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East African Megacity Air Quality: Rationale and Framework for a Measurement and Modeling Program

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ABSTRACT: Air pollution in Africa is a significant public health issue responsible for 1.1 million premature deaths annually. Sub-Saharan Africa has the highest rate of population growth and urbanization of any region in the world, with substantial potential for future emission growth and worsening air quality. Accurate and extensive observations of meteorology and atmospheric composition have underpinned successful air pollution mitigation strategies in the Global North, yet Africa in general and East Africa in particular remain among the most sparsely observed regions in the world. This paper is based on the discussion of these issues during two international workshops, one held virtually in the United States in July 2021 and one in Kigali, Rwanda, in January 2023. The workshops were designed to develop a measurement, capacity building, and collaboration strategy to improve air quality-relevant measurements, modeling, and data availability in East Africa. This paper frames the relevant scientific needs and describes the requirements for training and infrastructure development for an integrated observing and modeling strategy that includes partnerships between East African scientists and organizations and their counterparts in the developed world.

SIGNIFICANCE STATEMENT: Air pollution is a leading environmental risk factor in East Africa that is expected to worsen with rapid urbanization and economic growth occurring in the region. The unique emission sources will impact atmospheric composition and chemistry and are of significant current interest to understand their impact on climate and air quality mitigation efforts everywhere. There is a need to quantify emission trends from different regions of the world and develop reliable methods for inventories. Relationships between scientists from both the Global North and the Global South will help to advance and implement measurements and to build global atmospheric chemistry capacity.

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1. Introduction

Air pollution is the leading environmental risk factor for premature death worldwide and is linked to multiple negative health outcomes (Amann et al. 2020; Christopher et al. 2020; Cohen et al. 2017; Kumie et al. 2021; Lelieveld et al. 2015; Pope et al. 2020; Pozzer et al. 2023; West et al. 2016). In Africa, air pollution was responsible for 1.1 million premature deaths in 2019 (Boogaard et al. 2019; Christopher et al. 2020; Fisher et al. 2021; Glenn et al. 2022; Isaxon et al. 2022; Nicholas Rees 2019; Rentschler and Leonova 2023; Fuller et al. 2022), of which approximately 63% were linked to exposure to household air pollution (Fisher et al. 2021; Gordon et al. 2023). It is also the third largest risk factor for death of children under 5 years of age, with over a quarter million deaths of newborns within the first month of life (Health Effects Institute 2022). Exposure to particulate matter (PM) has been linked to 400 000 preventable infant deaths per year in sub-Saharan Africa and is projected to account for 32% of deaths in this age group by 2025 (EPA 2021). These estimates are based on integrated exposure–response (IER) models that are derived largely from studies in Europe and North America, where ambient $PM_{2.5}$ levels are considerably lower than those in Africa (Amegah et al. 2022; Fuller and Amegah 2022). Hence, these studies may not be reliable predictors of African mortality and may be underestimates (Haakenstad et al. 2022).

A limited number of short-term $PM_{2.5}$ datasets in East Africa have shown concentrations nearly 10 times higher than the yearly average World Health Organization (WHO) guideline values (5 $\mu g\ m^{-3}$) and approximately 4 times higher than the 24-h average (15 $\mu g\ m^{-3}$) (Amegah and Agyei-Mensah 2017; deSouza et al. 2020; Egondi et al. 2013; Gaita et al. 2014; Kume et al. 2010; Ngo et al. 2015; Pope et al. 2018; Schwander et al. 2014; Singh et al. 2021; van Vliet and Kinney 2007). The three most polluted cities in sub-Saharan Africa are Lagos, Nigeria, in West Africa, and Nairobi, Kenya, and Addis Ababa, Ethiopia (Okafor 2023), in East Africa.

Demographic trends compound these severe health impacts. Over half of the projected increase in global population between 2020 and 2050, and 90% from 2050 to 2100, is from countries in sub-Saharan Africa, where the population is expected to triple by 2100 (Gu et al. 2021). At the current 3.5% growth rate, Africa is expected to comprise 21% of the world's urban population by 2050, and by 2100, 13 of the 20 megacities in the world will be in Africa (Hoornweg and Pope 2017; Hoornweg and Freire 2013). With this rapid urbanization and industrialization, sub-Saharan Africa faces increasingly severe air quality problems and sharply increasing costs (Hove et al. 2013). In Ethiopia, Ghana, and Rwanda, ambient air pollution resulted in losses of economic production between 0.08–0.3% of gross domestic product (GDP) and 0.95%–1.2% of GDP across the continent (Fisher et al. 2021). Despite strong evidence of the economic benefits of cleaner air, the investment for air quality research is only 1% of the approximately $2.5 billion spent on international development funding (Ayompe et al. 2020).

African air pollution is driven by a complex range of emissions that include fossil fuel combustion, biomass and trash burning, biogenic volatile compound emissions, agriculture, and dust (Fig. 1). Detailed information on emissions, production, transport, and loss mechanisms of pollutants is required to accurately model air quality and associated health impacts. There are, however, relatively little reliable data on air pollution concentrations for sub-Saharan Africa (Fuller and Amegah 2022; Vilcassim and Thurston 2023). According to the World Air Quality Report, only 19 of 54 countries in Africa have sufficient public air quality data (IqAir 2022). The 2020 OpenAQ global assessment on the availability of air quality measurements found that governments in only 49% of countries produce publicly accessible air quality data and that four of the seven countries in which such data could have the greatest impact on public health policy are in East Africa (Brauer et al. 2020). A study by United Nations International Children's Emergency Fund (UNICEF 2019) estimated that only 6% of African children live within 50 km of an air quality monitor compared to 70% in Europe and North America. This limitation points to the lack of basic research to address the unique aspects of the pollutants found in Africa, and the lack of data needed to reduce uncertainties for model predictions (Agbo et al. 2021; Al-Zu'bi et al. 2022; Makoni 2020). A larger number of observations for species such as carbon monoxide (CO), nitrogen oxides (NO_x), and ozone (O_3) would provide better statistics against which models could be tested in this data-poor region, while more detailed chemical measurements that allow source apportionment of trace gases and aerosols could help to constrain emission inventories and model representation of chemical processes and transport. A recent study points out that more in situ observations in the East Africa could substantially improve the predictive skill of atmospheric chemistry model(s) in the region (Tang et al. 2023).

