

Figure 3: *Mortality rates attributed to joint effects of household and ambient air pollution (elaborated from the Global Health Observatory data repository, WHO, 2016). The bars show the 95% confidence intervals.*

as well as in the diseases that cause those death (Figure 3). According to the Global Health Observatory (WHO, 2016), lower respiratory infections are the leading cause of air pollution-related mortality in Ghana and Kenya, while ischemic heart disease dominates such deaths in Egypt. These two conditions have a similar contribution to premature deaths in Senegal and South Africa. Overall, Senegal presents the highest mortality rate due to air pollution.

Approach and data sources

The research relies on a desk review of scientific papers published in international journals as well as official reports and thematic studies from reference international organizations. No specific search or selection criteria were set regarding the type of documents or production dates, although preference was given to contrasted sources and updated information. Data scarcity (e.g. the lack of local emission inventories or reliable air quality data) prevents us from performing a fully consistent comparison and analysis. Therefore, any reliable source that may help understanding the current status and trends of emissions (any potentially relevant pollutant), air quality, or impacts has been considered. To present a synthetic and harmonized view of the status of the five cities analysed, we rely on the combination of: (i) fully comparable, globally available data with (ii) any other local or national specific data and references that may be relevant to illustrate the relative stages of progress towards a comprehensive air quality management strategy. The information discussed in the following section consists of:

- Emissions and air quality: estimated emissions of organic carbon (OC) and black carbon (BC) emissions elaborated from the most updated and comprehensive regional inventory available for Africa (Keita et al., 2018), available at the Emissions of atmospheric Compounds and Compilation of Ancillary Data (ECCAD) website. The DACCIWA (Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa) inventory provides emission fields at 0.125° x 0.125°

spatial resolution (broadly 10 km horizontal resolution) for the entire African continent from 1990 to 2015. It extends and improves the only previous regional inventory available (Liousse et al., 2014) by establishing an African database on fuel consumption and new emission factor measurements, including biofuel and fossil fuel emissions as well as open waste burning emissions. Primary (directly emitted) anthropogenic particles are largely made of OC and BC (Bond et al., 2004) and therefore, they constitute a good proxy of combustion-related PM emissions. The reference inventory provides emission estimates from the main anthropogenic sources (energy, industries, residential, transportation, waste, and other sectors). This is complemented with city-specific information and references including technical reports, journal papers, plans and strategies related to air quality measurements from permanent monitoring networks or ad hoc experimental monitoring campaigns, emission inventories, air quality modelling activities, source apportionment studies, health impact assessments, cost-benefit analyses, etc.

- Summary of the response given to the air quality issues portrayed in the previous point under a common structure (UNEP, 2016): relevant initiatives regarding 1) air quality standards, regulations and plans, 2) vehicle emissions, 3) public and non-motorized transport, 4) industrial emissions, 5) open burning of waste, and 6) indoor air pollution are briefly summarized. The main interest is to discuss the lessons learned from recent actions as well as ongoing initiatives that may be relevant for future planning or inspiring other urban areas with similar status. The discussion for each city includes national (even international) instruments and then those that are primarily driven by regional or local administrations and try to make links among them since very often they are tightly interrelated given the multi-level nature of air quality governance.

The Conclusions section is structured following the six framework areas proposed in the Guidance Framework for Better Air Quality in Asian Cities developed by UN Environment and Clean Air Asia (Clean Air Asia, 2016).

Discussion

Emissions and air quality issues

The sources of emissions vary considerably from city to city. While the five case study cities share some commonalities, they show considerable variations (Figure 4). The residential sector appears to be the main source of emissions of organic carbon for four of the five cities (Dakar, Accra, Cape Town and Nairobi); however, in the megacity of Cairo, the waste sector predominates. For black carbon, the dual importance of the waste and residential sectors appears evident in Dakar and Cape Town. In Cairo, nonetheless, the waste sector dominates BC emissions, with the residential sector assuming little importance, while the reverse is true in Nairobi. The reasons for such differences are complex but are partly related to the varying levels of socio-economic development achieved in their respective countries. The main implication of these differences is that, when addressing air quality at the city level, customized, well-targeted clean air action plans should be specifically designed.

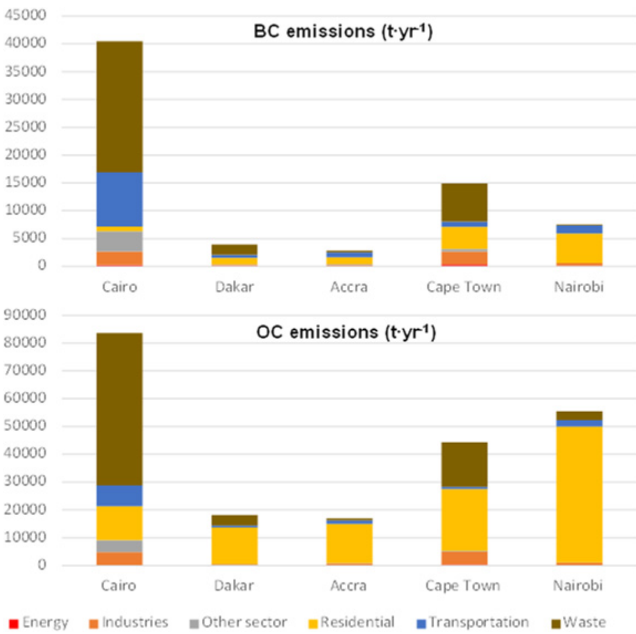

Figure 4: *PM emissions in the five target cities (t) in 2015. Elaborated from DACCIWA gridded inventory (Keita et al., 2018). BC = black carbon, OC = organic carbon*

Emission rates shown in Figure 4 originate from the overlapping of the DACCIWA gridded inventory in a 120x120 km geographical domain for each city. Total emissions in those reference areas are shown in Figure 5 (black carbon) and Figure 6 (organic carbon). The maps show the road network according to the information published by SEDAC from Global Roads Open Access Data Set, Version 1 (gROADSv1) (Columbia University and University of Georgia, 2013) and administrative boundaries, taken from the GADM database version 3.4 (GADM, 2018).

Accra

According to air quality data from Accra's monitoring network (EPA, 2018), annual average concentration in Accra in the 2006-2017 period ranged from 55-78 µg/m^3, and 85-130 µg/m^3 for $PM_{2.5}$ and PM_{10} respectively, without a clear trend (Appoh, 2018). According to Ghanese EPA (EPA, 2016), 90.2% of PM_{10} measurements from roadside monitoring sites levels recorded in 2015 exceeded the EPA guideline for that particulate matter (70 µg/m^3 for the 24-h mean). Although the network suffers from frequent breakdowns and data availability is below 50% (Schwela, 2012), $PM_{2.5}$ present a remarkable monthly variability reaching up to 209 µg/m^3 in December 2015 (EPA, 2018). Such high pollution episodes during the dry season have been related to the Harmattan wind, a natural phenomenon that contributes to the load of particulate matter travelling south from the Sahara Desert (Zhou et al., 2013).

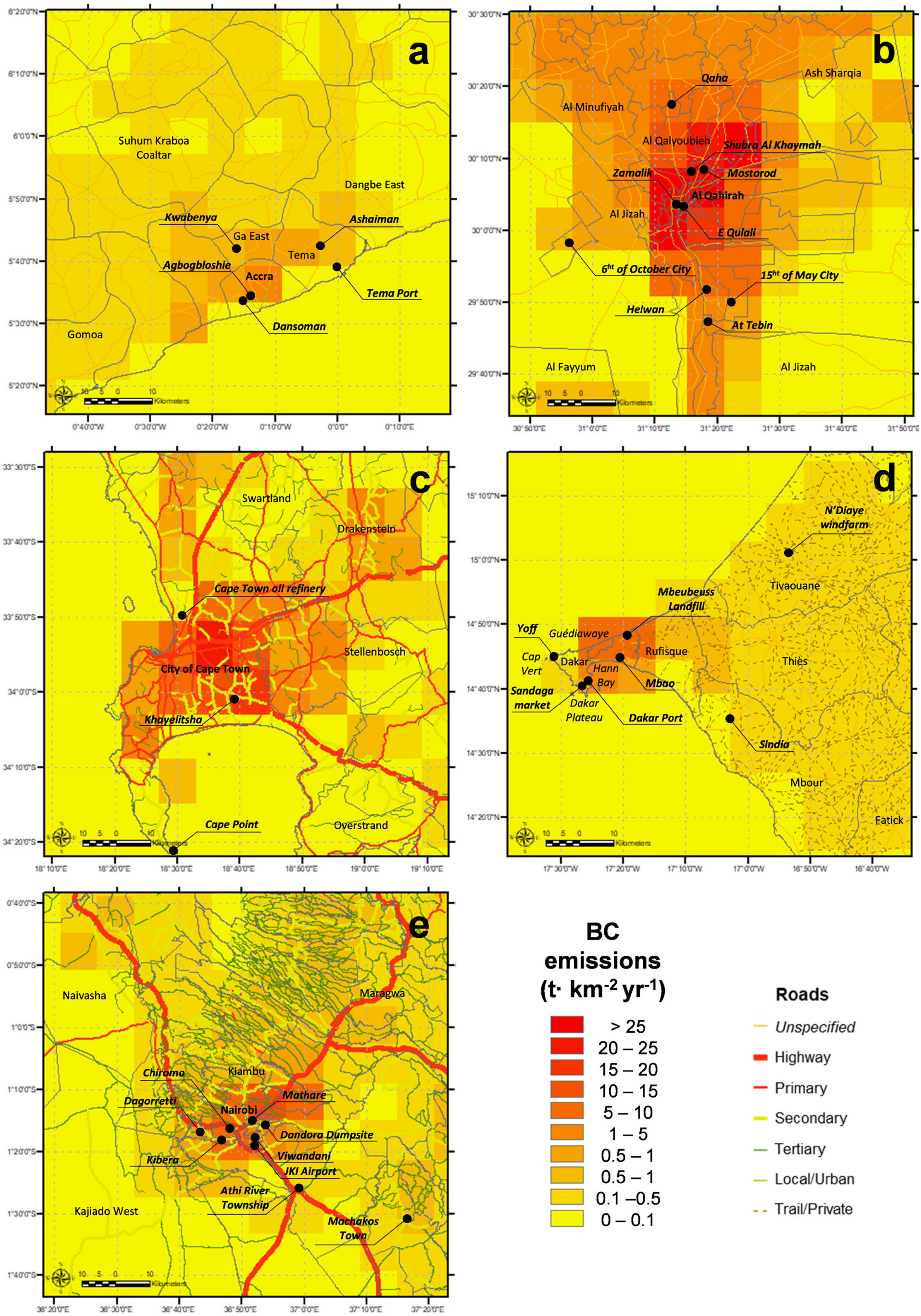

***Figure 5:** Black carbon emissions in the five target cities (t) in 2015, a) Accra, b) Cairo, c) Cape Town, d) Dakar and e) Nairobi. Elaborated from DACCIWA gridded inventory (Keita et al., 2018)*

