Review Article

Challenges and Prospects of Aerosol-Cloud-Precipitation Studies Over Africa

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Africa's distinctive climate and varied terrain present a crucial domain for examining the intricate relationships between aerosol-cloud-precipitation and their implications for regional climate, water resources, and agriculture. Advances in satellite technology, field research, and numerical modeling have propelled progress in this field. Satellite instruments have facilitated the understanding of aerosol properties and their interplay with clouds and precipitation, while ground-based and airborne measurements from initiatives like Aerosols, Radiation, and Clouds in southern Africa AEROCLO-sA, and Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa DACCIWA have provided essential data complementing satellite observations. However, challenges persist, including data scarcity, rugged landscapes, and uncertainties in feedback mechanisms. State-of-the-art satellite sensors and advanced high-resolution lidar systems offer promise in enhancing the observation of aerosol-cloud-precipitation dynamics. Collaborative research efforts, such as the EU–Africa research and Innovation Cooperation Programs, which engage international partnerships, have the potential to facilitate knowledge exchange, improve skills, and promote data sharing.

1. Introduction

The study of aerosol-cloud-precipitation interactions is an important frontier in atmospheric science and has a significant impact on understanding and reducing the impact of climate change. In Africa, these interactions are particularly complex due to the different climate zones, the different topography, and the unique composition of the continent's atmosphere. Aerosols, which encompass suspended particles in the atmosphere, interact with clouds and precipitation processes, affecting regional climate models, water resources, agricultural productivity, and public health. Consequently, the objective of effectively predicting climate modeling, resource management and policy formulation is to gain a comprehensive understanding of these interactions over Africa.

Aerosols are one of the most important influences on precipitation. The exact mechanism of these influences is complex, but numerous observation and modeling studies have shown that precipitation is heavily influenced by atmospheric aerosols (Mashayekhi & Sloan, 2014). Aerosols have a major impact on the dynamics, microphysics, and electrification properties of convective clouds in continental mixed phases. Furthermore, high concentrations of aerosols in urban environments can affect precipitation variability by providing an important source of cloud condensation nuclei (CCN) (Tao et al., 2012).

Africa's aerosol-cloud-precipitation research represents both challenges and opportunities that require focused research attention. First, the limited observation infrastructure of the continent, especially in remote and inaccessible areas, poses significant challenges in obtaining high-quality data to validate models and understand processes. Sparse ground measurements, combined with the uneven distribution of monitoring stations, exacerbate these challenges (Gatebe et al., 2001). Secondly, the diverse terrain of Africa, ranging from dry deserts to dense rainforests, introduces complexity in accurately simulating aerosol clouds and precipitation processes (Deetz et al., 2018b). This variability requires individualized modeling approaches to effectively capture regional nuances (Weston et al., 2022).

Despite these challenges, some factors have stimulated research efforts in this field. First, the potential impact of aerosol cloud-precipitation interactions on climate resilience, food security, and public health in Africa underscores the need for more scientific understanding in this area (Deetz et al., 2018a). Secondly, recent advances in remote sensing technologies, such as satellite sensors and lidar systems, have created unprecedented opportunities to improve the continent's observation capabilities. These cutting-edge tools allow the monitoring of aerosol properties, cloud dynamics, and rainfall patterns with greater accuracy and spatial coverage (Gorman et al., 2019). In addition, joint research initiatives, including international partnerships and cross-disciplinary cooperation, provide opportunities for knowledge exchange, capacity-building, and data sharing. These initiatives can promote synergies between scientists, policy makers, and stakeholders to address the complexities of aerosol-cloud- precipitation studies in Africa in a comprehensive way.

In view of these considerations, this paper examines the current state of aerosol-cloud-precipitation studies in Africa, determines key challenges that prevent progress in this field, and explores

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promising prospects for future research. This research seeks to understand evidence-based strategies for climate adaptation, resource management, and sustainable development across the African continent, involving the complex interactions between aerosols, clouds, and precipitation processes.

2. Field campaigns

There are scientific campaigns that have been carried out in various parts of Africa in an attempt to understand the climatic implications of aerosols in the context of atmospheric chemistry and meteorology. In the southern part of Africa, the Southern Africa Fire-Atmosphere Research Initiative (SAFARI-92) was established to understand how vegetation fires,, especially savanna fires affect climate, atmospheric chemistry and ecology comprehensively (Lindesay et al., 1996). In 2000, the campaign expanded to encompass airborne, surface, and spaceborne equipment to investigate the interactions between land and the atmosphere. The campaign brought to light biogeochemical cycling on a regional scale, which helps to validate remote sensing instruments (Swap et al., 2003). There were ObseRvations of Aerosols above Clouds and their intEractionS (ORACLES) for three consecutive years (2016-2018) to characterize the seasonal evolution of a single scattering albedo in aerosol-cloud interactions and offshore biomass-burning aerosol (Ryoo et al., 2022; 2021). Layered Atlantic Smoke Interactions with Clouds (LASIC) was also performed using an Atmospheric Radiation Measurement (ARM) mobile facility equipped with in situ and remote sensors on Ascension Island (Zuidema et al., 2018). LASIC equipment includes a Lidar that can profile the vertical structure of the aerosol, and multiple radiosondes were employed to monitor the diurnal cycle of smoke cloud interaction.

