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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. Machine learning, 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.

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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 atmosphere displays a unique composition shaped by its diverse climatic regions, ecosystems, and industrial activities. This diversity includes desert dust emissions from the Sahara and a mix of biogenic and anthropogenic aerosols prevalent in industrialized areas such as South Africa. Aerosols in South Africa reflect a complex interplay between natural sources, such as vegetation, and human activities, with studies that highlight the significant impact of absorptive aerosols on atmospheric dynamics[1].

Southern Africa's changing climate has altered human-wildlife dynamics and increased aerosol loading, reflecting the region's atmospheric response to both natural and anthropogenic pressures[2]. Sub-Saharan Africa's vegetation plays a crucial role in global CO_2 fluxes, underscoring its importance in atmospheric carbon modeling. In addition, the Sahara Desert contributes large quantities of mineral dust, which significantly influences transcontinental atmospheric conditions and deposition patterns.

Geological studies have revealed unique trace metal cycling, driven by ancient microbial photosynthesis, providing evidence of early atmospheric compositions in Africa[3]. Furthermore, research on Southeast African savannas and forests underscores the importance of evapotranspiration dynamics in shaping atmospheric surface layer interactions, which are critical for understanding local climate models[4]. Investigations into nitrogen cycling during Earth's oxygenation phases further emphasize distinctive atmospheric developments in Africa's cratonic regions[5].

Africa's aerosol-cloud-precipitation research represents both challenges and opportunities that require focused research attention. The diverse terrain of Africa, ranging from dry deserts to dense rainforests, introduces complexity in accurately simulating aerosol clouds and precipitation processes[6]. This variability requires individualized modeling approaches to effectively capture regional nuances[7]. 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[8]. 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[9]. 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, policymakers, and stakeholders to address the complexities of aerosol-cloud-precipitation studies in Africa comprehensively.

In view of these considerations, this paper takes a quick review, examines past field campaigns, the current state of aerosol-cloud-precipitation studies in Africa, determines key challenges that prevent progress in this field, and explores promising prospects for future research.

2. Quick review

Aerosols play a critical role in the influence of cloud properties and precipitation, particularly in regions such as the West African Monsoon zone. Studies utilizing remote sensing tools such as MODIS (Moderate Resolution Imaging Spectroradiometer) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) have demonstrated that aerosols from biomass burning and desert dust significantly impact cloud microphysics. Depending on local atmospheric conditions, these aerosols can either suppress or enhance precipitation[10]. Seasonal trends in aerosol optical depth (AOD) have been mapped using remote sensing, revealing correlations with cloud cover and precipitation. In South Africa, higher AOD levels are associated with changes in cloud albedo and rainfall patterns, emphasizing the dynamic interactions between aerosols and regional climate[11]. ENSO (El Niño-Southern Oscillation) events further influence aerosol-cloud interactions in Southern Africa, affecting austral summer precipitation. Satellite data highlight how these climatic variations alter aerosol concentrations and cloud development[12].

Biomass burning during the dry season is a major source of aerosols in sub-Saharan Africa, significantly influencing cloud droplet size distributions and precipitation patterns. Taylor et al. [13] provided the first comprehensive set of in situ measurements of cloud microphysics from this region, offering critical insights into these aerosol-cloud interactions. Integration of satellite data from platforms such as MODIS and fire hotspot data from the Visible Infrared Imaging Suite (VIIRS) has significantly advanced the understanding of how aerosols influence precipitation events, particularly in East Africa[14]. Also, the WRF model has shown strong potential to simulate precipitation when combined with satellite-derived aerosol inputs, demonstrating the utility of such integrations for regional weather forecasting[15]. Research combining ground-based and satellite data in southern Africa has provided valuable insight into aerosol properties and types, demonstrating clear correlations with biomass burning and precipitation patterns[16]. Furthermore, satellite observations have also documented an unusually low dust aerosol optical depth (AOD) in North Africa during June 2023; this was attributed to reduced atmospheric circulation. This highlights the critical role of remote sensing in monitoring climate anomalies and understanding their effects on precipitation[17].