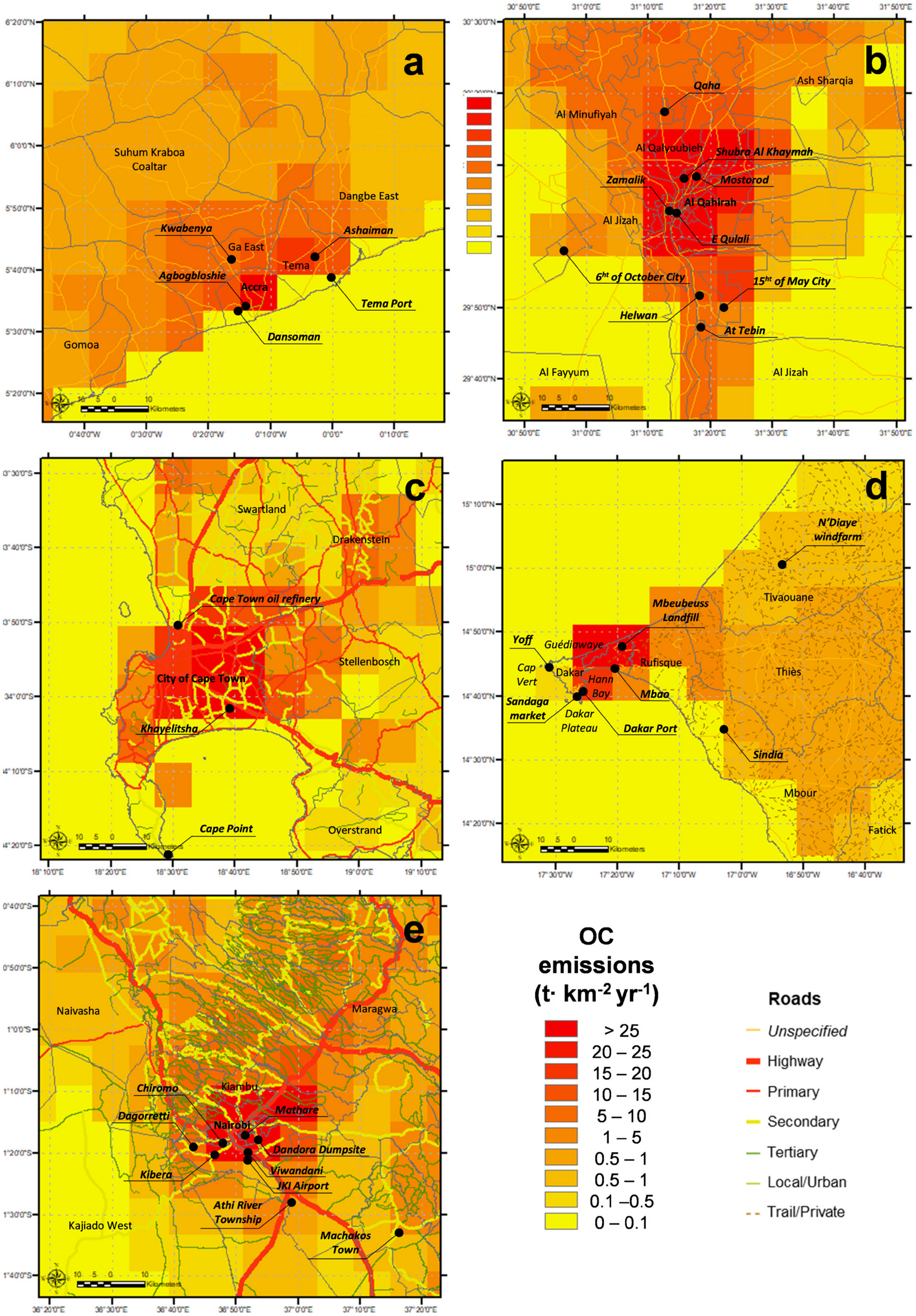

Figure 6: *Organic carbon emissions in the five target cities (t) in 2015, a) Accra, b) Cairo, c) Cape Town, d) Dakar and e) Nairobi. Elaborated from DACCIWA gridded inventory (Keita et al., 2018)*

Besides permanent monitoring schemes, air quality in Accra has been addressed by a number of limited time-frame studies and ad-hoc campaigns. Zhou et al. (2013) found that sea salt (up to 13.9 µg/m^3) and mostly mineral dust, were large contributors to ambient PM concentrations. During Harmattan wind episodes, crustal particles accounted for 55 µg/m^3 (37%) of $PM_{2.5}$ mass and 128 µg/m^3 (42%) of PM_{10} mass. This is consistent with the study of Aboh et al. (2009) that found PM crustal elements (dust) fraction to increase more than tenfold during the Harmattan period in Kwabenya, a suburb of Accra that is frequently exposed to dust from the Sahara–Sahel region during the dry season. Outside Harmattan, road traffic was found to be one of the largest contributors to PM, being responsible for approximately 12-33% of PM concentration. Biomass combustion was responsible for between 10.6 and 21.3 µg/m^3 of particulate matter in the study areas, affecting most of the poorest neighbourhoods.

Other relevant sources identified were vehicle emissions, tire and brake wear, road dust, and solid waste burning. While total PM_{10} concentration reached values as high as 179 µg/m^3, BC contents were only four µg/m^3 during 2006-2007 period analysed, highlighting the huge influence of natural PM. Arku et al. (2015) reported an average exposure of 56 µg/m^3 to $PM_{2.5}$ for school children in Accra (more than double the average exposure levels in the US or Europe) although there were large variations, from less than 10 µg/m^3 to more than 150 µg/m^3. They identified residential emissions (wood and charcoal burning for cooking) and dust emissions from unpaved roads as the most influential sources of exposure. Exposure to emissions from household cooking and garbage burning has been found to impact even the unborn. According to Amegah et al. (2012), these pollution sources significantly reduce birth weight in Accra. Studies carried out in cities like Kumasi (Bandowe et al., 2019) or Ashaiman (Ofosu et al., 2012) confirmed the influence of road traffic, including PM resuspension, particularly in low-income neighbourhoods. Industry (e.g. Tema Oil Refinery) emits considerable amounts of PM and other pollutants (NO_x, SO_2) and has a clear impact in closer urban areas such as the Tema Metropolis (Amoatey et al., 2018; Amoatey et al., 2019).

Cairo

As in many megacities in the world, air pollution has been a chronic problem in Greater Cairo. The first air quality measurements (SO_2 and smoke) were carried out by the Ministry of Health (MoH) in 1973 (Nasralla, 2001). In 1999, the Egyptian Environmental Affairs Agency (EEAA) initiated a more systematic air quality monitoring strategy towards the current National Air Quality Network of Egypt that includes 24 real-time continuous air monitoring and 25 sampling stations in the Greater Cairo Metropolitan Area (GCMA).

According to the PM_{10} levels recorded, air quality in Cairo met Egyptian air quality standards for that pollutant 72% of the time while $PM_{2.5}$ levels of 60-99 µg/m^3 have been reported for the city as an annual mean (EEAA, 2018). A significant drop between 1999-2009 has been observed for all pollutants, except for O_3 (WB, 2013). This trend has been observed in other urban areas where reduced NO_x emissions reductions from traffic lead to higher O_3 concentration levels due to non-linear photochemical processes (Saiz-Lopez et al., 2017).

Despite the declining trend, the rapid population growth (by more than 3 million from 1999 to 2010) has led to a net increase in population exposure to air pollution. Wheida et al. (2018) found an average PM_{10} of 155 (±35) µg/m^3 during the 2010-2015 period in GCMA, although large concentration gradients exist within the megacity. Similarly, average $PM_{2.5}$ concentrations varied from 50 to more than 100 µg/m^3. Both PM levels were affected by massive wind-blown desert dust since the city is within the Sahara region. With the exception of a few traffic hot spots, NO_2 concentrations were found to be below 40 µg/m^3, defined as an air quality standard in Egypt in accordance with the 2005 WHO guidelines (WHO, 2006). Some authors (Ndour et al., 2008) suggest that high natural dust loads in urban atmospheres may enhance the photocatalytic uptake of NO_2. Despite the increase of tropospheric O_3, further recent analyses confirm that current air quality issues in Cairo primarily concern PM (Mostafa and Zakey, 2018).

According to WB (2013), approximately 35–55% and 25-35% of the total concentration of PM_{10} is attributable to airborne geological material during the summer and winter, respectively. This is consistent with the findings of Boman et al. (2013) that also found a significant influence of marine aerosols. Earlier, Favez et al. (2008) observed maximum dust concentrations in spring and winter due to the higher frequency of dust storms, but noted high dust contribution throughout the year (around 50 µg/m^3). In addition, they reported that natural dust interacting with NO_x and SO_2 emissions adds secondary compounds to the atmospheric aerosol. Similarly, Hassanien and Abdel-Latif (2008) reported significant amounts of toxic polycyclic aromatic hydrocarbons (PAH), in road dust samples collected across Cairo.

An episodic deterioration in air quality through the so-called Black Cloud phenomenon is observed every October and November (WB, 2013) due to rice straw burning in the governorates around Cairo coinciding with typical autumn thermal inversions (Marey et al., 2010; Zakey et al., 2008). During these events, the aerosols originating from the burning of agricultural residue account for 12% of BC and up to 50% of OC (soluble fraction) (Favez et al., 2008). On the other hand, Mahmoud et al. (2008) concluded that traffic was the majority source of BC in Cairo during the daytime, even in autumn when biomass burning takes place in the Nile Delta.

Cape Town

The City of Cape Town (CCT) and the Department of Environmental Affairs and Development Planning (DEA&DP) operate an air quality network that measures criteria pollutants based on reference analytical techniques in accordance with the US EPA standardized methods (DEA&DP, 2019a). All the information is submitted to the South African Air Quality Information System (SAAQIS) where nearly real-time air quality information can be visualized and downloaded (https://saaqis.environment.gov.za).

Historically, SO_2 and PM_{10} have been the air pollutants of concern in South Africa (UNEP, 2016). Recent data show a general decrease in SO_2 ambient concentration levels, while there is not a clear trend regarding PM_{10} and increasing exceedances of O_3 (DEA&DP, 2019a). Currently air quality in the Western Cape Province is generally good, below the South African National Ambient Air Quality Standards (SANS). However, some hot spots, such as the Khayelitsha informal settlement, remain. The eight-hour mean SANS for ozone was exceeded on 19 occasions in 2018 at Khayelitsha, with values up to 175 µg/m³. High PM levels have been usually reported due to residential wood burning, waste burning and dust from unpaved roads, among other sources in this area (DEA&DP, 2016). A few, exceptionally high values (up to 387 µg/m³ in 1 hour) have been linked to wildfires in the surroundings of the city as well as windblown dust episodes responsible for daily PM_{10} levels up to 82 µg/m³ (DEA, 2012). Of note, no PM data from Khayelitsha station were available for the year 2018 due to insufficient measurements. Such information gaps are common throughout the country with less than 40% of the 94 monitors included in the national network meeting the minimum 70% data recovery rate for PM measurements (DEA, 2019) due to aging infrastructure and insufficient funding (DEA&DP, 2019a).

Wicking-Baird et al., (1997) studied the causes of pollution in the city using the Chemical Mass Balance (CMB) model (Watson et al., 1990) and concluded that visibility issues during brown haze episodes were mainly related to road traffic, responsible for 65% of total $PM_{2.5}$ mass. Other important sources of pollutants were combustion (14%), boilers (6%) and natural PM sources (5%). This situation has not changed significantly according to more recent studies that identified traffic, domestic burning of fuels, industry and waste burning as the major pollution sources in Cape Town (Mbow-Diokhane, 2019; Keen and Altieri, 2016).

Measurements of relevant anthropogenic VOC concentrations in Cape Town suggest that urban background concentrations of these pollutants are dominated by traffic or industrial sources in different areas of the city (Kuyper et al., 2020). Mumm et al. (2017) concluded that low socioeconomic districts generally experienced higher levels of air pollution. Similarly, Hersey et al. (2015) identified low-income townships and informal settlements as the worst-polluted areas in South Africa. This supports the claim made by Keen and Altieri (2016) that the largest health benefits of improving air quality in the city would be found in the Khayelitsha. Hersey et al. (2015) identified biomass burning (veld fires) and domestic burning in informal settlements as significant sources of PM_{10}. These authors found that dust enhancement was particularly high in May-July; contributions from the nearby Namib Desert may make up to 25% of total PM_{10}. Sea salt represented around 20% of total PM_{10} in Cape Town.