Data assimilation models incorporating satellite remote sensing observations are in some cases global in scope and therefore provide information on air quality over Africa (Agusti-Panareda et al. 2017, 2019). Due to missing information on actual emissions, and the lack of ground-based in situ and remote sensing data, accurate ground-level air pollution levels and validation of such models are challenging. Despite the worldwide coverage of

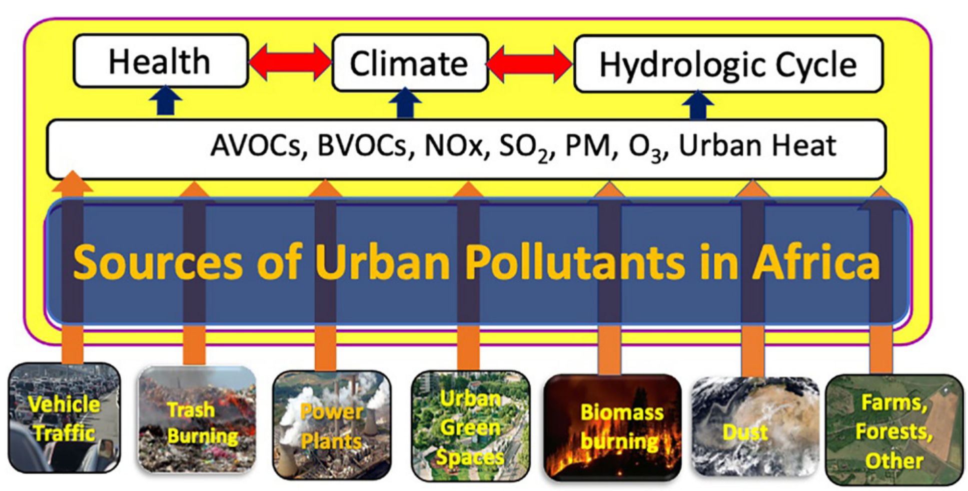

Fig. 1. African pollution emission sources.

satellite data, their use in monitoring air quality (AQ) over Africa is infrequent due to capacity limitations for these large datasets (Dekker et al. 2023).

Many of the scientific challenges in atmospheric chemistry are global in nature and affect everyone (National Academies of Sciences, Engineering, and Medicine 2016). A significant portion of future emissions affecting global atmospheric composition may come from Africa (Ayompe et al. 2020), and hence, there is a need to understand and characterize these emissions. The urgency stems not just from the population of Africa, but from worldwide climate and air quality. These low-latitude emissions have a greater impact on oxidation and radiative forcing than northern midlatitude emissions (Scott et al. 2018; Zhang et al. 2016a). For example, if emissions are left unabated, sources of African PM emissions are expected to contribute 50% to the global total by 2030 (Liousse et al. 2014).

Field campaigns observing detailed atmospheric composition and meteorology have been an effective means to achieve scientific results that inform air quality policy. Examples of regionally focused airborne and ground-based research in the United States include the 2002 and 2004 New England Air Quality Studies (NEAQS) (Fehsenfeld et al. 2006), the 2000 and 2006 Texas Air Quality Studies (TexAQS) (Parrish et al. 2009), and the 2010 California Research at the Nexus of Air Quality and Climate Change (CalNex) (Ryerson et al. 2013). Major scientific results from these studies have been the recognition of the role of secondary organic aerosol as a major component of particulate matter together with gaps in emissions and process chemistry of volatile organic compounds (VOCs) (de Gouw et al. 2005), the importance of petrochemical emissions in ozone formation in Texas (Gilman et al. 2009), and the identification of volatile chemical products as a major driver of VOC emissions in California and elsewhere (McDonald et al. 2018). In China, the Campaigns of Air Quality Research in Beijing and Surrounding Regions (CARE-Beijing) took place in a series of years between 2006 and 2014 and were followed by an additional series of campaigns, such as the study of air pollution sources and processes within Beijing (APHH Beijing) (Lu et al. 2019a; Shi et al. 2019). This research has elucidated the major mechanisms responsible for summertime ozone and winter haze formation in China (Guo et al. 2023; Lu et al. 2019b) and has occurred concurrently with significant emission reductions in East Asia (Liu et al. 2017; Xia et al. 2016).

Research efforts at this scale have been limited to nonexistent in much of Africa. Here, we review the current state of air quality research in Africa and East Africa and discuss the potential outcomes of more detailed atmospheric chemistry measurements using research-grade instruments, field intensives, satellite observations, and modeling. We provide a framework for multiplatform observations, measurement, modeling, and capacity-building program for the region.

2. Existing datasets

a. Reference monitoring. Reference monitors are key for air quality management and research. A survey of the data available on OpenAQ as of September 2023 (Fig. 2) shows that there are three reference-grade O_3 monitors in Africa (all in South Africa) and 123 $PM_{2.5}$ reference monitors (97 in South Africa and 26 in the rest of the continent). $PM_{2.5}$ reference monitors such as the federal reference method (FRM) instruments and federal equivalence method (FEM) instruments, commonly used in the United States, are rare in Africa. The largest repository of reference $PM_{2.5}$ data outside of South Africa comes from the U.S. State Department AirNow program, where reference monitors are placed at U.S. diplomatic posts, which are publicly available. Most regulatory monitoring efforts are recent, resulting in only a few years of data. Some long-term measurement sites were also available including the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) stations specially the one located in Mount Kenya and the Rwanda Climate Observatory which provided information on greenhouse gas emissions relevant for air quality assessment in East Africa.

