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The UCAR Africa Initiative: recent insights, challenges, and opportunities to foster collaborative research for environmental sustainability

Tang, W.; Kumari, R.; Moral Méndez, A. del; Ahafiany, F.; Akintomide A.A.; Dekkers, M.; ... ; Levelt, P.J.

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Wenfu Tang¹, Rajesh Kumar¹, Anna Del Moral Méndez¹, Felicity Ahafianyo², Akintomide A. Akinsanola^{3,4}, Agbeli Ameko¹, Marleen Dekker⁵, Rong Fu⁶, Benjamin Gaubert¹, Samson Hagos⁷, Cenlin He¹, Forrest Lacey¹, Kelly M. Núñez Ocasio⁸, Isla R. Simpson¹, Kassahun Ture⁹, Christopher D. Wirz¹⁰, Ronnie Abolafia-Rosenzweig¹, Emmanuel O. Audu¹¹, Shima Bahramvash-Shams¹, Solomon Bililign¹², Roelof Bruintjes¹, Cyndi Castro¹, Belay Demoz¹³, Ismaila Diallo^{14,15}, Ross D. Dixon¹⁰, Jimy Dudhia¹, Abdulamid A. Fakoya¹⁶, Rebecca M. Garland¹⁷, Cindy Halley-Gotway¹, Yaoxian Huang¹⁸, Ata Hussain¹⁹, Dorcas Idowu²⁰, Yan Jiang²¹, Agnieszka H. Kazimierczuk⁵, Peter Lawrence¹, Danny M. Leung¹, Samar Minallah¹, Naoki Mizukami¹, Israel R. Orimoloye²², Paul A. Kucera²³, Kwesi A. Quagraine¹, Addisu Semie²⁴, Simone Tilmes¹, Daniel M. Westervelt^{25,26}, Daile Zhang²⁷, Zhe Zhang¹, Helen Worden¹, Pieternel F. Levelt^{1,28,29}

¹NSF National Center for Atmospheric Research (NSF NCAR), Boulder, CO, USA

²Central Analysis & Forecasting Center, Synoptic Meteorology and Forecasting Department, Ghana Meteorological Agency, Accra, Ghana

³Department of Earth and Environmental Sciences, University of Illinois Chicago, Chicago, IL, United States of America

⁴Environmental Science Division, Argonne National Laboratory, Lemont, IL, USA

⁵African Studies Centre, Leiden University, the Netherlands

⁶Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA

⁷Pacific Northwest National Laboratory, Richland, WA, USA

⁸Department of Atmospheric Sciences, Texas A&M University, College Station, TX, USA

⁹Centre for Environmental Science, Addis Ababa University, Ethiopia

¹⁰Agricultural Leadership, Education and Communications Program, University of Illinois Urbana, Champaign, Urbana, IL, USA

¹¹Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE, USA

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¹²Department of Physics and Applied Sciences and Technology North Carolina Agricultural and Technical State University, NC, USA

¹³University of Maryland Baltimore County, Baltimore, USA

¹⁴Department of Meteorology and Climate Science, San Jose State University, San Jose, CA, USA

¹⁵Wildfire Interdisciplinary Research Center, San Jose State University, San Jose, CA, USA

¹⁶School of Meteorology, University of Oklahoma, OK, USA

¹⁷Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa

¹⁸Department of Civil and Environmental Engineering, Wayne State University, Detroit, Michigan, USA

¹⁹World Meteorological Organization

²⁰Department of Civil and Environmental Engineering, Syracuse University, Syracuse, NY, USA

²¹School of Global Policy & Strategy, Scripps Institution of Oceanography, University of California, San Diego, CA, USA

²²School of Environment, Geography and Sustainability, Western Michigan University, Kalamazoo, MI, USA

²³COMET, University Corporation for Atmospheric Research, Boulder, CO, USA

²⁴Computational Data Science Program, Addis Ababa University, Ethiopia

²⁵Columbia University, Lamont Doherty Earth Observatory, Palisades, NY, USA

²⁶University Mohammed VI Polytechnic, African Research Center on Air Quality and Climate Benguerir, Morocco

²⁷University of North Dakota, North Dakota, USA

²⁸Royal Netherlands Meteorological Institute (KNMI), the Netherlands

²⁹University of Technology Delft, the Netherlands

Corresponding to Wenfu Tang, wenfut@ucar.edu

Abstract

Africa is increasingly being exposed to the negative impacts of climate and environmental change, while having less capacity to respond compared to other continents. The vulnerability partially results from unprecedented demographic growth, urbanization, and industrialization. However, the

continent has still largely been underserved by the broader Earth System Science (ESS) community, as evidenced by the limited amount of ESS data and research that cover Africa compared to other areas of the world. Here we present the recent University Corporation for Atmospheric Research (UCAR) Africa Initiative that aims to enhance environmental sustainability in Africa by fostering international collaborative research partnerships co-led by African scientists. Specifically, we outline urgent challenges and opportunities identified through an international workshop in six areas of ESS namely (1) air quality and health, (2) weather, (3) climate, (4) land and water, (5) social science perspectives, and (6) developing equitable collaboration and sustainable infrastructure. We highlight examples of successful partnerships and conclude with recommendations to advance collaborative, actionable ESS research that addresses Africa's critical environmental challenges.

Significance Statements

Africa is experiencing the negative impacts of climate and environmental change. However, relevant research and hence suggested solutions are very limited. As a key outcome of the UCAR Africa Initiative, we highlight the importance of the international community in supporting and co-leading successful collaborative efforts with African scientists that can address Africa's environmental challenges through equitable partnerships. This paper provides a forward-looking perspective by highlighting collaborative research opportunities in six critical ESS areas and identifies practical directions to advance environmental sustainability in Africa through more coordinated scientific engagement.

1. Introduction

Africa is undergoing rapid demographic and environmental change, with its population projected to reach 2.5 billion by 2050 – one quarter of the world's total (United Nations (UN), 2022). Urbanization, agriculture, and deforestation are intensifying pressure on water, land, air quality, and other various environmental sustainability issues. Climate change is driving more frequent and severe extreme events such as floods, droughts, heatwaves, and fires, which already impact Africa more acutely than many other regions (e.g., Boone et al., 2016; Baudoin et al., 2017; Güneralp et al., 2017; Fisher et al., 2021). These challenges, combined with rising emissions of pollutants and greenhouse gases (GHGs) from economic growth, pose serious risks to health,

ecosystems, and the continent's capacity to respond to future environmental threats (World Meteorological Organization (WMO), 2023; Greenstone et al., 2024).