Higher-resolution modelling exercises confirm that high PM_{10} episodes in Cape Town are related to air masses travelling over major dust source regions such as the Kalahari or Namib Deserts (Molepo et al., 2019). The growing influence of windblown dust and wildfires on PM_{10} levels in Cape Town has been also linked to increasingly severe droughts in the Western Cape (DEA&DP, 2019a). In addition to negative air quality ramifications, climate change has been identified as a major health threat in South Africa, especially for vulnerable groups (Chersich et al., 2018). Nonetheless, greenhouse gas emissions in the country have raised by 20% in the 2000-2010 period (DEA, 2016) because of the coal dependency in the country (Klausbruckner et al., 2016).

Dakar

Senegal is the only country in West Africa that has set up a continuous air quality monitoring network (5 monitors) and created the Centre for Air Quality Management (Centre de Gestion de la Qualité de l'Air; CGQA) within the Urban Mobility Improvement Programme (PAMU). (Mbow-Diokhane, 2019). Frequent power failures (Cissokho & Seck, 2013) combined with specific technical and maintenance issues or the network (CGQA, 2018) result in low data availability. Nonetheless, data captured is made publicly available by CGQA (https://www.air-dakar.org) and through annual reports regarding air quality in Dakar (CGQA, 2018).

These reports suggest that PM is the most problematic pollutant, with annual average urban background levels as high as 182 µg/m³. Although PM is strongly affected by marine aerosols and windblown dust from the Sahara, air quality can be classified as good or moderate 52% and 34% of the time, respectively. Concentration peaks have been associated with the westward propagation of Harmattan pulses loaded with mineral dust from the desert (Rodríguez et al., 2019). On average, levels of PM_{10} are twice as high during the nine driest months than in the three wet months. AQI interannual evolution does not exhibit a clear pattern, and data deficiencies (average data availability range from 5% to 67% depending on the monitoring station) make it difficult to further identify pollution trends.

There are several studies that delve further into the pollution levels and causes in Dakar. Ndong Ba et al. (2019a) reported ambient PM_{10} average concentrations around 100 µg/m³ during the dry season in the 2017-2018 period. Previous campaigns revealed average $PM_{2.5}$ levels of 87 µg/m³ in a traffic location in Dakar, much higher than the concentrations measured in a rural area some 40 km away from the city (32 µg/m³) (Ndong Ba et al., 2019b). The coarser fraction of suspended PM, however, was quite constant in both locations (57 and 56 µg/m³ respectively), probably due to natural dust contributions. A comparison with the results from Dieme et al. (2012) suggests an increase of $PM_{2.5}$ levels in Dakar and its surroundings during recent years due to an increasing influence of traffic and of biomass burning. Several studies have identified traffic as the main source of air pollution in the city (Schwela, 2012; Sarr et al., 2018) with clear health implications, especially for individuals working along major streets (Ndong Ba et al., 2019a). Adon et al., 2016 monitored the concentration of the main gaseous pollutants in Dakar for two years (2008 and 2009) using passive samplers and found average NO_2 concentration levels of 31.7 ppb at a traffic site – three-fold higher than the corresponding value for urban background areas. In addition to the spatial variability, this study found that NO_2 concentrations over the dry season were 1.5 times higher than those of the wet period (three times higher for SO_2). The authors point out that besides favourable meteorological conditions, the wet period in Dakar coincides with a lower activity period (school vacation) and consequently, less emissions.

These findings are consistent with those of Doumbia et al. (2012) regarding particulate matter. Similarly, they identified traffic as the main pollution source, with an average contribution of 87% and 89% to total BC during the dry and wet seasons, respectively. The remaining 13%-11% was apportioned to biomass burning emissions. Besides anthropogenic sources, the contribution of natural windblown dust from the Sahara to PM levels in Dakar is well documented (Oluleye & Folorunsho, 2019). During Saharan dust episodes, PM_{10} and $PM_{2.5}$ ambient concentrations in Dakar can reach values in excess of 800 µg/m^3 and 350 µg/m^3, respectively (Jenkins & Diokhane, 2017). Although natural dust dominates PM concentration in Senegal, the largest burden of asthma and bronchitis in the country is found in Dakar (Toure et al., 2019), suggesting that urban emission sources also play a vital role on human health, and synergistic negative effects can be significantly diminished by cutting down anthropogenic emissions.

Nairobi

Despite the lack of a comprehensive, consistent and transparent city-wide monitoring strategy, some monitoring campaigns and pilot projects have been undertaken in Nairobi (Nthusi, 2017), including the use of novel sensor technology (Kumar et al., 2015). Despite technical limitations and issues related to data quality (WHO, 2018), such initiatives can contribute to increase awareness and thus, support for more effective air quality regulation (Ngo et al., 2017). This technology was used by de Souza et al. (2017) to monitor $PM_{2.5}$ and PM_{10} over an eight-month period (May 2016 to January 2017). They reported concentrations between 11 and 23 µg/m^3 and 26 and 59 µg/m^3, respectively. The NO_2 observed level oscillated between 8 and 12 ppb while the highest mean level of SO_2 was recorded at Viwandani (40 ppb), an informal settlement in the industrial area of Nairobi. Although these instruments were not calibrated with reference air quality monitors, the study suggests that pollution levels are usually higher in Kibera and Viwandani slums.

This is consistent with previous studies (Gulis et al., 2004; Egondi et al., 2016) that highlight that air quality issues are particularly serious in deprived neighbourhoods of Nairobi, a pattern also found in other African urban areas (Dionisio et al., 2010). Pope et al. (2018) also used low-cost sensors (calibrated against gravimetric measurements, in this case) to monitor $PM_{2.5}$ in Nairobi in February-March 2017 and found an average concentration of 36.6 µg/m^3 at a roadside; considerably higher than the 24.8 µg/m^3 observed in an urban background site and the 8.8 µg/m^3 measured in a rural location more than 100 km away from the city. The relevance of traffic to PM levels in the city was also pointed out by Kinney et al. (2011). They estimated a 24-hour average $PM_{2.5}$ personal exposure of 45-85 µg/m^3 along busy roads in Nairobi.

Similarly, van Vliet and Kinney (2017) estimated that roadway concentrations of $PM_{2.5}$ in Nairobi were approximately 20-fold higher than urban background levels (around 20 µg/m^3). Gatari et al. (2019) found that BC represented 34-56% of the total $PM_{2.5}$ mass during a one-month monitoring campaign (July 2019), with levels reaching 24-hour average values as high as 43 µg/m^3. This demonstrates that road traffic emissions are the dominant source of airborne $PM_{2.5}$ in curb-side locations. The proximity to traffic emissions was also found to be a key factor by Ngo et al. (2015). They found that a large fraction of $PM_{2.5}$ consisted of BC (vehicle smoke) due to poor engine maintenance of Nairobi's fleet. They further found that women in the Mathare slum experienced exposure to $PM_{2.5}$ at levels similar to roadside mechanics and street vendors (hawkers), since they spend a substantial amount of time near roadways.

This is again, directly related to environmental justice since poor pedestrians who cannot afford motorized transport are forced to walk long distances near traffic emissions (Klopp, 2012). Egondi et al. (2016) also demonstrated that residents in slums are continuously exposed to $PM_{2.5}$ levels exceeding hazardous levels according to the WHO guidelines, reaching average concentrations up to 166.4 µg/m^3, considerably higher values than those reported in other studies, even at curbside sites (Pope et al., 2018; Kinney et al., 2011). High concentrations in poor neighbourhoods in Nairobi may be attributed to very local sources, such as street markets that increase traffic as well as street cooking using biomass fuels.

The strong seasonality of pollution that peaks during the dry season (July in particular) suggests that PM levels may also be affected by dust transport and PM resuspension processes. The longest period of recorded ambient PM concentration in Nairobi is that reported by Gaita et al. (2014) who found average $PM_{2.5}$ urban background and suburban pollution levels of 21 (± 9.5) µg/m^3 and 13 (± 7.3) µg/m^3, respectively (at 17 m and ten m above the ground level). This study identified traffic as the largest contributor to airborne PM (39%). Despite the large emission share attributed to regional inventories (Figure 5 and Figure 6), waste burning, open fires and charcoal burning, typical of low-income households were responsible for six percent of total $PM_{2.5}$. A very high contribution of mineral dust, presumably from unpaved roads (35% on average; up to 74% of $PM_{2.5}$ in Nairobi during the dry season) was also highlighted.

Air quality management and responses

Accra

According to Appoh & Terry (2018), air quality management in Ghana can be considered advanced and the recent evolution of the country can be considered as an instructive case study of air quality management planning in a sub-Saharan Africa context. During recent decades, the country has developed an organizational structure and regulatory framework, including National Ambient Air Quality Guidelines (24-hour PM_{10} mean ≤ 70 μg/m^3). Ghana EPA expected the full implementation of AQ standards by June 2019 (EPA, 2018), although they are not enforced so far. Together with partners, launched a series of initiatives, many of them targeting Accra.

The development of the air quality monitoring network in Accra sets up a good example of the potential benefits of international collaboration, in this case in the context of the Air Quality Monitoring Capacity Building Project in cooperation with the United States Environmental Protection Agency (USEPA), the United States Agency for International Development (USAID) and UNEP. In Accra, we also see the fledgling work of the WHO's Urban Health Initiative to raise the necessary awareness through community-based actions and campaigns.

The consolidation of a robust democracy in Ghana provides the enabling environment (appropriate institutional, legal, and regulatory structures) for the successful development and implementation of air quality management systems. Building on these technical capacities and multi-level governance scheme, Ghana's Environmental Protection Agency (EPA) launched the Greater Accra Metropolitan Areas Air Quality Management Plan in 2018 (EPA, 2018). The first comprehensive air quality strategy for the Greater Accra Metropolitan Area intends to deal with a number of potential sources of air pollution, especially road traffic, which is becoming the main source of air pollution in Accra (Naidja et al., 2018). The plan establishes links to other relevant environmental strategies that can provide the framework for the promotion of recent successful sector-specific measures implemented in Accra, such as the Bus Rapid Transit System (BRT) project (EPA, 2017) or the Greater Accra Scrap Dealers Association (GASDA) in Agbogbloshie (Pure Earth, 2015). The plan includes specific indicators, time frames, responsibilities and collaborations needed that intend to comply with the national ambient air quality standards. The plan also contemplates the involvement of stakeholders and the population. More importantly, it identifies the capacity gaps that should be addressed for a successful implementation. Other initiatives to install new improved clean stoves and to promote the use of liquefied petroleum gas (LPG) have demonstrated a high potential to reduce personal exposure to $PM_{2.5}$ also in rural areas (Piedrahita et al., 2017).

Cairo

During the last decades, Cairo has faced virtually all of the underlying drivers that contribute to air quality degradation in megacities: a rapidly growing population and urban expansion, uncontrolled rural-to-urban migration, inadequate land use planning, as well as the unsustainable growth of the industrial zones and other heavy infrastructure sectors in and around the city. However, most ministries of the Egyptian government have established an environmental unit or department to deal with air pollution in their respective sectors (WB, 2013). As a result, considerable progress has been made in tackling air quality issues in the GCMA. Egypt has been able to channel international collaboration (DANIDA, USAID) to develop a full-scale urban air quality monitoring system in the Greater Cairo Metropolitan Area (Nasralla, 2011).