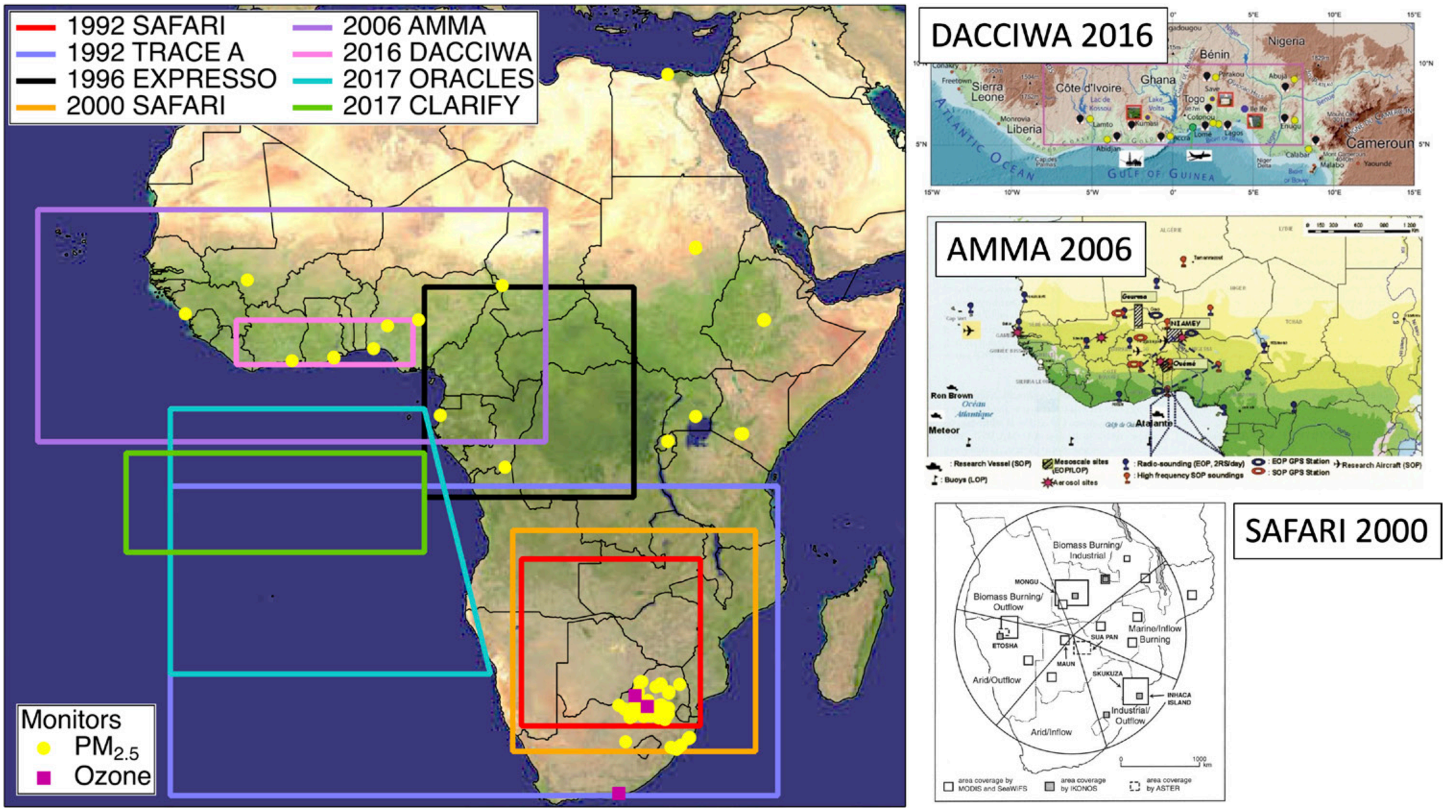

Fig. 2. **Locations of reference-grade $PM_{2.5}$ and O_3 monitors in Africa available on OpenAQ as of September 2023. The map also shows domains of field intensives in and near Africa since 1992 and is described in section 3. Illustrations at right show expanded views of SAFARI 2000, AMMA 2006, and DACCIWA 2016. Reproduced with permission from Knippertz et al. (2017), Redelsperger et al. (2006), and Swap et al. (2002).**

b. Low-cost sensors. Consumer-grade, "low-cost" air sensor data (henceforth referred to as LCS) have been embraced across Africa to fill air quality data gaps. Typically, LCSs have measured PM rather than gases. Many LCS deployments have had limited reference data to calibrate against. Their deployments, however, have been vital to understand PM levels in African cities, many of which were previously unmonitored. For instance, McFarlane et al. (2021b) presented the first $PM_{2.5}$ measurements in Kinshasa, Democratic Republic of Congo using a calibrated network of PurpleAir sensors. Example LCS deployments in West Africa include locally calibrated LCSs in Lomé, Togo (Raheja et al. 2022), the Greater Accra, Ghana region (Raheja et al. 2023), and Gabon (Ngo et al. 2019). In East Africa, work has focused in cities such as Addis Ababa (Singh et al. 2021), Nairobi (Pope et al. 2018), Kigali (Subramanian 2020), and Kampala (Okure et al. 2022).