While these environmental and climate challenges are significant in Africa, they are not unique to the continent, as many regions worldwide face similar issues. However, Africa along with Asia and South America, remains underrepresented in scientific research (Klingelhöfer et al., 2020). Although it contributes only 3.8% of the global GHG emissions, Africa is among the most vulnerable due to limited adaptive capacity (UNEP, 2022). In contrast, Asia and North America together account for over 50% (International Energy Agency, 2023). Extreme weather events are rising globally, with regional differences: Asia faces frequent floods and typhoons, North America sees hurricanes and wildfires, and Africa experiences worsening droughts, heatwaves, and floods (Emergency Event Database (EM-DAT), 2023). Our focus on Africa stems not from uniqueness of challenges, but from persistent research and resource gaps. This work seeks to bring greater attention to these issues and accelerate efforts to address them through an international collaborative approach.

The local and international funding for climate and atmospheric science and air quality research in Africa has been limited compared to elsewhere, consequently limiting the results, improvements, or suggested solutions (Overland et al., 2022; Garland et al., 2024). At the 27th UN Climate Conference (COP27), it was pointed out that since 1990, only 3.8% of climate change research has focused on Africa. In 2017, research spending averaged US\$1,064 per capita in high-income countries (North et al., 2020), compared to US\$42 in Africa, US\$80 in South America, and US\$1 to US\$90 in frontier and emerging Asian countries (World Bank, 2024) (Figure 1). Even within the global South, large swaths of sub-Saharan Africa and the Middle East/North Africa remain severely under-researched (Vincent et al., 2022). Taking expertise and educational level as an example, Climate Change Education (CCE) remains limited in African Higher Education Institutions (HEIs), with only 15 PhD-level programs identified as of 2024 – 11 of them in West Africa (Kemeni and Mbah, 2025). Overall, West Africa accounts for 44% of CCE course offerings, followed by East Africa (27%) and Southern Africa (23%), while North and Central Africa each contribute only around 2% (Kemeni and Mbah, 2025) (Figure 1). Gaps in climate adaptation research are especially pronounced in North Africa and Central Asia (Ford et al., 2015). From 1990 to 2020, research funding in Africa was unevenly distributed, with East Africa receiving ~US\$190M (2010 USD), followed by West (~150M), Southern (~130M), Central (~60M), and

North Africa (~40M) (Overland et al., 2022) (Figure 1). Within each sub-region, funding is also not distributed evenly among countries (Overland et al., 2022). Therefore, there is an urgent need to increase support to these areas in Africa. Bibliometric evidence (World Bank, 2014) shows that international collaboration, measured by co-authored outputs with non-African partners during 2003–2012, is significantly higher in Eastern and Southern Africa (>60%) compared to West & Central Africa (~42%).

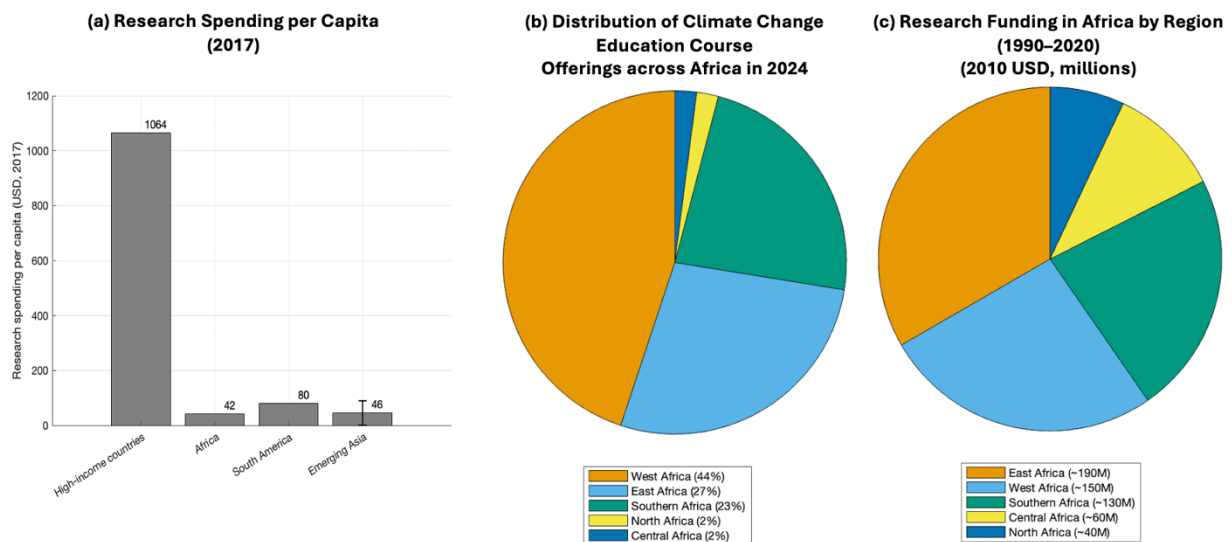


Figure 1. Research investment and capacity indicators for Africa: (a) research spending per capita in 2017 (North et al., 2020; World Bank, 2024); (b) distribution of Climate Change Education course offerings across African sub-regions in 2024 (Kemeni and Mbah, 2025); and (c) regional distribution of research funding in Africa from 1990–2020 (2010 USD) (Overland et al., 2022).

On the positive side, improvements have been made. An example is the Systematic Observations Financing Facility (SOFF), which aims to close observational gaps and is a key component of the Early Warning for All (EW4All) initiative by the UN. In addition, there is an active and growing African-based community working on atmospheric science research such as climate change, atmospheric composition, and air quality (e.g., Bililign et al., 2024). Effective environmental management in Africa also relies on strong policy tools like Environmental Impact Assessment (EIA), a key mechanism for evaluating and mitigating development impacts. While several countries—including Egypt, Ghana, Mauritius, South Africa, Kenya, and Tanzania—have

advanced EIA implementation (Bhatt, 2023), strengthening these frameworks alongside advances in Earth system science is vital for informed decision-making and resilience. Collaborative international efforts are also essential. This paper presents the UCAR Africa Initiative and associated activities, summarizing insights from two years of engagement and highlighting challenges, opportunities, and recommendations for advancing Earth system science (ESS) in Africa.

2. UCAR Africa Initiative

In recent years, several international efforts have been initiated in this regard. For example, the DEveloping Country Impacts Modelling AnaLysis for SRM fund through The World Academy of Sciences provides grants to teams in developing countries to assess regional impacts of Solar Radiation Management (SRM; proposed climate intervention methods aimed at reducing the amount of solar radiation absorbed by the Earth; Crutzen, 2006). Other examples are the WMO SOFF initiative, the UN EW4All initiative, the African Development Bank, the Consultative Group on International Agricultural Research (CGIAR), the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) project, the Climate Risk and Early Warning Systems initiative, the Weather and Climate Information Services in Africa, and the U.S.-Africa Frontiers of science, engineering, and medicine program (Najib et al., 2024), among others. The WMO-coordinated Regional Climate Outlook Forums (RCOFs) also enhance climate resilience by improving access to climate information and early warning systems (Patt et al., 2007). The UCAR Africa Initiative aims to complement these efforts by further strengthening international collaboration.