Projects such as EIMP or CAIP have been instrumental to identify the main issues and orientate national policies. In addition to the development of an emission inventory (WB, 2013), Cairo is the only city in this paper that has done a strategic analysis of future emission scenarios. Health impact assessment studies revealed that 4 550 premature deaths would be avoided every year in the GCMA if the PM_{10} Egyptian standard (annual average concentration of 70 μg/m^3) was met (Wheida et al., 2018), although other authors (Safar and Labib, 2010) suggest that the natural contribution to PM_{10} background will prevent Cairo from ever attaining this standard. Standards for NO_2, SO_2 and O_3 are relatively stringent for the region, comparable to the European ones. In addition, it has been estimated that air pollution represents 3 to 6% of the GDP (UNEP, 2004), making a clear economic case for emission abatement.

Conceptually, a multi-level governance scheme matches better the multi-scale reality of air quality. However, Egypt demonstrates that a strongly centralized management system may be more effective in the initial stages. Despite a lack of a specific plan per se, the massive introduction of natural gas in the domestic, industrial (EEAA, 2004), power generation (WB, 2013), and traffic sectors (Thomas, 2016), along with the development of large-scale engineering projects (Korkor, 2014) in Egypt has allowed improving air quality in Cairo despite intense population and traffic growth. Up to nine ministries have been actively developing legal and institutional mechanisms as well as programs and projects with international development cooperation partners to improve air quality in their respective sectors, often structured as Public Private Partnerships (WB, 2013). Some of them, such as the valorisation of agricultural waste in cement clinks have demonstrated the benefits of cross-sectoral measures to prevent pollution, improve the local economy and report climate co-benefits.

Cape Town

Air quality has drawn the attention of policymakers in South Africa for nearly two decades, making the country a reference point regarding air quality management in sub-Saharan Africa (Schwela, 2012). In addition to the national framework, the Provincial Government's 2016 Air Quality Management Plan (DEA&DP, 2016) is the current regional strategy that aims at improving air quality.

The South African air quality management system is arguably the most advanced one in the African continent. The administration decentralization in the country has allowed a multi-level governance scheme for air quality action, with a nationally set policy and regulatory framework (Republic of South Africa, 2013), and enforcement and compliance conducted by regional and local governments. The national air quality standards (SANS) are comprehensive and stringent (DEA, 2012), comparable to those of Europe (EC, 2008), currently under review.

The country has also made efforts towards effective ambient air quality monitoring and communication through the South African Air Quality Information System (SAAQIS) or the National Association for Clean Air (NACA) dissemination activities (Mbow-Diokhane, 2019). A number of projects have conducted meaningful modelling and health assessment studies (e.g. Muchapondwa, 2010). While this is the ideal situation for the implementation of mature air quality management systems, the experiences from Cape Town also inform us about the difficulties and potential shortcomings of this approach (Naiker et al., 2012). The Western Cape Province and Cape Town Municipality have been very active in developing regulations, operational frameworks, air quality management plans, climate strategies and mobility plans among others in the last two decades (TDA, 2005; CCT, 2007; CCT, 2011; DEA&DP, 2014; TDA, 2017; City of Cape Town / 100 Resilient Cities, 2019 among others).

However, progress regarding air quality is still lagging behind the strategic goals (Tshehla and Wright, 2019). Despite fragmented planning, this may be related to the lack of concretion of the majority of these strategies, lack of political will as well as insufficient funding (DEA&DP, 2019). Even in a city of relative prosperity on the continent, mobilizing the resources for all these activities is an ongoing challenge. In addition to the challenges of administrative transitions and a complex regulatory framework, Cape Town faces the problem of persistent poverty and social inequity that shapes its physical reality and results in an unbalanced burden of air pollution-related disease. It has been suggested that previous plans did not address the problems surrounding poverty as the underlying cause of environmental deterioration (Language et al., 2016).

Dakar

In the review provided by Schwela (2012), Senegal was depicted as a country at an intermediate stage of air quality management maturity. Among other gaps, Senegal was noted as lacking a comprehensive air quality management strategy while multi-level governance was considered blurred; a specific urban air quality plan for Dakar was also lacking. Being a country particularly vulnerable to the effects of climate change (Zamudio and Terton, 2016), current action plans pay more attention to Greenhouse Gases (GHG) mitigation (MEDD, 2015), with a focus on the promotion of renewable energies such as the 159 MW N'Diaye windfarm nearby Dakar (IISD, 2019a) and adaptation, such as the Dakar Resilience Strategy (Ville de Dakar/100 Resilient Cities, 2016).

However, significant advances have been made recently. Senegal has one of the oldest and more stable democracies in Africa and recent reforms favoured the decentralization and strengthening of the administration. This provides the enabling environment (appropriate institutional, legal, and regulatory structures) for the successful development and implementation of a comprehensive air quality management system in the future (WB, 2015). Presently, Senegal has a comprehensive and well-structured strategy to keep strengthening its administration and to foster collaboration with private stakeholders and the international community under the Emerging Senegal Plan (ESP), and overarching framework for the structural transformation of the country and the improvement of governance and living conditions in Senegal by 2035 (MEPC, 2014; MEPC, 2018). This instrument encompasses 27 key infrastructure projects, such as the development of the Bus Rapid Transit (BRT) system in Dakar, an 18.3 km separate corridor (currently serving 144 buses), with23 BRT stations and three terminals covering Dakar Plateau and Guédiawaye (IISD, 2019b). At the local level, the Dakar Master Plan (MURHLE & JICA, 2016) is another key instrument to improve living conditions and it is also expected to provide large air quality co-benefits. Previous strategies, mainly the Urban Mobility Improvement Program (PAMU) have contributed to tackling air quality issues and have been key for the development of incipient monitoring capabilities in the city (WB, 2009).

Despite considerable technical limitations that seriously hinder data availability, Dakar's air quality network can be pointed out as an example of transparency and environmental data. Still, Dakar is aware of the pressing need to further control emissions from road traffic (Ndong Ba et al., 2019a; Adon et al., 2018; Sylla et al., 2018). Furthermore, officials understand that the transport and waste management problems (Yaah, 2018) cannot be seen exclusively from a technological point of view but must also be addressed from an urban planning perspective, since they are linked to the rapid expansion of the city.

Nairobi

Kenya lacks a comprehensive urban air quality management programme. The air quality management responsibility is with the Ministry of Environment and the National Environment Management Authority (NEMA), in collaboration with other partners. Despite weaknesses detected in terms of enforcement and compliance practices (Schwela, 2012), there are some recent actions undertaken by the national government as well as local initiatives that are expected to benefit air quality in Nairobi.

Until very recently, most efforts to address air pollution in Nairobi were undertaken at the national level (MoEF, 2014; MoEP, 2016). A profuse and fragmented environmental regulation in Kenya has hindered the effective linkage with operational programs and strategies at the local level, making air quality management difficult (Shilenje, 2014). On the other hand, the paucity of administrative capacity, weakness of institutions and high corruption levels (Transparency International, 2019) have been identified as essential factors for the lack of progress. Lack of public awareness (Ngo et al., 2017) and very limited monitoring capacity are also major barriers to developing a comprehensive, multi-level air quality strategy.

Nairobi has now the necessary regulatory framework and instruments to tackle air quality issues in the city. The Nairobi Integrated Urban Development Master Plan (NIUPLAN) (NCC & JICA, 2014) includes a comprehensive and accurate diagnosis of the environmental challenges in the city and establishes the general strategy for a balanced and sustainable urban development, in line with the general national strategy given reflected in Kenya's Vision 2030 (Government of Kenya, 2018). More recently, Nairobi launched the first Air Quality Plan in Kenya, the Air Quality Plan 2019-2023, along with the Nairobi City County Air Quality Policy to tackle air quality issues specifically (NCC & UNEP, 2019).

Conclusions and recommendations

The lack of consistent information prevents from a formal comparison of the status of air pollution and policies in Africa. Nonetheless, the findings of air quality management in the 5 case studies included in this research are summarized in Table 2 with the aim of assessing whether interventions are adequately targeted to air quality issues and identifying action needed within the 6 framework areas Clean Air Asia, (2016). More research is needed to fully characterize the drivers of air pollution action in the region and formulate evidence-based plans to improve air quality in affected cities in coordination with climate policies and general development strategies. Nonetheless, some general conclusions and recommendation can be drawn from the 5 major cities scrutinized based on the available information discussed in the previous section. More specific recommendations and particularly interesting interventions for each city are discussed in UN Habitat (2023).

Air quality standards and monitoring

- Air quality standards are typically set up at the national level and most of the countries have moved from air quality guidelines to formal and rather comprehensive air quality standards. As much as possible, $PM_{2.5}$ standards should be considered a priority. However, more than the lack of air quality standards the problem in Africa seems to be the lack of effective enforcement. Consequently, providing the enable conditions and resources for actual enforcement should be encouraged.
- Air quality data in the continent is very limited. Even where monitoring stations exist, maintenance or reliable power supply are lacking, and data is therefore of poor quality or consistency. International collaboration seems to be key for the initial development of monitoring capabilities, but it is essential to secure adequate funding to guarantee the sustainability of urban air quality monitoring networks.
- New technologies based on low-cost sensors may help improving monitoring capabilities but significant investments for capacity building and maintenance and closer collaboration with local universities and research institutes are still needed.

Emissions inventories and modelling

- While national GHG inventories are usually available, city-scale emission inventories are mostly missing and should be developed to prioritise action on the variety of emissions sources affecting urban air quality and to assess the efficiency of plans and measures.
- Some cities have been able to channel international cooperation into the development of incipient modelling capabilities. The literature discussed throughout this work illustrate relatively simple modelling exercises that may be useful as a first step to understand local air quality issues for specific sources or neighbourhoods. Further support and scientific collaboration are needed to move towards more complex tools to deal with emerging air quality issues such as tropospheric ozone or secondary aerosols. A stronger network of researchers in Africa would be instrumental to foster scientific knowledge and capabilities in this area.

Health and other impacts

- While some general estimates exist, more localised epidemiological and cost-benefit studies are needed for a better understanding of the health impacts of poor air quality in African cities, prioritize measures and make a stronger case for action. Health impact models based on assumptions drawn from higher income countries may underestimate impacts in Africa due to synergies with weather risks, communicable diseases and food security issues. Meeting the WHO air quality guidelines, or even the national air quality standards, would bring extensive health benefits, especially for the most vulnerable communities.
- The evidence offered by the 5 case studies point out that low-income citizens in African cities may disproportionally bear the impacts of air pollution. Emissions from indoor dirty fuels combustion, waste open burning and unpaved roads among others create pollution hot spots in informal settlements. Exposure to air pollution from traffic is particularly high among the poor as well, since they mostly rely on non-motorized transport routes along heavily polluted environments. Tackling these issues will contribute not only to improve air quality but also environmental justice.

Communication

- Education and public awareness towards air pollution processes and air quality health effects is alarmingly low in Africa and it may be a major hindrance to implement emission abatement measures. Any intervention or strategy needs to emphasise communication actions for a successful result.
- Open access to air quality data, emission inventories and health indicators is an essential need to involve policy makers and to engage relevant stakeholders and the general public in improving air quality. Channels for communicating the impacts of poor air quality are also essential since only an informed citizenry can demand additional measures to preserve public health.

Clean Air Action Plans

- Air quality action can be driven by dedicated Air Quality Action Plans but also by integrating air pollution actions into national and city development plans that guide infrastructure development. The choice of adopting either approach will depend on the local context. While both approaches will yield positive effects, it is important to explicitly consider emissions and exposure in all the plans and strategies, including urban planning instruments, as an effective way to maximize health benefits.

