PROJECT SUMMARY

Overview: Air quality is a serious issue affecting health, mortality, and human productivity in the megacities of Africa. Africa is the least studied region of the world and the study of African megacity air quality has received very little attention from the global atmospheric chemistry community relative to other regions. For example, the successful application of advances in atmospheric chemistry in improving air quality in the US has been applied in improving air quality in Mexico City. However, this success did not extend to other areas such as parts of Africa, where indoor and urban air quality remain poor and the depth of air quality problems is largely unquantified. Urbanization, coupled with increased industrialization, growing ownership of motor vehicles, and continued use of biomass as domestic energy source, may lead to a substantial worsening of air quality across the continent. This proposed workshop will bring together experts from the U.S., Ethiopia, and Europe to develop a roadmap for future research to advance the fundamental understanding of emitted chemical species, particles, and formation of secondary particle. The workshop will formulate research methodology and measurement approaches to understand the long-range transport mechanisms that control the spread of pollutions in highly polluted emerging megacities in Africa, such as Addis Ababa, Ethiopia.

Intellectual merit: For developing country megacities there are diverse sources of VOCs. African cities have several distinct emission sources which are not common in European and North American cities. Emission estimates are uncertain, and detailed emission inventories are still required for a better estimation of their impacts on climate change and health. A key question in this respect is *what are the unique reactive volatile organic compounds (VOCs) their sources and their influence on O_3-NOx-VOC-PM chemistry that is different from well-studied regions of the world?* Growing megacities, such as those found in Africa may promise to be an apt testbed to address these scientific questions. Detailed air quality studies in Africa may reveal novel atmospheric chemistry processes that may not be common in highly sampled regions in the northern mid latitudes. *This new information could have significant implications for improved chemical mechanisms for air quality models and could provide guidance for laboratory-scale process studies.* The workshop will identify and report on the observational and modeling requirements for rigorous experimental design addressing the unique needs from an African megacity point of view. *It will discuss the requirements for a long-term data collection effort* to quantify emitted chemical species and primary particles and secondary particle formation *that may assist air quality regulators in Africa.*

Broader Impact: Urban air pollution is a pressing and multi-sectoral development challenge, representing a major health, economic, and social threat to cities of the global north and south. Poor air quality acts as an impediment to development through increasing expenditure on health, loss of labor productivity; lowering educational attainment due to illness; and reduced agricultural yields. Air pollution is a leading cause of morbidity and mortality in East Africa. However, the evidence base of its causes and effects in the regional context is currently insufficient. We expect that participants from underrepresented groups from minority-serving institutions – specifically HBCUs and HSIs, that will acquire knowledge and research skills in international collaborations and the development of field campaigns through their participation in this workshop. Students engaged in this workshop will gain experience in field project planning. These students will interact with peers, NCAR scientists, and international partners during the workshop and serve as facilitators of the breakout sessions and note-takers.

Air Quality Pilot Study Design in Addis Ababa, Ethiopia
June 11 -13, 2020
Project Description

Background and motivation:

Emissions and ambient concentrations of pollutants in the growing number of megacities are expected to increase significantly and are expected to have widespread local effects on the health of the population, on ecosystem degradation, and onvisibility due to urban haze [1, 2]. Specifically, the regional tropospheric volatile organic compounds (VOCs) composition, reactive gasses (Ozone and NOx) and particle concentrations are modified by economic growth and anthropogenic emissions. A recent study has suggested that VOCs from consumer products such as solvents are ever growing in the US and are dominating the reactive gas-phase atmosphere [3]. The impact of high concentrations of VOCs from industrial sources in the urban environment is not clear. For megacities in developing countries, there are diverse sources of VOCs. African cities have several distinct emission sources which are not common in European and North American cities. Emission estimates are uncertain, and detailed emission inventories are still required for a better estimation of their impacts on climate change and health. A key question in this respect is: *What are the unique reactive volatile VOCs their sources and their influence on* O_3*-NOx-VOC-PM chemistry that is different from well-studied regions of the world?* Growing megacities, such as those found in Africa may promise to be an apt testbed to address these scientific questions. Thus, understanding the evolving influence of African megacities on regional to global atmospheric chemistry is critical for both air pollution control at local scale levels as well as predicting their role in climate change [1]. Understanding the contributions of ambient VOCs and their sources to ozone formation potential would be helpful in developing atmospheric control measures.

About 3 billion people in the world rely on traditional biomass (fuel wood, charcoal, dung, and agricultural residues) for cooking; mainly in rural areas and even in cities in developing countries [4]. For Africa, this is not likely to change soon, as nine out of ten people, or 573 million people in sub-Saharan Africa, will remain without access to electricity by 2030 [5] and that will lead to continued biomass burning (BB) emissions. In addition to indoor use of biomass fuels, there is significant open BB activity in Africa. Africa is the single largest continental source of BB emissions, with recent studies estimating ~55 % of the global contributions to BB aerosols [6-11]. Savanna fires are the largest source of biomass burning emissions Africa [12]. African combustion emissions from all sources are expected to grow with increasing population, currently growing at 2.5% annualy, and economic growth.

Many of the scientific challenges in atmospheric chemistry are global in nature and affect individuals from a wide array of backgrounds [13]. Due to the very limited available data, the models being used for air quality and climate change in Africa rely on global inventories that are primarily collected from North America, Europe and Asia, which are also based on certain assumptions [9, 14-18]. Recent studies have shown that these modeled outputs are not consistent with satellite observations [19, 20] over Africa [21]. While the research findings of atmospheric chemistry and their implications for climate and health in regions that are well studied can, in principle, be applied to other situations, the unique mix of pollutants, emissions and emission sources, meteorology, and economic development of African megacities should be considered as distinct from other more well-studied regions in the US and Europe [13]. Effective policies to control this pollution will require state of the art research and expertise in atmospheric chemistry in combination with knowledge and understanding of the local-scale social and cultural factors intrinsic to the countries involved.