UCAR serves as a hub for U.S. university collaborations in atmospheric research and manages the National Science Foundation National Center for Atmospheric Research (NSF NCAR). A key element of NSF NCAR's mission is to foster the transfer of knowledge and technology for the betterment of life on Earth. The expertise and tools that exist within UCAR including NSF NCAR are highly relevant for addressing the environmental challenges faced by populations in Africa (Figure 2a). As such, they can play a significant role in supporting international research communities and collaborating on research initiatives aimed at developing solutions for the continent. The UCAR Africa Initiative started within UCAR and NSF NCAR and

discussions among African and international scientists involved in the Initiative, highlight recent UCAR-affiliated efforts, progress in the field, and concrete recommendations for future research directions. This paper addresses six focus areas (Figure 3): (1) air quality and health, (2) weather, (3) climate, (4) land and water, (5) social science perspectives, and (6) developing equitable collaboration and sustainable infrastructure. For each area, we highlight “scientific knowledge and challenges” and “recent efforts from the UCAR Africa Initiative community”. We acknowledge that the issues and gaps are highly varied across the continent. In this paper, we aim to highlight those that are common across many areas in Africa. To ensure research is locally relevant, these topics should be further refined in collaboration with local researchers to address the most pressing needs on the ground.

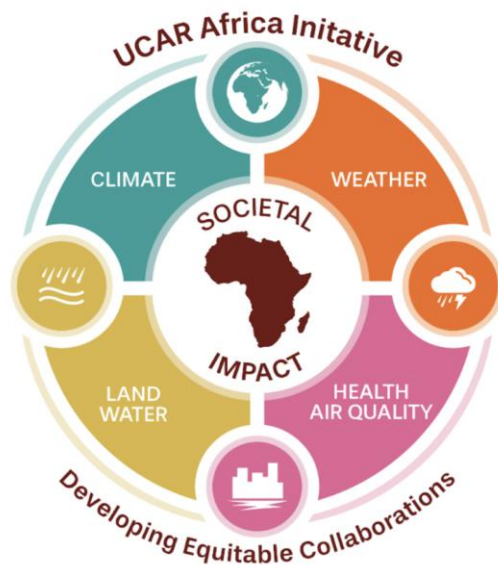


Figure 3. Focus areas of collaborative research covered in this paper.

3. Scientific challenges identified by and contributions from the UCAR Africa Initiative Community

3.1. Air quality and health

3.1.1 Scientific knowledge and challenges

The combination of anthropogenic, natural, and fire-influenced emissions has resulted in adverse ambient air pollution in Africa, contributing to lung cancer, diabetes, heart disease, stroke, pneumonia, and other preventable deaths (McDuffie et al., 2021; UN Environment Programme (UNEP) et al., 2023a; Health Effects Institute, 2025). For example, while fine particulate matter (PM_{2.5}) exposure is highest in South and East Asia, major African cities like Lagos, Cairo, and Nairobi often exceed WHO PM_{2.5} guidelines by several-fold. Unlike regions with strong regulations, Africa lacks consistent air quality monitoring, leading to large data and health impact uncertainties. To better understand air quality in Africa, there must be an expansion of observational networks (surface, airborne, in-situ, and space-based) with a focus on establishing a baseline for African air quality in vulnerable areas, data-sparse regions, and for areas where there are high-emitting sectors (Katoto et al., 2019; Pinder et al., 2019).

Addressing air quality issues requires expanded observational networks, improved modeling tools, and better emission inventories using local data (Katoto et al., 2019; Pinder et al., 2019; Keita et al., 2021). Limitations in satellite coverage further highlight the need for a geostationary atmospheric composition satellite over Africa (Marais & Chance, 2015; Millet et al., 2024). High-resolution chemical transport model development and applications associated with air quality and human health over Africa are limited (Kumar et al., 2022; Tang et al., 2023; Huang et al., 2018, Gnamien et al., 2024), and the transition to newer, more computationally expensive models poses challenges for ongoing research. While global models like European Centre for Medium-Range Weather Forecasting (ECMWF) Copernicus Atmosphere Monitoring Service (CAMS) and National Aeronautics and Space Administration (NASA) Goddard Earth Observing System-Composition Forecasting (GEOS-CF) offer useful outputs without high computational costs to the end users, their performance in Africa remains largely unverified. Alternatively, reduced complexity models (RCMs) offer promise for local decision-making but require further development and validation (Gilmore et al., 2019). Although environmental challenges vary widely across the African continent, Bililign et al. (2024) provide an overview of air quality in East Africa that sheds light on some common issues, such as a lack of observations, affecting other African regions as well.

There are significant health and economic burdens associated with air quality in Africa, many of which need enhanced epidemiological studies (Lacey et al., 2017, Isaxon et al., 2022, Health Effects Institute, 2022). While some outcomes are globally recognized, others—like dust-

related health effects and high exposure among women and children due to indoor cooking—are more region-specific (e.g. indoor air pollution from solid fuel use in cooking). Air quality is influenced by rapid urbanization, solid fuel use for cooking, inefficient combustion, and poor waste management (Mead et al., 2013), with factors varying widely across regions (Marais et al., 2016; Abera et al., 2021). Other climate-related issues, such as the impacts of heat on human health, are also important but not covered in this paper.

3.1.2 Efforts from UCAR Africa Initiative Community

Members of the UCAR Africa Initiative have ongoing projects throughout Africa to improve understanding of air quality and address challenges related to ambient pollution. Several groups have implemented and maintained observation networks in specific cities and regions, using a combination of low-cost sensors (LCS) and research-grade monitors (e.g., Njeru et al., 2024; Westervelt et al., 2023; Grutter et al., 2021; Xie et al., 2021). While research-grade instrumentation remains less widespread than in the Global North, LCS have been pivotal in expanding coverage and offering valuable insights in many regions (Lasman et al., 2020; Anand et al., 2024; Green et al., 2022).

Emissions, pollutant concentrations, and associated disease burdens were quantified. Emissions estimates have often relied on sociodemographic and activity data combined with emission factors, though locally derived values remain limited (e.g., Marias and Wiedinmyer, 2016; Pfothenauer et al., 2019; Keita et al., 2021; Mbandi et al., 2023). These efforts have supported the development of regional Africa-specific emission inventories for use in modeling (e.g., Kumar et al., 2022; Mazzeo et al., 2022), but large uncertainties persist across regions and sectors. Further progress depends on incorporating local activity data and enhancing locally developed inventories (e.g., through the Global Emissions Initiative African Working Group: <https://igacproject.org/africa-working-group>). In parallel, the application of global satellite imagery in Africa continues to improve constraints on pollutant distributions and related health impacts (Martínez-Alonso et al., 2023; Dekker et al., 2025; Millet et al., 2024).

