KADI

Report on optimum integration of science into the envisaged research infrastructure

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Executive Summary

The KADI project (Knowledge and Climate Services from an African Observation and Data Research Infrastructure) is a Horizon Europe funded project building the foundations for a research infrastructure to enhance climate research and observation capabilities across Africa, addressing critical environmental and climate change challenges. Since every research infrastructure needs to ensure the scientific usage of its data, this document provides an inventory of research projects, institutions and data collection infrastructure related to climate studies over African sub-Saharan regions. It highlights the implication of the science on the fight against the climate change and networking approaches throughout the trans- and interdisciplinary projects. The deliverable focuses on existing infrastructure on (1) Data collection such as meteorological data from national meteorological services, regional data providing networks and environmental measurement and observations. All these contribute to climate prediction and environment monitoring system. (2) The atmospheric composition, in GHG and SLCF, which have been studied through different research projects all over Africa with a focus on atmospheric pollutants and health. (3) Biodiversity programmes aimed at protecting the endangered species (plants, animals etc.) over indigenous areas. (4) Marine sciences linking ocean to climate change impact studies, the sea level raise and coastal erosion threaten for coastal cities. (5) Earth system modelling building decision support tools based on climate models, climate services, (6) Carbon exchange to benefit from GHG emission reduction policies, to support the (7) Resilience and adaptation projects studying climate extremes, proposes innovative approaches. Based on the mapping of these broad scientific activities, further conclusions will be drawn, and recommendations will be given.

This work will support the co-conceptualisation of a Pan-African research infrastructure on climate services. To set up this infrastructure, it is essential to integrate existing programs and facilities as much as possible. It analyses key research centres and programs such as the LAMTO Geophysical Station, OREN Observatory in Côte d'Ivoire, SODEXAM, the INDAAF Network across the continent, and the Mt Kenya and Cape Point Global Atmospheric Watch Stations and their current science components. Data storage and computing services are also crucial, with the Côte d'Ivoire National Computing Centre (CNCCI) and the South African Environmental Observation Network (SAEON) playing significant roles in enhancing data processing capabilities for scientists. Training systems such as WASCAL-CCBAD, WASCAL, SASSCAL, and ACDI support capacity building for running and using research infrastructure focusing on climate change, biodiversity, and sustainable agriculture. The DACCIWA project is highlighted for its research on aerosol chemistry and cloud interactions in West Africa, but also for providing critical data on air pollution and health impacts. This report underscores the KADI project's commitment to integrating diverse components into a cohesive research infrastructure. By leveraging existing infrastructures, fostering international partnerships, and advancing training systems, KADI aims to improve climate resilience and sustainable development across Africa, aligning with global climate objectives like the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs).

Inventory of observation data collection stations and data gathering projects and training infrastructure, atmospheric composition, biodiversity, marine science: coastal area management, Earth System Modelling (ESM), carbon exchange, adaptation/resilience to climate extremes.

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Acronyms

ACDI: African Climate and Development Initiative

ACE: African Centres of Excellence

ACMAD: African Centre of Meteorological Applications for Development

ACTS: African Centre for Technology Studies

AMMA: African Monsoon Multidisciplinary Analysis

AMMA-CATCH: AMMA Hydrometeorological observatory for West Africa

AMCC+ or GCCA+: Alliance Mondiale pour le Changement Climatique Plus

AEMET: State Meteorological Agency, Spain

AFRIMET: Conference of Directors of the West African National Meteorological and Hydrological Services

AGRHYMET: Regional Centre of the Inter-states permanent Comity against drought in the Sahel

ANADER : Agence Nationale d'Appui au Développement Rural

BSC: Barcelona Supercomputing Centre

BMBF: German Ministry of Education and Research

CCKE: Coordination, Capacity Development and Knowledge Exchange Unit

CEA-CCBAD: African Centre of Excellence on Climate Change, Biodiversity and Sustainable Agriculture

CNCCI : Centre National de Calcul de Côte d'Ivoire

CNRS : Centre National de Recherche Scientifique

CTBT: Comprehensive Nuclear Test Ban Treaty

EACSAP: Eastern Africa Climate Smart Agriculture Platform

Empa: Swiss Federal Laboratories for Material Science and Technology

FCFA: Future Climate for Africa

FSRP: Food System Resilience Program

GFCS: Global Framework for Climate Services

INDAAF: International Network to study Deposition and Atmospheric composition in Africa

INSU : Institut National des Sciences de l'Univers

IRD : Institut de Recherche pour le Développement

KADI: Knowledge and climate services from an African observation and Data research Infrastructure

LAERO : Laboratoire d'Aérologie

LISA : Laboratoire Interuniversitaire des Systèmes Atmosphériques

MeteoSwiss: Federal Office of Meteorology and Climatology MeteoSwiss, Federal Department of Home Affairs (FDHA)

MRP-CCMS: Master Research Programme on Climate Change & Marine Sciences

NESA: New South Wales Education Standards Authority

NMHS: National Meteorological and Hydrological Services

PRA/GRN(CC) : Programme Régional d'Appui – Gestion des Ressources Naturelles et Changement Climatique

OREN : Observatoire de Recherche En Environnement De Nambékaha

OSU-EFLUVE : Observatoire des Sciences de l'Univers – Enveloppes Fluides de la Ville à l'Exobiologie

PASMU: Air Pollution and Health in Urban Environments in Côte d'Ivoire

RNER-CC : Réseau National d'Enseignement et de Recherche - Centre de Calcul

SAEON: South African Environmental Observation Network

SASSCAL: Southern African Science Service Centre for Climate Change and Adaptive Land Management

SAWS: South African Weather Service

SDG : Sustainable Development Goals

SODEXAM : Société d'Exploitation et Développement Aéroportuaire, Aéronautique et Météorologique

STEM: Science, Technology, Engineering and Mathematics

WACA ResIP-CCA: West Africa Coastal Areas Resilience Investment Project for Climate Change Adaptation

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Introduction

This inventory compiles elements of current research infrastructures across the African Continent that are operating in the provision of data or facilities to support scientists and projects in science-based atmospheric and climate services across the African continent. This is a prerequisite for making suggestions on enhanced integration of science into the envisaged research infrastructure.

The African Continent has an increasing number of observational networks, field stations and computational centres serving scientific users, which are dedicated to several fields of environmental science. These currently existing elements will play a major role in the provision of climate services to address environmental change and the fight against climate change. In parallel with these elements, a range of research programmes have been set up. These programmes are helping to strengthen North-South and South-South collaboration and to enlarge the measurements and data collection networks. However, there are still huge challenges to be met in terms of training, research and achieving the global objectives set out in the various agreements, such as the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs).

With the contribution of international institutions, a research network on climate, air quality and the environment is now being set up. The KADI (Knowledge and climate services from an African observation and Data research Infrastructure) aims to enhance research and climate observation capacities across the African continent. The primary objective is to optimally integrate scientific advancements into the envisioned research infrastructure to better understand and address climate challenges specific to Africa.

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Part I: Inventory of Research Infrastructures and Programmes in Africa that contribute to the delivery of Climate Services in Africa

1 Inventory of Observation Data, Collection Stations and Data Gathering Projects and Training Systems

A range of projects and research infrastructures have been developed across the continent. In this section we highlight some of the most significant ones that we expect to form the nucleus of the continental scale research infrastructure (RI) to support atmospheric and climate services in Africa. This assessment is about the observatories and projects. In this overview we highlight the existing infrastructure by region and type of infrastructure.

1.1 Atmospheric observations to support human and environmental health

1.1.1 Continental and regional

1.1.1.1 African Centre of Meteorological Applications for Development (ACMAD)

Established in 1987, the African Centre of Meteorological Applications for Development (ACMAD) focuses on enhancing meteorological services across Africa. It fosters networking by collaborating with international and regional organizations like the World Meteorological Organization (WMO) and the African Union. ACMAD is deeply involved in scientific research on climate variability, weather prediction, and early warning systems, conducting studies on climate change impacts. The centre supports mobility through training programs, workshops, and exchange visits, enabling African scientists to collaborate globally. Its achievements include enhancing the capacity of National Meteorological and Hydrological Services (NMHSs), developing early warning systems, and improving climate models for Africa. ACMAD significantly contributes to research

infrastructure in Africa by improving meteorological observations, developing early warning systems, and promoting international collaboration for sustainable development and climate resilience. Challenges faced include limited financial resources and the need for ongoing capacity building. It would benefit from improved scientific education at African Universities and enhanced scientific cooperation with research centres and programs.

1.1.1.2 Regional collaboration centres (RCC) West and Central Africa (WAC)

RCC WAC Africa was established in 2013 by UN Climate Change and Banque Ouest Africaine de Développement to drive national climate action through capacity-building, technical assistance and strategic networking. As objectives they spread the benefits of the Clean Development Mechanism (CDM) spurring investments into sustainable development by rewarding projects that reduce greenhouse gas emissions. Since the adoption of the Paris Agreement in December 2015, the RCCs have the broad task of supporting the implementation of Nationally Determined Contributions (NDCs), Article 6, Adaptation, Climate Finance, Stakeholder engagement and more. Since the Paris Agreement calls for 'best available science', RCC WAC Africa builds on enhanced scientific competences in Africa.

1.1.1.3 International Network to study Deposition and Atmospheric chemistry in Africa (INDAAF)

INDAAF (https://indaaf.obs-mip.fr/) is a network dedicated to the long-term monitoring of the atmospheric composition and deposition fluxes in Africa. INDAAF results from the merging of the IDAF (IGAC-DEBITS Africa) observation service (labelled INSU/CNRS since 1995) and the "Sahelian Dust Transect" network deployed in 2006 in the framework of the African Monsoon Multidisciplinary Analysis (AMMA) international program.

INDAAF is a national observation service (Service National d'Observation, SNO) of the Institut National des Sciences de l'Univers (INSU) of the Centre National de Recherche Scientifique (CNRS), and supported by the Institut de Recherche pour le Développement (IRD). The network is also supported by the Observatoire Midi-Pyrénées (OMP) and the Observatoire des Sciences de l'Univers – Enveloppes Fluides de la Ville à l'Exobiologie (OSU-EFLUVE). It is piloted by the Laboratoire d'Aérologie (LAERO, Toulouse, France) and the Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA, Créteil, France) with the contribution of the Institut d'Ecologie et des Sciences de l'Environnement de Paris (iEES-Paris, Bondy, France). The INDAAF Network occurs primarily in West and Central Africa, however observation in South Africa is included and have now been extended into the EFTEON Network in South Africa.