- Ad-hoc experimental campaigns and research projects highlight that, despite the diversity of city-specific conditions, PM-related pollution is common factor to all of them and should be prioritized.
- For countries and cities in which data and financial resources are lacking, a strategic focus on sector-targeted, short-term actions to reduce air pollution may be a wise investment, even before the creation of long-term monitoring and management capacity. Effective banning of open burning, accompanied by a transition to a more responsible recycling local industry, or improved fuel standards may represent illustrative 'no regrets' actions.
- Road traffic is a key sector in all the cities analysed. Stronger emission inspection schemes and interventions to promote clean, affordable and efficient public transport must be prioritized. In this context, soft mobility offers significant health benefit potentials and it should be promoted in the local agendas.
- While rapidly growing cities pose a major challenge in terms of mobility demand and resource consumption, this also provides an opportunity to integrate air quality criteria in the general urban planning of new settlements and city enlargement.

Governance

- While multi-level governance and planning may be complicated at initial stages of air quality management, it is a powerful combination that matches the multi-scale reality of air pollution and may provide the most effective and sustainable response in the long term.
- Switching to renewable energy sources constitutes an example of national-scale strategy that will always report local air quality co-benefits. A harmonized and coordinated response to climate change and air quality is a pressing need to meet national climate commitments and local air quality standards.
- It is key to improve local governance to achieve real changes by strengthening institutions and collaborations among administrations, companies and other stakeholders. In addition to official plans and strategies, there is a breadth of projects and initiatives in collaboration with multiple international organisms that would benefit from a closer coordination. The creation of centralized emissions and air quality department in the cities may facilitate the allocation of responsibilities and an effective allocation of resources.
- Public-private partnerships have demonstrated to be an effective way to promote social development and air quality improvement in the cities analysed. The case studies also inform that involving actors of the informal economy is essential to provide a consistent response to air pollution and social issues in urban areas.
- A multi-national organism to coordinate national air quality plans and measures into a common African strategy may be instrumental to boost cooperation among countries, share experiences, exploit synergies and to deal with transboundary pollution issues. This may provide a fruitful framework to exchange experiences and harmonize criteria and methodologies.

Although information regarding emissions and air quality data in African cities is limited, the findings of this paper support the urgency to advocate form immediate action. Improving air quality in Africa involves addressing sprawling, dysfunctional cities, and urban planning in the context of a wider social and environmental considerations since poverty and air pollution are closely intertwined and the causes of social inequity and environmental deterioration must be dealt with consistently. The magnitude of the challenge requires long-term collaborations with international institutions, the private sector and the civil society at large. This applies to the scientific community as well. Cooperation among African universities and research groups would be instrumental to fill knowledge gaps and support better informed policies.

Note

An earlier version of this paper was presented at the International Conference on Air Quality in Africa (ICAQ' Africa 2022) in October 2022 and was published in its Proceedings.

References

Adon, M., Yoboue, V., Galy-Lacaux, C., Liousse, C., Diop, B., Doumbia, E. H. T., Gardrat, E., Ndiaye, S. A., Jarnot, C., 2016. Measurements of NO_2, SO_2, NH_3, HNO_3 and O_3 in West African urban environments. Atmospheric Environment 135, 31-40. https://doi.org/10.1016/j.atmosenv.2016.03.050

Adon, M., Yoboue, V., Galy-Lacaux, C., Liousse, C., Diop, B., Doumbia, E. H. T., Gardrat, E., Ndiaye, S. A., Jarnot, C., 2016. Measurements of NO_2, SO_2, NH_3, HNO_3 and O_3 in West African urban environments. Atmospheric Environment 135, 31-40. https://doi.org/10.1016/j.atmosenv.2016.03.050

Amoatey, P., Omidvarborna, H., Affum, H. A., Baawain, M., 2019. Performance of AERMOD and CALPUFF models on SO_2 and NO_2 emissions for future health risk assessment in Tema Metropolis. Human and Ecological Risk Assessment: An International Journal 25(3), 772-786. https://doi.org/10.1080/10807039.2018.1451745

Amoatey, P., Omidvarborna, H., Baawain, M., 2018. The modeling and health risk assessment of $PM_{2.5}$ from Tema Oil Refinery. Human and Ecological Risk Assessment: An International Journal 24 (5), 1-16. https://doi.org/10.1080/10807039.2017.1410427

Appoh, E., 2018. U.S. Overview of Air Quality Monitoring in Accra, Ghana-2. UC Davis Air Sensors International Conference, September 2018, Oakland, CA. [Available online at: https://asic2018.aqrc.ucdavis.edu/sites/g/files/dgvnsk3466/files/inline-files/Emmanuel%20Appoh%20-%20Ghana%20%20International%20Plenary%20Presentation%20at%20%208am%20of%2014%20Sept%202018.pdf]

Appoh, E., Terry, S., 2018. Clean Air for Ghana. Building on success. The Magazine for Environmental Managers. A&WMA. [Available online at: http://pubs.awma.org/flip/EM-Jan-2018/appoch.pdf]

Arab Republic of Egypt Ministry of Environment (EEAA), 2004. National Strategy for Cleaner Production in Egyptian Industry. [Available at: http://www.eeaa.gov.eg/portals/0/eeaaReports/IndUnit/CP.pdf]

Arab Republic of Egypt Ministry of Environment (EEAA), 2018. Annual report of the Ministry (2016). http://www.eeaa.gov.eg/portals/0/eeaaReports/achievements2016/%D8%A5%D9%86%D8%AC%D8%A7%D8%B2%D8%A7%D8%AA%D9%88%D8%B2%D8%A7%D8%B1%D8%A9%D8%A7%D9%84%D8%A8%D9%8A%D8%A6%D8%A9%D9%A2%D9%A0%D9%A1%D9%A6.pdf

Assamoi, E.M., Liousse, C., 2010. A new inventory for two-wheel vehicle emissions in West Africa for 2002. Atmospheric Environment 44, 3985-3996. https://doi.org/10.1016/j.atmosenv.2010.06.048

Bandowe, B. A. M., Nkansah, M. A., Leimer, S., Fischer, D., Lammel, G., Han, Y., 2019. Chemical (C, N, S, black carbon, soot and char) and stable carbon isotope composition of street dusts from a major West African metropolis: Implications for source apportionment and exposure. Science of The Total Environment 655, 1468 – 478. https://doi.org/10.1016/j.scitotenv.2018.11.089

Boman, J., Shaltout, A. A., Abozied, A. a. M., and Hassan, S. K., 2013. On the elemental composition of $PM_{2.5}$ in central Cairo, Egypt, X-Ray Spectrum., 42, 276–283, doi:10.1002/xrs.2464. https://doi.org/10.1002/xrs.2464

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C.A., Apte, J.S., Brauer, M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., Lim, S.S., Kan, H., Walker, K.D., Thurston, G.D., Hayes, R.B., Lim, C.C., Turner, M.C., Jerrett, M., Krewski, D., Gapstur, S.M., Diver, W.R., Ostro, B., Goldberg, D., Crouse, D.L., Martin, R. V, Peters, P., Pinault, L., Tjepkema, M., van Donkelaar, A., Villeneuve, P.J., Miller, A.B., Yin, P., Zhou, M., Wang, L., Janssen, N.A.H., Marra, M., Atkinson, R.W., Tsang, H., Quoc Thach, T., Cannon, J.B., Allen, R.T., Hart, J.E., Laden, F., Cesaroni, G., Forastiere, F., Weinmayr, G., Jaensch, A., Nagel, G., Concin, H., Spadaro, J. V, 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proc. Natl. Acad. Sci. U. S. A. 115, 9592. https://doi.org/10.1073/pnas.1803222115

Center for International Earth Science Information Network (CIESIN), Columbia University, and Information Technology Outreach Services (ITOS), University of Georgia, 2013. Global Roads Open Access Data Set, Version 1 (gROADSv1). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4VD6WCT

Chersich, M. F., Wright, C. Y., Venter, F., Rees, H., Scorgie, F., Erasmus, B., 2018. Impacts of Climate Change on Health and Wellbeing in South Africa. International Journal of Environmental Research and Public Health 15, 1884. https://doi.org/10.3390/ijerph15091884

Cissokho, L., Seck, A., 2013. Electric Power Outages and the Productivity of Small and Medium Enterprises in Senegal. ICBE-RF Research Report N0. 77/13 for the Investment Climate and Business Environment Research Fund (ICBE-RF). [Available online at: http://www.trustafrica.org/en/publications-trust/icbe-research-reports?download=354:electricpower-outages-and-the-productivity-of-small-andmedium-enterprises-in-senegal]

City of Cape Town (CCT) Environmental Planning Department, 2007. Cape Town Energy and Climate Change Strategy. ISBN: 0-9584719-3-2 [Available online at: http://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Energy_+_Climate_Change_Strategy_2_-_10_2007_301020079335_465.pdf]

City of Cape Town (CCT), 2011. Cape Town's Action Plan for Energy and Climate Change. ISBN 978-0-9802784-9-1. [Available online at: http://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Cape%20Town%20Energy%20and%20Climate%20Action%20Plan%20(ECAP).pdf]

City of Cape Town / 100 Resilient Cities, 2019. City of Cape Town Resilience Strategy. [Available online at: http://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Resilience_Strategy.pdf]

Clean Air Asia, 2016. Guidance Framework for Better Air Quality in Asian Cities. Pasig City, Philippines. ISBN: 978-621-95434-0-8. https://cleanairasia.org/ibaq/wp-content/themes/ibaq/pdf/GASOURCEBOOK.pdf

Clean Air Asia, 2016. Guidance Framework for Better Air Quality in Asian Cities. Pasig City, Philippines. ISBN: 978-621-95434-0-8. [Available online at: https://cleanairasia.org/ibaq/wp-content/themes/ibaq/pdf/GASOURCEBOOK.pdf]

De Souza, P., Nthusi, V., Klopp, J.M., Shaw, B.E., Ho, W.O., Saffell, J., Jones, R., Ratti, C., 2017. A Nairobi experiment in using low cost air quality monitors. Clean Air Journal 27 (2), 12-42. http://dx.doi.org/10.17159/2410-972X/2017/v27n2a6

Dieme, D., Cabral-Ndior, M., Garçon, G., Verdin, A., Billet, S., Cazier, F., Courcot, D.,Diouf, A., Shirali, P., 2012. Relationship between physicochemicalcharacterization and toxicity of fine particulate matter ($PM_{2.5}$) collected inDakar city (Senegal). Environmental Research 113, 1–13 https://doi.org/10.1016/j.envres.2011.11.009

Dionisio, K. L., Arku, R. E., Hughs, A. F., Vallarino, J., Carmichael, H., Spengler, J. D., Agyei-Mensah, S., Ezzati, M., 2010. Air pollution in Accra neighbourhoods: spatial, socioeconomic, and temporal patterns. Environmental Science & Technology 44, 2270-6. DOI: DOI: 10.1021/es903276s

Doumbia, E. H. T., Liousse, C., Galy-Lacaux, C., Ndiaye, S. A., Diop, B., Ouafo, M., Assamoi, E. M., Gardrat, E., Castera, P., Rosset, R., Akpo, A., Sigha, L., 2012. Real time black carbon measurements in West and Central Africa urban sites. Atmospheric Environment 54, 529-537. https://doi.org/10.1016/j.atmosenv.2012.02.005

Egondi, T., Muindi, K., Kyobutungi, C., Gatari, M., Rocklöv, J., 2016. Measuring exposure levels of inhalable airborne particles ($PM_{2.5}$) in two socially deprived areas of Nairobi, Kenya. Environmental Research 148, 500–506. http://dx.doi.org/10.1016/j.envres.2016.03.018

Environmental Protection Agency (EPA) Ghana, 2016. 2015 Annual Progress Report. [Available at: http://www.epa.gov.gh/epa/sites/default/files/downloads/publications/2015%20Annual%20Report.pdf]

Environmental Protection Agency (EPA) Ghana, 2017. Roadmap for the Promotion of Cleaner Buses in Accra, Ghana. [Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/21447/Final%20Roadmap%20for%20the%20Promotion%20of%20Cleaner%20Buses%20in%20Accra%20Ghana.pdf]

Environmental Protection Agency (EPA) Ghana, 2018. The Greater Accra Metropolitan Areas Air Quality Management Plan. ISBN 978-9988-2-8509-8. [Available at: http://www.epa.gov.gh/epa/sites/default/files/downloads/publications/Greater%20Accra%20Region%20Air%20%20Quality%20Management%20Plan%202%20Oct%20%202018%20updated.pdf]

European Commission (EC), 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. [Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0050&from=EN]

Favez, O., Cachier, H., Sciare, J., Alfaro, S., El-Araby, T. M., Harhash, M. A., Abdel Wahab, M. M., 2008. Seasonality of major aerosol species and their transformations in Cairo megacity. Atmospheric Environment 42 (7), 1503–1516. http://dx.doi.org/10.1016/j.atmosenv.2007.10.081.