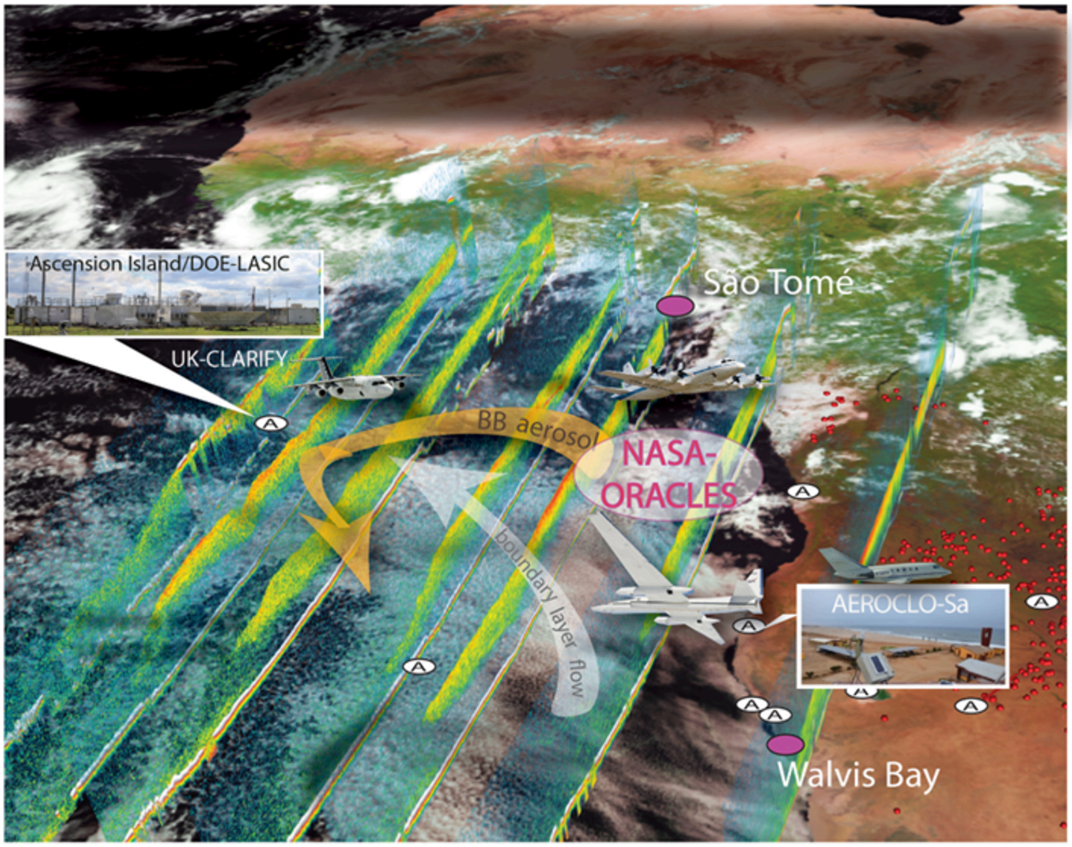

Figure 1. Deployment sites for the 2016–2018 ORACLES field experiments and collaborative international deployment activities, along with CALIOP curtain data visualized by Charles Trepte (NASA Langley), adapted from Google Maps 2020. Ovals with the letter A indicate new or refurbished AERONET sites (Holben et al., 2018). Adapted from (Redemann et al., 2021)

Furthermore, CLARIFY (CLouds and AeRosol Impacts and Forcing: Year 2017) was sponsored by the UK to improve the representation and reduce the uncertainty of the direct, indirect, and semidirect radiative effects of the UK Met Office model (Haywood et al., 2020). Formenti et al. (2019) and Redemann et al. (2021), captured the various field experiments in their context and as shown in Figure 1.