The project promotes mobility by facilitating international collaborations and researcher exchanges. While it has provided essential data on atmospheric conditions, INDAAF faces challenges, particularly in securing continuous funding. The network contributes to the research infrastructure by supporting climate and environmental monitoring, enhancing data sharing, and fostering collaborative research efforts.

Figure 1 below shows the INDAAF network and shows various monitoring sites across Africa. The map highlights eight primary INDAAF sites and two partner sites, marked by numbers on the map and accompanied by images of the equipment at each location.

These sites are distributed across different ecological zones. Banizoumbou, Niger (Site 1) includes two sub-sites, one focused on chemistry and the other on dust, both monitoring atmospheric conditions in a semi-arid environment. Cinzana, Mali (Site 2) is located in a dry savanna region, equipped to monitor various atmospheric and environmental parameters. Katibougou, Mali (Site 3), similar to Cinzana, is also situated in a dry savanna region, focusing on atmospheric deposition studies. M'Bour, Senegal (Site 4) is another site in a dry savanna, collecting data related to regional atmospheric composition and deposition. Lamto, Côte d'Ivoire (Site 5) is in a mosaic forest/savanna region, crucial for studying the impact of atmospheric deposition in a mixed landscape. Djougou, Benin (Site 6) is situated in a wet savanna environment, focusing on the effects of atmospheric conditions in a more humid climate. Zoétélé, Cameroon (Site 7) is in a forested area, monitoring atmospheric composition and deposition in a tropical rainforest setting. Bomassa, Congo (Site 8) is in the Congo Basin, one of the largest tropical rainforests, focusing on monitoring atmospheric changes and their impact on this critical ecosystem.

The partner sites include Welgegund in South Africa (Site 9), located in an agricultural region, and Medenine in Tunisia (Site 10), situated in a desert environment. These sites contribute to comparative studies in different climatic conditions.

The map also includes a color-coded legend that indicates various types of land cover across Africa, such as evergreen forests, mosaic forest/savanna, wet savanna, dry savanna, desert and dunes, and agricultural areas. This network of monitoring stations across diverse ecological zones of Africa allows for comprehensive research on atmospheric deposition and its impact on different environments.

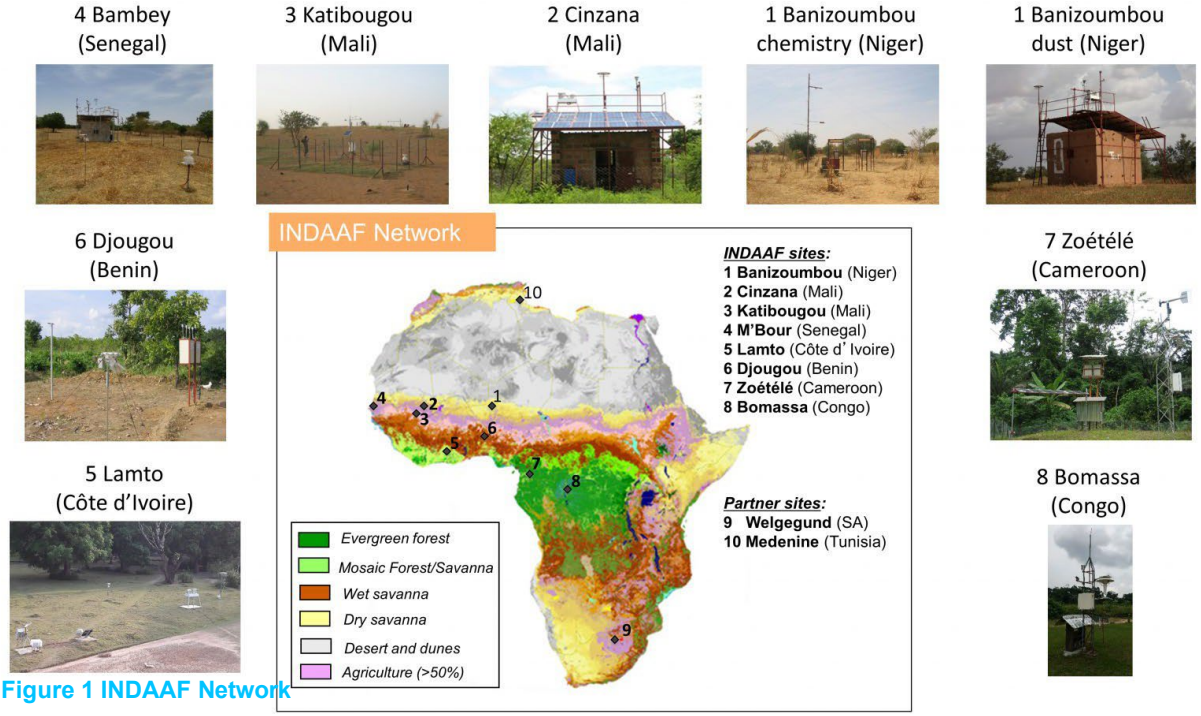

Figure 1 INDAAF Network

1.1.1.4 SDS-WAS (Sand and Dust Storm Warning Advisory and Assessment System)

Since 2010 Spain hosts the Northern Africa-Middle East-Europe Regional Node of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS NA-ME-E Regional Centre), jointly managed by AEMET and the Barcelona Supercomputing Centre (BSC). SDS-WAS is a program of the WMO that aims to enhance countries' capacity to provide timely and high-quality information related to atmospheric dust and sandstorm predictions. It also focuses on observations targeted at end-users and increasing knowledge about this phenomenon. AEMET-BSC are responsible for the development of modelling products and the Regional Centre's website (https://dust.aemet.es/), which offers atmospheric dust predictions (surface dust concentration and dust optical thickness at 550 nm) generated by 12 modelling systems, as well as the multi-model median. They are also involved in the process of evaluating and assimilating the available products with surface observations.

1.1.1.5 Climate Risk and Early Warning Systems (CREWS)

This WMO initiative funded by the World Bank aims at - inter alia - implementing a sand and dust storm warning system in the countries of Niger, Chad, and Mali. In this project, AEMET, in collaboration with the BSC (Barcelona Supercomputing Centre), provides the necessary human and technical resources for the development of a sand and dust storm warning system as well as for the installation of particle measurement equipment and hand-held sun photometers. More information available at https://crews-initiative.org/landing/projects/.

1.1.2 Western Africa

1.1.2.1 Société D'exploitation, du Développement Aéroportuaire, Aéronautique et Météorologique de Cote D'Ivoire (SODEXAM)

SODEXAM is responsible for national meteorology, the operation and development of airports, air navigation and aeronautical and airport medicine. This national meteorological service is useful in Côte d'Ivoire: "It takes part in inter-ministerial disaster management committees when floods or heavy rainfall occur. In fact, it is based on the information provided by SODEXAM that the government can adjust its measures". SODEXAM supports several data acquisition projects and research programmes. It is involved in designing climate services on a national scale. Despite challenges such as resource limitations, SODEXAM's efforts in providing meteorological data are pivotal for research infrastructure, particularly in disaster management. SODEXAM will provide important support in the co-design of the climate service.

1.1.2.2 AFRIMET

Since 2007, Spain, through AEMET and in collaboration with the WMO, has been running the AFRIMET program within the framework of the Meteorological Cooperation Program for West Africa and its managing

body, the Conference of Directors of West African National Meteorological and Hydrological Services (AFRIMET, http://afrimet.aemet.es/afrimet_old/esp/whoweare_esp.html). In its meetings, AFRIMET members establish common projects and priorities, specifically targeting parameters such as meteorology (enhancing weather forecasting and monitoring), atmospheric composition (monitoring air quality and pollutants), and climate services (providing climate information for decision-making). The experience gained from decades of cooperation in Ibero-America has been applied to Africa, yielding tangible results very quickly. For example, the implementation of advanced weather forecasting techniques and training programs initially developed in Ibero-America has significantly improved the accuracy and reliability of weather predictions in West Africa. The AFRIMET program is structured around strategic lines and various projects, strongly aligned with the priority areas of the Global Framework for Climate Services (GFCS), among which the following stand out:

HEALTHMET

Institutional strengthening and creation of links with health authorities: This project promotes the training of meteorological services in the study and prediction of dust and sandstorms with the aim of creating an alert system that, in coordination with health authorities, allows for the implementation of health measures to protect the population. This project actively involves the Northern Africa-Middle East-Europe Regional Node of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS NA-ME-E Regional Centre), jointly managed by AEMET and the Barcelona Supercomputing Centre (BSC).

METAGRI

Alignment with food security policies: The first AFRIMET project, continued with METAGRI OPERATIONAL, encourages independent farmers to generate their own climate information and make decisions based on it, resulting in crop yield increases of around 30%.

MARINEMET

Pioneering project for the improvement of maritime forecasting in the waters of West Africa, enabling the NMHS of Mauritania, Senegal, Cape Verde, and Gambia to provide new services to their users through the observation of automatic stations, numerical modelling, training courses in maritime meteorology, and the use of web tools. Future extension of the project to countries in the Gulf of Guinea. More information available at http://afrimet.aemet.es/afrimet_old/marinemet/index.html.

1.1.2.3 AGRHYMET

The AGRHYMET Regional Centre is an agency of the Permanent Inter-State Committee for Drought Control in the Sahel (CILSS), which brings together thirteen west African countries (Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Guinea, Guinea-Bissau, Mali, Mauritania, Niger, Senegal, Chad and Togo: Benin, Burkina Faso, Cape Verde, Chad, Côte d'Ivoire, Gambia, Guinea, Guinea-Bissau, Mali, Mauritania, Niger, Senegal and Togo). AGRYHET is specialized in the sciences and techniques applicable to the sectors of agricultural development, rural planning and natural resource management to contribute to food security and

increased agricultural production, and to help improve the management of the region's natural resources by providing information and training to development players and their partners in the fields of agro-ecology (agro-climatology, hydrology, plant protection, etc.).