Furthermore, it is necessary to develop international cooperative efforts to meet the objectives of all the priority science areas described in the 2016 National Academies of Sciences (NAS) report [13]: The NAS recommendations specifically state that a "… more sustainable approach is to build strong collaborations between U.S. atmospheric chemists and scientists who focus on these developing regions and their international counterparts to build human capacity and observational and modeling capability in those regions. (2) An equally important approach is providing support for peer-to-peer relationships between scientists from the United States and those in developing countries to advance and implement measurement as an approach to building global atmospheric chemistry capacity is supporting in developing countries."

There have been a few smaller-scale NSF-funded efforts that have focused on atmospheric phenomena or contributed to international field studies in Africa, but none were comprehensive nor address the megacities air pollution issue e.g. SAFARI [22, 23], AMMA-NAMMA [24, 25], and a recent study in Namibia [26]. In contrast, there have been several major US field campaigns in China [27], South Korea (KORUS-AQ) [28], India [29], and Nepal [30-32] that have focused on air quality. Many of these have received NSF funding. Few have developed or leveraged the extensive relationships between African scientists and their counterparts in historically black colleges and universities (HBCUs). This is despite the fact that HBCUs have a three-quarter century legacy of educating and developing African scholars in a range of disciplines including those supporting the geosciences [33, 34]. This proposal seeks to take advantage of these established relationships to address an important science question in air pollution. It also uses this opportunity to incorporate a diversity of thought by leveraging the experiences of HBCU faculty and graduate students conducting R1-level research in under-resourced environments, quite like the conditions experienced by African scientists.

This proposal requests support for a US-Ethiopia planning workshop to define and focus the broad research methods and approaches to answer the science questions posed and establish the linkages and responsibility of the contributing scientists. Our initial test site of focus is chosen to be Addis Ababa, Ethiopia and the title of the proposal is "Workshops for an Air Quality Pilot Study Design in Addis Ababa, Ethiopia." This workshop will be jointly organized by University faculty- Professors Solomon Bililign, (North Carolina A&T State University (NCATSU)), Professor Vernon Morris (Howard University), Professor Belay Demoz (UMBC and an adjunct at Howard), representatives from NCAR-ACOM, and university faculty from UK and Ethiopia. There will be a follow up workshop to be organized by the Ethiopian team in Addis Ababa. This meeting will engage federal and municipal stakeholders, academic institutions, and NGO's to further discuss the science ideas and outcomes of the US workshop and cultivate support for a future joint field study.

Workshop location and date:

The workshop will be held at the Kim Engineering Building: 8228 Paint Branch Dr, College Park, MD 20742. The workshop is planned for June 11 -13, a 2.5-day meeting. A workshop web page will be used to announce workshop agenda and presentations as well as final consensus reports. Experts in the field and potential participants have been contacted and solicited for input. Although there is a great interest and communications are ongoing, at present about thirty scientists have expressed interest and plan to attend. Participants will be formally invited by the committee organizers and Co-Chairs. The workshop has already been endorsement by International Global Atmospheric Chemistry (IGAC).

The need for the workshop and topics for discussion:

Air quality is a serious issue affecting health, mortality, and human productivity in the megacities of Africa. Nevertheless, this topic has received very little attention from the global atmospheric chemistry community relative to other regions. For example, the successful application of advances in atmospheric chemistry in improving air quality in the US has been applied in improving air quality in Mexico City. However, "this success does not extend to many other areas such as parts of Africa, where indoor and urban air quality remain poor and the depth of air quality problems is essentially unknown" [13].

One of the research priorities in a 2016 National Academy of Sciences (NAS) report on the future of atmospheric chemistry includes [13] "quantifying trends in emissions from different regions of the world and their impacts on atmospheric composition and chemistry over scales from local to global and developing reliable approaches to integrating "top down" and "bottom up" results for emission inventories."

However, one of the least studied regions of the world is Africa. Africa currently has the fastest growing population in the world; projected to more than double between 2010 and 2050, [35], and 21 of the 30 fastest growing cities are in Africa [36]. By 2050, nearly 60% of the population in Africa is predicted to be living in cities, compared to less than 40% in 2011 [37]. Urbanization, coupled with increased industrialization, growing ownership of motor vehicles, and continued use of biomass as domestic energy source, will certainly lead to a substantial worsening of air quality across the continent [38]. For example, population increases in Nairobi produced a ~250% increase in particulate matter (PM) air pollution from 2007-2017 [39].

Unfortunately, the true complexities of the problem in other African cities are not known because few African cities have air quality monitoring capabilities that would enable detailed studies to characterize the unique chemistries in these environments [38], with impacts on the global atmosphere. The data sets that do exist are not always publicly available and/or strategically communicated, which limits public knowledge as well as effective policy making. Thus, the challenge is multifaceted.

Recently, several observational studies of regional atmospheric phenomena have been conducted in Africa. The most recent study through the Dynamic-Aerosol-Chemistry-Cloud Interaction in West Africa (DACCIWA) project that measured a wide range of atmospheric constituents and up to 56 VOCs, some unique to the region and missing in the global anthropogenic emission profiles [40]. However, these efforts have been limited in duration, locally or regionally isolated, and did not result in local capacity development for sustained observation and research. There is also a growing recognition of the significance of African megacity development and expansion for regional and global-scale tropospheric chemistry and climate, as evidenced by several recent meetings and workshops [41, 42]. Event organizers have included the World Meteorological Organization (WMO), local and international groups, and international initiatives such as Environmental Compliance Institute (ECI) in Kenya, the National Association for Clean Air (NACA) in South Africa, the European Centre for Medium-Range Weather Forecasts (ECMWF), the US-EPA's environmental program in sub-Saharan Africa and a Systems Approach to Air Pollution in East Africa (ASAP), the World Resources Institute (WRI), and the International Global Atmospheric Chemistry (IGAC) African Group on Atmospheric Sciences (ANGA).