However, analyses of CMIP6 climate models reveal notable biases in simulating AOD and precipitation across Africa, underlining the need for enhanced models that incorporate detailed aerosol properties[18]. Dust aerosols, in particular, significantly influence precipitation dynamics in Central Africa, affecting its amount, frequency, and intensity. The integration of remote sensing data with weather models has offered a comprehensive understanding of these interactions[19]. Tools such as MODIS have also been employed to study how aerosol particles impact cloud properties and precipitation in Ethiopia, offering detailed assessments of local atmospheric processes[20]. The application of remote sensing methods has also been pivotal in analyzing significant events, such as the March 2022 dust storm over the Algerian Sahara. By incorporating HYSPLIT modeling, researchers have gained a deeper understanding of dust transport and deposition dynamics[21]. Furthermore, climatological studies project decreasing AOD levels in North Africa, accompanied by increases in precipitation, reinforcing the importance of remote sensing in long-term climate modeling[22].

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3. 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[23]. 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[24]. 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[25][26].

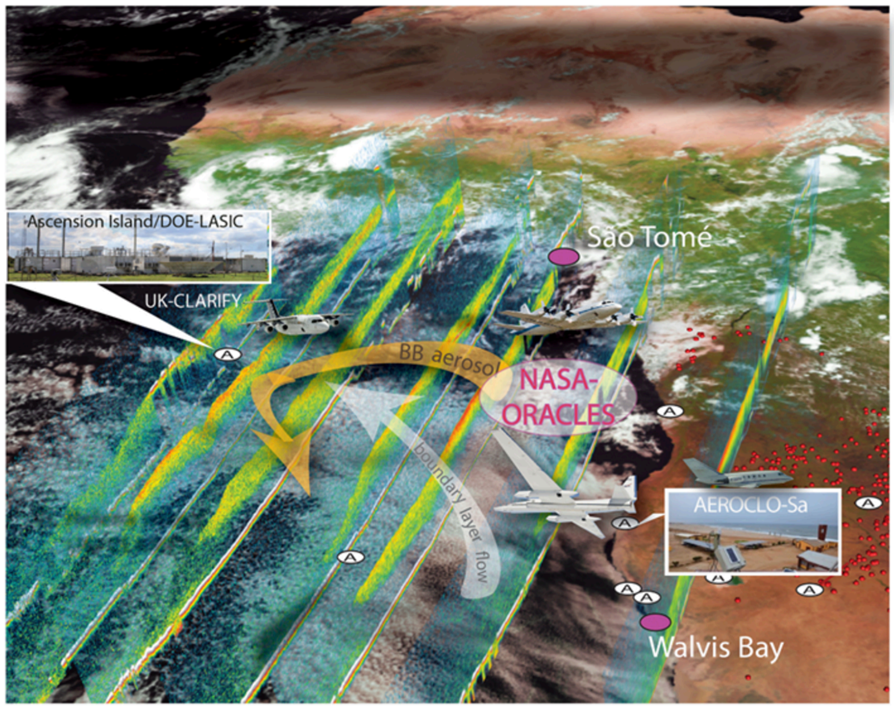

Figure 1. The 2016–2018 ORACLES field experiments, along with the international collaborative deployment sites and the CALIOP curtain data presented by Charles Trepte (NASA Langley), are based on Google Maps 2020. The oval-shaped letter "A" denotes a new or upgraded AERONET site. Adapted from[27]

Layered Atlantic Smoke Interactions with Clouds (LASIC) were also performed using an Atmospheric Radiation Measurement (ARM) mobile facility equipped with in situ and remote sensors on Ascension Island[28]. LASIC equipment includes a Lidar that can profile the vertical structure of the aerosol, with multiple radiosondes employed to monitor the diurnal cycle of smoke-cloud interaction. 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 semi-direct radiative effects of the UK Met Office model[29]. Formenti et al.[30] and Redemann et al.[27] captured the various field experiments in their context and as shown in Figure 1.

In the West African region, an international campaign called African Monsoon Multidisciplinary Analysis (AMMA) was conducted in 2006. The aim was 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[31]. AMMA and DABEX were designed to learn the optical and physical properties of biomass combustion aerosols and natural mineral dust aerosols and to

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determine their interaction by performing high-quality remote sensing and in-house measurements.

Ten years later, another major campaign took place named Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (Figure 2). Knippertz et al.[32] explained the motivation for the campaign as surrounding the estimated population growth in southwestern Africa by 2030 and its socioeconomic importance. Three main areas were identified: (a) human health on the urban scale, (b) ecosystem health, biodiversity, and agricultural productivity on the regional scale, and (c) regional climate. The campaign covered aerosol science, climate science, air pollution, cloud microphysics, and so on.