AGRYMET is a centre of excellence in the sciences and techniques applicable to agricultural development, rural development and natural resource management. It carries out agrometeorological and hydrological monitoring at regional level, maintains meteorological instruments and strengthens inter-state cooperation through the exchange of methodology and technology. It produces agricultural and crop monitoring statistics and manages regional databases. It is a reference centre for executive training, and for the management and dissemination of information on natural resource monitoring in the Sahel, including documentation on agrometeorology, plant protection, environmental monitoring, desertification, natural resource management.

1.1.2.4 The AMMA-CATCH observatory

The AMMA-CATCH observatory documents the climatic and hydrological variability associated with the West African Monsoon in order to understand the interactions between the water cycle, the dynamics of the vegetation and the variability of the climate at intra-seasonal to multi-annual scales. It is composed of gathered data from densely instrumented mesoscale sites that provide continuous information of more than 30 years on the water cycle (precipitation, runoff, piezometry of aquifers, river flow rates, pond limnimetry, soil humidity, evapotranspiration, water quality, etc.),, the local meteorology (air pressure, temperature, humidity, wind, radiation balance) and micrometeorology (sensible and latent heat, carbon flux) and the seasonal dynamics of vegetation (LAI, fAPAR, biomass, etc.), land use and surface conditions. The locations of the sites are stratified in latitude in order to sample the eco-climatic gradient characteristic of the region: the Mali Gourma (34000 km^2), the region of Niamey (the Niamey square degree, Niger; 20000 km^{2e}) and the upper valley of the Ouémé River in Benin (14000 km^2).The southernmost site of the observatory lies in the centre of Benin and coincides with the upper watershed of the Ouémé River (14,000 km^2), which flows southward to the Atlantic Ocean. It is located in the Sudanian climate regime, with an average rainfall of about 1200 mm yr^{-1} falling in a single rainy season extending from April to October and with a mean annual temperature of ~25°C. Mean potential evapotranspiration is ~1500 mm yr^{-1}.The Sahelian Site (Niger) The ~20,000-km^2 central Sahelian mesosite (roughly 1.6–3° E, 13–14° N) is located in the south-west of the Republic of Niger. It includes the capital city of Niamey (~1.3 million inhabitants in 2017), close to the Niger River. The area has a typical semiarid tropical climate, with a long dry season (October–May) and a single wet season, from June to September and peaking in August. The mean annual temperature over 1950 to 2010 at Niamey Airport was 29.2°C, with an increase of approximately 1°C during the six-decade period. Daily maximum temperatures are between 40 to 45°C from mid-March to mid-June. Mean potential evapotranspiration is ~2500 mm yr^{-1}. The mean post-drought annual rainfall (1990–2007) is 520 mm in Niamey, still below the long-term (1905–2003) average of 560 mm yr^{-1}. The observatory is connected to several international networks or research infrastructures: GEWEX (Global Energy and Water cycle Experiment); FLUXNET (Integrating Worldwide CO2, Water and Energy Flux Measurements) ; ISMN

(International Soil Moisture Network) ; e-LTER (European Long-Term Ecosystem and socio-ecological Research Infrastructure)).

AMMA-CATCH is an excellent example of how science is supported by and integrated into long-term research infrastructure.

1.1.2.5 WASCAL measurement sites

WASCAL is supporting the research by co-developing a regional observation network to ultimately contribute to filling the climate data gap in West Africa. In December 2015, an international open public tender was launched for the procurement, supply and delivery of 50 Automatic Weather Station (AWS) with software, according to WMO, including training and after-sales support over 5 years. The project was entirely financed by KfW (German Development Bank) and final award to NESA (New South Wales Education Standards Authority) was issued in March 2016.

The solution proposed by Nesa and chosen by the Customer complies to all the industrial standard for the meteorological monitoring according to WMO. Factory training for technicians and administrators, supply of spare parts and remote after sales assistance are included.

This project of WASCAL has the aim to allow the collection of reliable data to allow measures according to WMO across the WASCAL members countries namely Benin, Burkina Faso, Côte d'Ivoire, The Gambia, Ghana, Mali, Niger, Nigeria, Senegal and Togo. WASCAL's personnel, highly trained have installed 50 AWS in 2017 and 2018 with the cooperation of beneficiaries' technicians and officers. It supports the scientific evaluation of ongoing climate change in Africa.

1.1.2.6 The Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA)

This programme mainly covered the coastal countries of Côte d'Ivoire, Ghana, Togo, Benin and Nigeria. The project used three research aircraft to monitor air pollution from ports and major coastal cities (Abidjan, Accra, Lomé, Cotonou, Lagos) inland. Major resources were also deployed on the ground: for two months, three heavily instrumented sites in Ghana, Benin and Nigeria continuously measured clouds and many of the physical phenomena that contribute to their formation or dissipation. In addition, meteorological balloons were released several times a day across the region, and ad hoc measurements of urban air pollution and health surveys were carried out in Abidjan (Côte d'Ivoire) and Cotonou (Benin) [1].

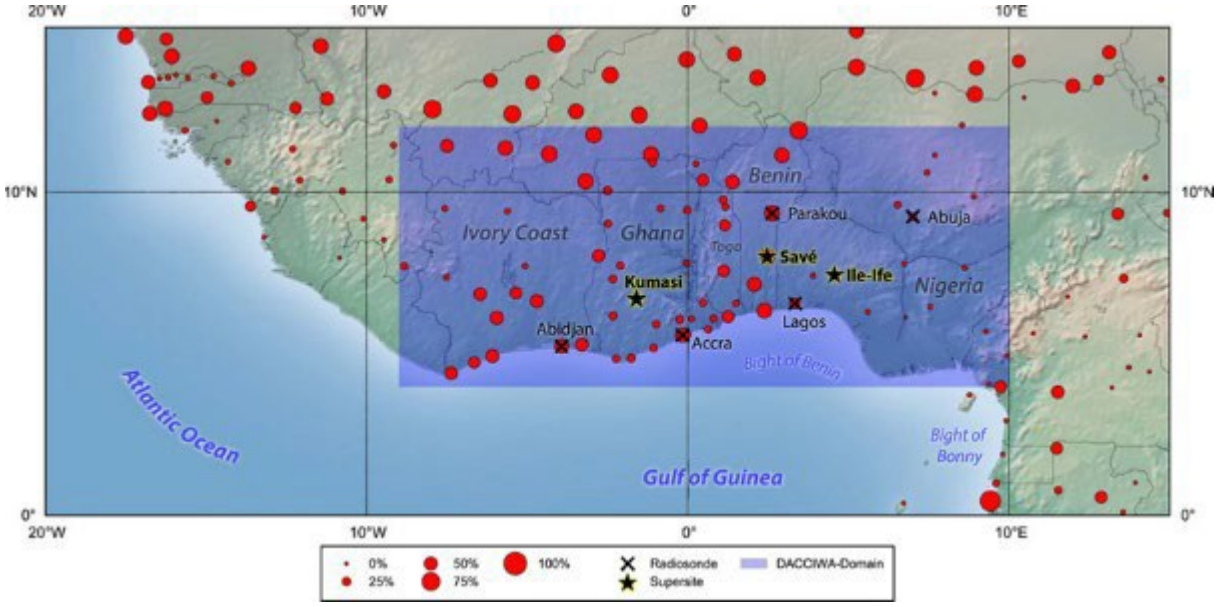

Figure 2 Geographical overview of the DACCIWA study area

Figure 2 shows the geographical overview of the DACCIWA study area in southern West Africa highlighted in blue. Black stars mark the three DACCIWA supersites at Kumasi, Ghana; Savé, Benin; and Ile-Ife, Nigeria. Radiosondes will be launched regularly from the supersites and the stations indicated by black crosses, some of which will get reactivated for the DACCIWA field campaign. Red dots mark synoptic weather stations (size proportional to available number of reports in the WMO Global Telecommunication System from 1998–2012). In addition, there will be longer-term measurements of air pollution in Abidjan and Cotonou, and a rainfall meso-network around Kumasi.

Massive economic and population growth and urbanisation are expected to lead to a tripling of anthropogenic emissions in southern West Africa (SWA) between 2000 and 2030, the impacts of which on human health, ecosystems, food security and the regional climate are largely unknown. An assessment of these impacts is complicated by:

- a superposition with effects of global climate change,
- the strong dependence of SWA on the sensitive West African monsoon,
- incomplete scientific understanding of interactions between emissions, clouds, radiation, precipitation and regional circulations
- by a lack of observations to advance our understanding and improve predictions.

DACCIWA will quantify the influence of anthropogenic and natural emissions on the atmospheric composition over Southwest Africa and assess their impact on human and ecosystem health and agricultural productivity. It will quantify the coupling between aerosols and clouds and identify controls on the formation and

persistence of low-level clouds. Further it will identify meteorological controls on precipitation, focusing the transition from stratus to convective clouds and the forcing from weather systems. DACCIWA will quantify the two-way cloud, and aerosol impacts on the radiation and energy budgets from the cloud scale to the scale of the West African monsoon circulation. State-of- the-art meteorological, chemistry and air-quality models, satellite retrievals of clouds, precipitation, aerosols and radiation will be assessed in close collaboration with operational centres and research findings will be communicated to policymakers, scientists, operational centres, students, and general public using a graded communication strategy.