In 2006, an international campaign called African Monsoon Multidisciplinary Analysis (AMMA) was conducted in the West African region. The aim is to investigate the interaction between the African monsoon, the hydrological cycle, and climate. During the Dust and Biomass Burning Experiment (DABEX), land-based measurement sites were located at several locations in West Africa and increased by aircraft measurements (Haywood et al., 2008). AMMA and DABEX were designed to learn the optical and physical properties of biomass combustion aerosols and natural mineral dust aerosols and determine their interaction by performing high-quality remote sensing and in-house measurements.

Another major campaign was Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (Figure 2) that took place in 2016. Knippertz et al. (2015) explained the motivation for the campaign as surrounding the estimated population growth in southwestern Africa by 2030 and its socioeconomic importance. Three main areas (a) human health on the urban scale, (b) ecosystem health, biodiversity, and agricultural productivity on the regional scale, and (c) regional climate were identified. The campaign covered aerosol science, climate science, air pollution, cloud microphysics, and so on.

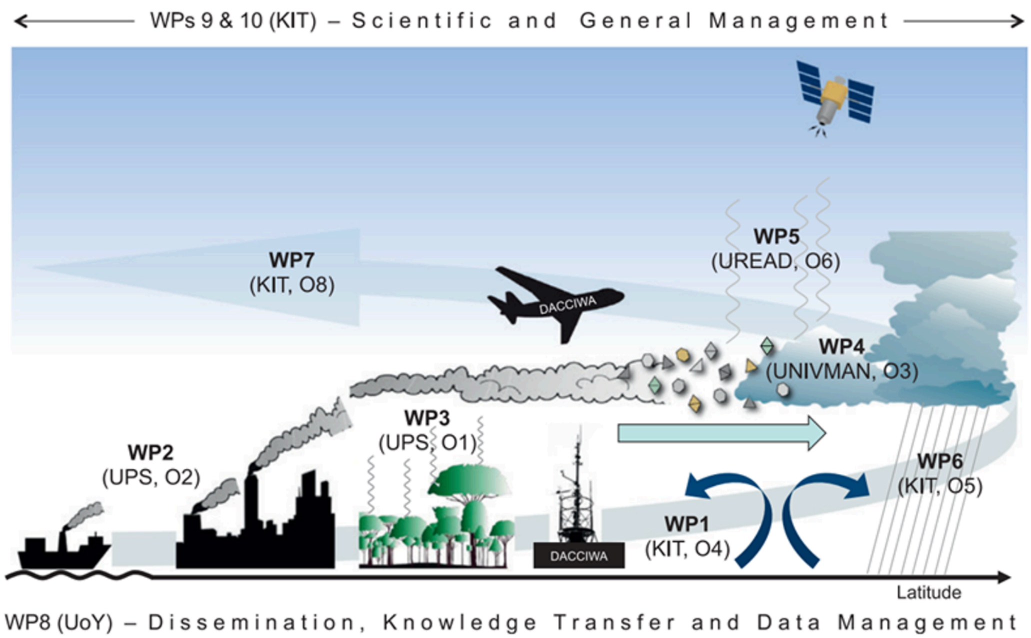

Figure 2. Schematic overview of the DACCIWA Work packages (WPs). The institution leading each WP is given in parentheses (see Fig. 3 for a list of abbreviations) together with the objective that the WP is the main contributor (WPs 1–7 only; see list of objectives in the original article). Adapted from (Knippertz et al., 2015)

In equatorial and eastern Africa, studies such as Dynamique et Chimie de l'Atmosphère en Forêt Equatoriale (DECAFE) focused on the effect of the forests and savannahs of African tropics on atmospheric chemistry (Fontan et al., 1992). To be able to address air pollution from the southeast and south of Asia to the Intertropical Convergence Zone (ITCZ) (Lelieveld et al., 2001), Gatebe et al. (2001), set up an experiment on Mount Kenya to sample and characterize the nature of aerosols transported across the equator of Africa. Aged and recirculated aerosols transported over 6000 km were observed at the site. Satellite sensors have been used to study the spatial and temporal characteristics of aerosols for 15 years in East Africa, as few field experiments have been carried out in this region (Boiyo et al., 2017).

Thirteen years of aerosol studies were carried out for North Africa using the Aerosol Robotic NETwork (AERONET), with aerosols of pure Saharan dust, urban and industrial (close to those of continental eastern Europe and the Middle East), and biomass burning was observed (Basart et al., 2009). Using six remote sensing platforms (satellite and ground-based), a model simulation of North African dust aerosols was carried out from five global models (Kim et al., 2014). The study underscores the challenges in simulating optical and physical processes.