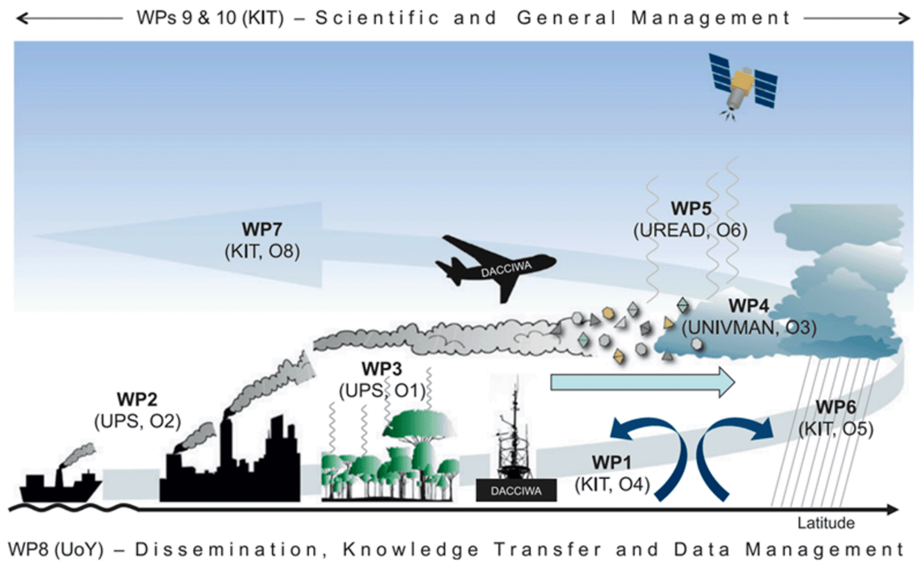

Figure 2. Schematic overview of the DACCIWA Work Package (WP). The organization leading each WP is listed in brackets (see abbreviations in **Figure 4**). Adapted from[32]

In central 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 the African tropics on atmospheric chemistry[33]. To be able to address air pollution from the southeast and south of Asia to the Intertropical Convergence Zone (ITCZ)[34], Gatebe et al.[35] 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[36].

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 observed[37]. Using six remote sensing platforms (satellite and ground-based), a model simulation of North African dust aerosols was carried out from five global models[38]. The study underscores the challenges in simulating optical and physical processes.

Concerning aerosol and precipitation, Solmon et al.[39] explored the climatic consequences of both short-wave and long-wave 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 were 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.[40] demonstrated the presence of dust

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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 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[41].

4. 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, CALIPSO, MISR (Multiangle Imaging Spectroradiometer), CloudSat (Cloud Satellite), etc., provide 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[42][43][44][45][46]. 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[47][48][49][50].

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[51][52][53][54]. 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[55][56]. 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[57][58][59].

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[60][61][62]. 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[63][64].

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[65][66][67]. Cloud-Resolving Models (CRM) simulate cloud processes at a higher spatial resolution, providing detailed insights into cloud dynamics, microphysics, and precipitation development[68][69][70]. 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[71][72]. 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[73][74].

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[75][24][76].

5. Key Challenges for Aerosol-Cloud-Precipitation Studies

Despite 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:

5.1. 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[77][78].

The limited vertical profile of aerosols, clouds, and precipitation prevents a comprehensive understanding of the three-dimensional atmospheric processes. Vertical information is crucial for the accurate modeling of cloud characteristics and precipitation formation[79][80]. 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.[81]. Mulcahy et al.[82] 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 the understanding of aerosol-cloud interactions, for example in AEROCLO-sA[30].

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.[83] 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.[32] 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.[84] 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[32].

5.2. 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[35]. 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

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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.[27] 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.[85] 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).