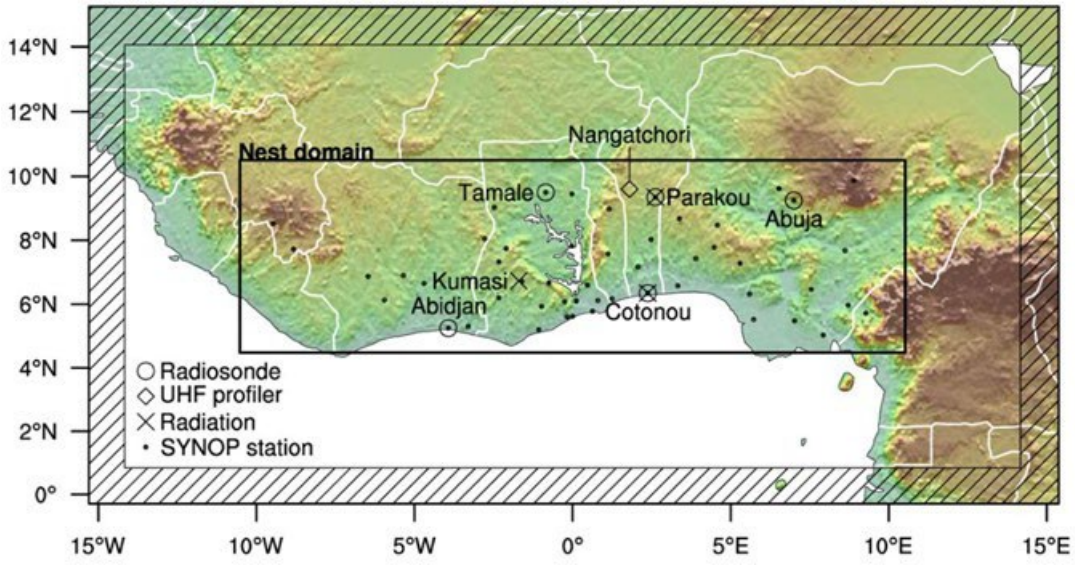

Figure 3.The DACCIWA field campaign from June to July 2015 [2]

1.1.2.7 APIMAMA (Air Pollution Mitigation Actions for Megacities in Africa)

APIMAMA, launched in 2022, aims to reduce the health and social risks associated with air pollution in African cities, using Abidjan, Côte d'Ivoire, as a laboratory city. The project brings together various institutions, including Université de Toulouse and CNRS, to conduct interdisciplinary research involving physicochemists, epidemiologists, and sociologists. APIMAMA's extensive fieldwork and data collection facilitate significant mobility for researchers. The project has developed a comprehensive methodology to assess and mitigate air pollution, though challenges include high pollution levels and limited resources. It has contributed to building research infrastructure by providing high-quality air quality data and supporting public awareness campaigns.

1.1.2.8 1.2.1.2.8 The Air Pollution and Health in Urban Environments in Côte d'Ivoire (PASMU)

The project has helped to extend the studies already carried out, to explore new avenues of study and thus to improve understanding of air pollution in African cities and its impact on people's health [3]. Specifically, in Côte d'Ivoire, the study focused on air pollution in relation to population health in Abidjan and Korhogo. The project was based on a network of medium-term (particulate matter, gas and rain) and short-term (particulate matter) observations and on health and epidemiological surveys. Unlike previous studies, it provided access to information that enabled the air quality of the cities studied to be determined. The observations came from aerosol collectors, developed as part of the INDAAF programme, which had been deployed at 3 sites in Abidjan and 2 in Korhogo.

In the PASMU project, extensive (medium-term) measurements were carried out using INDAAF-type aerosol collectors. One of the results was the mapping of particulate pollution in the cities of Abidjan and Korhogo. These collectors (cabinets) have also been used as part of the DACCIWA programme in Côte d'Ivoire and Benin.

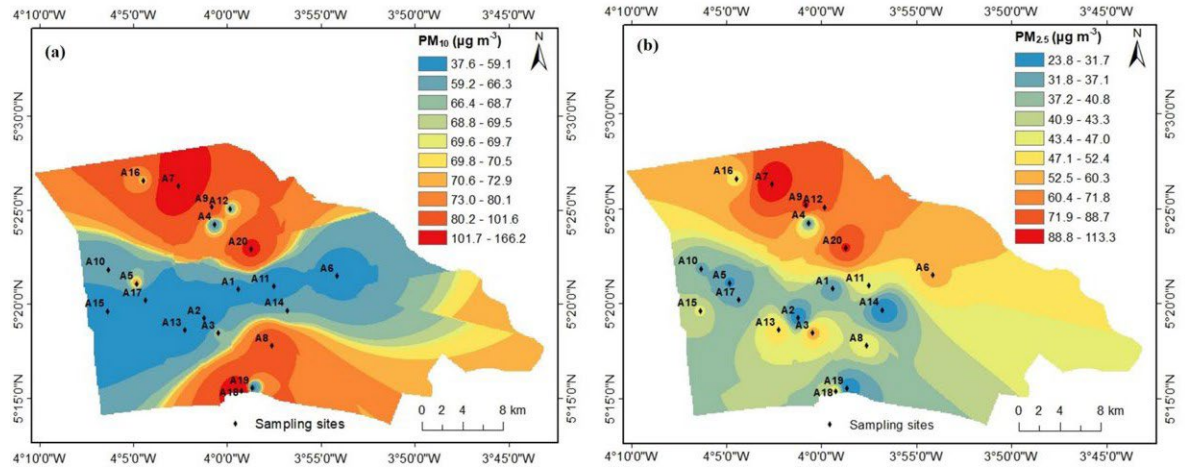

Figure 4 Maps of spatial variation in PM10 (a) and PM2.5 (b) concentrations in Abidjan (Côte d'Ivoire), where the black diamonds represent each measurement site [4]

1.1.2.9 Ecohealth Chair in Air Pollution (CHAIREPOL)

The Ecohealth Chair in Air Pollution, entitled "ChairePol", is a regional initiative aimed at generating knowledge based on Ecohealth principles relating to the link between non-communicable respiratory diseases (NCDs) and urban pollution. The Chair will use the evidence produced to strengthen policies and interventions to reduce air pollution and prevent NCDs in West Africa.

1.1.2.10 Air quality in Dakar (Senegal)

The air quality agency of Dakar (Centre de Gestion de la Qualité de l'Air, CGQA) is in charge of monitoring atmospheric pollutants (SO_2, NOx, NO_2, O_3, PM2.5, PM10), to facilitate access to information on air quality and decision-making and to promote realistic measures to improve air quality. The monitoring network is composed of six stations and one mobile station. They have been deployed in 2009 by the council of urban transportation of Dakar (Conseil Exécutif des Transports Urbains de Dakar, CETUD) funded by Nordic Fund for Development with the support of the NILU (Norway) for the implementation of the instruments. The CGQA provides information to the population and alerts in situation of very low air quality due to high PM10 concentrations. The CGQA is involved in the inventory of pollutant emitters in order to reduce emissions. They support the collaboration at the regional level with members of the CEDEAO, with the support of French air quality associations (ATMO-Grand Est; AIRPARIF) with the support of the IRD and the UN-Environment programs and the GUAPO network (Global Urban Air Pollution Observatory) initiated by the "Ville de Paris".

1.1.3 Eastern Africa

1.1.3.1 Intergovernmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAD)

ICPAC provides climate information and early warning services across the region. Founded to enhance adaptive capacity in response to climate risks, it collaborates with eight East African nations. ICPAC's research focuses on climate change adaptation and mitigating climate-related security risks. Despite challenges such as insufficient funding, ICPAC plays a vital role in building research infrastructure by supporting the development of early warning systems and climate services crucial for regional security and resilience.

1.1.3.2 AirQo system

AirQo system (https://www.airqo.net/): An air quality smart sensing and management system has been developed from the ground up, considering the unique and contextual needs of African cities. This system aims to generate evidence and facilitate actions for improving air quality management in urban areas. Low-resource settings often face numerous challenges, including limited capacity and trained personnel, inadequate infrastructure for power and data transmission, scarce funding, and a lack of high-end equipment.

The AirQo system has been implemented in major cities across East Africa and is currently being expanded to additional cities throughout the region. These digital air quality platforms are utilized to raise citizen awareness about air quality issues, provide data and evidence for decision-makers, and offer training and skill development for students and researchers in various fields such as Engineering, Computer Science, and Public Health, among others.

The AirQo system represents the largest sensing network operating in low-resource settings, thus revealing new design and deployment requirements. Furthermore, the AirQo system is linked to actionable steps that can be taken by communities and city leaders.

1.1.3.3 Afriq'AIr network

AfriqAir (Africa qualité de l'air, https://www.cmu.edu/epp/afriqair/index.html) is a hybrid air quality monitoring network with (as of June 2020) over 50 low-cost sensors and reference-grade monitors mainly in urban areas across 11 African countries. Research objectives include evaluation of sensor performance across the different climates in Africa, integration of ground sensor data with satellite data to expand spatial data coverage, verification of air quality models, and investigation of air pollution health effects. AfriqAir operates under the principles of inclusivity, openness, and capacity-building. Long-term sustainability of this network requires local knowledge and expertise, and so AfriqAir is committed to sharing knowledge of sensor selection, network operation, and data analysis with local researchers, students, and technicians. The network is supported by numerous African US and French Universities and research organisms.

This network is an example of optimized combination of classical reference instrumentation and low-cost sensors to increase the spatial coverage of air quality sensors at reasonable cost in terms of instrument and manpower.

Figure 5 Location of the sites of the AfriqAir network

1.1.4 Southern Africa

1.1.4.1 South African Weather Service (SAWS)

SAWS is crucial for climate and meteorological research. It provides weather and climate-related services to the public and various sectors, contributing to research on climate change and its impacts on South Africa and the broader region. Collaborating with WMO and other international entities, SAWS contributes to climate research by developing advanced forecasting products.

1.1.4.2 1.2.1.4.2 South African Air Quality Information System (SAAQIS)

SAAQIS is a web-based platform dedicated to air quality management and monitoring across South Africa. The system collaborates with various governmental and private organizations to support extensive data collection and analysis. The mobility within SAAQIS involves researchers engaging in detailed air quality monitoring. The system has established a comprehensive network for air quality management, although challenges include maintaining data quality and coverage. SAAQIS has contributed to research infrastructure in Africa by providing high-quality data for air quality management and supporting public awareness campaigns.