A challenge with LCS is data quality. Proper calibration is needed for reliable data since they are biased high for $PM_{2.5}$ in most environments. Since environmental conditions and aerosol properties affect the measurements, calibration of LCS against reference monitors is ideally conducted locally with higher time resolution FEM instruments (e.g., BAM 1020, Teledyne T640, and TEOM 1405). Calibration methods include simple models such as linear regression and more complex approaches such as machine learning (McFarlane et al. 2021a). Across the continent, more work is needed to go beyond characterizing concentrations and leverage well-calibrated LCS for source attribution, data fusion with other sources such as satellites and models, and health and policy studies.

c. Visibility networks as a proxy for air quality. The lack of long-term air quality data introduces uncertainty in assessing trends in East Africa's air quality. The satellite record provides column observations since the 1990s, but for earlier data, the only records are from air quality proxies. Singh et al. (2020) used visibility data (1970s–2010s), which are routinely measured at airports, as a proxy for PM. Visibility in the three studied locations (Addis Ababa, Kampala, and Nairobi) decreased significantly over this period, suggesting that PM levels have increased between 62% and 182%.

d. Satellite remote sensing instruments. Owing to their greater spatial coverage, satellite measurements are an important supplement to sparse in situ monitoring (Fig. 3). Information about multiple trace gases (O_3, CO, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (HCHO), ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), methanol (CH3OH), nitrous acid (HONO), glyoxal (CHOCHO), isoprene, and a few other VOCs), aerosol parameters [aerosol optical depth (AOD), vertical profiles of aerosol extinction coefficient, and refractive index (RI)], and fire activity can be retrieved from space. Over Africa, satellite data of atmospheric composition have been used for studying air quality and its trends (Duncan et al. 2016; Shikwambana et al. 2020), improving information from low-cost sensors

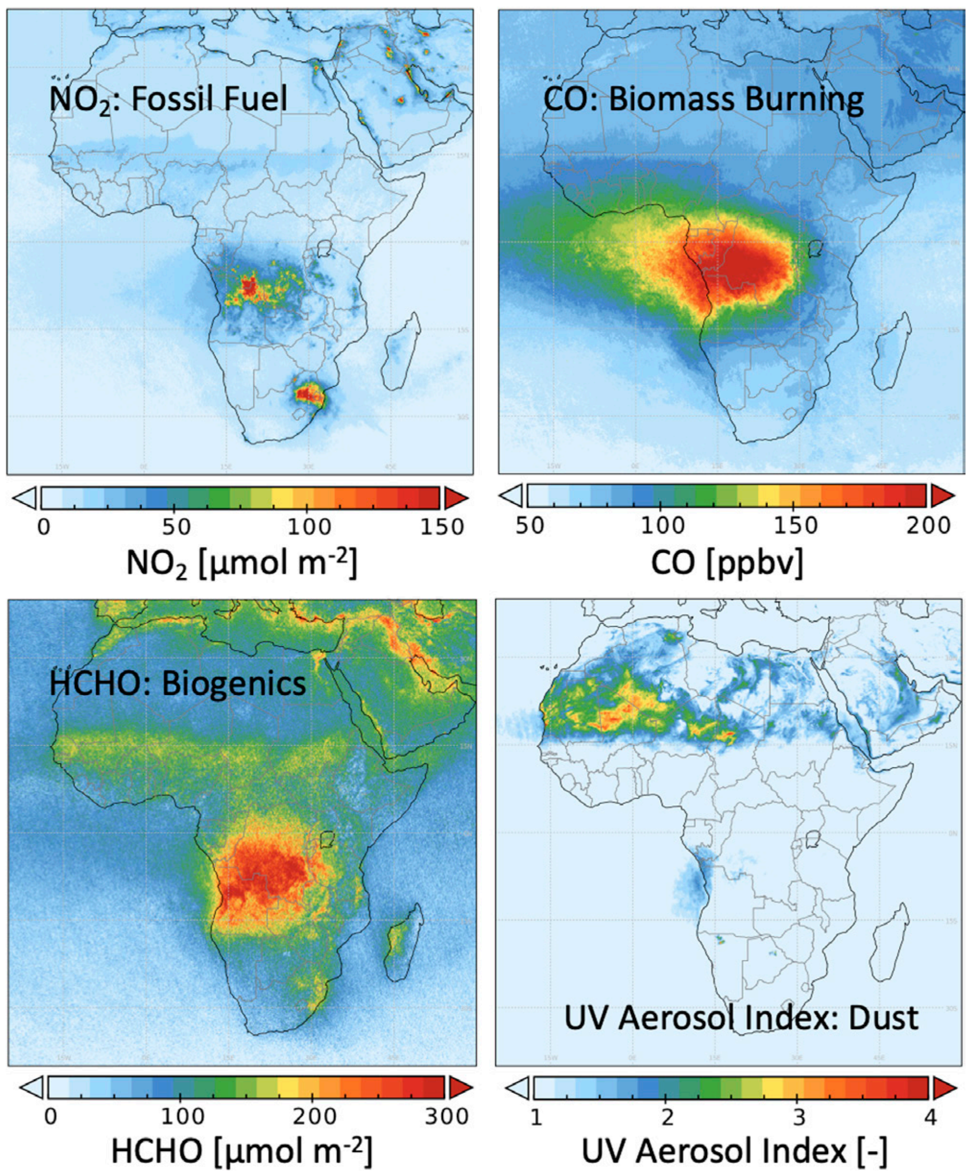

Fig. 3. Tropospheric Monitoring Instrument (TROPOMI) NO_2, CO, HCHO, and UV aerosol index (UVAI), averaged over July 2019 over the African continent. NO_2 is an indicator for fossil fuel burning, CO is an indicator for biomass burning, HCHO is an indicator for biogenic emissions, and UVAI is an indicator for Sahara dust. The data represent all major air pollutants, and all of them are present in Africa. Image courtesy Pepijn Veefkind, Royal Netherlands Meteorological Institute (KNMI).