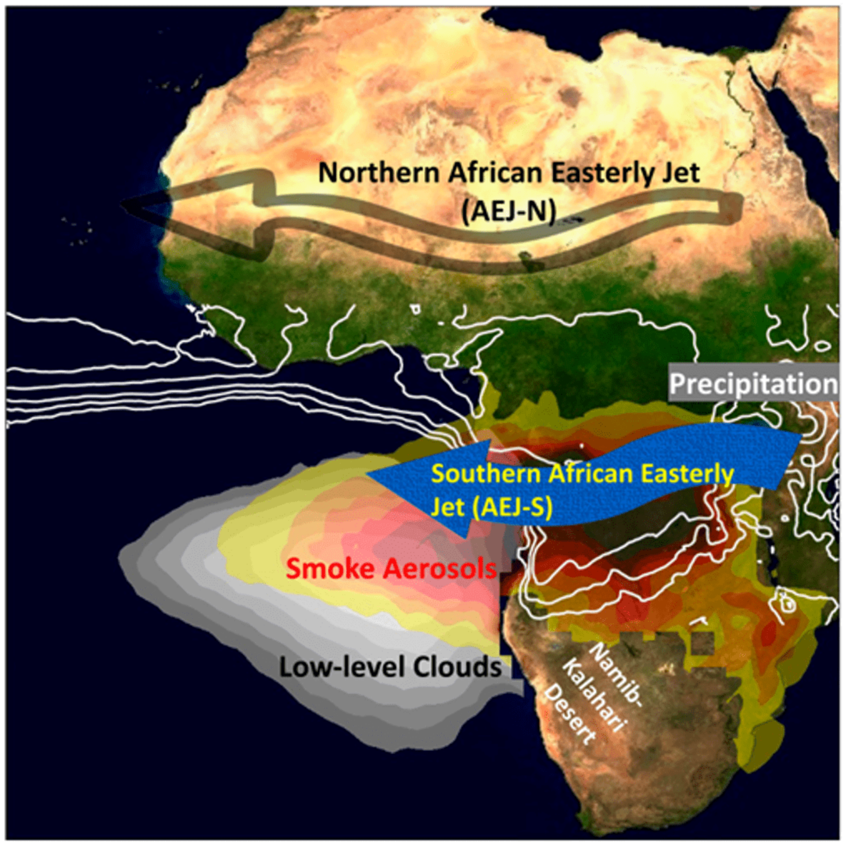

Figure 3. Representation of the southern African easterly jet (AEJ-S) as the central dynamical feature over central Africa and the southeast Atlantic Ocean. In addition, the image shows the northern African easterly jet (AEJ-N), which is the Northern Hemisphere counterpart of AEJ-S. The image also shows 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 a description of TRMM and MODIS datasets. Adapted from[85]

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 issues, reducing the reliability of observations during field campaigns[31]. 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 a narrower scope of observations, which limits the overall comprehensiveness of the collected data.

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The DACCIWA and ORACLES field campaigns, for example, could not have been possible without international collaboration to pool resources and share instrumentation and personnel (Figure 4).

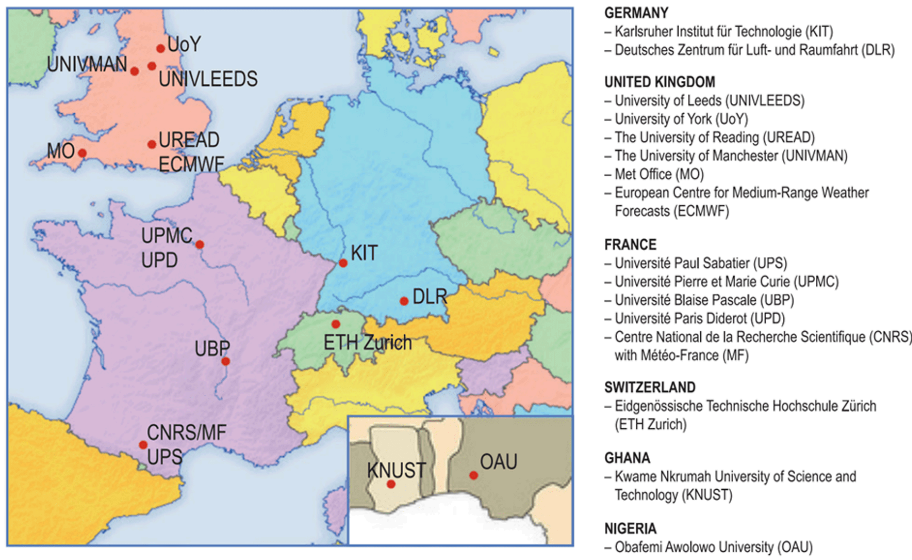

Figure 4. Overview of DACCIWA EU-funded participants. Adapted from[32]

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 the collected information[76]. 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 analyses, affecting the reliability of findings and hindering the ability to draw meaningful conclusions from field observations. Kacenelenbogen et al.[86] 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 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[27]. Overcoming these challenges requires a combination of technological advancements, collaborative efforts, increased funding, and effective project planning.