1.1.5 Northern Africa

1.1.5.1 Global Atmospheric Watch (GAW-Sahara)

One of the GAW stations deployed in Africa allows the development of the GAW-Sahara project whose main goal is to obtain accurate and quality assured total column ozone and spectral UV over the Sahara within the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) programme. The projects provide funds to set up a double Brewer spectrophotometer at the Tamanrasset Meteorological Regional Centre and a NILU multifilter radiometer at the high-altitude Assekrem GAW station. As an operational Dobson spectrophotometer is at Tamanrasset, this station would be one of the few sites in the world where a permanent and long-term intercomparison between the Dobson, the Brewer and the present and future satellite-based sensors could be performed on a routine basis. This initiative is strongly recommended by the WMO Ozone Scientific Advisory Group and will be a unique contribution to the total ozone global network Quality Assurance. On the other hand, the installation of a NILU multifilter radiometer at Assekrem station will allow obtaining UV radiation, Photosynthetic Active Radiation (PAR) and deriving total column ozone at a mountain station in the middle of the Sahara. The Brewer at Tamanrasset and the NILU at Assekrem will also fill a big gap existing nowadays of spectral UV and Umkehr observations in this region. Routine validation of new satellite-based sensors will be one of the main goals of these new measurement programs. This project will also finance a short mission of the Brewer spectrophotometers from Morocco to participate in the ozone and UV intercomparisons for Brewer spectrophotometers organized by the Regional Brewer Calibration Centre for RA-VIEurope (RBCC-E).

1.2 Atmospheric Composition Observations to address Climate change (GHG and short-lived atmospheric species)

1.2.1 Continental

Known flux and atmospheric observation stations in Africa are shown in Figure 6.

Blue points represent the Global Atmosphere Watch (GAW) regional stations, green points the GAW global stations, black points represent the identified Flux sites from SEACRIFOG, the orange triangles are the most recent compilation of flux measurements in South Africa and the green stars are the IDAAF sites.

The SEACRIFOG project started a mapping exercise that has been continued within KADI. Figure 6 shows the known atmospheric composition and terrestrial flux stations in Africa. While they are lacking coordination in many ways, it is key to create a pan-African scientific community that can support the measurements as well as use the data for scientific studies.

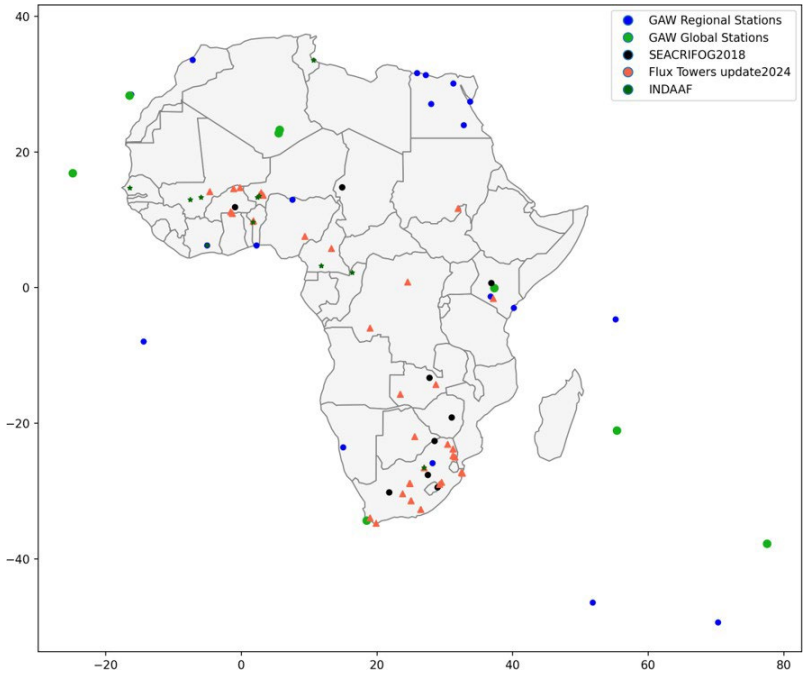

Figure 6 Known flux and atmospheric observation stations in Africa

1.2.1.1 Global Atmospheric Watch stations

The Global Atmosphere Watch (GAW) Programme of WMO promotes coordinated global monitoring of atmospheric composition and its change as well as scientific analyses to improve the understanding of interactions between the atmosphere, the oceans and the biosphere. It coordinates high-quality atmospheric composition observations across global to local scales to drive high-quality and impact science while co-producing a new generation of research enabled products and services. Some components of the GAW observational network are recognized as comprehensive and baseline networks of the Global Climate Observing System (GCOS).

Figure 7 Global Atmospheric Watch stations in Africa

Among the 39 global stations of the Global Atmosphere Watch (GAW) Programme of WMO, 8 stations are located on the African continent as shown in Figure 7 (Assekrem, Tamanrasset, Algeria; Mount Kenya, Kenya; Cape Point, South Africa) and two downwind of West Africa (Cape Verde Atmospheric Observatory, Cape Verde; Izaña, Tenerife, Spain). Additional regional stations are located in Morocco, Egypt, and Nigeria (https://oscar.wmo.int/surface; https://gawsis.meteoswiss.ch)

1.2.1.2 CO2 flux towers

During the SEACRIFOG project, which aimed to establish 50 observation sites, an inversion modelling study was conducted to identify the optimal locations to reduce uncertainty in the atmospheric CO_2 and CH_4 concentrations. Figure 8 indicates the optimal location over the African continent for both November, December, January (NDJ) and June, July and August (JJA) periods of an atmospheric network with an additional 12 observation sites, this highlights the need for observations in the tropical forested regions and transition zones. Many of these sites are still observation sites for other parameters than greenhouse gases.

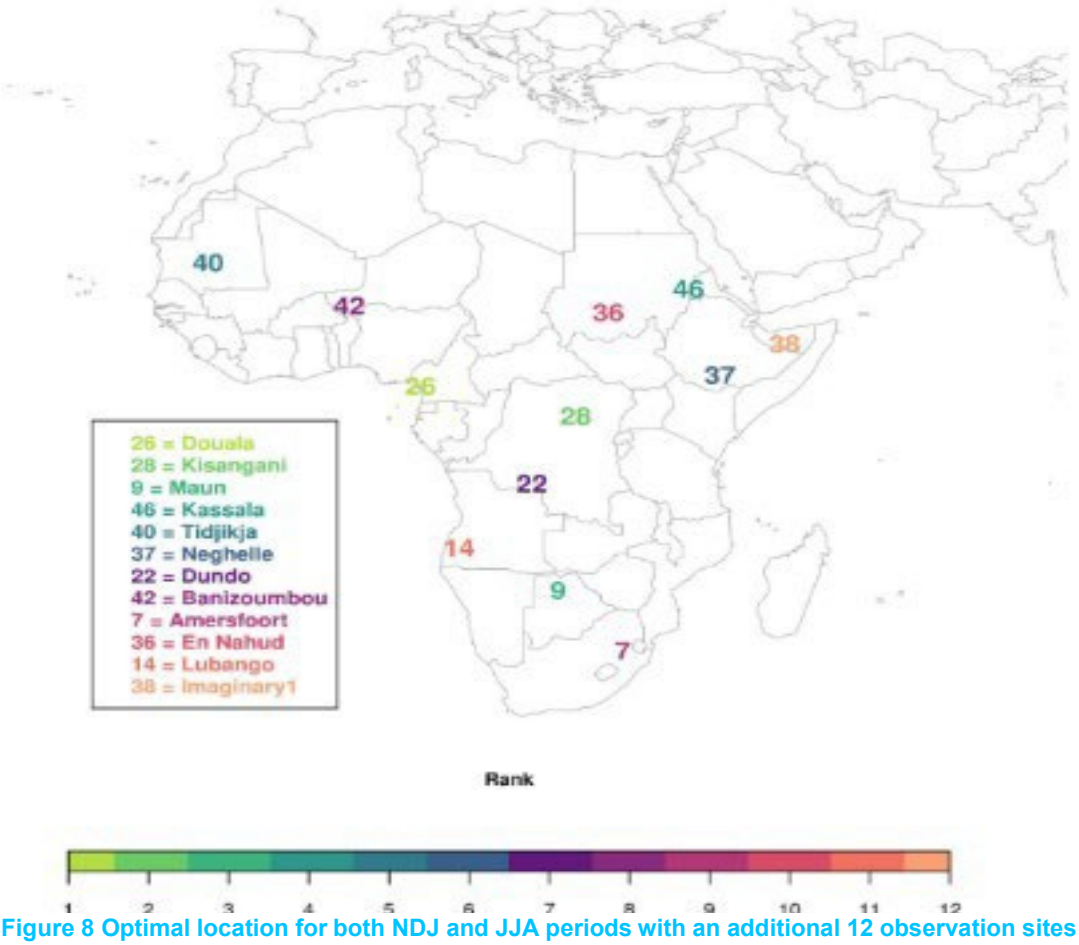

Figure 8 Optimal location for both NDJ and JJA periods with an additional 12 observation sites [5]

This research highlights the necessity of scientific reflection on network design. It shows how science can guide to the optimum network reducing uncertainties in the best way. The following text will further explore the existing stations and analyse the related science.

1.2.1.3 AERONET Network

The AERONET (Aerosol Robotic Network) program is a federation of ground-based remote sensing aerosol networks established by NASA and PHOTONS (Photométrie pour le Traitement Opérationnel de Normalisation Satellitaire; Univ. of Lille 1, CNES, and CNRS-INSU) and is greatly expanded by networks (e.g., RIMA, AeroSpan, AEROCAN, AEROSPAIN, NEON, and CARSNET) and collaborators from national agencies, institutes, universities, individual scientists, and partners. For more than 25 years, the project has provided long-term, continuous, and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases. The network imposes standardization of instruments, calibration, processing and distribution. This network is composed of automatic sun-photometers (CIMEL CE318) operating in near real time and providing aerosol optical and columnar microphysical properties (size distribution, optical properties). The instrument is simple to instal and to maintain and is adapted to African conditions.

Figure 9 AERONET stations in operation on the African continent in 2024

Several stations have been deployed in Africa in the 90's and provided times series over almost 30 years of the aerosol atmospheric load. Thaks to this temporal and spatial coverage, AERONET data are among the most widely used data set for the validation of global aerosol models.