(deSouza et al. 2020; Malings et al. 2020), model evaluation (Kumar et al. 2022; Ridley et al. 2012; Tang et al. 2023), emission estimates (Marais et al. 2012; Martinez-Alonso et al. 2023) and health impacts (Heft-Neal et al. 2018). Nevertheless, there are several challenges to applying satellite data over Africa. Satellite products provide vertically integrated information at coarser spatial resolution than ground-based local sensors. It is thus important to better connect satellite column retrievals to surface concentrations, such as AOD to $PM_{2.5}$ and NO_2 to NO_x. However, the rapidly improving spatial resolution of satellite observations will provide more accurate information in the future (Alvarado et al. 2019; Cooper et al. 2020, 2022; Shindell et al. 2022). Currently, Africa is only covered by polar-orbiting satellites rather than geostationary satellites, which introduces temporal representativeness errors (Tang et al. 2021). The quality of satellite products relies heavily on ground and aircraft validation and calibration (Paton-Walsh et al. 2022). The limited number of ground measurements and ground-based remote sensing measurements in Africa hinders the interpretation of satellite observations and introduces uncertainties in retrievals. The quality of the atmospheric models is another uncertainty in Africa, since in most cases retrievals are dependent on model assumptions. The uncertainty in emissions and trace gas and aerosol vertical profiles, and a lack of proper surface albedo data, also influences retrieval accuracy. Air quality field intensives benefit from a better understanding of satellite column retrievals and their relationships with surface concentrations and vice versa. A geostationary satellite for air quality over Africa in the future (Marais 2015), model development, and more in situ monitoring and ground-based remote sensing measurements for satellite validation would address these data gaps.

e. Model studies. Atmospheric chemistry models simulate detailed chemical and transport processes controlling air quality and are therefore useful for understanding and predicting air quality. Modeling studies on African air quality have focused on evaluating the impacts of dust (Flaounas et al. 2017; Gueye and Jenkins 2019; Saidou Chaibou et al. 2020), fire impacts (Kuik et al. 2015; Opio et al. 2022; Wang et al. 2018), and regional carbon monoxide transport (Kumar et al. 2022) and assessing the impact of economic growth and mitigation policies on air quality (Bockarie et al. 2020; Lacey et al. 2017; Marais et al. 2019). Models have been used to quantify the contribution of different sources to air pollution and their impacts on human health. Examples of such studies include those that investigate emissions from fugitive and inefficient combustion sources (Marais and Wiedinmyer 2016), charcoal production (Bockarie et al. 2020), residential emissions (Lacey et al. 2017), electric power generation plants (Marais et al. 2019), fertilizer use (Garland et al. 2017; Huang et al. 2018), and trash burning (Gordon et al. 2023).

The Weather Research and Forecasting Model coupled with chemistry (WRF-Chem), the Multi-Scale Infrastructure for Chemistry and Aerosols version 0 (MUSICAv0) (Tang et al. 2023), the Goddard Earth Observing System driven atmospheric chemistry (Marais et al. 2019) (GEOS-Chem), the Comprehensive Air Quality Model with Extensions (CAMx), and CHIMERE (Mazzeo et al. 2022) are among the modeling systems used to study air quality in Africa. These can be accessed from the quasi-operational to operational air quality forecasting systems run by different centers including the European Centre for Medium-Range Weather Forecasts (ECMWF), the Global Modeling and Assimilation Office (GMAO) of the National Aeronautics and Space Administration (NASA), the National Center for Atmospheric Research (NCAR) in the United States, and ensemble dust forecasts generated by the Barcelona Supercomputing Center (BSC).

3. Field intensives

Field campaigns, or intensive operating periods (IOPs), are a common tool for understanding atmospheric composition and air quality. IOPs augment long-term, routine monitoring from surface sites and observations from satellite remote sensing instruments, providing more detailed chemical and meteorological measurements over a defined period. IOPs may involve enhanced observations at fixed sites, or mobile measurements utilizing instrumented vehicles, research aircraft, or ships. They often incorporate or are conducted in conjunction with observations from satellite instruments. They are useful for source apportionment, understanding of process chemistry, pollutant spatial distributions, and transport and loss mechanisms.

a. Previous field intensives in Africa. There have been a limited number of field campaigns over or near the African continent during the last 3 decades (Table 1 and Fig. 2). Early missions, Southern African Fire Atmospheric Research Initiative (SAFARI) (Lindesay et al. 1996) and Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A) (Lindesay et al. 1996) in 1992, were designed to better understand ozone over the Atlantic basin as observed by satellite instruments. The Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO) 1996 campaign (Delmas et al. 1999) focused on regional oxidants and biogenic and biomass burning emissions.

Since the year 2000, there have been only two large-scale field campaigns in West Africa and one in southern Africa. This number pales in comparison with the intensively sampled regions of North America, Europe, and Asia. No campaign has taken place in East Africa (Fig. 2). SAFARI 1999–2001 (Otter et al. 2002; Swap et al. 2003, 2002) incorporated ground sites with multiple aircraft to understand terrestrial ecosystems, land-use change, aerosols, trace gases, clouds, radiation, and hydrology. The 2000 dry season campaign involved investigators from 18 countries and 5 aircraft (Swap et al. 2002). The 2006 African Monsoon Multidisciplinary Analysis (AMMA) campaign in West Africa (Haywood et al. 2008; Liousse et al. 2010; Redelsperger et al. 2006) incorporated ground sites and aircraft oriented around IOPs during the dry season (January–February) and different monsoon phases (June–September) to understand the meteorology of the West African monsoon (WAM), emissions, chemical processes, aerosol properties, and regional biomass burning. The 2016 Dynamics–Aerosol–Chemistry–Clouds Interactions in West Africa (DACCIWA) campaign in southern West Africa (SWA) (Flamant et al. 2018; Knippertz et al. 2015, 2017) included ground sites and aircraft, with major scientific goals focused on meteorology, and the chemical evolution of pollution plumes originating from the urban areas of Accra, Ghana, and Lomé, Togo. The campaign also focused on biomass burning plumes advected from southern Africa. DACCIWA also emphasized capacity building through partnerships between European institutions and local scientists.