3.2 Weather

3.2.1 Scientific knowledge and challenges

Weather in Africa is shaped by circulation patterns across scales—from strong diurnal convection (Jenney et al., 2025) and mesoscale convective systems (MCSs; Núñez Ocasio et al., 2020a; del Moral Méndez et al., 2023; Feng et al., 2025) to synoptic disturbances like African Easterly Waves (AEWs) and the broader West African Monsoon system (Thorncroft et al., 2008; Núñez Ocasio et al., 2020b, 2021). AEWs are westward-propagating, high-impact weather disturbances that typically form over East or Central Africa and are closely linked to instabilities in the African Easterly Jet (AEJ)—a mid-level jet that arises from the meridional temperature gradient between the hot, dry Saharan air to the north and the cooler, moist air from the Gulf of Guinea to the south (e.g., Burpee, 1972). The AEJ serves as a waveguide for AEWs and supports their development through a combination of barotropic and baroclinic instability mechanisms. These waves strongly modulate convective organization across the Sahel and play a critical role in rainfall variability. Additionally, AEWs are the primary precursors of tropical cyclones in the Atlantic basin (Núñez Ocasio et al., 2020b, 2024). Moisture dynamics and topography further influence convection and precipitation variability (Hamilton et al., 2020; Núñez Ocasio et al., 2024; Mayta et al., 2025). Thus, understanding the complex, multiscale AEW-AEJ systems is highly relevant for African communities whose livelihoods depend on rain-fed agriculture. These weather patterns directly affect ecosystems, food security, and daily life across the region.

The West African Monsoon (WAM) is another key phenomenon operating on weather to sub-seasonal timescales that governs rainfall patterns over Africa (Hamilton et al., 2017). The WAM initiates during the boreal summer driven by the temperature gradient between the hot Saharan surface and the cooler Gulf of Guinea, which draws moist Atlantic air inland and helps establish the Intertropical Discontinuity (ITD) (Cook, 1999). It is also influenced by the seasonal migration of the Inter Tropical Convergence Zone (ITCZ), which produces two distinct rainy seasons across the continent. The southern half of Africa experiences a well-defined rainy season from November to March, also influenced by subtropical high-pressure systems, the Agulhas Current, and tropical cyclones in the southwest Indian Ocean (Silverio & Grimm, 2022). Meanwhile, the boreal summer monsoon season, occurring between June and September, brings rainfall to West and parts of Central Africa.

On top of these general weather patterns, Africa also faces high-impact extreme weather events. Here, we use the African Great Lakes—particularly Lake Victoria—as an illustrative case, drawing on work by multiple members of our community. Lake Victoria is a complex natural

laboratory where compound-type events show the interaction of multiple physical processes across temporal and spatial scales, leading to high-impact weather events, also evident when considering future climate projections (e.g., Van der Walle et al., 2022; Finney et al., 2020), and with a high impact on local communities. Severe convection over Lake Victoria is organized by the lake–land-breeze circulation, nocturnal convergence and enhanced low-level winds, with topographic and moisture controls favoring an early-morning MCS maximum (Camberlin et al., 2018; Woodhams et al., 2019). These dynamics yield predictability at different temporal scales: minutes–hours from radar/lightning/satellite nowcasting, 0–3 days from convection-permitting models, and sub-seasonal to seasonal (S2S) outlooks from S2S forecast systems (e.g., Bedka et al., 2010; Roberts et al., 2022). With the increase of extreme weather events and rapid urbanization (Seto et al., 2012), improved monitoring through satellite and ground-based systems is increasingly vital. Building on the work initiated by the WMO High Impact Weather Lake System project, collaborative work has improved diurnal-cycle representation and short-term forecasts (Roberts et al., 2022). Radar studies over Lake Victoria have demonstrated potential for forecasting deep convection (Waniha et al., 2019; Wilson & Roberts, 2022) and winds that trigger waves over the lake (Roberts & Wilson, 2023). Recent work has developed storm catalogs (del Moral Méndez et al., 2023; 2025) and even used radar to detect crop pests like fall armyworm in Rwanda (Maniraguha et al., 2024).

Despite recent advances, major gaps remain due to sparse observations and relatively limited understanding of tropical dynamics relative to the midlatitudes. High-impact extremes are widespread: in 2022, Africa recorded 80 hydrometeorological disasters, over half of them floods that caused more than 2,000 deaths (EM-DAT, 2023). The April 2024 floods in East Africa displaced nearly half a million people (UNICEF, 2024), while other regions faced severe heatwaves, droughts, dust storms, and wildfires. Strengthening dynamical understanding and predictability, as illustrated in the Lake Victoria case, is crucial to support early warnings and resilience across the continent.

3.2.2 Efforts from the UCAR Africa Initiative Community

Recent efforts have advanced the dynamical understanding and prediction of African weather extremes. Recently, using observations and models, a link between the activity of the African monsoon over eastern Africa and the MJO has been shown (Hagos et al., 2023). Moisture plays a significant role in modulating the growth of AEWs and MCSs, and the intensity of the

AEJ, which serves as both an energy source and the background flow for these waves and MCSs across Africa (Núñez Ocasio et al., 2021).

A new storm-resolving regional MPAS configuration introduced by Núñez Ocasio et al. (2024) made significant strides in explaining the extreme weather events of the 2024 WAM season, particularly the deadly floods across Nigeria, Niger, Mali, and Chad. These heavy rains, fueled by a more active and moisture-laden monsoon, have resulted in widespread devastation, as reported by humanitarian agencies (Maclean and Alfa, 2024). Núñez Ocasio et al. (2024) shows how the intensified WAM and northward-shifted AEJ-AEW system in a moister atmosphere contribute to a delay in tropical cyclone formation, a pattern observed in the 2024 Atlantic hurricane season. Moreover, Núñez Ocasio and Dougherty (2024) have led the first-ever future warming climate simulations using MPAS with the pseudo-global warming approach. The study focuses on Africa and the Atlantic, and in agreement with Núñez Ocasio et al. (2024), the future position of the AEJ is projected to shift northward. Additionally, a more intense AEJ and WAM will result in rainier future MCSs and more intense AEWs (Núñez Ocasio et al., 2025).

Gbode et al. (2021) used a pseudo-global warming approach to project increased rainfall in future climates across parts of West Africa, especially over the Guinea Coast, Cameroon Mountains, and the Bight of Benin coast. Similarly, EAGLE (Grim et al., 2020) generated convection-permitting climate datasets to improve understanding of extreme weather and precipitation in East Africa, supporting better forecasting and planning under climate change.

Lightning is another weather-related hazard. The African Centres for Lightning and Electromagnetics Network (ACLENet; Cooper and Holle, 2019) is building the largest publicly available database of lightning injury reports across 40+ African countries, providing critical information for impact-based warnings and risk reduction.