1.2.1.4 IAGOS

IAGOS is a research infrastructure that combines the expertise of European scientific institutions and weather services with the global infrastructure of civil aviation to provide essential data on climate change and air quality. It builds on the scientific and technological experience gained within the research projects MOZAIC (Measurement of Ozone and Water Vapour on Airbus in-service Aircraft), which was funded by the EC between 1993 and 2004 under FP 4 and FP 5, and CARIBIC (Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container). For 30 years now, IAGOS provides regular global-scale

Figure 10 AERONET stations in operation on the African continent in 1996

in-situ monitoring of atmospheric composition (ozone, water vapour, greenhouse gases, reactive gases, aerosols, clouds) in terms of vertical profiles. About 50 airports on the African continent are covered by the IAGOS IR (Figure 11). The inclusion of Eurowings Discover to IAGOS in 2022 allows to cover many new routes in Africa

IAGOS is a contributing network to the WMO Global Atmosphere Watch program, and our data are used in the daily monitoring of global air quality models via the Copernicus Atmosphere Monitoring Service. Data distribution procedures according to FAIR Standards data have been adopted through the ENVRI-FAIR project. A series of recommendations for establishing a comprehensive and sustainable framework for access to distributed atmospheric Research Infrastructures, including ICOS, ACTRIS and IAGOS is developed in the frame of the ATMOACCESS project.

The success and the durability of the IAGOS IR illustrates the possibility of fruitful collaboration with private company in the domain of atmospheric science without sacrificing the high level of quality of standardized observations.

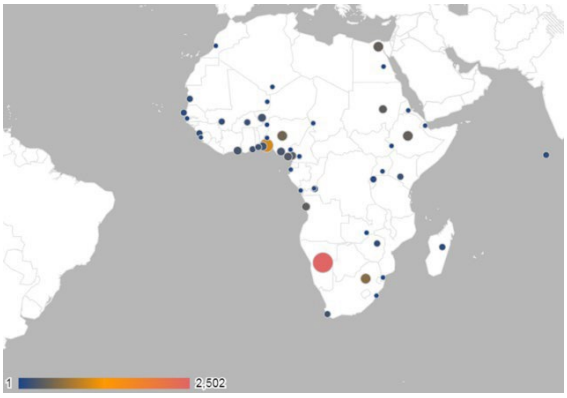

Figure 11 IAGOS visited airports on the African continent

1.2.2 Western Africa

1.2.2.1 LAMTO geophysical station

In 1962, Lamotte and Tournier (hence the name LAMTO) created in Ivory Coast an ecological station in a typical Sudano-Guinean savannah about ten kilometres from the town of Taabo, in a reserve of 2,700 ha. A geophysical station has then been installed with a research centre in internal geophysics (seismology) and external geophysics (climatology). The geophysical station is part of the global monitoring network for the Comprehensive Nuclear Test Ban Treaty (CTBT)/monitoring of all types of ground movement (particularly earthquakes). Following its initial set-up as a Geophysical observatory, additional observations of climate and the impact of climate change on agricultural activities were established monitoring of climate change and seismic and climatic watches. It detects and analyses seismic waves and studies the impact of climate change on agriculture. Research programme on seismicity in the West African sub-region and the impact of climate change on agricultural yields. The station is in partnership with several institutions, including the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO/Austria), the French Atomic Energy Commission (CEA/France), the French Laboratory for Climate and Environmental Sciences (LSCE/France), Paul Sabatier University (Toulouse/France), SODEXAM (Côte d'Ivoire), Uncle Ben (Côte d'Ivoire), etc.

The LAMTO Station has proven to be a significant location to provide support for Support for training: Numerous international CTBTO courses Research results (major findings): - Seismicity map of Côte d'Ivoire. The station is hosting several measuring instruments (meteorology, air quality, atmospheric chemistry, seismology) and has contributed to the production of observation data for many research projects. Atmospheric wet deposition measurements started in 1988 and became part of the IGAC/DEBITS international network and then a reference site of the INDAAF international network that is related to the research Infrastructure ACTRIS-FR. As part of the European CarboAfrica project (2006-2009),

measurements of CO2 and CH4 concentrations was installed at the Lamto observatory in 2008 and maintained until now by ICOS-FR.

Figure 12 LAMTO station, Côte d'Ivoire

(Https://oscar.wmo.int/surface/#/search/station/stationreportdetails/0-20008-0-lto)

The long-term evolution of the LAMTO station highlights the key role played by the insertion in international network in the maintenance and the upgrade of African observation stations.

1.2.3 Northern Africa

1.2.3.1 Saharan Air Layer Analysis and Monitoring (SALAM)

Tamanrasset (https://oscar.wmo.int/surface/#/search/station/stationReportDetails/0-20008-0-TAM) was considered a key place to initiate the Saharan Air Layer Analysis and Monitoring (SALAM) project as part of the Global Atmospheric Watch (GAW) twinning cooperation program between l'Office Nationale de la Météorologie (ONM, Algeria) and the Meteorological State Agency of Spain (AEMET) through the Izaña GAW station (Canary Islands, Spain).

In the framework of this project, at the end of September 2006, a Cimel sun photometer was set up at Tamanrasset and integrated into the Aerosol Robotic Network (AERONET). This project has the following objectives:

a. Monitoring and characterization of the Saharan Air Layer.

b. Validation of regional and global dust models.

c. Validation of satellite-based dust measurements.

d. Enhance the dust early warning system in Northern Africa.

1.2.3.2 Atlas Mohamed V Atmospheric Research station

The ATLAS-MOHAMMED V Atmospheric Research Station (ATLASM5) is operated by Mohammed V University (UM5) Rabat, Centre National de la Recherche Scientifique (CNRS-ICARE, Orléans) and Orléans University. It is a facility that has been continuously monitoring and collecting data related to atmospheric chemical composition since July 2017. It is located about 19 km south from downtown of the Ifrane at an altitude of about 2000 meters above sea level in a remote area with minimal influence of human activity which makes it ideal for monitoring constituents in the atmosphere that can cause climate change and alter air quality. The objective is to monitor long-term trends of atmospheric composition change, air pollution and climate variables.

In addition to the initial aerosol (High Volume aerosol sampler, Light Optical Aerosol Counter) and gas (NO, NO2, O3) instrumentation and meteorological measurements (wind speed, direction, precipitation, visibility and UV radiation), ATLAS M5 has started (since mid-October 2018) to provide long-term, continuous observations of concentrations of the greenhouse gases (GHGs) carbon dioxide (CO2) and methane (CH4) in the frame if the ICOS Atmospheric thematic centre.

1.2.4 East Africa

1.2.4.1 GAW Kenya

The GAW Station at Mount Kenya (https://oscar.wmo.int/surface/#/search/station/stationReportDetails/0-20008-0-MKN) was established in 1994 as part of a Global Environment Fund's (GEF) effort to launch new atmospheric composition monitoring stations in data sparse regions. Nowadays, ground-based in-situ trace gas, aerosol and meteorological measurements are operated by the Kenya Meteorological Department (KMD) with long-term support by MeteoSwiss, Empa and the Paul Scherrer Institute. Nearly three decades of Kenya-Swiss collaboration make the Mount Kenya stations a perfect pilot within the KADI project summarising the technological and scientific experiences gathered so far. They also highlight the challenges in developing the scientific capacity needed to operate complex measurement equipment. The outcome of this pilot will provide important insights on the scientific cooperation between weather services and related education demands.

1.2.4.2 Nairobi Ozone Soundings and surface air quality

Since 1998, regular balloon soundings for ozone profile measurements are performed at KMDs campus in Nairobi (https://oscar.wmo.int/surface/#/search/station/stationReportDetails/0-20008-0-NRB). Supported by MeteoSwiss, KMD launches about 1 sounding per week, resulting in more than 1000 soundings since the beginning. These are unique observations in continental Africa, contributing to the SHADOZ (Southern Hemisphere Additional Ozonsondes) initiative (https://tropo.gsfc.nasa.gov/shadoz/).

1.2.4.3 Mount Mugogo Atmospheric Station (Rwanda)

MIT and the Government of Rwanda have collaborated to build this world-class observatory on Mt. Mugogo measuring climate change and the atmospheric species forcing climate change.

This AGAGE station, the first in all of Africa, is located on the summit of Mt. Mugogo – a rural area about 70 km from Kigali, the capital city of Rwanda, and 13 km away from the nearest town of Musanze. Seven-day back trajectories of air masses sampled at Mt. Mugogo stretch Northeast as far as Saudi Arabia and the Indian West Coast. In the Southeast direction the air masses come from as far away as Madagascar. The air masses from the East travel over the East African region characterized by a high population density, urban areas and intense agricultural activities. West of Mt. Mugogo, air parcels come mainly from the equatorial forests in the Democratic Republic of Congo and Central African Republic. Measurements taken at Mount Mugogo are also occasionally influenced by local sources identified by enhanced black carbon aerosol and carbon monoxide levels.

1.2.5 Southern Africa

1.2.5.1 Gobabeb (Namibia)

Gobabeb site is in the heart of the hyperarid Namib Desert. It provides easy access to the three distinct ecosystems of the Namib: the Sand Sea to the south, the Gravel Plains to the north, and the riparian woodlands of the ephemeral Kuiseb River. These three ecosystems provide a rich diversity of arid-adapted organisms. The Namib biota includes a number of endemic taxa. Gobabeb is situated on the ecotone between fog and rain precipitation, enhancing further Gobabeb's unique capacity for desert research. Measurements of PM10 concentrations, aerosol optical properties (scattering and absorption), particle number concentration, chemical composition, ozone in the frame of a collaboration between the North-West University (NWU) and the LISA (CNRS). The Gobabeb station also hosts an AERONET sunphotometer, solar and IR radiatiometers, ceilometers, meteorological station. The station has obtained the regional GAW label.

1.2.5.2 Welgegund Atmospheric Monitoring Site

The Welgegund atmospheric measurement station is located on a grazed grassland-savannah approximately 100 km west of Johannesburg (Gauteng) metropolitan area in South Africa. The site is frequently hit by pollution plumes from Johannesburg metropolitan area and the western Mpumalanga industrial Highveld, with frequent clean air injections from the west. The site is operated jointly by the North-West University (NWU), the Finnish Meteorological Institute (FMI) and the University of Helsinki (UH). It contains extensive air quality and atmospheric composition measurements and measurements of the flu of CO_2 and water vapour between the lands surface and the atmosphere.