Additional recent campaigns over the Atlantic basin (Table 1) have largely been focused on understanding the westward transport of African biomass burning emissions. These include the 2016–18 U.S. NASA Observations of Aerosols above CLouds and their intEractionS (ORACLES) campaign based in coastal Namibia and São Tomé (Redemann et al. 2021) and the U.K. Cloud–Aerosol–Radiation Interaction and Forcing (CLARIFY) aircraft campaign based in Ascension Island (Haywood et al. 2021). Last, limited flight altitude data and profiles over selected airports are being collected on passenger aircraft equipped by the European Research Infrastructure In-Service Aircraft for a Global Observing System (IAGOS) project (Petzold et al. 2015).

A campaign in East Africa would very likely build on the limited existing work that has gone before it on the continent, particularly SAFARI, AMMA, and DACCIWA. Section 4 outlines the major goals for such a campaign. Observations to address air quality in East Africa would ideally include the tools described above, up to and including aircraft observations. Partnerships and capacity building are an essential component of a campaign to ensure the

Table 1. **Historical field intensives and scientific goals in or near Africa.**

Campaign	Year	Region	Platforms	Scientific goals
SAFARI	1992	Southern Africa	Ground sites	Biomass burning
			Light and heavy aircraft (DC-3)	Tropospheric O_3
			Remote sensing	
TRACE-A	1992	Southern Africa and southern and tropical Atlantic	U.S. NASA DC-8	Tropospheric O_3
			Remote sensing	
EXPRESSO	1996	West central Africa	Ground site	Biogenic emissions
			Light aircraft	Regional oxidants
			Remote sensing	Biomass burning
SAFARI	1999–2001	Southern Africa	Ground sites	Terrestrial ecosystems
			U.S. NASA ER-2 and University of Washington's Convair	Land-use change
			U.K. C-130	Aerosols, trace gases, clouds, and radiation
			South African Aero Commander	Hydrology
AMMA	2006	West Africa	Ground sites	Meteorology of the WAM
			U.K. BAE 146	Emissions and aerosol properties
				Biomass burning
DACCIWA	2016	SWA	Ground sites	Meteorology
			German DLR Falcon	Urban pollution plumes
			French SAFIRE ATR 42	Biomass burning
			U.K. Twin Otter	Aerosol–cloud interactions
ORACLES	2016–18	Southern and tropical Atlantic	U.S. NASA P-3 and ER-2	Biomass burning transport
CLARIFY	2017	Tropical Atlantic	U.K. BAE 146	Aerosol–cloud interactions
				Biomass burning

best use of the observations by the local scientific and policy communities. These aspects are described further below.

b. Interaction of meteorological and atmospheric composition measurements. The changes and influencing factors of air pollution in East Africa over a period from 2001 to 2021 have been investigated using remote sensing data (Kalisa et al. 2023). The analysis demonstrated increasing and decreasing air pollution in hotspots (PHS) and cold spots (PCS), respectively, and showed that average AOD values and burned areas varied significantly between PHS and PCS. The findings highlight the spatial and temporal heterogeneity of air pollution in East Africa and emphasize the importance of considering meteorological factors such as high sea level pressure in the upper latitudes, the cold air masses from the Northern Hemisphere, and dry vegetation in the study region coupled with a dry and less humid atmosphere from the boreal winter in understanding air pollution patterns and concentrations.

4. Approaches and next steps

There are multiple challenges to conducting a comprehensive air quality field intensive in Africa. 1) There is a lack of capacity of basic research infrastructure for atmospheric and air quality research, including a lack of capacity in using satellite data. 2) There is a lack of effective communication such as understanding the local cultural meanings and data sharing among groups working on air quality research in the region. Reference data exist on the continent, but they are mainly controlled by individual research groups or environmental management authorities. Some of these data may publicly be available upon request. 3) Lack of local technical capacity and resources limits the utility of air quality instruments owned and run by local governments in East Africa. 4) General lack of awareness of the dangers of air pollution and governmental reluctance to invest in mitigation hinders large-scale research efforts.

a. Major scientific objectives. The scientific goals associated with fieldwork in East Africa may include, but would not be limited to, the following.

1) Emissions in East Africa specific to the region. The region has a unique mixture of emission sources as depicted in Fig. 1. Quantifying anthropogenic and natural emissions and developing a representative epidemiological model is the cornerstone to accurate predictions of air quality and health impacts.

2) Chemical transformations that lead to secondary pollutants such as $PM_{2.5}$ and O_3. Chemical transformations of primary emissions produce secondary pollutants that are harmful to human health and therefore regulated in the Global North. Such chemical transformations depend on atmospheric conditions and the amounts and characteristics of primary emissions (Jimenez et al. 2009; Seinfeld 1989) and are therefore specific to a given region. There is a general lack of process-level understanding for the formation of ozone and secondary aerosols in Africa.

3) Meteorology and transport relevant to regional air quality. Prevailing weather patterns and synoptic conditions control the spread and mixing of pollutants and their long-range transport (Lai et al. 2023). Interaction of topography and prevailing wind patterns prolongs the duration of pollution events in valleys, for example, or facilitates the "cleaning" of polluted air near mountain passes (Wolf et al. 2020). For example, the prevailing wind patterns over Addis Ababa tend to be from east and south-southeast, where the rift valley and large drop in topography are located leading to downslope wind ventilation and complex interaction between the urban and topographic wind controls (Weiß et al. 2022). Other diurnal wind patterns, like the low-level jet (LLJ) and the extent of the Somali jet on pollution and its recirculation, are not known (Samman and Gallus 2018; Wei et al. 2023). The urban micrometeorology over megacities and its control on diurnal boundary layer evolution and its interaction and modification by the synoptic conditions are all important factors that are not well reported and understood in most of the African cities.