Concerning aerosol and precipitation, Solmon et al. (2008) explored the climatic consequences of both short-wave and longwave radiative forcing resulting from Saharan dust on the West African monsoon and Sahel precipitation. Using a regional climate model (RCM) dynamically coupled with a dust model, simulations are conducted for the period spanning 1996 to 2006. The analysis reveals two contrasting effects. First, the presence of Saharan dust leads to cooling of the surface, consequently inducing a reduction in monsoon intensity within the lower troposphere, which subsequently decreases precipitation. Second, a phenomenon termed the "elevated heat pump effect" occurs in the higher troposphere due to diabatic warming caused by the presence of dust, resulting in an increase in precipitation. In another study, Creamean et al. (2013) demonstrated the presence of dust and biological aerosols originating from regions as distant as the Sahara in high-altitude clouds that contain elevated concentrations of ice nucleating particles (IN) and are associated with ice-induced precipitation. This research provides the initial direct observations of clouds and precipitation indicating that dust and biological aerosols from the Sahara and Asia likely act as IN, influencing orographic precipitation mechanisms in the western United States.

Furthermore, an investigation into the connection between the African easterly jet (AEJ), the Saharan mineral dust (SMD) aerosols, and the West African precipitation was carried out using data from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim), the NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), the NASA Tropical Rainfall Measuring Mission (TRMM), and The Multisatellite Precipitation Analysis (TMPA) spanning July to September from 1998 to 2017. In years with higher dust levels, the AEJ shifts eastward, and in wetter years, the AEJ shifts northward; these alterations in the AEJ are attributed to the combined influences of SMD and WAP on the thermal field (Bercos-Hickey et al., 2020).

However, conducting comprehensive aerosol-cloud-precipitation studies in Africa poses several unique challenges. Gaining a better understanding of the impacts on clouds and rainfall over Africa through advanced research will provide invaluable information for climate change projections and adaptation strategies across the continent.

3. Aerosol-Cloud-Precipitation Measurement Techniques and Modeling

Researchers employ a variety of measurement techniques and modeling to study aerosol-cloud-precipitation interactions. This helps to understand the complex processes that occur in the atmosphere. Satellites equipped with various sensors, such as MODIS (Moderate Resolution Imaging Spectroradiometer), CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), MISR (Multiangle Imaging Spectroradiometer), CloudSat, etc. provides invaluable data for studying aerosol-cloud-precipitation interactions. These satellites offer information on cloud properties, aerosol concentrations, and precipitation patterns on regional and global scales (Benas et al., 2020; Gettelman et al., 2021; Goren et al., 2023; Kant et al., 2019; Painemal et al., 2020). Ground-based observations include sunphotometers that measure aerosol properties and lidar systems that emit laser beams to measure the backscattered light, allowing researchers to analyze the vertical structure of clouds and aerosols. Lidar is particularly useful for understanding the vertical distribution of particles in the atmosphere (Bhattacharyya et al., 2023; Chen et al., 2021; Dai et al., 2018; Huang et al., 2022).

Ground-based radars, such as weather radars, help monitor precipitation intensity, cloud structure, and storm dynamics. Dual-polarization radar can provide information on the type and size of hydrometeors in clouds (Lonitz et al., 2015; Montopoli et al., 2023; Mroz et al., 2023; Satoh et al., 2022). The ceilometer instruments measure the height of the cloud base and vertical visibility. They contribute to understanding cloud cover and vertical distribution in the atmosphere (Lee et al., 2018; Zheng et al., 2019). Instrumented aircraft, such as those used in field campaigns, carry a suite of instruments to collect in situ data on aerosols, cloud particles, and precipitation. These measurements help researchers understand the microphysical properties of clouds and their interactions with aerosols (Wehbe et al., 2021; Wendisch et al., 2016; Xiong et al., 2023).

Instruments attached to weather balloons provide vertical profiles of temperature, humidity, and aerosol concentrations. These measurements offer insight into the atmospheric conditions that influence cloud formation (Cha et al., 2023; Duan & Barros, 2017; Shi et al., 2023). Surface-Based Instruments, including aerosol samplers and precipitation gauges, help collect data at the Earth's surface. These measurements help to understand local variations in aerosol concentrations and precipitation (Cho, 2023; Foat et al., 2016).

Numerical climate models simulate atmospheric processes and are essential to predict regional and global climate behavior. These models incorporate data on aerosols, clouds, and precipitation to simulate interactions and predict future climate scenarios (Adhikari & Mejia, 2023; Dziekan et al., 2021; Yang et al., 2020). Cloud-Resolving Models (CRM) simulate cloud processes at a higher spatial resolution, providing detailed insights into cloud dynamics, microphysics, and precipitation development (Jeon et al., 2018; Lebo et al., 2017; Masrour & Rezazadeh, 2023). Satellite-Based Radiative Transfer Models simulate the radiative transfer of solar and terrestrial radiation through the atmosphere. These models help us to understand how aerosols and clouds influence Earth's energy balance (Román et al., 2014; Yan et al., 2020). Data assimilation techniques integrate observational data into numerical models to improve their accuracy and reliability. These help researchers refine model predictions and better understand aerosol-cloud-precipitation interactions (Rubin et al., 2017; Saide et al., 2012).