Taken together with the NAS recommendations, this suggests an urgent need for a detailed study of African anthropogenic primary and secondary emissions to reduce uncertainties in the estimates of emissions. These uncertainties remain large and cannot currently be assessed due to the lack of adequate ground truth data [43-45]. Pollutant emissions in sub-Saharan Africa and their contribution to global burden show considerable variation with latitude and introduce significant regional variability in the radiative forcing and regional climate [46-48].

This workshop will bring together experts from the U.S., Ethiopia, and the UK to develop a roadmap for future research to advance the fundamental understanding of emitted chemical species and secondary particle formation, as well as formulate questions pertaining to long-range transport mechanisms that control the spread of pollutions in emerging megacities such as Addis Ababa, Ethiopia. The workshop will *focus on the following central themes:*

(1) *Solidify a set of specific science questions to be addressed that are the most critical for understanding O_3-NOx-VOC-PM chemistry in designing a future pilot study to establish a baseline to formulate an in-depth research plan to address the science questions.*

(2) *A detailed plan for leveraging the experiences of HBCU faculty for training and conducting air-quality research in under-resourced environments and creating a possible path for graduate student exchange in the study of air pollution measurements and modeling.*

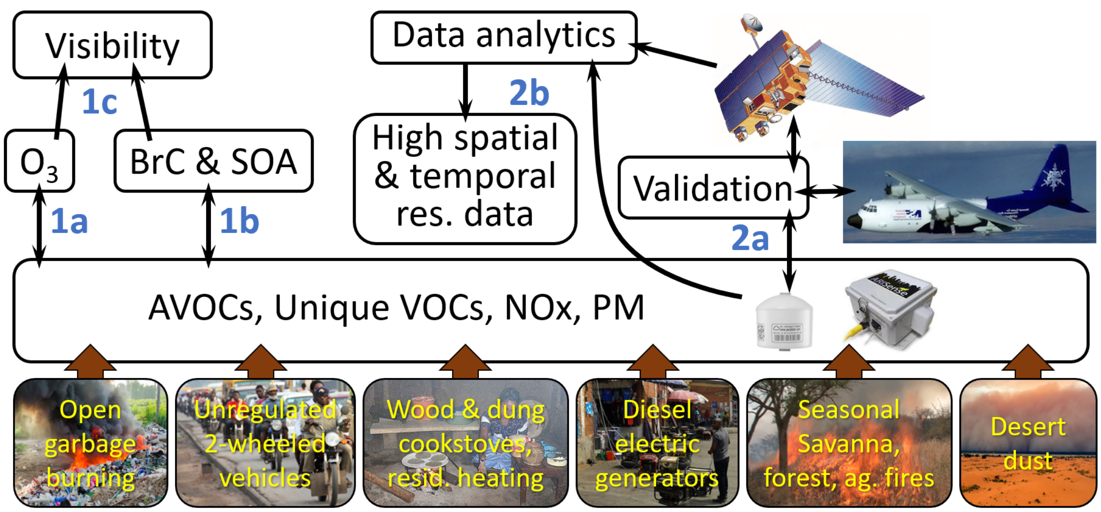

Figure 1. Various sources (bottom) produce pollutants in the African atmosphere showing the interplay between these emissions and the formation of secondary organic aerosol (SOA), brown carbon (BrC) aerosol and ozone, as well as the resulting effect on visibility. A combination of satellite, aircraft, and low cost monitoring network measurements are shown.

The overarching science question to be discussed in this workshop is: ***What are the unique reactive volatile organic compounds (VOCs) their sources and their influence on O_3-NOx-VOC-PM chemistry that is different from well-studied regions of the world?*** *Subtopics include:*

1.a. *To what extent do natural emissions contribute to atmospheric composition, and how does the natural background interact with the unique anthropogenic source from an African megacity such as Adis Ababa.*

1.b. *What are the unique VOCs and atmospheric chemical processes in the multi-pollutant and multiphase urban environment of Addis Ababa that control the abundance and production mechanisms of O_3 $PM_{2.5}$ brown carbon and secondary organic aerosols?*

1.c. What are the roles of VOCs in the formation mechanisms of regional haze and reduction in visibility?.

2. These fundamental science questions will also provide insight on the measurement techniques and sensors that are appropriate for fast growing cities in developing countries of Africa for investigating urban air pollution. These discussions will address the role of low cost sensors (LCS), and methods to synthesize disparate data streams, and satellite measurements. The following questions related to measurement techniques will be discussed:

2.a. What are the best analytical approaches for quantifying trends in emissions and developing emission inventories and quantifying emission trends from African megacities using available satellite data?
2.b. What is the maximum achievable accuracy for low cost air pollution monitoring networks in environmental conditions typical of Africa, and is this accuracy sufficient to support air quality management decision making?

Expected outcomes

- This will be the first workshop on atmospheric chemistry of African megacities held in the US and funded by NSF. The workshop will help define consensus methods to (1) quantify trends in emissions from a severely under-sampled region of the world and understand their impacts on atmospheric composition and chemistry over multiple scales, from local to global, and (2) identify and report on the observational and modeling requirements for a rigorous experimental design addressing the unique needs from an African megacity point of view.
- The workshop will provide recommendations on economically viable and scientifically appropriate air quality monitors for the understanding the specific atmospheric chemistry questions to the city government, national agencies, and scientists involved in Addis Ababa and future projects. Trends in ground-level air quality are best revealed through long-term *in situ* monitoring.
- The workshop will examine ways to develop sustainable approaches to building strong collaborations between U.S. atmospheric scientists, US underrepresented minority scientists from HBCUs with their African counterparts and develop peer-to-peer relationships, as recommended by the NAS. The workshop will strive to recommend (possibly create) a path for easier collaboration between existing scientists, measurement networks, and/or ad-hoc measurements.
- This workshop will also examine perceived logistical problems that have been cited as the reason for not conducting field campaigns by US institutions in Africa, and will aim to find ways to overcome them by cultivating networks that engage government agencies, key policy makers, and leading scientists in the host African megacity and other international groups working on the issue.