Fisher, S., Bellinger, D.C., Cropper, M.L., Kumar, P., Binagwaho, A., Koudenoukpo, J.B., Park, Y., Taghian, G., Landrigan, P.J., 2021. Air pollution and development in Africa: impacts on health, the economy, and human capital. The Lancet Planetary Health 5 (10), 681-688. https://doi.org/10.1016/S2542-5196(21)00201-1

GADM database (www.gadm.org), version 3.4, April 2018.

Gaita, S. M., Boman, J., Gatari, M. J., Pettersson, J. B. C., Janhäll, S., 2014. Source apportionment and seasonal variation of $PM_{2.5}$ in a Sub-Saharan African city: Nairobi, Kenya. Atmospheric Chemistry and Physics 14, 9977–9991. https://doi.org/10.5194/acp-14-9977-2014

Gatari, M. J., Kinney, P. L., Yan, B., Sclar, E., Volavka-Close, N., Ngo, N. S., et al., 2019. High airborne black carbon concentrations measured near roadways in Nairobi, Kenya. Transportation Research Part D: Transport and Environment 68, 99–109. https://doi.org/10.1016/j.trd.2017.10.002

Government of the Republic of Kenya, 2018. Kenya Vision 2030. Third Medium Term Plan 2018 – 2022. Transforming Lives: Advancing socio-economic development through the “Big Four”. [Available online at: http://vision2030.go.ke/inc/uploads/2019/01/THIRD-MEDIUM-TERM-PLAN-2018-2022.pdf]

Gulis, G., Mulumba, J. A. A., Juma, O., Kakosova, B., 2004. Health status of people of slums in Nairobi, Kenya. Environmental Research 96, 219-27. DOI: 10.1016/j.envres.2004.01.016

Hassanien, M. A., Abdel-Latif, N. M., 2008. Polycyclic aromatic hydrocarbons in road dust over Greater Cairo, Egypt. Journal of Hazardous Materials 151 (1) 247-254. https://doi.org/10.1016/j.jhazmat.2007.05.079

Heft-Neal, S., Burney, J., Bendavid, E., Burke, M., 2018. Robust relationship between air quality and infant mortality in Africa. Nature 559 (7713), 254–258. https://doi.org/10.1038/s41586-018-0263-3

Heft-Neal, S., Burney, J., Bendavid, E., Burke, M., 2018. Robust relationship between air quality and infant mortality in Africa. Nature 559 (7713), 254–258. https://doi.org/10.1038/s41586-018-0263-3

Hersey, S. P., Garland, R. M., Crosbie, E., Shingler, T., Sorooshian, A., Piketh, S., Burger, R., 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. Atmospheric Chemistry and Physics 15, 4259–4278. https://doi.org/10.5194/acp-15-4259-2015

Jenkins, G.S., Diokhane, A. M., 2017. WRF prediction of two winter season Saharan dust events using PM_{10} concentrations: Boundary versus initial conditions. Atmospheric Environment 167, 129-142. http://dx.doi.org/10.1016/j.atmosenv.2017.08.010

Karagulian, F., Belis, C. A., Dora, C. F. C., Prüss-Ustün, A. M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. Atmospheric Environment 120, 475-48. https://doi.org/10.1016/j.atmosenv.2015.08.087

Keen, S., Altieri, K., 2016. The health benefits of attaining and strengthening air quality standards in Cape Town. Clean

Air Journal 26 (2), 22 – 27. http://dx.doi.org/10.17159/2410-972X/2016/v26n2a9

Keita, S., Liousse, C., Yoboúe, V., Dominutti, P., Guinot, B., Assamoi, E.-M., Borbon, A., Haslett, S. L., Bouvier, L., Colomb, A., Coe, H., Akpo, A., Adon, J., Bahino, J., Doumbia, M., Djossou, J., Galy-Lacaux, C., Gardrat, E., Gnamien, S. , Léon, J. F., Ossohou, M., N'Datchoh, E. T., Roblou, L., 2018. Particle and VOC emission factor measurements for anthropogenic sources in West Africa. Atmospheric Chemistry and Physics 18 (10), 7691-7708. https://www.atmos-chem-phys.net/18/7691/2018

Kinney, P. L., Gichuru, M. G., Volavka-Close, N., Ngo, N., Ndiba, P. K., Law, A., Gachanja, A., Gaita, S. M., Chillrud, S. N., Sclar, E., 2011. Traffic Impacts on $PM_{2.5}$ Air Quality in Nairobi, Kenya. Environmental Science & Policy 14, 369–378. https://doi.org/10.1016/j.envsci.2011.02.005

Klausbruckner, C., Annegarn, H., Henneman, L. R. F., Rafaj, P., 2016. A policy review of synergies and trade-offs in South African climate change mitigation and air pollution control strategies. Environmental Science & Policy 57, 70–78. https://doi.org/10.1016/j.envsci.2015.12.001

Klopp J. M., 2012. Towards a political economy of transportation policy and practice in Nairobi. Urban Forum 23(1), 1-21. https://doi.org/10.1007/s12132-011-9116-y

Korkor, H., 2014. Promoting energy efficiency investments for Climate Change mitigation and sustainable development. Case study: Egypt. Policy reforms that were implemented to Promote Energy Efficiency in the Transportation Sector. Prepared for UN Economic and Social Commission for Western Asia. [Available online at: https://www.unescwa.org/sites/www.unescwa.org/files/page_attachments/escwa-casestudy-ee_transport-egypt_final.pdf]

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L., Britter, R., 2015. The rise of low-cost sensing for managing air pollution in cities. Environment International 75, 199–205. https://doi.org/10.1016/j.envint.2014.11.019

Kuyper, B., Wingrove, H., Lesch, T., Labuschagne, C., Say, D., Martin, D., Young, D., Khan, M. A. H., O'Doherty, S., Davies-Coleman, M. T., Shallcross, D. E., 2020. Atmospheric Toluene and Benzene Mole Fractions at Cape Town and Cape Point and an Estimation of the Hydroxyl Radical Concentrations in the Air above the Cape Peninsula, South Africa. ACS Earth and Space Chemistry 4 (1), 24-34. https://doi.org/10.1021/acsearthspacechem.9b00207

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., Pozzer A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367. https://doi.org/10.1038/nature15371

Liousse C., E. Assamoi, P. Criqui, C. Granier and R. Rosset, 2014. African combustion emission explosive growth from 2005 to 2030. Environ. Res. Lett. 9 035003. doi:10.1088/1748-9326/9/3/035003

Mahmoud, K.F., Alfaro, S.C., Favez, O., Abdel Wahab, M. M., Sciare, J., 2008. Origin of black carbon concentration peaks in Cairo (Egypt). Atmospheric Research 89, 161–169. https://doi.org/10.1016/j.atmosres.2008.01.004

Marey, H. S., Gille, J. C., El-Askary, H. M., Shalaby, E. A., El-Raey, M. E., 2010. Study of the formation of the "black cloud" and its dynamics over Cairo, Egypt, using MODIS and MISR sensors. Journal of Geophysical Research 115, D21206. https://doi.org/10.1029/2010JD014384

Mbow-Diokhane, A., 2019. Air Quality in African Cities. In: Mboup G., Oyelaran-Oyeyinka B. (eds) Smart Economy in Smart African Cities. Advances in 21st Century Human Settlements. Springer, Singapore. ISBN 978-981-13-3470-2. https://doi.org/10.1007/978-981-13-3471-9_9

Mbow-Diokhane, A., 2019. Air Quality in African Cities. In: Mboup G., Oyelaran-Oyeyinka B. (eds) Smart Economy in Smart African Cities. Advances in 21st Century Human Settlements. Springer, Singapore. ISBN 978-981-13-3470-2. https://doi.org/10.1007/978-981-13-3471-9_9

Ministry of Environment and Forestry (MoEF), 2014. Cabinet Secretary for Environment, Water and Natural Resources. The Environmental Management and Co-ordination Act (No.8 of 1999). Legal Notice No. 34 Kenya Gazette Supplement No.41. [Available online at: http://kenyalaw.org/kl/fileadmin/pdfdownloads/LegalNotices/34-EnvironmentalManagementandCo-ordination(AirQuality)Regulations2014.pdf]

Molepo, K. M., Abiodun, B. J., Magoba, R. N., 2019. The transport of PM_{10} over Cape Town during high pollution episodes. Atmospheric Environment 213, 116-132. https://doi.org/10.1016/j.atmosenv.2019.05.041

Mostafa, A. N., Zakey, A. S., 2018. Analysis of the surface Air Quality Measurements in The Greater Cairo (Egypt) Metropolitan. Global Journal of Advanced Research 5 (6), 207-214. ISSN: 2394-5788. [Available online at: http://gjar.org/publishpaper/vol5issue6/d843r9.pdf]

Muchapondwa, 2010. A cost-effectiveness analysis of options for reducing pollution in Khayelitsha township, South Africa. The Journal for Transdisciplinary Research in Southern Africa 6 (2), 333 - 358. https://doi.org/10.4102/td.v6i2.268

Mumm, R., Diaz-Monsalve, S., Hänselmann, E., Freund, J., Wirsching, M., Gärtner, J., Gminski, R., Vögtlin, K., Körner, M., Zirn, L., Wittwer-Backofen, U., Oni, T., Kroeger, A., 2017. Exploring urban health in Cape Town, South Africa: an interdisciplinary analysis of secondary data. Pathogens and Global Health 111 (1), 7-22. https://doi.org/10.1080/20477724.2016.1275463

Naidja, L., Ali-Khodja, H., Khardi, S., 2018. Sources and levels of particulate matter in North African and Sub-Saharan cities: a literature review. Environmental Science and Pollution Research 25, 12303–12328. https://doi.org/10.1007/s11356-018-1715-x

Naiker, Y., R.D.Diab, R. D., Zunckel, M., Hayes, E. T., 2012. Introduction of local Air Quality Management in South Africa: overview and challenges. Environmental Science & Policy 17, 62-71. https://doi.org/10.1016/j.envsci.2011.11.009

Nairobi City Country (NCC) supported by United Nations Environmental Programme (UNEP), 2019. Air Quality Action Plan (2019-2023). [Available online at: https://www.eci-africa.org/wp-content/uploads/2019/05/Nairobi-Air-Quality-Action-Plan_Final_ECI_31.12.2018.pdf]

Nairobi City County (NCC) and the Japan International Cooperation Agency (JICA), 2014. The Project on Integrated Urban Development Master Plan for the City of Nairobi in the Republic of Kenya [Available online at: http://www.kpda.or.ke/documents/Nairobi%20Integarted%20Urban%20Development%20Master%20Plan.pdf]