Field campaigns involve the deployment of a network of ground-based and airborne instruments to collect comprehensive data during specific meteorological events. These methodologies and technologies work synergistically to provide a comprehensive understanding of aerosol-cloud-precipitation interactions and contribute to advances in climate science and atmospheric research. Ongoing technological developments and interdisciplinary collaborations continue to improve the precision and scope of observations in this field (Flamant et al., 2018; Swap et al., 2003; Zuidema et al., 2016).

4. Key Challenges for Aerosol-Cloud-Precipitation Studies

Despite significant advances in the study of aerosol-cloud-precipitation interactions, there are still significant data limitations and gaps in understanding that present challenges to researchers.

Addressing these gaps is crucial to improving climate models, predicting weather patterns, and enhancing our understanding of the Earth's atmospheric processes. The key challenges in conducting aerosol-cloud-precipitation studies in Africa are in two broad categories:

4.1. Data limitations and gaps in understanding

The problem of spatial and temporal resolution is an essential challenge in the study of aerosol-cloud-precipitation interactions. It is important to resolve the spatial and temporal variability of air-cloud interactions on the cloud scale to accurately quantify the radiation pressure caused by anthropogenic aerosols. It is necessary to extract the concentration of ice crystals from satellite observations and to capture variations in the microphysics of ice clouds (Painemal et al., 2014; Sourdeval et al., 2018).

The limited vertical profile of aerosols, clouds, and precipitation prevents a comprehensive understanding of the three-dimensional atmospheric processes. Vertical information is crucial for accurate modeling cloud characteristics and precipitation formation (Chernykh & Aldukhov, 2020; Zhou et al., 2020). Integrating observational data into numerical models (data assimilation) faces challenges due to the complex and nonlinear nature of aerosol-cloud-precipitation interactions. This can lead to uncertainties in the model predictions. The challenges of assimilating IASI satellite data into a regional dust model over northern Africa and the difficulties in translating aerosol perturbations to changes in cloud properties and precipitation through data assimilation techniques were explored by Yu et al. (2019). Mulcahy et al. (2018) looked at the improvements in aerosol processes and effective radiative forcing in the HadGEM3 and UKESM1 climate models, including the assimilations of aerosol observations and representations of aerosol-cloud interaction. In situ measurements, especially at remote or challenging geographical locations in Africa, are sparse. This increases the uncertainty in the local aerosol and precipitation characteristics. The need for comprehensive in situ measurements and remote sensing observations was demonstrated to improve understanding of aerosol-cloud interactions, for example in AEROCLO-sA (Formenti et al., 2019).

Understanding the composition and sources of aerosols is critical to assessing their impact on cloud and precipitation processes. However, comprehensive information on aerosol composition is often lacking, making it challenging to identify specific sources. Due to the varying hygroscopic and optical properties of mineral dust, Formenti et al. (2014) focused on characterizing the mineralogical composition in western Africa to properly understand its interactions with clouds and precipitation.

Long-term observational records are essential to detect trends and changes in aerosol-cloud-precipitation interactions over time. However, in some regions of Africa, there may be a scarcity of long-term continuous observational data. Knippertz et al. (2015) outline the objectives and motivation for the DACCIWA project, which aimed to address the lack of long-term observational data and understanding of aerosol-cloud interactions in the region.

Validating climate models that simulate aerosol-cloud-precipitation interactions is challenging because of uncertainties in observational data and the complex nature of the atmosphere. Mallet et al. (2020) used observations from the ORACLES field campaign to evaluate the performance of models in simulating the direct and semidirect radiative forcing of biomass-burning aerosols over the southeast Atlantic region. Limited access to observational datasets and challenges in collaborative data sharing initiatives can hinder comprehensive analyses and model validation. Addressing these data limitations and understanding gaps will require a concerted effort from the scientific community, which will involve interdisciplinary collaborations, technological innovations, and sustained investments in observational infrastructure. Knippertz et al. (2015) gave an overview of the funding and participants of the DACCIWA project.