3.3. Climate

3.3.1 Scientific knowledge and challenges

In recent decades, considerable advances have been made in understanding African climate and its governing processes. Large observational campaigns, such as the African Monsoon Multidisciplinary Analysis (AMMA) (Redelsperger et al., 2006) and the Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIIWA) project (Knippertz et al., 2015), have provided valuable insights. Global modeling efforts like Coupled Model Intercomparison Project

(CMIP; Eyring et al., 2016) and Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al., 2009), along with regional projects such as AMMA-MIP (Model Intercomparison Project), AMMA-ENSEMBLES (Ensemble-based Predictions of Climate Changes and their Impacts), and West African Monsoon Modeling and Evaluation (WAMME) project (Xue et al., 2010), have improved understanding of climate variability and change in Africa. These efforts have supported future projections and produced valuable datasets, particularly for key features like the West African Monsoon (Sylla et al., 2013). Particularly precipitation variability in the Sahel is an aspect where models have achieved some success in reproducing historical evolution, although biases and weaknesses remain (e.g., Gbobaniyi et al., 2014; Akinsanola et al., 2020).

A key global challenge is understanding regional climate impacts and effective adaptation and mitigation strategies. For Africa, further evaluating and improving climate models (James et al., 2018; Akinsanola et al., 2025a) and advancing methods for understanding the major sources of uncertainty in future climate projections is essential (Quagraine et al., 2020; Bobde et al., 2024). As with global climate projections, sources of uncertainty to project African climate include model uncertainties, uncertainty in future emission scenarios, and internal variability which is an irreducible, although quantifiable, component of uncertainty given that the single future that we will experience will have contributions that arise from unpredictable internal variability, even on multi-decadal timescales (Monerie et al., 2020; Klutse et al., 2021; Audu et al., 2024). There is also an urgent need to enhance subseasonal-to-seasonal predictions to support climate-sensitive sectors like agriculture and hydropower. Earth System Prediction is an emerging priority within the UCAR community, and the Community Earth System Model (CESM) Earth System Prediction Working Group now provides seasonal-to-decadal datasets accessible to researchers without requiring high-performance computing.

Carbon dioxide (CO₂) emissions from burning of fossil fuels across Africa nearly doubled between 1990 and 2018 (Mostefaoui et al., 2024), and agricultural expansion and intensification is likely to further increase GHG fluxes, including methane (CH₄) from livestock and rice production (Ernst et al., 2024; Chen et al., 2023). The Regional Carbon Cycle Assessment and Processes Phase 2 found that Africa is becoming a small net source of carbon (Ernst et al., 2024), with its sink capacity decreasing. Monitoring of carbon stocks and fluxes remains limited. Differences exist between atmospheric inversions and bottom-up estimates due to flux

uncertainties, transport error and the sparse observation network (e.g., Nickless et al., 2020; Ernst et al., 2024). Emerging direct satellite observations of CO₂ and CH₄ are providing improved monitoring capabilities (Lunt et al., 2019), with potential to reduce flux uncertainties if seasonal biases in satellite sampling due to clouds (Frankenberg et al., 2024) and systematic errors are well characterized (Gaubert et al., 2023).

Aerosols remain a major source of uncertainty in estimating radiative forcing (e.g., IPCC, 2021; Mahowald et al., 2024). Africa is a key aerosol source particularly for desert dust and fire emissions (Prospero et al., 2005; Schreuder et al., 2019) and currently accounts for about half of global dust emissions (Kok et al., 2023), which have a net cooling effect due to their scattering properties (Leung et al., 2025). Uncertainty arises from both prescribed emissions and the representation of aerosol processes and aerosol-cloud interactions in climate models (Andela et al., 2017; Leung et al., 2024). Changing dominance of different aerosol types with distinct optical and cloud-forming abilities also contributed to the uncertainties of aerosol radiative forcing estimation (Storelvmo, 2017; Mahowald et al., 2024). More observations are needed to improve process modeling and tuning, especially for the fields of aerosol–radiation and aerosol–cloud interactions (e.g., Mallet et al., 2021).

Climate intervention research, particularly on SRM, is gaining attention as a potential tool to mitigate climate impacts. Most SRM studies have been led by institutions in the Global North, supported by advanced computing infrastructure and expertise (Tilmes et al., 2018). However, it is critical for African nations to engage in these discussions to ensure regional vulnerabilities and priorities are addressed, given the potential effects of SRM on agriculture, water, and ecosystems (UNEP, 2023b). Greater involvement of African researchers and policymakers is essential for a balanced global assessment of SRM risks and benefits. Initiatives such as the Degrees Initiative (<https://www.degrees.ngo/>) are empowering scientists from the Global South—including Africa—to build the capacity.

3.3.2 Efforts from UCAR Africa Initiative Community

Recent developments in kilometer-scale convection-permitting models offer significant potential to improve understanding of the African climate. For example, the DYNamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) project (Stevens et al., 2019) has produced global storm-resolving simulations. Similarly, the Pan-African

Convection-Permitting Regional Climate Simulation (CP4A) from the UK Met Office (Stratton et al., 2018) delivered km-scale regional simulations over Africa for present and future climates. Within the UCAR Africa Initiative Community, efforts are underway to apply regional refinement using Model for Prediction Across Scales (MPAS; Skamarock et al., 2012) and CESM (Tang et al., 2023). These models enable comparative studies with DYAMOND and CP4A and support exploration of future climate impacts and intervention scenarios.

Understanding Africa's changing climate is also critical from a global perspective due to its significant influence on global systems. African Easterly Waves, for instance, play a critical role in Atlantic basin tropical cyclone formation (e.g., Martin and Thorncroft, 2015) and UCAR Africa initiative participants are actively working in this area (e.g., Akinsanola et al., 2025b). Many are also investigating sources of uncertainty in future climate projections for Africa (e.g., Quagraine et al., 2020, Monerie et al., 2020, Klutse et al., 2021).

The UCAR Africa Initiative members have recently developed new dust emission parameterizations accounting for wind fluctuations and land use changes, particularly over the Sahara and Sahel (e.g., the Bodélé Depression and El Djouf; Leung et al., 2023). Other advances in CESM include improved representations of dust size, composition, and deposition, informed by field campaigns and satellite data (Li et al., 2022; Ryder et al., 2015; Gonzalez-Florez et al., 2023). Furthermore, a historical dust dataset (DustCOMM; Leung et al., 2025) helps track dust trends in Africa since the 1850s.

Gaubert et al., (2023) compared CO₂ fluxes and concentrations simulated by several models with independent in-situ airborne observations collected in airborne campaigns. Their emergent constraint approach combining CO₂ inversions using in-situ and satellite data with additional constraints from the aircraft data, suggest an approximately neutral CO₂ fluxes over the annual cycle. These findings highlight the importance of integrating multiple observational platforms to accurately assess the regional carbon budget of northern tropical Africa and thus highlight the need for rigorously calibrated in-situ observations.