Intellectual Merit:

Given the large uncertainties in emissions and the potential for novel chemistry and boundary-spanning climate impacts that are regionally-specific, a focused workshop to identify the science questions unique to African megacities is critical and *the first step* to addressing the problem. Moreover, the local knowledge of vegetation, cultural practices, and seasonality of events that influence air quality demand a cooperative approach that engages African scientists and stakeholders. Optimal science questions can be synthesized only through open and inclusive dialogue and sharing of diverse observations and information. Based on this realization, we seek to develop a collaborative pilot study to understand the unique VOCs and characterize the chemical mechanisms, temporal trends of the air-quality problem, and emissions and source characteristics that are distinct from European, North American, and Asian megacities. This approach has been successful in other parts of the globe. For example, observations in Delhi and Beijing have shown that atmospheric particulate constituents, such as sulfate and secondary organic aerosols formed by oxidation of VOCs or other multiphase processes, are not only present in greater overall concentrations but their distributions and relationships to other species are distinct from what has been seen in northern mid latitudes [49-51]. Wintertime studies in China have revealed much about the relative contributions of coal burning, mineral dust, transportation, and secondary sources of $PM_{2.5}$ [52]. Recent measurements in Delhi and outside Kathmandu reveal signatures in the aerosol chemical composition that are common to both locations but have not been observed elsewhere [32]. Despite the importance of these regionally dependent findings, an in-depth study of air pollution in Africa is severely lacking. In addition to long-term data collection, short-term intensive measurement campaigns with advanced instrumentation for detailed chemical analysis can provide deeper insight into the underlying sources and chemistry of $PM_{2.5}$. A detailed air quality study in a representative African city may reveal novel atmospheric chemical processes that may not be common in highly sampled regions in the mid latitudes. *This new information could have significant implications for improved chemical mechanisms for air quality models and could provide guidance for laboratory-scale process studies.* The workshop will identify and report on the observational and modeling requirements for rigorous experimental design addressing the unique needs from an African megacity point of view. *It will discuss what science goals can be accomplished from a short-term intensive measurement campaign and discuss requirements for a long-term data collection effort that may assist air quality regulators in Africa***.**

Broader impact

Urban air pollution is a pressing and multi-sectoral development challenge, representing a major health, economic, and social threat to cities of the global north and south. Poor air quality acts as a brake on development through increasing expenditure on health, loss of labor productivity, lowering educational attainment due to illness, and reduced agricultural yields. Air pollution is understood as a leading cause of morbidity and mortality in East Africa. However, the evidence base of its causes and effects in the regional context is currently insufficient. In East Africa, the multi-scalar and interdependent nature of urban air pollution (indoor-outdoor) presents a complex landscape for air quality studies. Better data and monitoring techniques, increased community awareness at all levels, combined with strong air pollution enforcement and management of synergistic transportation, land use management, and urban planning strategies at this stage of East Africa's development have the potential to generate sustainable frameworks that encourage economic growth and create more livable environments [53]. Given the current rapid growth of Addis Ababa, it is at a critical juncture, where decisions in these areas will have long-lasting effects. A recent study of air pollution by researchers at NASA reported that air pollution causes about 780,000 premature deaths per year in Africa [54]. To put this into perspective, around 11,000 people died in the recent Ebola epidemic [5]. Emissions from one region often affect the air chemistry of regions far-removed from the source.

The discussions and deliberations at the workshop will aid the effort of developing a globally-engaged workforce in the US and provide the opportunity for students to tackle problems of global magnitude as members of the world community. We expect that participants will acquire knowledge and research skills in international collaborations and the development of field campaigns through their participation in this workshop. Students from HBCU and HSIs will be engaged in this workshop, which will provide them with experience in field project planning. These students will interact with peers, NCAR scientists, and international partners during the workshop, serve as facilitators of the break-out sessions and note-takers. We also expect that the workshop will serve as a launching point for future discussions, planning, and long lasting relationships that create the conditions for joint global projects. The proportion of traditionally underrepresented minorities (URMs) in the atmospheric sciences is abysmal. African Americans in atmospheric sciences occupations were only 0.4% in 2006 and 2.7% in 2013 with no significant change since then [55, 56]. ***Over this period of increase, a significant number (if not the majority) of African American and Hispanic/LatinX PhDs in Atmospheric Sciences have been produced by HBCUs like Howard University or North Carolina A&T, or benefitted from programs at HBCUs specifically targeted at increasing the numbers of URMs in the geosciences. However, many professional networks at majority institutions are closed and/or incestuous, effectively locking out many talented professionals. An inclusive workshop is led by HBCU minority faculty that lead in the production of minority postdocs and students and may contribute to increasing minorities in the geosciences.***

US-Workshop organizing committee:

Name	Affiliation
Solomon Bililign Chair	North Carolina A&T State University
Vernon Morris Co-Chair	Howard University
Belay Demoz Co-Chair	UMBC
Akua A. Asa-Awuku (member)	University of Maryland, College Park
Francis Pope (member)	University of Birmingham
Iqbal Mead (member)	Cranfield University
Paul Kucera (member)	UCAR
Guy Brasseur (member)	NCAR-ACOM
Gizaw Mengistu Tsidu (member)	AAU (Ethiopia) and BIUST (Botswana)
Bikila Teklu Wodajo (member)	Addis Ababa Institute of Technology

Unique aspects of African megacity pollution:

Air quality is a complex, nonlinear response to a combination of anthropogenic emissions and natural factors and there is a huge variation in sources and degree of emission between megacities by geographic region [19-21, 51]. There are strong indications that African air quality problems are different from the rest of the world, but several factors confound the current ability to clarify these presumed differences [57]. Unlike the European, North American, and Chinese megacities, air quality in many African megacities is almost completely unmonitored [45]. South Africa is the only exception. They also have some similarities to megacities in developing countries.