1.2.5.3 GAW Cape Point (South Africa)

The Cape Point Global Atmosphere Watch (GAW) station (https://oscar.wmo.int/surface/#/search/station/stationReportDetails/0-20008-0-CPT), located in South Africa, is an integral part of the World Meteorological Organization's Global Atmosphere Watch program. This station is among the few globally that monitor background concentrations of greenhouse and reactive gases, playing a crucial role in understanding atmospheric composition and changes. The station began its operations in 1978, initially focusing on measuring carbon monoxide (CO) and chlorofluorocarbons (CFCs) and achieved official GAW status in 1995.The Cape Point GAW station collaborates extensively with various national and international organizations, including the South African Weather Service (SAWS) and the WMO. It is part of a network of 31 global GAW stations, with only three located on the African continent. The station is deeply involved in long-term monitoring of atmospheric species, including greenhouse gases, reactive gases, and aerosol properties, contributing valuable data on more than 25 different atmospheric species to global research on atmospheric composition and climate change. It also participates in mercury monitoring programs, providing crucial data on mercury concentrations in the Southern Hemisphere.

The station actively supports research exchanges and collaborative projects, offering scientists and researchers opportunities to engage in atmospheric monitoring and data analysis. Additionally, it facilitates training and capacity-building initiatives for researchers and students. The station's achievements are notable, including being the first in the Southern Hemisphere to conduct continuous mercury monitoring since 1995. Its data has been extensively used in international reports and publications, such as the UNEP Mercury Report 2018, and it has contributed to numerous scientific studies and theses, significantly enhancing global understanding of atmospheric processes.

However, the station faces challenges, particularly in maintaining continuous funding and ensuring the sustainability of long-term monitoring programs. There is also the complexity of integrating diverse data sources and maintaining high-quality data standards. Despite these challenges, the Cape Point GAW station remains a vital contributor to global atmospheric monitoring capabilities. It provides high-quality data essential for climate and atmospheric research, supports the development of early warning systems, and contributes to international efforts to understand and mitigate climate change. The station's data is publicly available, promoting transparency and supporting global scientific collaboration.

1.2.5.4 South African Environmental Observation Network (SAEON)

South African Environmental Observation Network (SAEON, https://www.saeon.ac.za/), founded in 2002, plays a pivotal role in long-term environmental monitoring and research across South Africa. SAEON is a long-term environmental observation and research facility of the National Research Foundation (NRF). SAEON’s three focus areas are environmental observation, data management and education outreach. The Department of Science and Innovation provides core funding for these activities. SAEON has a distributed network of seven nodes, two research infrastructures and a national office. The research network covers the

major terrestrial and marine ecosystems in South Africa and supports well over 100 researchers and students a year.

Long-term research sites, where repeated observations, experimental treatments and related data are permanently maintained. Laboratories, in situ instruments, vehicles, boats and other equipment needed for conducting environmental research

The environmental science education programme (ESEP) is implemented through inter-actions with SAEON science engagement officers, scientists and technicians. Through these programmes SAEON seeks to attract, expose and encourage 14–17-year-old students to pursue science careers.

1.2.5.5 La Réunion Observatory

The Observatory of La Réunion Island is composed of three sites (St Denis, Gillot, Maido) and has been upgraded from a regional to a global GAW station (https://oscar.wmo.int/surface/#/search/station/stationReportDetails/0-20008-0-RUN). The Maido observatory (2200 m) was built with the support of the region, the French state and the European Union (FEDER project). The station is situated far away from the substantial anthropogenic pollution source in the south-west Indian Ocean. Three observational platforms allow for sampling the air impacted by marine emissions and partly by urban emissions (on the University campus) or free tropospheric air. The combination of the three platforms allows for comprehensive studies of atmospheric chemistry, evaluation of the long-range transport of pollutants and impacts of the boundary layer and biospheric processes on the atmospheric composition over the island. The observational platforms constituting the Global station are not only used for continuous long-term measurements but also serve as a platform for the intensive measurement campaigns. The observatory is hosting instruments (Lidar and FTIR) from the NDAAC international network and ICOS-FR measurements of GHG concentrations.

1.2.5.6 Henties Bay Aerosol Observatory (HBAO), discontinued

The Henties Bay Aerosol Observatory (HBAO) was established in 2011 at the SANUMARC Research Centre of the University of Namibia at Henties Bay (22°6'S, 14°30'E, elevation 20 m). It was funded by the French Centre National de la Recherche Scientifique (CNRS) and the South African National Research Foundation (NRF) through the Bilateral research Project "Atmospheric Research in Southern Africa and the Indian Ocean" (GDRI-ARSAIO) as well as by the Partenariats Hubert Curien (PHC) PROTEA of the French Ministry of Foreign Affairs and International Development. The observations included aerosol mass concentrations, black carbon, aerosol scattering, aerosol size distribution, ozone, meteorology and aerosol optical depth. The site was discontinued in 2020.

1.2.5.7 Okavango Atmospheric Monitoring Site

The Okavango atmospheric measurement station is a savannah location approximately 20 km south of town of Shakawe in Northern Botswana. The site is in a rural area with no major anthropogenic sources in the vicinity. The site is operated jointly by the University of Botswana, the Department of Waste Management and Pollution Control in Botswana, the North-West University (NWU) and the Finnish Meteorological Institute (FMI). It contains extensive air quality and atmospheric composition measurements.

1.3 Carbon Exchange between the land and Atmosphere

1.3.1 Continental

The EC technique measures the transfers of heat, mass, and momentum between a horizontally homogeneous surface and its surroundings. For example, turbulent air eddies travel over the surface of the ecosystem, bringing atmospheric air into the ecosystem and bringing ecosystem air into the atmosphere. The vertical flux density may be determined by computing the covariance between vertical wind variations and CO_2 concentration in upward and downward flowing air parcels in a one-dimensional net transfer between the atmosphere and the surface (Baldocchi, 2003; Rinne, 2012). The technique requires measurement with fast response sensors (typically a gas analyser and 3D sonic anemometer) to record the full spectrum of turbulent fluctuations. It is generally accepted that measurements of wind, temperature, humidity, and other gas constituent fluctuations are done at a frequency of 10 or 20 Hz. Sensors for this method are normally mounted on a tower where the flux is measured from the contributing area seen by the instruments. This area is known as the footprint which varies as its dimensions and orientation are dependent on measuring height, surface roughness and atmospheric stability, surface roughness length, wind speed and direction (Schmid & Lloyd, 1999).

A representative, systematic and harmonized greenhouse gas observations platform currently is lacking on the African continent. While Africa is identified as a continent highly vulnerable to climate change due to both ecological and socio-economic factors, it remains the part of the least covered regions in the Global South by studies on climate change (Sietsma et al., 2021). However, while experiments and campaign studies have not been absent in Africa, the long-term coordination, operation and continuation of these efforts has been missing (Bieri et al., 2022). One of the first experiments to monitor greenhouse gas (GHG) fluxes in Africa was achieved through the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX) (Moncrieff, Monteny, et al., 1997) with the aim to study the process of evaporation and water balance in the Sahel region. With the still present need to quantify the exchange of carbon and assess the net contribution to the global carbon balance of the African continent, this experiment made use of three supersites in Niger during 1997 where little was known of the processes relating to vegetation responses to atmospheric water demand, soil moisture stress as well as the water use and radiation use efficiencies characterising the capability of the vegetation to utilise available resources.

After the HAPEX-Sahel project, the CARBOAFRICA project (Saint-André et al., 2007) followed as the first attempt to set up a monitoring network to quantify, understand, and predict GHG emissions in Sub-Saharan

Africa and its associated spatial and temporal variability by using a multi-disciplinary approach. This project aimed to build state of the art carbon studies in Africa, filling knowledge gaps while utilising and expanding existing carbon observing systems. Furthermore, establishing new infrastructure and improving the required monitoring system was key to this project. The idea to focus on key areas by performing specific regional studies focusing on both carbon sinks and sources proved necessary towards contribution to the enhancement of an Earth Observations system to strengthen the understanding of global change processes. The scientific efforts from CARBOAFRICA resulted in several publications observing ecosystem scale trends in carbon and water exchange and their responses to a suite of covarying environmental factors like incoming solar radiation, temperature, soil moisture, and rainfall using the eddy covariance technique (Ardö et al., 2008; Kutsch et al., 2008; Merbold et al., 2009; Williams et al., 2009).

These studies have laid the foundation towards understanding the role African terrestrial ecosystems play in the global carbon cycle. While the efforts of the HAPEX-Sahel and CARBOAFRICA resulted in a first glance of carbon exchange patterns over varying vegetation structures and ecosystems, the density of measurements cannot be compared to other global studies. Thus, Africa's contribution to the carbon cycle and global carbon emissions still largely remains understudied in time and in space. The most recent efforts towards constraining this uncertainty have been achieved by Valentini et al. (2014) where a complete estimate of the African carbon budget applying various methodologies including inventory data, ecosystem flux measurements, modelling approaches as well as atmospheric inversion techniques was presented. Here, the results highlighted the importance of Africa in the global C cycle contributing 16% and 33% of the total C sink and tropical C biomass reservoir, respectively in addition to about 25% of its inter-annual variability. Net C balance for Africa is estimated to range from a small source of 0.05 ± 0.28 Pg C yr^{1} to a sink or -1.34 ± 1.32 Pg C yr^{-1}, depending on the method applied. In getting a more holistic estimate of GHG emissions, Valentini et al. (2014) combined their median estimate for net biome C balance with estimates for fossil fuel carbon dioxide emissions and non-CO2 GHG emissions leading them to conclude that Africa is a net source of GHG emissions. With development in Africa expected to increase in the future, the aim to keep global temperatures below 1.5°C and cut global emissions by 45% by 2030 with the target to reach net zero by 2050 requires the understanding of the potential contribution of African terrestrial ecosystems as carbon sinks to offset future carbon emissions.

There are several long-term eddy-covariance measurement records in Africa available through the network called FLUXNET (https://fluxnet.org/) (Ref: DOI: 10.1080/16000889.2020.1824486) which has last compiled a global data set in 2015. Thus, some flux observations that are not documented in Fluxnet provided in the figure below.