Several UCAR Africa Initiative members have participated in climate intervention research through international collaborations. NSF NCAR produced various modeling datasets including Geoengineering Large Ensemble Simulations (GLENS; Tilmes et al., 2018), overshoot model scenarios (Tilmes et al., 2020), and simulations as part of ARISE-SAI (Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection;

Richter et al., 2022), shared via the Degrees Initiative. Using these and other model data, Pinto et al. (2020) found climate intervention may benefit Central and East Africa, but effects could be mixed in West and Southern Africa. Carlson et al. (2022) found SRM could limit malaria in East Africa's highlands but worsen transmission in lowland sub-Saharan Africa and South Asia. Ahead, the development of improved dynamical downscaling will help to assess uncertainties in the impacts of SRM on the regional and local climate.

3.4. Land and water

3.4.1 Scientific knowledge and challenges

Rapid population growth and human activities have driven major land use and land cover changes (LULCC) across Africa, including urbanization, agriculture, deforestation, and wetland encroachment (Herrmann et al., 2020; Kibet et al., 2021). However, unsustainable land use practices in some parts of Africa are found to have many negative consequences which exacerbate environmental challenges faced by the continent, such as flooding linked to land reclamation in West Africa and declining water resources in sub-Saharan Africa (Mosnier et al., 2015; Govender et al., 2022). Accurate and up-to-date LULCC data remain limited, hindering effective land use planning (Chisanga et al., 2024).

Urbanization is a major driver of land use change in Africa, with about 4,500 new cities emerging in recent decades (OECD, 2022). African cities face growing environmental risks, including air pollution, flooding, heatwaves, and droughts (Mishra et al., 2015; Rusca et al., 2023), although these extremes are not unique to urban areas in Africa. Some African cities experienced significant increasing flood risks from extreme precipitation and other factors (Tazen et al., 2019; Umer et al., 2023). Urban heat island and heatwave conditions are also exacerbating in many African urban regions and are projected to intensify (Li et al., 2022; Geleta et al., 2022). Many African coastal cities are also increasingly exposed to flooding due to sea-level rise (Higuera Roa et al., 2022). Albeit these critical issues, only few African cities have been studied, which does not represent the heterogeneous African urban environments (Li et al., 2022). Interactions between urban settings and climate extremes—especially compound events at local scales—remain poorly understood.

Africa's diverse hydrologic systems—including the Nile, Congo, Okavango Delta, and Great Lakes—are also highly vulnerable to drought. In regions like the Congo Basin, moisture

deficits result from reduced oceanic transport and limited local recycling through evapotranspiration (Sori et al., 2022). Given limited in-situ monitoring, efforts have been made to develop drought prediction systems using models and satellite data to improve early warnings and impact assessments (Mwangi et al., 2014; Hao et al., 2018). Studies show that El Niño–Southern Oscillation (ENSO) is a key driver of precipitation predictability linked to droughts across Africa (Shanahan et al., 2009; Rodriguez-Fonseca et al., 2015). Despite advances in modeling capabilities, large uncertainties remain in quantifying key hydrometeorological variables in Africa partially due to sparse and uneven observations (Satgé et al., 2020; Mbuviha et al., 2023). This makes providing accurate spatiotemporally continuous estimates of terrestrial water cycle challenging and inhibits the ability for comparison to process-level model diagnostics. The region's susceptibility to drought is further exacerbated by limited understanding of processes such as flash droughts and drought response to future climate.

Only ~6% of Africa's land is used for arable and permanent crops, with the majority being smallholder rain-fed farms. Improving the productivity of smallholder farmers is crucial for poverty reduction and achieving Sustainable Development Goal 2 (Lobell et al., 2019). Only 4% of sub-Saharan Africa's farmland is irrigated, despite 40 million hectares being suitable—limiting the potential to meet growing food demands. African agriculture is highly sensitive to drought (Ifejika Speranza et al., 2008), and many smallholder farmers have taken various drought adaptation measures (e.g., increased water storage and improved infrastructure) to offset agricultural losses (Anderson et al., 2021; Wens et al., 2020), which however require significant capital, or migrated to regions with more reliable rainfall (Gray and Mueller, 2012; Henry et al., 2003).

Fires alter ecosystems and atmospheric composition (Andela et al., 2017), with human activity increasingly driving ignition in Africa (Shaffer, 2010). Long-term satellite records support analyses of fire trends and their links to climate and human factors (Andela and Van der Werf et al., 2014). Over the past two decades, fire activity in Africa has declined, reflecting a global shift from savanna to forest-dominated fire regimes (Andela et al., 2017). Despite progress in wildfire research in Africa, key challenges remain. Satellite fire products often miss small fires (<25 ha), which may increase global burned area and emissions by up to 35%. This is critical to regions like Africa, where small-scale agricultural burning is common (Randerson et al., 2012; Van der Werf et al., 2017). Also, diurnal cycle of fires is important (Tang et al., 2022) but is not well documented

due to limited data. In addition, detailed plant-fire-climate interactions and physical mechanisms need further studies via advanced Earth system modeling and causality analysis.

3.4.2 Efforts from UCAR Africa Initiative Community

The UCAR Africa Initiative community has helped address key land and water challenges in Africa. Advances in global LULCC data and modeling (Lawrence et al., 2016) provide critical support for tracking LULCC and its climate impacts, helping to fill satellite and ground data gaps. An improved LULCC map over Lagos highlights increased flood risk from wetland conversion to developed areas (Idowu & Zhou, 2021). Studies by community members show urbanization intensifies extreme precipitation and heat stress in African megacities (Guo et al., 2022; Doan et al., 2023), offering insight for urban hazard and management. Additionally, four World Climate Research Programme “My Climate Risk” hubs have been launched in African cities, involving several of our community members.

To improve hydrologic assessments in Africa, the UCAR Africa community has led coordinated efforts to develop high-quality data and modeling tools. The East African Great Lake Environments project (EAGLE) provides ~3 km hourly downscaled climate data for the Great Lakes region to support hydroclimate monitoring (Grim et al., 2020).

The NCAR Weather Research and Forecasting model (WRF) hydrological modeling system (WRF-Hydro; Gochis et al., 2018) and MizuRoute river routing model (Mizukami et al., 2016) have been used to simulate streamflow across over 60,000 river reaches, aiding water resource analysis (Akpoti et al., 2024). A user-friendly platform (<https://nasa-ucla.rap.ucar.edu/>) now supports reservoir operations in East Africa, and collaborations are underway to develop operational hydrologic prediction services with local partners. One outcome is that WRF-Hydro was recently calibrated for eastern Ethiopia (Lahmers et al., 2019), and the model was able to replicate the timing of recent flood events by accurately simulating the onset and cessation of the flood event (Semie, 2023).