Nasralla, M. M., 2001. Greater Cairo Air Quality profile. Egyptian Environmental Policy Program Support Unit. Prepared under the Environmental Policy and Institutional Strengthening Indefinite Quantity Contract (EPIQ) for U.S. Agency for International Development, Cairo and Egyptian Environmental Affairs Agency (EEAA). [Available online at: https://rmportal.net/library/content/tools/environmental-policy-and-institutional-strengthening-epiq-iqc/egyptian-environmental-policy-program-eepp-program-support-unit-psu-task-order-cd-vol-2/epiq-reports-technical-area-dissemination-of-policy-knowledge-environmental-communication/034-cairoairprofile-nasrala.pdf/at_download/file]

Ndong Ba, A., Cazier, F., Verdin, A., Garçon, G., Cabral, M., Courcot, L., Diouf, A., Courcot, D., Gualtieri, M., Fall, M., 2019b. Physico-chemical characterization and in vitro inflammatory and oxidative potency of atmospheric particles collected in Dakar city's (Senegal). Environmental Pollution 245, 568-581. https://doi.org/10.1016/j.envpol.2018.11.026

Ndong Ba, A., Verdin, A., Cazier, F., Garçon, G., Thomas, J., Cabral, M., Dewaele, D., Genevray, P., Garat, A., Allorge, D., Diouf, A., Loguidice, J.M., Courcot, D., M., Courcot, L., Fall, M., Gualtieri, 2019a. Individual exposure level following indoor and outdoor air pollution exposure in Dakar (Senegal). Environmental Pollution 248, 397-407. https://doi.org/10.1016/j.envpol.2019.02.042

Ndour, M., D’Anna, B., George, C., Ka, O., Balkanski, Y., Kleffmann, J., Stemmler, K., Ammann, M., 2008. Photo-enhanced uptake of NO_2 on mineral dust: laboratory experiments and model simulations. Geophysical Research Letters 35, L05812. https://doi.org/10.1029/2007GL032006

Ngo, N. S., Kokoyo, S., Klopp, J., 2017. Why participation matters for air quality studies: risk perceptions, understandings of air pollution and mobilization in a poor neighbourhood in Nairobi, Kenya. Public Health 142, 177–185. https://doi.org/10.1016/j.puhe.2015.07.014

Ngo, N.S., Gatari, M., Yan, B., Chillrud, S.N., Bouhamam, K., Kinney, P.L., 2015. Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: a pilot study in Nairobi, Kenya. Atmospheric Environment 111, 179–184. https://doi.org/10.1016/j.atmosenv.2015.04.008

Nthusi, V., 2017. Nairobi Air Quality Monitoring Sensor Network Report. Technical report published April 2017 via Science Division, UN Environment. [Available online at: https://doi.org/10.13140/rg.2.2.10240.64009]

Ofosu, F. G., Hopke, P. K., Aboh, I. J. K., Bamford, S. A., 2012. Characterization of fine particulate sources at Ashaiman in Greater Accra, Ghana. Atmos. Pollut. Res. 3, 301–310. https://doi.org/10.5094/APR.2012.033

Oluleye, A., Folorunsho, A., 2019. Influence of Atmospheric Dynamic Factors on Dust Aerosol Mobilization Over West Africa: Simulations from WRF-Chem. Aerosol Science and Engineering 3, 132–149. https://doi.org/10.1007/s41810-019-00048-z

Piedrahita, R., Kanyomse, E., Coffey, E., Xie, M., Hagar, Y., Alirigia, R., Agyei, F., Wiedinmyer, C., Dickinson, K. L., Oduro, A., Hannigan, M., 2017. Exposures to and origins of carbonaceous $PM_{2.5}$ in a cookstove intervention in Northern Ghana. Science of The Total Environment 576, 178-192. https://doi.org/10.1016/j.scitotenv.2016.10.069

Pope, F. D., Gatari, M., Ng'ang'a, D., Poynter, A., Blake, R., 2018. Airborne particulate matter monitoring in Kenya using calibrated low-cost sensors. Atmospheric Chemistry and Physics 18, 15403–15418. https://doi.org/10.5194/acp-18-15403-2018

Pure Earth, 2015. Project Completion Report: Making Electronic Waste Recycling in Ghana Safer Through Alternative Technology, Accra Ghana. [Available online at: https://www.pureearth.org/wp-content/uploads/2014/01/Ghana-Pilot-PCR-2015.pdf]

Republic of Kenya. Ministry of Energy and Petroleum (MoEP), 2016. Sustainable Energy for All. Kenya Action Agenda. Pathways for Concerted Action toward Sustainable Energy for All by 2030. [Available online at: https://www.se4all-africa.org/fileadmin/uploads/se4all/Documents/Country_AAs/Kenya_SE4ALL_AA_January_2016.pdf]

Republic of South Africa, 2013. The 2012 National Framework for Air Quality Management in the Republic of South Africa. Government Gazette No. 36161 (volume 572). Pretoria, 15 February 2013. [Available online at: https://www.environment.gov.za/sites/default/files/gazetted_notices/nema_national_framework_aqm_gn115.pdf]

Republic of South Africa. Department of Environmental Affairs (DEA), 2012. National Ambient Air Quality Standard for particulate matter with aerodynamic diameter less than 2.5 micron metres ($PM_{2.5}$). 29 June, 2012. [Available online at: https://cer.org.za/wp-content/uploads/2010/03/National-Ambient-Air-Quality-Standard_PM2.5.pdf]

Republic of South Africa. Department of Environmental Affairs (DEA), 2019. Department of Environmental Affairs annual report 2018/2019. ISBN: 978-0-621-45872-5. [Available online at: https://www.environment.gov.za/sites/default/files/reports/annualreport201819.pdf]

République du Sénégal. Ministere de L'environnement et du Developpement Durable. Centre de Gestion de la Qualite de L'air (CGQA), 2018. Suivi de la qualité de l'air à Dakar Rapport annuel 2017. [Available online at: https://www.air-dakar.org/images/pdf/bulletins/rapport_annuel_2017.pdf]

Republique du Senegal. Ministry for Urban Renewal, Housing and Living Environment (MURHLE) and the Japan International Cooperation Agency (JICA), 2016. Project for Urban Master Plan of Dakar and Neighboring Area for 2035. [Available online at: http://open_jicareport.jica.go.jp/618/618/618_526_12250007.html]

Republique du Senegal. Ministry of Economy, Planning and Cooperation (MEPC), 2014. Plan for an Emerging Senegal. Phase I PSE 2014 2018. [Available online at: https://www.economie.gouv.sn/sites/default/files/fichier/Phase%20I%20PSE%202014-2018.pdf]

Republique du Senegal. Ministry of Economy, Planning and Cooperation (MEPC), 2018. Plan for an Emerging Senegal. Phase II PSE 2019 2023. [Available online at: https://www.economie.gouv.sn/sites/default/files/fichier/Phase%20II%20PSE%20 2019-2023.pdf]

Rodríguez, S., Calzolai, G., Chiari, M., Nava, S., García, M. I., López-Solano, J., Marrero, C., López-Darias, J., Cuevas, E., Alonso-Pérez, S., Prats, N., Amato, F., Lucarelli, F., Querol, X., 2019. Rapid changes of dust geochemistry in the Saharan Air Layer linked to sources and meteorology. Atmospheric Environment 27, 117186. https://doi.org/10.1016/j.atmosenv.2019.117186

Roy, R., 2016. The cost of air pollution in Africa, OECD Development Centre Working Papers, No. 333, OECD Publishing, Paris. ISSN: 18151949. https://www.oecd-ilibrary.org/the-cost-of-air-pollution-in-africa_5jlqzq77x6f8.pdf?itemId=%2Fcontent%2Fpaper%2F5jlqzq77x6f8-en&mimeType=pdf

Safar, Z., Labib, M. W., 2010. Assessment of particulate matter and lead levels in the Greater Cairo area for the period 1998-2007. Journal of Advanced Research 1, 53-63. https://doi.org/10.1016/j.jare.2010.02.004

Saiz-Lopez, A., Borge, R., Notario, A., Adame, J.A., de la Paz, D., Querol, X., Artíñano, B., Gomez-Moreno, F.J., Cuevas, C.A., 2017. Unexpected increase in the oxidation capacity of the urban atmosphere of Madrid, Spain. Scientific Reports 7, 45956. https://doi.org/10.1038/srep45956

Sarr, D., Diop, B., Farota, A. K., Sy, A., Diop, A. D., Wade, M., Diop, A. B., 2018. Atmospheric Circulation in Low Troposphere-Effect On NO_x and CO Emissions in Traffic and Air Quality in Dakar. Journal of Pollution Effects & Control 6 (3). DOI: 10.4172/2375-4397.1000230

Schwela, D., 2012. Review of urban air quality in Sub-Saharan Africa region - air quality profile of SSA countries (English). Washington, DC: World Bank. [Available online at: http://documents.worldbank.org/curated/en/936031468000276054/Review-of-urban-air-quality-in-Sub-Saharan-Africa-region-air-quality-profile-of-SSA-countries]

Shilenje, Z. W., 2014. Development in Air Pollution Measurement Technologies in Kenya. TECO-2014. WMO technical conference on meteorological and environmental instruments and methods of observation. [Available online at: https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-116_TECO-2014/Session%201/P1_47_Shilenje_Air_Pollution_Measurement.pdf]

Stanaway, J. D., Afshin, A., Gakidou, E., Lim, S. S., Abate, D., Abate, K. H. et al., 2018. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. Lancet 392, 1923–1994. https://doi.org/10.1016/S0140-6736(18)32225-6

Sylla, F. K., Faye, A., Diaw, M., Fall, M., Tal-Dia, A., 2018. Traffic Air Pollution and Respiratory Health: A Cross-Sectional Study among Bus Drivers in Dakar (Senegal). Open Journal of Epidemiology 8, 1-13. https://doi.org/10.4236/ojepi.2018.81001

Tang, C., Garshick, E., Grady, S., Coull, B., Schwartz, J., Koutrakis, P., 2018. Development of a modeling approach to estimate indoor-to-outdoor sulfur ratios and predict indoor PM2.5 and black carbon concentrations for Eastern Massachusetts households. Journal of Exposure Science & Environmental Epidemiology 28, 125–130. https://doi.org/10.1038/jes.2017.11

The City of Cape Town's Transport and Urban Development Authority (TDA), 2017b. City of Cape Town Cycling Strategy. [Available online at: https://tdacontenthubfunctions.azurewebsites.net/Document/1403]

The City of Cape Town's Transport and Urban Development Authority (TDA), 2005. Non-Motorised Transport (NMT) Strategy Volume 1 (Status Quo Assessment) & Volume 2 (Policy Framework). [Available online at: https://tdacontenthubfunctions.azurewebsites.net/Document/30 and https://tdacontenthubfunctions.azurewebsites.net/Document/31]

The International Institute for Sustainable Development (IISD), 2019a. Sustainable Asset Valuation (SAVi) of the N'Diaye Wind Farm in Senegal. Summary of results. [Available online at: https://www.iisd.org/sites/default/files/publications/savi-senegal-ndiaye-wind-farm-en.pdf]

The International Institute for Sustainable Development (IISD), 2019b. Sustainable Asset Valuation (SAVi) of the Bus Rapid Transit Project in Senegal. Summary of results. [Available online at: https://www.iisd.org/sites/default/files/publications/savi-senegal-bus-rapid-transit-en.pdf]

The World Bank (WB), 2009. Senegal - Urban Mobility Improvement Program Project (English). Washington, DC: World Bank. Implementation Completion and Results Report. Report No: ICR0000955 [Available online at: http://documents.worldbank.org/curated/en/576841468103767226/pdf/ICR9550P0554721C0Disclosed051221091.pdf]

The World Bank (WB), 2013. The Arab Republic of Egypt. For better or for worse: air pollution in Greater Cairo. A sector note. Sustainable Development Department. Middle East and North Africa Region. Report No. 73074-EG. [Available online at: http://documents.worldbank.org/curated/en/972321468021568180/pdf/730740ESW0P09700Final0April02202013.pdf]