African cities have several distinct emission sources which are not common in European and North American cities. In developing countries there is limited solid waste collection and management, thus, open garbage burning is widespread throughout urban areas [58]. Due to the lack of regulation traffic emissions are major sources of air pollution for African cities [44]. As a result, two-wheel vehicles are widely used in the cities for short-distance travel. Maximum measured molar mass emissions were observed from two-wheel vehicles, surpassing other regional sources by 2 orders of magnitude [40]. There is ever-increasing vehichular traffic characterized by a large number of old vehicles [59]. Over the next few years, African emissions from the combustion of fossil fuels, biofuels, and trash are expected to increase considerably and could represent about 50 % of the global emissions of organic carbon [43, 60].

This unregulated burning of refuse (garbage) is a significant source of volatile organic compounds (VOCs). VOCs can affect air quality by producing secondary pollutants such as ozone and secondary organic aerosols. Given the reactive nature of VOCs [61], VOC emissions need to be disaggregated by species to understand their chemical features and to access their impacts on the secondary formation processes. Because VOCs are significant pollutants present in urban atmospheres, and *in situ* VOC observations are necessary to directly assess exposure and to improve the prediction of secondary product formation. However, emission estimates are uncertain, and detailed emission inventories are still required for a better estimation of their impacts on climate change and health over this highly sensitive region [60].

Compounding this problem is the prevalence of inefficient wood-burning cookstoves, extensive use of cow dung as fuel, millions of small diesel electricity generators, and unregulated petrochemical plants. In most cases the municipal solid waste (containing about 12% plastics) is burnt, releasing toxic gases such as dioxins, furans, mercury, polychlorinated biphenyls, and reactive trace gases [62, 63].

Another distinctive source of emissions comes from seasonal biomass burning, which is known to release large amounts of partially oxidized organics and particulate into the regional atmosphere. These sources can also increase the black carbon and brown carbon (BrC) concentrations in cities and add complexity to ambient photochemistry in adjacent regions [44, 64]. Smoke from seasonal forest fires and Savanna fires (the main source of biomass burning) can drift over population centers and potentially lead to novel chemistry that is unlike that found in the US. However, chemicals emitted by these fires may magnify the impact of human emissions in the same way as they do in the southeastern US.

Desert dust storms represent another significant source of particulate in African megacities. Source regions of mineral dust from north Africa [65], the Arabian Peninsula, and the Middle East regularly reach East African megacities [66].

Suggested scientific questions to be addressed by the workshop:

1-a. To what extent do natural emissions contribute to atmospheric composition, and how does the natural background interact with the unique anthropogenic source from an African megacity such as Adis Ababa?

VOCs are important for urban air quality. When combined with nitrogen oxides (NO_x; defined as the sum of nitric oxide [NO] and nitrogen dioxide [NO_2]), they can lead to the production of secondary air pollutants through complex and nonlinear photochemical cycles, resulting in tropospheric ozone and secondary organic aerosols. Understanding types of VOC and VOCs sources apportionments are needed. Source profiles measured in U.S cities are found not to be applicable in other cities [67, 68].

For example, in a recent study in Abidjan Côte d'Ivoire, a city with a comparable population to Addis Ababa road transport and wood burning VOC emission factors spanned 2 to 100 orders of magnitude, respectively, when compared with those from the literature [40].

However ambient observations that were lower by factors of 10 to 400 suggest that wind speeds have an important role in the mixing and dilution of the anthropogenic emissions leading to low VOC concentrations in the Abidjan atmosphere [40]. The distribution of VOC emissions (magnitude and composition) was also found to be different for each evaluated source. The sources related to burning processes, such as waste and wood burning, also presented a significant contribution to VOC emissions.

Interestingly, monoterpene emissions were observed in anthropogenic emission sources from biomass burning to road transportation sources, in Abidjan. These compounds are generally missing in the global anthropogenic emission profiles, which would underestimate their impacts on air quality [40].

The Abidjan study further shows the underestimation of VOCs from the residential sector in the global emission inventories, by factors of 13 to 43. For example, for only the entire country of Côte d'Ivoire alone, these new VOCs estimates are found to be 3 to 6 times higher than the whole of Europe [40]. This suggests a need to build more realistic and regionally specific emission inventories for Africa not only for VOCs, but also for all atmospheric pollutants.

Another major source of VOCs in African megacities is garbage and trash burning. Recent field measurements in central Mexico have shown that garbage burning may have been overlooked as a global source of emissions [69, 70]. Despite the uncertainties, the results suggest that global emissions from open waste burning are substantial and current estimates of emissions are underestimating total emissions by omitting this source [71]. This is particularly critical for African megacities, where there is no solid waste management plan and backyard burning and open burning in garbage dumps is often located within or close to city limits [72].

Mexico City has a somewhat similar geography and altitude, and lessons learned in the Mexico City studies can be applied, but the unique features of Addis Ababa, its meteorology, and other co-emitted pollutants need to be considered. In Africa, the amount of municipal solid waste is expected to rise quickly, due to growing populations, increasing urbanization, changing consumption patterns, and absence of waste management [73]. Several studies have also identified a correlation between a rise in income, leading to a rise in consumption, and a consequent rise in the amount of municipal solid waste generated.