To enhance the food-water security in Africa, previous studies (Burney et al., 2013) by the UCAR Africa community show that expanding smallholder irrigation could help mitigate climate impacts, reduce hunger, and raise incomes. Our community also developed the FLDAS (Famine Early Warning Systems Network Land Data Assimilation System) tool to support early warning of droughts and floods (McNally et al., 2017; Hazra et al., 2023). In rural areas, researchers are

addressing water insecurity by evaluating surface water stress and flood risks linked to mobility and resilience (Macharia et al., 2023).

To better understand fire behavior in Africa, our community members have developed advanced algorithm to more accurately characterize fire patterns based on satellite data, revealing significant decrease in fire frequency and size mainly over tropical savannas and grassland in central Africa due to suppressed fuel, reduced rainfall, and lengthened dry season (Jiang et al., 2020). This helps fill knowledge gaps and supports better fire risk assessment and resource management.

3.5. Social science perspectives

3.5.1 Scientific knowledge and challenges

Key dimensions for understanding ESS and the impacts of climate change in Africa are the human and social components of the broader system. Similar to the physical sciences, there is a diversity of disciplines and approaches within the social sciences that approach the interactions of humans and the earth system in slightly different ways. Human geography explores spatial relationships between people, communities, economies, and their environments. Human geographers are concerned with how the spatial distribution of phenomena develops, and changes over time (Mercier and Norton 2019) with central questions focusing on what is where, why there, why care? Past research on climate and seasonality has focused on spatial distribution of standards of living across the globe and highlights, among others, the impact of seasonality and environmental risks on livelihoods in Africa (Ellis, 1998, Dietz et al., 1992, Dekker 2004).

Communication is a broad discipline that covers research on how information is developed, communicated, interpreted, and acted upon by various audiences. Research has examined topics such as forecasters' decision-making processes (Fine, 2009; Daipha, 2015; Hoffman et al., 2023) and public responses to weather hazards (Demuth et al., 2012; 2022). Past research has begun analyzing the communication of weather and climate information across various regions of Africa (e.g., Agyekum et al., 2022; Makuvaro et al., 2023; Singh et al., 2018). Despite this important work, there is a pressing need for more communication related research that focuses specifically on issues related to weather, climate, and the environment in Africa.

A priority area is expanding our understanding of the key decision makers, their decision-making environments, and needs so that the research community, both within and beyond Africa,

can better support these key players through research and development. Work that focuses on supporting and working with local decision makers and communities, also known as user-engaged research, is essential for a more robust and people-centric approach to addressing weather, climate, and environmental risks. For effective user-engaged research further work is needed to understand the spatial and socio-economic distribution of exposure and responses to environmental risks. This is especially important in the African context, where vulnerabilities to environmental risks are high and growing, assessment of these risks is in its infancy due to a lack of data and monitoring systems (e.g., Hsu et al., 2013; Liu et al., 2013). As environmental risks often disproportionately affect already marginalized communities (Jbaily et al., 2022), it is necessary to recognize heterogeneity in the impact of environmental risks across different levels of scale; countries, regions (e.g. across the rural and urban areas) as well as communities (socio-economic status).

Another key priority is the integration of social science perspectives into ESS. Social science is a necessary dimension of effective and impactful research collaborations on African weather, climate and environment. Many of the key motivations, such as improving community resilience or lessening the effects of climate change and air pollution on various communities, are rooted in social science. Addressing them requires the deep integration of social science research, which can broaden the questions that can be asked and the approaches that can be taken to answer them. To be effective this integration must be deeper than “translating” or “educating” different communities and stakeholders about the physical science efforts. Instead, social scientists need to be involved from the beginning of the collaborative efforts and have a formative role in the research. Social science perspective also help contextualize the data. That is often needed to effectively influence policy and practice. Up until now, the evidence of such interdisciplinary collaborations is limited (Dekker et al., 2025).

3.5.2 Efforts from UCAR Africa Initiative Community

The UCAR Africa Initiative community acknowledges the importance of interdisciplinary perspectives and members of the community have started to explore these linkages, both conceptually as well as in practice, in a series of workshops and conference sessions. The 2022 Lorentz workshop in the Netherlands (Lorentz Center, 2022) was co-organized with participation of UCAR Africa Initiative community members and identified key dimensions of convergence between social science and natural science, including (i) co-creation of research agendas with

users, (ii) integration of satellite and in-situ data with translation to policy action, (iii) capacity-building and sustainable data/observational infrastructure, and (iv) equitable data practices and access in North–South collaborations. Although the conference was focused on air pollution, the identified themes can be applied more generically.

3.6. Other scientific challenges and directions

Across all working groups, several shared challenges emerged, cutting across air quality, land, water, weather, and climate in Africa. To avoid redundancy, we summarize these common challenges here. A consistent message from all groups is the urgent need to strengthen observational infrastructure across Africa. Ground-based monitoring stations for land surface and hydrometeorological conditions remain sparse, resulting in heavy reliance on satellite and reanalysis datasets. While valuable, these remote sources must be complemented by in-situ observations to improve the accuracy and relevance of environmental assessments and modeling efforts. Examples of efforts to address these gaps include the Trans-African Hydro-Meteorological Observatory (TAHMO; van de Giesen et al., 2014), which aims to deploy up to 20,000 affordable weather stations across the continent, and the 3D-Printed Automatic Weather Station project (3D-PAWS; Kucera & Steinson, 2016), which enables in-country partners to fabricate and maintain their own networks.

Closely tied to this is the need for greater investment in modeling capacity focused on Africa. Land surface and hydrological models must be improved through sustained collaboration between the modeling and observational communities. Developing regional and local modeling capabilities to generate actionable products is also a pressing priority from an operational perspective. Strengthening these models will support the development of early warning systems critical for managing climate and weather extremes. There is also a need for holistic assessments of hazard risks—such as heatwaves, floods, droughts, and compound events—including their drivers and regional expressions. Cross-regional collaborations could leverage shared hydroclimatic patterns to co-produce knowledge and scalable solutions. Despite wide recognition of these needs (e.g., World Bank, 2021; Lamptey et al., 2024; Carter et al., 2020; North et al., 2020), major challenges persist. These include limited scientific capacity, insufficient training, technical gaps, and fragmented governance structures—all exacerbated by chronic underfunding. Notably, funding in the region is often short-term and project-based—prioritizing immediate risk-

reduction and service delivery—while core operations, maintenance, and foundational research capacity are relatively underfunded (World Bank, 2021; Lamptey et al., 2024).

4. Developing equitable collaboration and sustainable infrastructure

Addressing the scientific challenges outlined in the previous section requires not only technical solutions but also strong, sustained investments in infrastructure, institutional capacity, and equitable partnerships. Scientific progress alone is insufficient without the systems and relationships needed to support long-term resilience, local ownership, and actionable outcomes.