The World Bank (WB), 2015. Senegal Urbanization Review. How can cities contribute to the "Senegal Emerging Plan"? [Available online at: https://knowledge.uclga.org/IMG/pdf/senegalurbanizationreview.pdf]

The World Bank (WB), 2016. The cost of air pollution: strengthening the economic case for action (English). Washington, D.C.: World Bank Group. [Available online at: http://documents.worldbank.org/curated/en/781521473177013155/pdf/108141-REVISED-Cost-of-PollutionWebCORRECTEDfile.pdf]

The World Bank (WB), 2019. World Development Indicators [available online at: http://datatopics.worldbank.org/world-development-indicators/]

Thomas, A., 2016. Reducing Air Pollution in Cairo: Raise User Costs and Invest In Public Transit. Economic Research Forum. Policy Brief. ERF Policy Brief No. 12 | May 2016. [Available online at: http://erf.org.eg/wp-content/uploads/2016/05/PB12_2016.pdf]

Toure, N. O., Gueye, N. R. D., Mbow-Diokhane, A., Jenkins, G. S., Li, M., Drame, M. S., Coker, K. A. R., Thiam, K., 2019. Observed and modeled seasonal air quality and respiratory health in Senegal during 2015 and 2016. GeoHealth, 3. https://doi.org/10.1029/2019GH000214

Transparency International, 2019. Corruption Perceptions Index 2018. ISBN: 978-3-96076-116-7. [Available online at: https://files.transparency.org/content/download/2383/14554/file/2018_CPI_Executive_Summary.pdf]

Tshehla C., Wright, C. Y., 2019. 15 Years after the National Environmental Management Air Quality Act: Is legislation failing to reduce air pollution in South Africa? South African Journal of Science 115 (9/10), Art. #6100. https://doi.org/10.17159/sajs.2019/6100

United Nations (UN), Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Online Edition. Rev. 1.

United Nations Environment Programme (UNEP), 2004. Air Quality and Atmospheric Pollution in the Arab Region. Manama: Joint Technical Secretariat composed of the League of Arab States; the United Nations Economic and Social Commission for Western Asia; and the United Nations Environment Programme, Regional Office for West Asia. [Available online at: http://www.un.org/esa/sustdev/csd/csd14/escwaRIM_bp1.pdf]

United Nations Environment Programme (UNEP), 2016. Actions on air quality. Policies & Programmes for Improving Air Quality around the World. UNEP Transport Unit. https://wedocs.unep.org/bitstream/handle/20.500.11822/17203/AQ_GlobalReport_Summary.pdf

United Nations Human Settlements Programme (UN Habitat), 2023. Air Quality in African Cities. [Available online at: https://unhabitat.org/sites/default/files/2023/03/un-habitat_2023_-_air_quality_in_african_cities.pdf]

United Nations Human Settlements Programme (UN Habitat), 2010. The State of African Cities 2010. Governance, Inequality and Urban Land Markets. ISBN Number: (Volume) 978-92-1-132291-0. http://www.citiesalliance.org/sites/citiesalliance.org/files/UNH_StateofAfricanCities_2010.pdf

United Nations Human Settlements Programme (UN Habitat), 2016. Urbanization and Development. Emerging Future. World Cities Report, 2016. https://unhabitat.org/sites/default/files/download-manager-files/WCR-2016-WEB.pdf

United Nations, Department of Economic and Social Affairs, Population Division (UN), 2019. World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations. ISBN: 978-92-1-148319-2. [Available online at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf]

van Donkelaar, A. et al. 2018. Global Annual $PM_{2.5}$ Grids from MODIS, MISR and SeaWiFS Aerosol Optical Depth (AOD) with GWR, 1998-2016. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4ZK5DQS

van Vliet, E. D. S., Kinney, P. L., 2007. Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. Environmental Research Letters 2 (4), 045028. https://doi.org/10.1088%2F1748-9326%2F2%2F4%2F045028

Ville de Dakar / 100 Resilient Cities, 2016. Dakar Resilience Strategy. [Available online at: https://www.100resilientcities.org/wp-content/uploads/2017/07/Dakar_Resilience_Strategy.pdf]

Watson, J. G., Robinson, N. F., Chow, J. C., Henry, R. C., Kim, B. M., Pace, T. G., Meyer, E. L., Nguyen, Q., 1990. The US EPA/DRI chemical mass balance receptor model, CMB 7.0. Environmental Software 5 (1), 38-49. https://doi.org/10.1016/0266-9838(90)90015-X

Western Cape Government. Department of Environmental Affairs and Development Planning (DEA&DP), 2019. Western Cape State of Air Quality Management Report 2018. [Available online at: https://www.westerncape.gov.za/eadp/files/atoms/files/SoAR_2018.pdf]

Western Cape Government. Department of Environmental Affairs and Development Planning (DEA&DP), 2016. Western Cape Air Quality Management Plan. ISBN: 978-0-621-45636-3. [Available online at: https://www.westerncape.gov.za/eadp/files/atoms/files/Western%20Cape%20Air%20Quality%20Management%20Plan.pdf]

Western Cape Government. Department of Environmental Affairs and Development Planning (DEA&DP), 2014. Western Cape Climate Change Response Strategy. [Available online at: https://www.westerncape.gov.za/text/2015/march/western_cape_climate_change_response_strategy_2014.pdf.]

Wheida, A., Nasser, A., El Nazer, M., Borbon, A., El Ata, G., Wahab, M., Alfaro, S., 2018. Tackling the mortality from long-term exposure to outdoor air pollution in megacities: Lessons from the Greater Cairo case study. Environmental Research 160, 223-231. https://doi.org/10.1016/j.envres.2017.09.028

Wicking-Baird, M. C., De Villiers, M. G., Dutkiewicz, R., 1997. Cape Town Brown Haze Study. Report No. Gen 182. Energy Research Institute, University of Cape Town, Cape Town. [Available online at: https://open.uct.ac.za/bitstream/handle/11427/23910/Wicking-Baird_ERC_1997.pdf]

World Health Organization (WHO), 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005. Summary of risk assessment. WHO/SDE/PHE/OEH/06.02. [Available online at: https://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf]

World Health Organization (WHO), 2016. Ambient air pollution: A global assessment of exposure and burden of disease. ISBN: 978 92 4 151135 3. [Available online at: http://apps.who.int/iris/bitstream/handle/10665/250141/9789241511353-eng.pdf]

World Meteorological Organization (WHO), 2018. Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications. WMO-No. 1215. Editors: Lewis, A.C., von Schneidemesser, E., Peltier, R.E. ISBN 978-92-63-11215-6. [Available online at: https://www.ccacoalition.org/en/file/4645/download?token=RprgoCCg]

Yaah, V. B. K., 2018. Improvement of the Waste Management System in Senegal. Mediterranean Journal of Basic and Applied Sciences (MJBAS) 2 (3), 105-126. [Available online at: http://mjbas.com/data/uploads/4008.pdf]

Zakey, A. S., Abdel-Wahab, M. M., Pettersson, J. B. C., Gatari, M. J., Hallquist, M., 2008. Seasonal and spatial variation of atmospheric particulate matter in a developing megacity, the Greater Cairo, Egypt. Atmosfera 21(2), 171–189. [Available online at: http://www.scielo.org.mx/pdf/atm/v21n2/v21n2a4.pdf]

Zamudio, A. N., Terton, A., 2016. Review of current and planned adaptation action in Senegal. CARIAA Working Paper no. 18. International Development Research Centre, Ottawa, Canada and UK Aid, London, United Kingdom. ISSN: 2292-6798. [Available online at: www.idrc.ca/cariaa] Republique du Senegal. Ministre de l’Environnement et du Developpement Durable (MEDD), 2015. Strategie Nationale de Developpement Durable (SNDD). [Available online at: https://chm.cbd.int/api/v2013/documents/1B1ECE54-E678-582A-3206-64226B5FF510/attachments/SNDD%202015_Fersion%20Finale.pdf]

Zhou, Z., Dionisio, K. L., Verissimo, T. G., Kerr, A. S., Coull, B., Arku R. E., Koutrakis, P., Spengler, J. D., Hughes, A. F., Vallarino, J., Agyei-Mensah, S., Ezzati, M., 2013. Chemical composition and sources of particle pollution in affluent and poor neighborhoods of Accra, Ghana. Environ Res Lett, 8–4. doi:10.1088/1748-9326/8/4/044025

Table 2: *Status of progress in addressing air quality & promising practices. Colours indicate the stage of development: green=mature, yellow=intermediate and red=early. Source: UN Habitat, 2023*

City (Country)	Stage in Air Quality Management Process						
	Air quality standards & monitoring		Emissions inventories and modelling	Health (and/or other) impact assessments	Communication	Clean Air Action plans	Governance
	Monitoring (# and type of stations)	National air quality standards**					
Accra (Ghana)	5 fixed reference stations*, 23 low-cost monitors	Air Quality Guidelines proposed only for PM_{10}	Some research-oriented emission estimates. Limited modelling capabilities	Some studies focussing on indoor air quality issues. Relevant impact from e-waste open burning traffic too	AirNow-Ghana system being developed to share AQ data	2018 Greater Accra Metropolitan Areas Air Quality Management Plan (Ghana's EPA)	Comprehensive legal and institutional framework. Lack of integration and operational capacity
Cairo (Egypt)	42 fixed reference stations and 25 sampling stations in GCMA	TSP, PM_{10} NO_2, SO_2 O_3 and Pb ($PM_{2.5}$ missing)	Urban emission inventory available for 2010, need to be updated. Limited modelling capabilities	Some studies highlight the impact of traffic	AQ reports issued but data not publicly available	Several national plans and instruments but no AQ-specific strategy	Poor ministerial coordination and lack of a clear institutional framework for local AQ management
Cape Town (South Africa)	17 fixed reference stations*	SO_2, NO_2, PM_{10}, O_3, C_6H_6, Pb, CO and $PM_{2.5}$	Some research-oriented emission estimates and industrial inventories. Limited modelling capabilities	Some studies quantify the impact of meeting air quality standards, particularly beneficial for vulnerable groups	South African Air Quality Information System (SAAQIS) and National Association for Clean Air (NACA)	2016 Western Cape Province Air Quality Management Plan along with many other national and local strategies	Multi-level distribution of competences and profuse regulation. Lack of centralized local AQM authority
Dakar (Senegal)	5 fixed reference stations*, 1 mobile lab	SO_2, NO_2, CO, PM_{10} and Pb ($PM_{2.5}$ missing)	Some research-oriented emission estimates. Limited modelling capabilities	Studies point out that indoor air quality is a major health issue. Traffic is also particularly relevant in Dakar	Centre de Gestion de la Qualité de l'Air (CGQA) oficial AQ data, forecast and information	National development strategy (ESP) and several relevant local instruments but no specific AQ strategy	Comprehensive strategy to keep strengthening administrations and increase cooperation. Limited integration.
Nairobi (Kenya)	2 fixed reference stations*, 1 mobile lab, 6 low-cost monitors	SO_x, NO_x, CO, O_3, Pb, PM_{10} and $PM_{2.5}$. (Not effectively enforced)	Some research-oriented emission estimates. No modelling activities	Some studies highlight the impact of traffic household combustion and open burning	Clean Air Nairobi platform to share AQ data. Small-scale demonstrative projects	Air Quality Action Plan (2019-2023), complementary to other local and national relevant plans	Instruments and structures available. Institutional weakness and corruption

* *Despite the existence of these stations, data is often outdated, inconsistent or missing.*
** *Not in cities' control; included to indicate existing enabling/legislative framework at national level.*