However, the emissions from open waste burning at homes and dumps are more challenging to characterize and are commonly absent from inventories in developing countries' megacities [74]. A clear procedure for incorporating garbage burning emissions in models and characterizing the emissions for African megacities is critical for understanding health impacts and chemistry on the local scale.

Daily emissions from the urban, commercial, vehicular, residential, biomass burning, and industrial activities of Addis Ababa with approximately 5 million inhabitants (projected to reach 8 million by 2030) combined with local topography, frequently stagnant meteorological conditions, and high altitude (2355 m above sea level) in a tropical region (latitude 8.9° north), result in optimal conditions for vigorous photochemical processes.

1-b. ***What are the unique VOC's and atmospheric chemical processes in the multi-pollutant and multiphase urban environment of Addis Ababa that control the abundance and production mechanisms of $PM_{2.5}$ brown carbon and secondary organic aerosols?***

VOCs NOx, SO_2 and NH_3 represent the major precursors for secondary urban PM formation. Addressing their roles in SOA formation in African megacities requires an accurate representation of their emission sources is critical for air quality modeling.

Brown carbon has emerged as a significant organic fraction of atmospheric aerosol found in megacities in recent literature. Nighttime atmospheric processing enhances the formation of brown carbon aerosols (BrC) in biomass burning plumes. Heterocyclic compounds, a group of VOCs' abundant in biomass smoke, are possible BrC sources [75, 76].

Evaluating the atmospheric impacts of BrC originating from BB requires not only an adequate description of its light absorption properties and molecular composition at the emission source, but also understanding atmospheric mechanisms resulting in its physical and chemical transformations in the presence of a multi-pollutant urban atmosphere. Our recent laboratory studies [77, 78] on optical and chemical properties of biomass burning aerosols emitted from biomass fuels from east Africa indicated fuel dependent optical and chemical properties. These properties changed as a function of photochemical aging in the presence of VOCs that represent a polluted urban environment.

To consider BrC in global climate simulations, one needs to constrain and parameterize the spectral optical properties and refractive indices (RIs) of BrC aerosols across the solar spectrum and fully account its global abundance. But this has been a challenging endeavor for the atmospheric aerosol community. Furthermore, because ambient particles are transported over long distances, climate models and satellite retrieval algorithms also rely on BrC information for accurate retrievals and predictions of aerosol optical depths [79].

It is therefore important to understand the sources and composition of BB plumes, its location throughout the atmosphere (especially as a function of altitude) as well as its absorption characteristics, how these might evolve in the atmosphere [80, 81], and how they change chemically in the presence of VOCs.

1-c. What are the roles of VOC's in the formation mechanisms of regional haze and reduction in visibility?

Haze formation in mega cities is associated with primary particles and gaseous VOC emissions from anthropogenic and biogenic sources and their photochemical oxidation, which leads to gas-to-particle conversion processes that contribute to particulate matter in the atmosphere. Adverse meteorological and climatic conditions contribute to the haze formation.

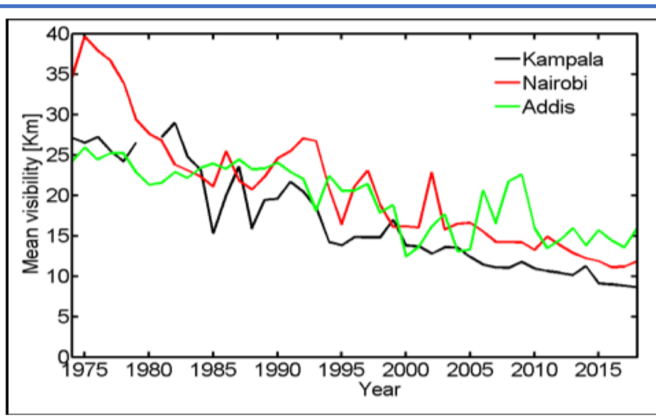

Figure. 2 Mean visibility change for three east African cities between 1975 to 2015

One of the symptoms of air pollution is the reduction of visibility and the formation of haze and fog. Visibility is affected by pollutant concentrations, the viewing angle, relative humidity, cloud characteristics, and other physical factors such as color contrast between objects. The natural visual range is limited because atmospheric gases and aerosols that absorb and scatter light.

In North America and Europe, emissions of sulfur dioxide and primary carbonaceous particulate urban emissions have been significantly reduced, but "photochemical smog" has become frequent due to VOC emissions. In African megacities, however all these emissions are still prevalent. For example, in studies in Chinese megacities, it was found out that BC aerosols play the key role in modifying the planetary boundary level (PBL) meteorology and hence the enhancement of haze pollution [82]. In these regions, reducing PM_{10} and SO_2 concentrations seemed to help with improving visibility [83]. It is not clear if the mitigation of unique aerosol sources in African megacities would also benefit from the same strategies.

A visibility model that incorporates parameterizations of aerosol hygroscopicity, particle concentration, particle scattering, and particle and gas absorption has been applied to determine long term visibility changes [84]. Visibility can also be used as a proxy for particulate matter concentration and to first order can be inversely proportional to the amount of PM. Historic visibility records suggest that PM has increased significantly in the last 50 years as shown in Figure 2; reproduced with permission from Prof. Francis Pope.

Leveraging Current and Past Measurements:

One of the primary outcomes of the two workshops that will benefit African scientists will be an assessment of how to better utilize current satellite capabilities and observations in concert with emerging low-cost trace gas sensor technologies to characterize lower atmospheric chemistry. Below, we present some of the guiding themes regarding this discussion topic.