4.2. Challenges related to Fieldwork and Data Collection.

Fieldwork and data collection in the study of aerosol-cloud-precipitation interactions present several challenges due to the dynamic nature of the atmosphere, the vast geographical scales involved, and the complex interactions between various atmospheric components. Many regions in Africa, particularly those with unique atmospheric conditions, are remote and difficult to access (Gatebe et al., 2001). This limits the availability of ground-based observational data and makes it difficult to establish monitoring stations in these areas; this poses a challenge for validating satellite retrievals and improving model simulations. Consequently, this hinders a comprehensive understanding of regional- and continental-scale aerosol-cloud-precipitation interactions, leading to uncertainties in model predictions for these areas.

The diverse terrain, including deserts, forests, and coastal regions, presents challenges in simulating aerosol-cloud precipitation processes accurately. Some regions lack the infrastructure necessary for comprehensive field campaigns, including adequate research facilities, transportation, and communication networks. Redemann et al. (2021) discuss the ORACLES project, which involved aircraft and ship-based measurements in the remote southeast Atlantic region off the coast of Africa, highlighting the logistical and infrastructure challenges associated with operating in such remote areas with limited support facilities. Limited infrastructure can hinder researchers' ability to conduct extensive and continuous field observations, particularly in regions with unique meteorological features. The variability and unpredictability of weather conditions pose challenges during field campaigns. Sudden changes in weather patterns can impact the success of planned observations and measurements. Researchers may face difficulties in capturing specific atmospheric events or phenomena due to unpredictable weather conditions, which affect the quality and completeness of the collected data. Adebiyi et al. (2023) highlighted how the Southern African Easterly Jet is being misrepresented in models and how this can complicate the study of aerosol-cloud-precipitation interactions and their impacts (Figure 3).

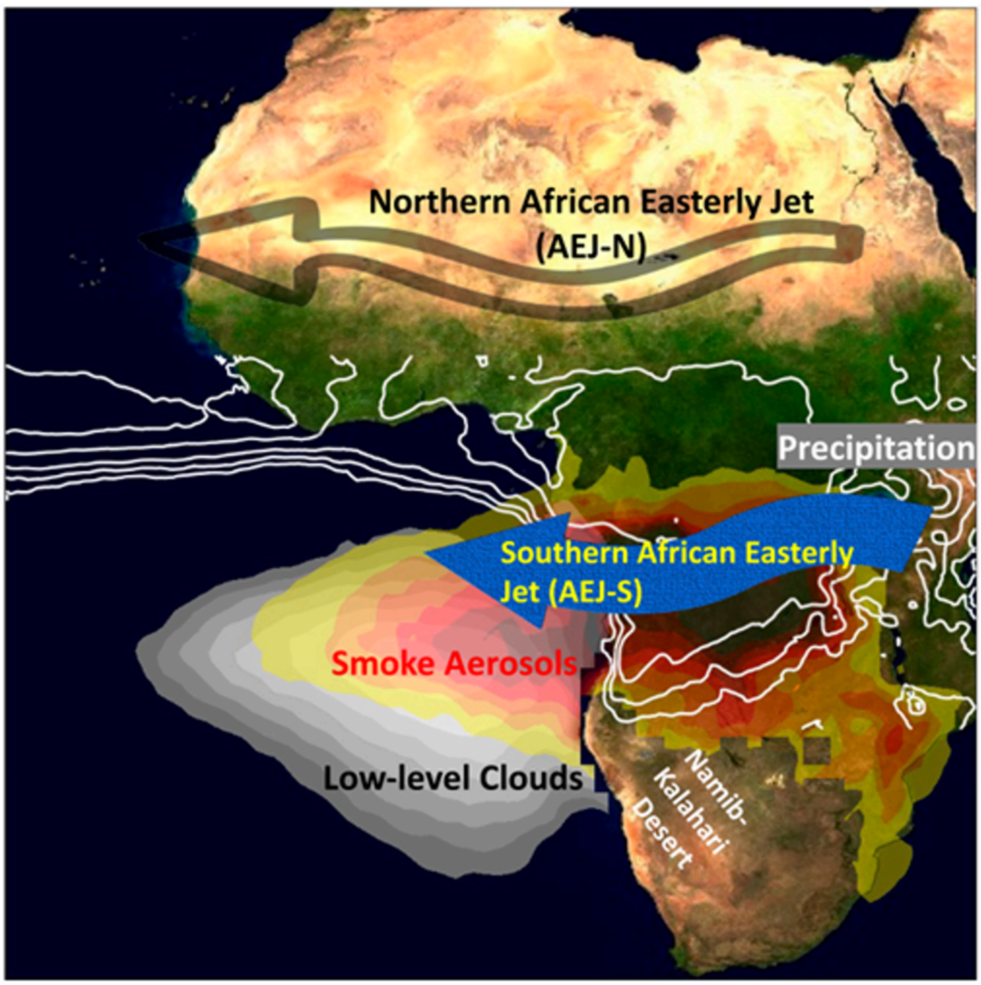

Figure 3. Representation of the southern African easterly jet

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(AEJ-S) as the central dynamical feature over central Africa and the southeast Atlantic Ocean. In addition, the image shows the northern African easterly jet (AEJ-N), which is the Northern Hemisphere counterpart of AEJ-S. The image also shows the precipitation (white contours) taken from TRMM, aerosol optical depth (red to yellow shades, indicating smoke aerosols), and the offshore low-level cloud (gray to white shades) fraction from MODIS. See Section 2a of the original article for description of TRMM and MODIS datasets. Adapted from (Adebiyi et al., 2023)