Across Africa, the infrastructure required to effectively respond to climate and environmental change remains limited. The limitations vary widely across countries, and span from limitations in operational forecasting and modeling, weather and climate research, and education and community outreach. As an example, Africa has one of the lowest densities of weather stations and sensing networks, posing an urgent infrastructure challenge (Dinku, 2019). This section focuses on the enabling conditions—physical infrastructure, human capital, data access, and collaborative models—that are essential for supporting climate and environmental research and its effective application across Africa.

Sustainable infrastructure is central to building long-term resilience, yet it is often constrained by limited and inconsistent financial resources. Infrastructure here includes not just physical assets (e.g., observational networks, computing systems) but also human capacity, institutional frameworks, and data management systems. Many African institutions lack reliable funding streams for maintaining and upgrading infrastructure, which undermines their ability to deliver timely and actionable environmental services. Long-term sustainability will therefore require innovative and context-appropriate financing strategies, along with partnerships that foster capacity development and technology transfer.

Equitable international collaboration can play a crucial role in supporting and strengthening the research infrastructure in Africa (Garland et al., 2024). Yet achieving equitable partnerships requires planning from the beginning of the proposal/project, especially where disparities in funding and capacity exist. Collaborations should aim to develop transformational relationships where the responsibilities and intellectual leadership is shared (Clayton et al., 2010; Annegarn and Swap, 2012). Such equitable collaborations not only improve project outcomes, but also empower

local researchers, strengthen community engagement, and lead to more impactful and sustainable results.

Here we identify several cross-cutting research and infrastructure priorities that can serve as starting points for collaborative environmental research in Africa. These recommendations—derived from UCAR Africa Initiative activities—are meant to guide practical steps toward strengthening regional infrastructure and equitable collaboration. While general in scope, they can be further refined through discussion within local and international collaborative teams to align with specific contexts. The following list outlines specific areas for action:

- (1) Sparsity of in-situ measurements and observations for model validation is one challenge. There is a need to enhance observational networks for model input and evaluation and developing a data sharing agreement and protocol.
- (2) The emissions and mitigation pathways in the African Assessment (UNEP et al., 2023a) can be downscaled and further modeled to produce local air quality and climate futures to support policy making.
- (3) Open-access data platforms are needed to improve data availability across Africa. Centralized repositories, cloud-based infrastructure, and clear data-sharing protocols can support local modeling efforts and ensure external model outputs are accessible. Transparency and collaboration with governments and communities are also essential.
- (4) There is a need to support Africa's effort to build their own model centers and to establish capabilities to develop their own climate scenarios and produce simulations. This includes in-person training and regular follow-on meetings from Global North researchers to assist with running complex model systems.
- (5) Climate attribution science in the context of loss and damage financing (established at COP27 and operationalized at COP28) can provide useful information for decision makers (Coumou et al., 2024).
- (6) With the changing nature of science and the globalization of society, many of the scientific challenges discussed are global in nature and affect individuals from a wide array of backgrounds. There is a growing need to facilitate integration of expertise across disciplines and across academia, institutes, government, and industry to address multidisciplinary grand challenges that increasingly require multinational, instead of bilateral, cooperation.

- (7) A growing reliance on expatriate professionals in the execution of Africa's complex and sophisticated development issues is worrisome. International collaborations can augment local research capacity and expertise to work together to solve these challenges. As noted above, international collaborations should aim to developing an independent and self-reliant local scientific community and encourage local investment.

In the absence of strong institutionalized local partnerships, even well-meaning and well-funded research and development agendas can end up being ineffective as the users (policymakers, managers, engineers, researchers, students, farmers, and the general public) are not adequately engaged in the design of long-term sustainability of the effort at the outset and therefore have little stake in the success of these efforts. Sustainability and equitable relationships should be an important consideration.

5. Conclusions and outlooks

Africa, one of the most dramatically changing continents both environmentally and demographically, is experiencing various climate and sustainable development challenges. International and interdisciplinary collaboration can play an important role in unlocking the potential for sustainable growth, particularly when designed to be equitable and locally relevant. This paper covered six areas: (1) air quality and health, (2) weather, (3) climate, (4) land and water, (5) social science perspectives, and (6) developing equitable collaboration and sustainable infrastructure. We highlighted advances in science that could help address the challenges through equitable international and interdisciplinary collaborations. For African nations to take advantage of these advances, international collaborations should focus on enhancing local research capacity and integrating local knowledge into the global picture to address challenges that are both region-specific and globally significant. We hope this paper motivates the scientific community to focus on African environmental challenges and research for further scientific advances and to adopt a systems approach from the perspective of how research can inform actions to achieve global sustainability.

Emerging approaches such as artificial intelligence (AI) and co-design/co-development/co-production frameworks are becoming increasingly important for advancing environmental research globally. While these approaches were not a primary focus of the UCAR Africa Initiative workshop discussions summarized here, we acknowledge their critical role in shaping future

research. Strengthening AI applications for Earth system science in Africa, in parallel with user-engaged co-design and co-production, represents an important direction to address both scientific and societal needs.

To ensure long-term sustainability and reduce overreliance on external aid, African nations should prioritize the development of endogenous climate financing mechanisms. This includes allocating dedicated national budgets to support climate and environmental research, monitoring infrastructure, and capacity-building initiatives. In parallel, the African Union and regional blocs – (i) Southern African Development Community (SADC); (ii) Arab Maghreb Union (AMU); (iii) East African Community (EAC); (iv) Economic Community of Central African States (ECCAS); (v) Economic Community of West African States (ECOWAS); (vi) Common Market for Eastern and Southern Africa (COMESA); (vii) Intergovernmental Authority on Development (IGAD); and (viii) Community of Sahel–Saharan States (CEN-SAD) – could play a vital role by establishing joint climate financing funds that are accessible to member states. These mechanisms can strengthen collaborative planning and implementation, and improve access to resources for climate adaptation, mitigation, and research efforts. A sustainable and diversified funding strategy that includes both domestic and international sources is essential to advancing environmental resilience and research leadership across the continent.

We acknowledge that many other environmental issues not covered here are equally important and also require immediate research and sustainable solutions. This paper aims to draw attention to African environmental challenges, summarize the insight we gained from our recent activities, and outline future research directions and actions to enhance environmental solutions on the continent. We hope that current and future collaborations, along with an expanding research network will help identify and establish sustainable partnerships to tackle these challenges.

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Data and Software Availability Statement

No datasets were generated during this study. CAMS data used in analysis is available at: <https://www.ecmwf.int/en/research/climate-reanalysis/cams-reanalysis> (accessed May 20, 2025). Research and development expenditure (% of GDP) is available at: <https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS> (accessed May 20, 2025). Information on UCAR Africa Initiative is available at: <https://www2.acom.ucar.edu/ucar-africa-initiative> (accessed May 20, 2025).

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