4) Regional emission trends and global impacts. Africa has approximately 15% of the global population but contributes only 4% of anthropogenic CO_2 emissions (Ayompe et al. 2020). Global demographic and emission trends suggest that this fraction will grow. Africa accounts for approximately 72% of the burned area worldwide and about 52% of the carbon emissions, which includes 44% of CO emissions, 36% of CH_4 emissions (van der Werf et al. 2010), and 60% of the total black carbon (BC) emissions. Recent estimates show that Africa's fire emissions are 31%–101% higher than previously estimated (Ramo et al. 2021). Africa is a large source of both dust and biogenic emissions (Guenther et al. 2012; Prospero et al. 2014; Scholes and Andreae 2000). Urban and other emissions that lead to ozone and secondary aerosol have been characterized from recent satellite and field observations but remain uncertain (Hickman et al. 2021; Liousse et al. 2014, 2010; Marais et al. 2019).

The equatorward shift in such emissions in the last 4 decades has led to increases in the global tropospheric ozone burden (Christiansen et al. 2022; Wang et al. 2022), and further emission shifts associated with continued midlatitude declines and increases in Africa may have similar but as yet undetermined effects.

5) Education and human and infrastructural capacity building in the region. Education of policymakers, citizens, and international collaborators is a critical component of sustainable air quality research. Training in effective communication helps foreign scientists gain a deeper understanding of the cultural context within which they are working. Local investment for infrastructure and training of technicians to maintain infrastructure and scientists that conduct the research is critical. Any effort by international groups needs clear coordination with local governments for infrastructure development and training to sustain the activity.

Figure 4 depicts interconnections among multiplatform observations, modeling frameworks, and societal impacts. The observations are required for evaluating air quality models, improving air quality forecasts and reanalysis through assimilation, constraining emissions through inverse modeling, and designing air quality mitigation strategies. Improved air quality simulations serve as the basis for societal impact analysis.

b. Approaches for observations and modeling in East Africa.

1) Ground-based chemical and meteorological observations. Ground-based physical and chemical measurements are required to understand the sources, transformation, transport, and fate of pollutants and their interaction with the structure of the planetary boundary layer. Even a modest expansion of long-term reference monitoring of standard pollutants in Africa, such as O_3, NO_x, CO, $PM_{2.5,}$ and $PM_{10,}$ and meteorology would substantially increase the currently available database in the region. Ground-based remote sensing instruments, such as Pandora, Micro-Pulse Lidar Network (MPLNET), Fourier transform infrared (FTIR) spectroscopy, or Aerosol Robotic Network (AERONET) (Crawford et al. 2021; García et al. 2021), connect observations of trace gases (HCHO and NO_2) and particulate matter to satellite columns. The optimal location for monitoring stations would include urban centers and/or suburban areas and receptor sites downwind of major source locations. Such long-term monitoring sites, once established, may then serve as potential host locations for shorter duration (e.g., 1–2 months) but more detailed field campaigns. Detailed, short-term chemical

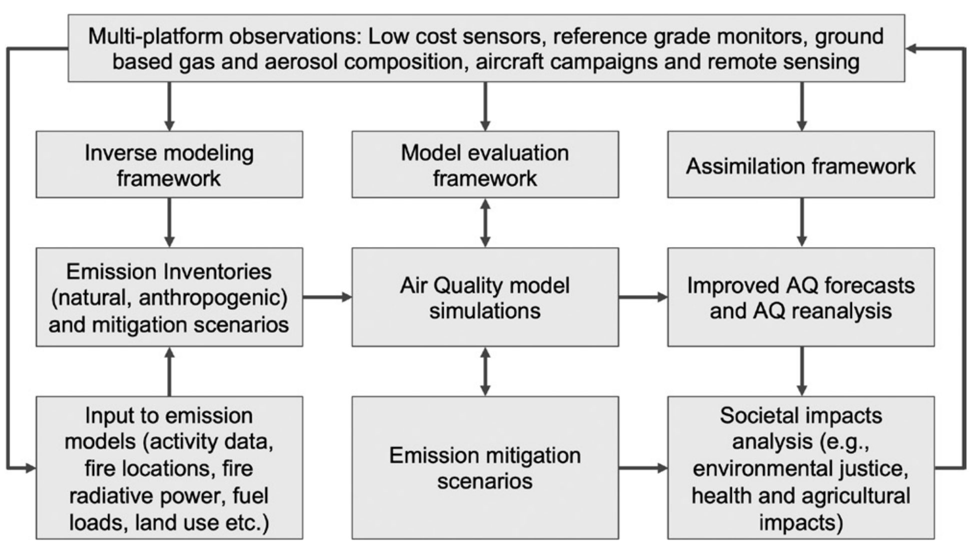

Fig. 4. Interconnections among multiplatform observations, modeling framework, and societal impacts.

measurements that augment longer-term monitoring include gas-phase speciated VOCs, speciated and total reactive nitrogen (NO_y), sulfur dioxide, ammonia, halogen compounds, greenhouse gases, and radicals [hydroxyl (OH), hydroperoxyl (HO_2), and nitrate (NO_3)]. Detailed aerosol measurements include composition, size distributions, hygroscopicity, and optical properties (extinction, scattering, and/or absorption). Meteorological measurements include high-frequency winds (e.g., for flux measurements) and vertical profiles of temperature, wind speed and direction, and boundary layer height. Sample towers that extend in situ chemical and meteorological observations to tens or hundreds of meters above ground level increase the footprint of stationary observations to larger areas and reduce sensitivity to localized emission sources. Field intensives incorporating part or all of this observational suite (detailed instrument descriptions are beyond the scope of this manuscript) are well suited to address the science questions outlined in section 4a.

2) Mobile platforms. Ground-based mobile platforms, typically instrumented vehicles often referred to as mobile laboratories, incorporate the routine measurements listed above and a targeted subset of the intensive observations listed above. They provide spatial distributions of pollutants to constrain emissions, transport, and chemical transformations and can be operated more routinely and at lower cost than research aircraft. Such an approach may be particularly attractive in East Africa as a first step to extend beyond stationary ground-based operations.