6. Prospects for advancing aerosol-cloud precipitation research

Despite the challenges, advances in ground and space measurements offer promising opportunities to better understand the interaction of aerosol clouds and precipitation in Africa. As high-performance computing resources become increasingly available, high-resolution models are being 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[9]. CALIPSO's lidar technology facilitates vertical profiling of aerosols, offering critical insights into their height and optical properties across Africa. This data is vital for modeling aerosol impacts on

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cloud formation and precipitation patterns[87]. The PACE mission improves aerosol retrieval accuracy, including fine-mode aerosols, which are key to understanding their role as cloud condensation nuclei[88].

By measuring cloud optical depth and droplet sizes, satellites provide valuable assessments of aerosol effects on cloud albedo and precipitation efficiency. The combination of CALIPSO's instruments with CloudSat data offers complementary perspectives for analyzing these interactions[10]. Additionally, satellites track interannual variations in aerosol concentrations and their influence on seasonal precipitation, particularly in regions affected by Saharan dust and biomass burning across Sub-Saharan Africa[89]. Both CALIPSO and PACE contribute to refining climate models by validating aerosol-cloud-precipitation interactions, offering critical feedback to reduce uncertainties in these processes[90]. Furthermore, PACE's Ocean color instrument tracks aerosol transport over oceanic regions adjacent to Africa, enhancing understanding of aerosol impacts on marine cloud systems and their influence on regional rainfall patterns[91].

The integration of machine learning (ML) with data analysis is transforming the understanding of aerosol-cloud-precipitation interactions over Africa. By harnessing the predictive power of advanced algorithms and leveraging the growing availability of satellite- and ground-based datasets, researchers have significantly improved model predictions. For example, ensemble learning methods were applied in South Africa to combine aerosol optical depth (AOD) and precipitation data, with ML algorithms such as Random Forests modeling PM_{10} concentrations. These techniques effectively addressed data sparsity and incorporated spatiotemporal variability, leading to improved predictions[92]. ML and deep learning models further advanced AOD forecasting by integrating diverse datasets, including meteorological and land use information, to predict aerosol behavior under various climatic conditions[93].

In West Africa, deep learning models applied to rainfall data revealed considerable potential to improve rainfall prediction accuracy by incorporating aerosol data as a key input[94]. To improve spatial resolution, a method was devised to downscale daily satellite-based precipitation estimates using ML, integrating the optical and microphysical properties of the MODIS cloud. This approach refined the resolution from 10 km to 1 km, enhancing forecasting capabilities[95]. ML has also been used to disentangle the thermodynamic effects of aerosols on cloud formation and precipitation. Long-term satellite datasets served as essential input, demonstrating the potential of ML to advance climate modeling[96].

In northern Africa, researchers developed a cloud-class climatology using ML, enabling detailed characterization of cloud properties. This dataset, which included features such as cloud height and precipitation, significantly improved the granularity of atmospheric models[97]. The application of XGBoost (Extreme Gradient Boosting) to model aerosol dynamics over the region provided valuable insights into spatio-temporal variability, drawing on extensive reanalysis data and satellite observations[98]. Lastly, advanced ML models reconstructed North African dust plumes using MODIS satellite data, offering a clearer view of aerosol distributions beneath clouds[99].

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[100]. Efforts to strengthen capacities in this field, including the training of young African scientists in aerosol-cloud-precipitation research, are crucial to ensuring the 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 observational 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[101], enhancing data assimilation techniques, and fostering international collaborations to address these challenges and advance our understanding of aerosol-cloud-precipitation interactions.

7. 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.

Statements and Declarations

Data Availability

Data supporting the findings of this review are available within the cited references. Further inquiries can be directed to the corresponding author upon reasonable request.

Author Contributions

Conceptualization: J.A.A.; Literature Search and Analysis: J.A.A.; Writing – Original Draft: J.A.A.; Writing – Review & Editing: J.A.A., O.B.W.

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