2-a. What are the best analytical approaches for quantifying trends in emissions and developing emission inventories from African megacities using available satellite data?

Despite the abundance of BB aerosol in sub-Saharan Africa, there are few (if any) land-based aerosol measurements in Ethiopia. Satellite-based aerosol retrievals of aerosol optical depth (AOD) provide exceptional spatial coverage but suffer over bright surfaces and regions with complicated surface terrain [85]. Addis Ababa has these challenging surfaces.

While satellite data alone cannot answer detailed questions regarding urban chemistry, there are useful applications and analyses that could deepen our understanding of emission trends and processes in African megacities. The topography and regional meteorology can also confound satellite studies but this also presents an opportunity to improve retrieval algorithms. Satellite validation campaigns are most effectively achieved with an aircraft component. We will explore the possibility and value of using surface and upper air measurements in African megacities to provide correlative data as an attempt for validation of environmental data records (EDRs) derived from various orbiting satellite sensors and geostationary payloads that observe a range of parameters from trace gases and aerosols to radiative fluxes and cloud optical properties. The recent development of the Multi-Angle Imager for Aerosols (MAIA) instrument. is expected to improve on the Multi-Angle Imaging SpectroRadiometers (MISR) instrument aboard NASA's Terra satellite sensitivity to airborne particle composition by incorporating polarimetry and expanded spectral range. Surface measurments will use collocated surface low cost monitors [86].

2.b. What is the maximum achievable accuracy for low cost air pollution monitoring networks in environmental conditions typical of Africa, and is this accuracy sufficient to support air quality management decision making?

Air-quality data varies widely in the areas of the world most affected by air pollution. But most African and South Asian countries, besides India, do not have monitoring networks. Data collection by government agencies may be supplemented by monitors operated by other entities, such as universities and foreign diplomatic posts. Africa's sparse network of *in situ* monitors makes this especially difficult. Standard air quality monitors are expensive and unaffordable by most developing nations and they lack the manpower to calibrate and maintain them.

One cannot depend on satellite data alone due to limited temporal and spatial coverage and sensitivity issues that limit high resolution information on chemical species within the boundary layer. Even during satellite passes that happen in hours or days, cloud cover or atmospheric irregularities can disrupt data acquisition, and some instruments only acquire daytime data. Some of the mountainous terrains in East Africa are also difficult to sample [87]. Satellites do not measure pollutant concentrations at or near ground level, where pollutants impact human health directly. Extraction of air quality information from satellite data using current algorithms are not necessarily applicable everywhere under all atmospheric conditions and terrain. This may introduce bias between remote data and true concentrations, especially for Africa, where dust and fine aerosols are often found much higher in the atmosphere than in other regions.

The emergence of low-cost sensor (LCS) packages represents one alternative for increasing the spatial density of air quality monitoring. While these sensors generally suffer from limited accuracy, data science techniques for merging LCS data with remote sensing data, models, and data from ground-based monitors have shown promise [88]. These devices may be of value in less-developed areas with sparse or no ground-based monitoring, or in circumstances where power is limited. Remote measurements from satellites can also help fill gaps where ground-based data are unavailable [89].

While use of LCS would be a great contribution to start monitoring air quality in countries with limited or no observations, this will by no means solve any of the complex science questions raised in this proposal. Amegah (2018) points out that LCS are an excellent opportunity for bridging the air pollution data gap, but caution that sensor performance may degrade in harsh environments [90]. LCS for measuring ambient fine particulate matter often underperform under the environmental conditions typical of air pollution events in the Global South (high humidity, high pollution loadings, light-absorbing particles) due to the physics of aerosol light scattering [91]. On the other hand, a study in the UK found that Plantower $PM_{2.5}$ sensors performed better at higher pollution levels, though not at levels as high as observed in sub-Saharan Africa, India, and China [92]. The impact of environmental conditions on different LCS technology remains a large knowledge gap that we will seek to address**.**

One of the major tradeoffs in the use of low-cost sensors, is the lower signal to noise ratios and higher cross sensitivities to other atmospheric pollutants and ambient environmental factors than traditional monitors [93]. Much work remains to be done to enable reliable quantitative measurements [94-97]. For measurement of $PM_{2.5}$ these sensors can supplement sparse networks of regulatory-grade instruments, perform high-density neighborhood-scale monitoring, and be used to better understand spatial patterns and temporal air quality trends across urban areas [98]. The primary advantage is cost and the ability to obtain qualitative trends in ambient concentrations and relative source strengths. ***To investigate all the emissions and their interactions with the natural background, "non-traditional" sources of air pollution, etc., there will be a need for a complex suite of instruments and a major field effort. This is a long-term goal of this effort.***

New data science techniques can also be used to synthesize disparate data streams into spatially and temporally coherent outputs, which can be used to understand historic, contemporary and future air quality [99, 100]. The workshop will provide a road map to harness the power of new data analytics and big data technologies. Machine learning techniques will be developed to generate algorithms that can accurately predict air quality indices based on pre-existing and proxy data, including visibility and other meteorological data. The model will be formulated as a regression problem, where a model is fitted that maps a series of inputs to the target size of particulate matter concentration. This will be done using a range of algorithms, including standard linear regression and more complex methods such as artificial neural networks.

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Recent meetings on related topics.