Aircraft research is often the capstone of an observing strategy that builds from stationary and mobile ground-based research. Aircraft are essential for validating and linking together space- and ground-based remote sensing measurements (Crawford et al. 2016; Judd et al. 2019; Nowlan et al. 2018; Zhang et al. 2016b). Airborne measurements are useful to observe atmospheric chemistry in real time through quasi-Lagrangian sampling (Adhikary et al. 2009), for example, in the outflow of large emission sources such as fires, urban areas, and industrial and energy generation point sources. Aircraft can characterize regional backgrounds as well as emission fluxes over large areas (Karion et al. 2015; Li et al. 2020).

Many of the aircraft programs in or near Africa in section 3 were designed, led, and instrumented by scientists and agencies from the United States and Europe. Recent campaigns, such as DACCIWA 2016, have made the participation of African scientists an integral component of the study design. Although we anticipate that any near-term aircraft campaign in East Africa will necessarily rely on the research capacity of the Global North, partnerships with and training of local scientists will be an essential component to ensure that research findings have the greatest relevance to local and regional air quality issues. The following sections on capacity building outline this concept in greater detail.

3) Model development: Emissions, meteorology, and chemistry. Due to large variation in sources and the intensity of emissions between megacities and geographic regions in Africa (Liousse et al. 2014, 2010; Malavelle et al. 2011), it is essential for atmospheric chemistry models to use information generated regionally from direct observations. To ensure accurate model development for the region, there is a clear need for both field data and new laboratory-based experimental data that are specific to the process chemistry associated with regional emissions. The WMO has a multimodel intercomparison exercise, Air Quality Prediction and Forecasting Improvement for Africa, to understand the ability of different models to simulate air quality in Africa (Sokhi et al. 2022; WHO 2022). Heterogeneous chemistry on dust surfaces can be an important process due to the high abundance of dust in Africa, but large variability in reactive uptake coefficient can lead to large errors in model simulations (Kumar et al. 2014). Measurements of these coefficients are essential for improving model simulations.

c. Capacity-building partnerships. The research and collaboration model for East Africa highlighted here is based on common scientific and research goals that focus on regional needs and priorities (Hickey et al. 2018). Costello and Zumla (2000) suggest that the components of a genuinely cooperative research partnership include 1) mutual trust and shared decision-making, 2) emphasis on transitioning research findings into practice, 3) the development of national research capacity, and 4) focus on solution development that is community centered.

It is useful to create partnerships and relationships with the local communities in order to be able to consider cultural expectations in creating cooperative strategies for improvement in air quality (Amey 2010) and build on existing knowledge (Black 2002). Consistent communication to revisit expectations for collaboration will help develop shared understanding on strategies and outcomes (Jie 2010).

Following the workshop in Kigali, air quality working groups in four East African cities have been formed. The groups consist of universities, city governments, relevant government agencies, local air quality regulators, international organizations and universities, and meteorological agencies. There are several other efforts at building international collaborations on African air quality. For example, the National Science Foundation-funded Clean Air Monitoring and Solutions Network (CAMS-Net) project seeks to close the African air pollution data gap. Other efforts include capacity-building programs funded by the U.S. State Department. AfriqAir is an international consortium of air quality experts interested in improving African air quality. AirQo works to empower African communities with accurate, hyperlocal, and timely air quality data to drive air pollution mitigation actions. The African Group on Atmospheric Sciences (ANGA), the African-led group, focused on atmospheric sciences aims on uniting atmospheric expertise across Africa.

The goals of these partnerships are to provide opportunities for infrastructure and human capacity building and creating a sustained power (human and infrastructure) and empower the partners in the developing countries to be equal partners who can contribute to the global effort to clean air and mitigate climate change. A concerted educational campaign to address the dangers of air pollution, the economic and health costs of air pollution, and the linkage between air pollution, climate change, and food and energy security would serve to foster such scientific partnerships. Local investment can also help sustain the efforts, and engaging diaspora scientists may help facilitate communication and overcome cultural barriers.

Finally, it is worth noting that any air quality research effort in East Africa will substantially contribute to United Nations-defined sustainable development goals (United Nations 2024). Although improved air quality is not itself one of these goals, it is a component of several others, including good health and well-being, affordable and clean energy, resilient infrastructure, sustainable cities and communities, and climate action. Clean energy and climate action are worth particular emphasis. Emission control strategies that benefit air quality very often have co-benefits for climate change. Research to identify such strategies has the potential to influence the trajectory of development at this critical period in Africa broadly and East Africa in particular. Rapid population growth and urbanization are in their early stages but will accelerate in the coming decades. Such growth need not take place in an information vacuum but could rather be informed by the best available scientific tools that have been developed in other nations. International partnerships are the key to realizing this critical need for environmental information. The Clean Air and Climate Coalition (CCAC) that met in 2022 included the United Nations Environment Program, and the African Union released a comprehensive report "Assessment of Air Pollution and Climate Change for Sustainable Development in Africa." The report shows how African leaders can act on key emission sources to fight climate change, reduce air pollution, and improve health in the continent (UNEP 2022).

5. Conclusions

Africa is already a large global source region for emissions from fire, the biosphere, and dust, and it is undergoing a period of rapid urbanization that has the potential to significantly increase its urban, agricultural, and other anthropogenic emissions. To date, there has been relatively little research to address this issue that will affect both the growing population in the region and the composition of the global atmosphere. Quantifying trends in emissions from different regions of the world and their impacts on atmospheric composition and chemistry to advance fundamental atmospheric chemistry knowledge has been one of the priorities identified by the U.S. National Academy of Sciences. The East African environment offers an opportunity to advance this fundamental understanding. This paper has summarized the state of air quality research capacity in Africa, with a focus on East Africa, and the challenges and opportunities for conducting coordinated research in the region. It suggests a roadmap and framework for observations, measurement, modeling, capacity building (both human and infrastructure), and education to address the challenges.

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