The deployment and maintenance of sophisticated instruments, such as lidar systems, radar, and specialized sensors, in challenging field environments can be logistically complex and expensive. Instrument malfunctions, calibration problems, or logistical constraints can lead to data collection, reducing the reliability of observations during field campaigns. Haywood et al. (2008) discuss the DABEX (Dust and Biomass Burning Experiment) and AMMA (African Monsoon Multidisciplinary Analysis) field campaigns, highlighting the challenges associated with deploying and operating aircraft instrumentation, ground-based lidars, and other advanced instruments in the harsh environmental conditions of West Africa. Field campaigns require substantial resources, including funding for equipment, personnel, transportation, and logistical support. The provision of adequate resources can be a challenge for researchers and institutions. Limited resources may result in shorter field campaigns, reduced instrument deployment, or narrower scope of observations, which limits the overall comprehensiveness of the collected data. The DACCIWA and ORACLES field campaign, for example, could not have been possible without international collaboration to pool resources and share instrumentation and personnel (Figure 4).

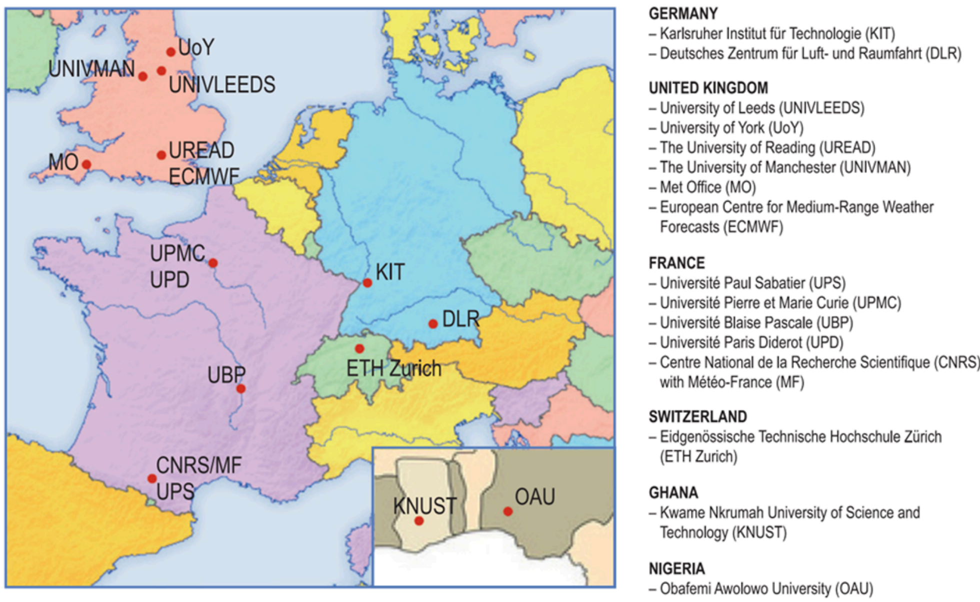

Figure 4. Overview of DACCIWA EU-funded participants. Adapted from (Knippertz et al., 2015)

Coordinating and integrating data from various instruments and platforms (satellites, aircraft, ground-based measurements) can be challenging, especially when these data are collected simultaneously during field campaigns. Inconsistent or poorly synchronized data may hinder the ability to analyze interactions between aerosols, clouds, and precipitation accurately, reducing the overall scientific value of collected information. Zuidema et al. (2016) discuss the upcoming field campaigns (at the time) aimed at studying the impact of biomass-burning aerosols on clouds and precipitation over the southeast Atlantic region, emphasizing the need for effective data integration and synchronization among different research groups and observational platforms. Ensuring data quality and validating measurements in real time during field campaigns is crucial but can be challenging due to the complex nature of atmospheric processes and the need for immediate decision-making. Inaccurate or unvalidated data can lead to uncertainties in subsequent analyzes, affecting the reliability of findings and hindering the ability to draw meaningful conclusions from field observations. Kacenelenbogen et al. (2011) evaluated the accuracy of aerosol extinction retrievals from the CALIPSO satellite lidar over southern Africa, highlighting the importance of data quality assessment and validation using multisensor and multi-platform observations.