- On January 2, 2020, one of the chair (Bililign) conducted a 1-day consultation meeting with key stake holders, Addis Ababa Environmental Protection and Green Development Commission (AAEPGDC), Environment Forest and Climate Change Commission (EFCCC), National Meteorological Agency (NMA), Ethiopian Public Health Institute (EPHI), Ministry of Transportation and Security, and faculty and graduate students from Addis Ababa University, Addis Ababa University of Science and Technology, World Resources Institute (WRI), Addis Ababa US Embassy, and AddisAir – a citizen science group in Addis Ababa.
- A recent workshop (2018) in Addis Ababa (Air Quality Measurement Workshop). Most of the focus of this workshop was on measurement of PM, mostly motivated by regulatory thoughts of improving resident health. Both the US Embassy and some researchers from Addis Ababa have been monitoring $PM_{2.5}$.
- IGAC ANGA held a workshop in June 2017 in South Africa. IGAC sponsored this workshop to foster the development of an atmospheric science community in Africa as part of its effort to create National/Regional Working Groups and promote scientific collaborations on scientific issues in Africa.
- WMO has also been holding modeling workshops in Africa regarding prediction of air pollution. They had workshops in South Africa in 2017 and Nairobi in October 2019.
- A workshop at the Columbia University Global Center in Nairobi, Kenya in August 2019 (Nairobi Air Pollution Roundtable) was hosted by Dr. Dan Westervelt. Researchers, students, and faculty from local universities and institutions in Kenya and Uganda participated in discussions on gas-phase and particulate measurements in the region, low cost sensor deployments, model simulations, and satellite estimates of air quality.

To our knowledge there were no other specific NSF funded workshops on African air quality held in the US.

Meeting organization and dissemination of results:
This will be a two and half-day workshop with invited presentation covering the science question by leading scientists in the US and Ethiopian experts who have accepted the invitation as shown in the draft agenda. Representatives from major funding agencies such NOAA, Word Bank, NASA, EPA, US State Department, USDA and World Meteorological Organization, World Health Organization and non-profit agencies will be invited. Invitation letters will be sent out to potential interested attendees. Breakout sessions on individual questions or groups of questions will report findings and observational, and modelling needs. The meeting will provide scientific basis and engineering needs for future Air Quality studies in megacities in developing countries. It will provide educational opportunities for US graduate students. A final comprehensive report will be available for users and stakeholders and will be used for writing larger proposal for future studies.

Meeting Code of Conduct:
CPAESS has adopted a *Meeting Code of Conduct* that makes it clear what constitutes expected behavior to create a welcoming environment, while also detailing procedures for report

inappropriate and unacceptable behavior. All attendees will have to actively agree to the code of conduct at the time of registration.

Tentative -line up of confirmed speakers and topics.

Speaker(s) /Affiliations	Title
Bililign (NCAT) **Morris** (Howard University) and **Demoz** (UMBC)	*Welcome introductions and purpose of the workshop*
Everette Joseph (NCAR)	Introduction and welcome (TBD)
James Crawford (IGAC)	*Workshops mutual benefit with IGAC in fostering a stronger voice for Africa*
Bililign (NCAT) **Pope** (University of Birmingham)/Wodajo (AAU)	*Unique Features and Challenges in Understanding the Chemistry of African Megacities- what is unique about Addis Ababa*
Steve Brown (NOAA-ESRL)	*Ozone-NO_x chemistry in the U.S., and inferences on how it might differ in an African Megacity*
Jim Roberts (NOAA-ESRL)	*How do laboratory studies help us understand about the connection between Air Pollution and Health Effects that would be pertinent to the African Mega City environment?*
Francis Pope (U of Birmingham)	*Air quality and visibility*
William Brune (Penn State)	*Linking in situ radical observations to pollution production in megacities*
William Vizuete (UNC-CH)	*Connecting aerosols and health: Engineering solutions for exposure and in vitro assessments*
Frank Flocke (NCAR-ACOM)	*Logistical needs to run a successful field campaign*
Rajesh Kumar (NCAR-ACOM)	*First assessment of the WRF-Chem air quality simulations for Africa and insights into carbon monoxide distribution and source attribution*
Akua A. Asa-Awuku (UM-College Park)	*Regional haze, visibility and hygroscopicity*
Christine Wiedinmyer (Colorado University) **Mike Hannigan** (UC)	*Trash burning emissions and emission inventories*
Paul Kucera (UCAR)	*Low cost sensors*
Iq Mead (Cranfield University)	*Low cost sensors and heterogeneous networks*
Xin-Zhong Liang (UM-College Park)	*CWRF Modeling Applications for African Megacities*
Xiao-Mong Hu (U.of Oklahoma)	*Spatiotemporal and Regional Transport over Tropical Megacities*
Bikila Teklu Wodajo (Addis Ababa University)	*Estimation of Vehicular Emissions for Addis Ababa City and an Overview of Policy and Regulatory Framework on Vehicular Emissions in Ethiopia*
Gizaw Mengistu Tsidu (Addis Ababa University and BIUST)	*Characterization of regional and local drivers of recent trends in air pollution indicators over Eastern Africa based on multi-platform observations and models*
Kassahun Ture (Addis Ababa University)	*Dynamical events associated with MOZAIC ozone enhancements over Equatorial and North Africa*
David Diner (JPL)	*Plans for integrating satellite aerosol data and surface measurements to map speciated PM2.5 in Africa as part of NASA's Multi-Angle Imager for Aerosols (MAIA) investigation*
Dan Westervelt (Columbia University)	*First measurements of PM2.5 in Togo and the Democratic Republic of Congo*

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CPAESS seeks to balance the need for expertise and capacity with the ability to contain costs and deliver flexibility. The CPAESS management structure for the conference consists of:

- PI, Ms. Hanne Mauriello, will guide the strategy for supporting the Space Weather Community. She serves as the Director of CPAESS, which has a staff of 130 and an annual budget of $25M contributed by 13 different sponsoring agencies and organizations. Ms. Mauriello has three decades of experience in scientific research administration, operations, and financial management.
- Meeting Planner will organize logistics, management of the timeline, present budget updates, negotiate vendor contracts, and provide on-site support at the workshops.
- Other CPAESS staff will handle details of budget and expense management and travel support and management.

Results from prior NSF support

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