Conducting fieldwork, especially in international settings, requires adherence to ethical standards, regulatory compliance, and respect for local communities. Obtaining the necessary permits and

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approvals can be time consuming. Delays or complications in obtaining approvals can disrupt planned field campaigns, affecting the overall success and timeliness of data collection efforts. Some articles do not directly focus on ethical and regulatory considerations; they touch upon the importance of engaging with local stakeholders, obtaining necessary permits and clearances, and adhering to local regulations when conducting research activities related to aerosol-cloud-precipitation interactions in various regions of Africa (Redemann et al., 2021). Overcoming these challenges requires a combination of technological advancements, collaborative efforts, increased funding, and effective project planning.

5. Prospects for advancing aerosol-cloud precipitation research

Despite challenges, advances in ground and space measurements offer promising opportunities to better understand the interaction of aerosol clouds and precipitation in Africa. The expansion of the ground monitoring network, promoted by international cooperation with local universities and institutions, aims to reduce observational gaps. With the deployment of advanced ground and satellite platforms such as lidar, radar, and hyperspectral sensors, it is possible to better characterize the properties of aerosols, cloud microphysics, and rainfall patterns on the continent. Coordinated field campaigns, such as the AEROCLO-sA initiative, play an essential role in providing valuable in situ measurements and validating remote sensing and model simulations. As high-performance computing resources become increasingly available, high-resolution models are developed to solve aerosol cloud-precipitation interactions on a smaller scale, thereby improving local processes and regional dynamics.

Future satellite missions, such as NASA's PACE mission, are expected to provide improved aerosol data over Africa, further supporting research efforts (Gorman et al., 2019). The airfield campaign, which offers an in situ sample of aerosol clouds and clouds, complements the data obtained from satellites and surface observations. With the accumulation of observational data, the opportunity is given to improve regional climate models on aerosol cloud effects through assimilation and machine learning techniques, thus improving their predictive capacity. The integration of various data sources, which include ground-based observations, satellite retrievals, and model simulations, through data assimilation techniques and machine learning approaches, serves to improve the understanding of aerosol-cloud-precipitation interactions while reducing uncertainties. Furthermore, collaborative research initiatives, such as EU-Africa research and innovation cooperation programs, foster knowledge exchange, capacity building, and data sharing, thus addressing challenges in studying aerosol-cloud-precipitation interactions across Africa (Cherry et al., 2018).

Efforts to strengthen capacities in this field, including the training of young African scientists in aerosol-cloud-precipitation research, are crucial to ensuring sustainable growth of local expertise and knowledge in this field. Coordination of efforts to overcome dominant challenges will lead to significant progress in the study in Africa in the coming decade. Collecting robust observation data and improving modeling approaches will provide more in-depth information about the impacts of aerosols on regional climate and rainfall patterns, ultimately influencing policies to improve resilience to climate change and pollution throughout the continent. Researchers can employ innovative solutions, such as using unmanned aerial vehicles (UAVs) for measurements in challenging terrain (Kezoudi et al., 2021), enhancing data assimilation techniques and fostering international collaborations to address these challenges and advance our understanding of aerosol-cloud-precipitation interactions.

6. Conclusions

Aerosol-cloud-precipitation interactions significantly influence precipitation patterns in Africa, with important implications for water resources, agriculture, and human livelihoods throughout the continent. However, comprehensive research in this field faces several limitations: limited ground data, logistical barriers, model inaccuracies, and limited funding. There are very few surface aerosol monitoring sites compared to other continents, which hampers the ground truth of satellite data. The lack of long-term in situ measurements also limits the analysis of aerosol trends. The operation of ground instruments and field campaigns in remote regions of Africa with extreme heat, limited infrastructure, and political instability can be a very challenging task. Frequent cloud cover and dense biomass burning smoke obscure satellite aerosol retrievals in parts of Africa. This leads to uncertainties in quantifying aerosol distributions.

Current regional climate models struggle to accurately represent key processes such as Saharan dust transport and biomass-burning smoke tendrils in Africa, as more observational constraints abound. Furthermore, conducting aerial and ground-based field studies in Africa is expensive. Limited funding for African science is a barrier to expanding aerosol-cloud-precipitation research activities. Upcoming improvements in remote sensing, field campaigns, modeling capabilities, and local training provide prospects for significant progress in understanding aerosol effects on African clouds and rainfall.

Addressing current challenges through global and regional partnerships will lead to critical new insights into climate change to guide adaptation policies that benefit African nations.

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Declarations

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