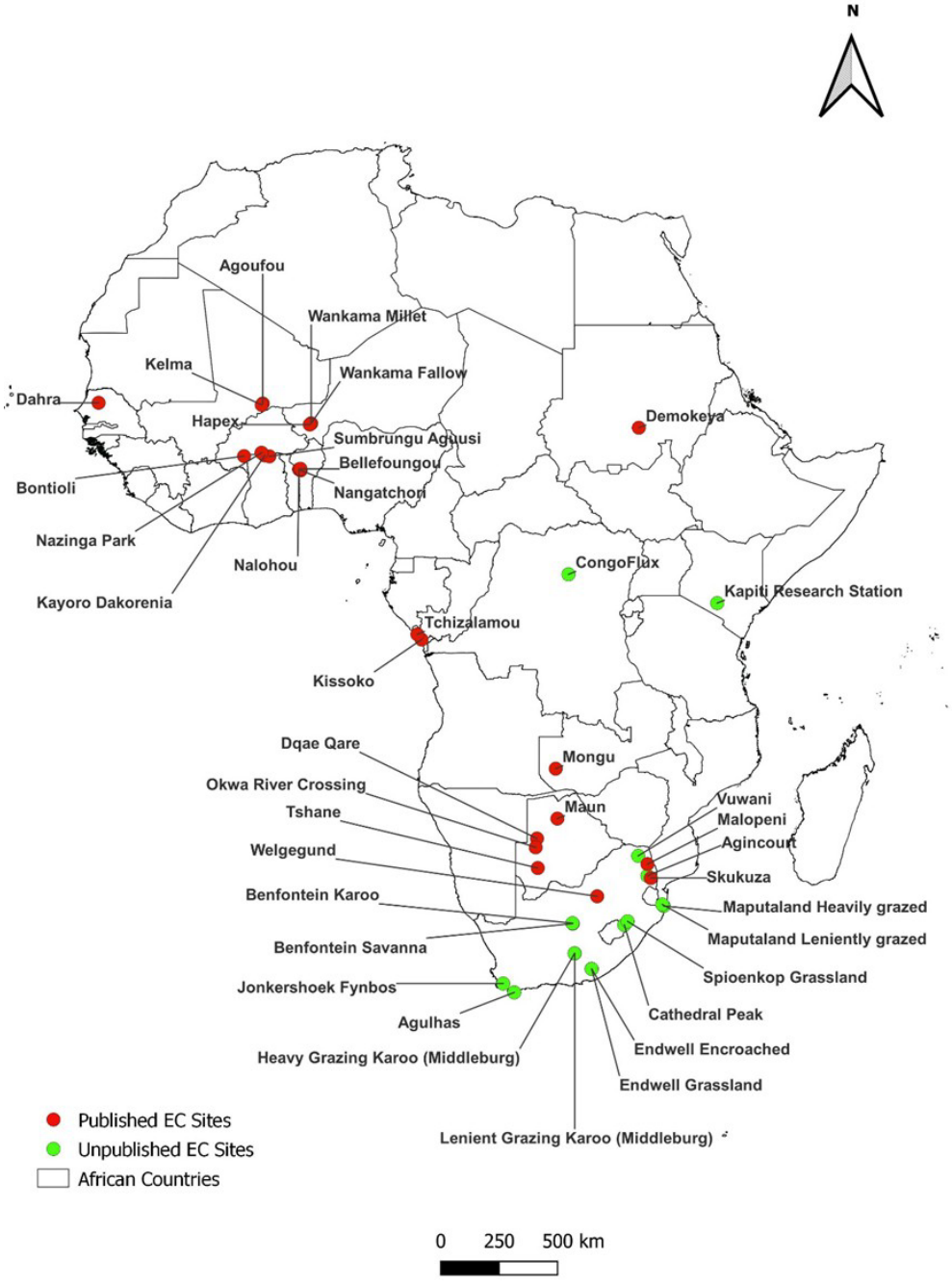

Figure 13 Published eddy covariance stations on the African continent

Approximately 26 published eddy covariance stations on the African continent (red). Sites currently under the administration of SAEON/EFTEON, the Council of Scientific, Industrial Research (CSIR) and Rhodes University in South Africa as well as new sites established in the Congo and Kenya are shown in green.

1.3.2 Western Africa

1.3.2.1 Observatoire de Recherche En Environnement De Nambékaha (OREN)

OREN, situated in northern Côte d'Ivoire, focuses on understanding the interactions between atmospheric dynamics, the hydrological cycle, and vegetation in the savannah. This observatory began collaborating with both national and international research institutions to gather critical data that supports climate research in the region. Through its involvement in scientific studies and mobility projects, OREN has contributed valuable insights into atmospheric and ecological processes. However, it faces challenges in maintaining its observational networks over the long term, which are vital for sustaining its contributions to regional climate research infrastructure.

1.3.2.2 Climate and Eddy-covariance (EC) stations of the Core Research Program

The EC stations are installed over 3 stations at Sumbrungu, Kayoro, and Nazinga in west Africa. The instrumentation at these stations is nearly identical but with individual measurement heights. This setup measures >20 variables at different height levels with a high temporal resolution. The core measurement devices of the EC stations are an open-path infrared gas analyzer (7500A, Li-COR) and a three-dimensional ultrasonic anemometer (CSAT3, Campbell). These devices measure atmospheric water vapor content, the atmospheric CO_2 content, and the horizontal and vertical wind components with a sampling frequency of 20 Hz. The measurement height of these devices is site dependent and varies between 2.65 m aboveground for the grassland site and 7.19 m aboveground for the near-natural site. The measurement height depends on the mean vegetation height within the fenced area of an EC station. Based on this setting, fluxes of sensible heat, latent heat, and CO_2 are calculated using the EC method. The information from the three-dimensional sonic anemometer can also be used to determine total wind speed, total wind direction, and corresponding two-dimensional variables such as the horizontal wind speed and direction.

1.3.2.3 The Ghana Flux Tower

The Ghana Flux Tower in Sunyani became operational in 2019. It is a key site for monitoring carbon and water fluxes, contributing valuable data to research on climate change and sustainable land management in the region. The Tower is part of the GhanaFlux initiative, which focuses on monitoring carbon and water fluxes in West African ecosystems. The tower uses eddy covariance technology to continuously monitor gas exchanges, providing real-time data on carbon dynamics and water vapor fluxes. This facility plays a vital role in understanding the interactions between land use, climate, and carbon dynamics in semi-deciduous forests and agricultural areas.

1.3.3 Northern Africa

1.3.3.1 Tamanrasset Station, Algeria

The Tamanrasset Station is situated in the southern part of Algeria, within the Sahara Desert. It is part of a network of eddy covariance stations that monitor atmospheric exchanges of gases, particularly carbon dioxide (CO2) and water vapor. Tamanrasset is located at an altitude of approximately 1,400 meters (4,600 feet) in the Hoggar Mountains region, known for its arid climate and unique ecosystems. The station primarily focuses on studying carbon fluxes and water vapor exchanges in arid and semi-arid environments. This is crucial for understanding how desert ecosystems respond to climate change and variability. The station employs eddy covariance technology to measure the turbulent fluxes of CO2 and other gases. This data is vital for assessing the role of desert ecosystems in the global carbon cycle.

1.3.3.2 Bou Arfa Station, Morocco

The Bou Arfa Station is an eddy covariance site located in eastern Morocco, primarily focused on monitoring gas exchanges between the atmosphere and various land cover types in a semi-arid environment. It is near the town of Bou Arfa. The station is in a region characterized by semi-arid conditions, agricultural fields, and shrubland. The primary objective of the station is to study carbon dioxide (CO2) and water vapor exchanges, particularly in relation to agricultural practices and land use changes. This research is vital for understanding the impacts of land management on carbon sequestration.

1.3.3.3 Sahara Ecosystem Flux Tower, Tunisia

The Sahara Ecosystem Flux Tower is aimed at monitoring and understanding gas exchanges in the unique desert ecosystems of the Sahara. It is in a semi-arid region of Tunisia and provides valuable insights into the dynamics of desert ecosystems and their responses to climate change. The primary focus is on measuring carbon dioxide (CO2) and water vapor fluxes. This research is essential for understanding how desert environments contribute to the global carbon cycle and how they are impacted by climate variability. The station employs eddy covariance technology to continuously monitor gas exchanges, along with meteorological data such as temperature, humidity, and wind speed. This comprehensive data set helps in assessing the ecological and climatic interactions in the Sahara.

1.3.4 Central Africa

1.3.4.1 The Congo Basin Flux Tower, Democratic Republic of Congo

The Congo Basin Flux Tower is in the Democratic Republic of the Congo (DRC) within the vast and ecologically significant Congo Basin rainforest. This station plays a crucial role in monitoring carbon and water fluxes in one of the world's largest tropical forest systems. The station is situated in a remote area of the

Congo Basin, known for its dense rainforest, rich biodiversity, and significant role in global carbon cycling. The primary focus is to measure the exchanges of carbon dioxide (CO2) and water vapor between the forest and the atmosphere. This research is essential for understanding the rainforest's role as a carbon sink and its responses to climate change.

1.3.5 Eastern Africa

1.3.5.1 Taita Research station, Kenya

Located in Kenya, the Tatia Research Station was established to study carbon exchange and ecosystem responses to environmental changes. This station collaborates with various national and international institutions, facilitating mobility and research exchanges that enrich the scientific community's understanding of carbon fluxes in the region. Its contributions to building research infrastructure in Eastern Africa are evident through the comprehensive data it generates. However, like other stations, it struggles with the challenge of sustaining long-term observational networks, which are crucial for continuous climate monitoring and research. The station is often involved in broader research networks, such as FLUXNET, which connects various eddy covariance sites globally to enhance the understanding of carbon dynamics across different ecosystems.

1.4 Biodiversity and response of Vegetation Change

1.4.1 Continental

1.4.1.1 Socio-ecological Observatory for studying African Woodlands (SEOSAW)

SEOSAW, a network of scientists working across Africa, began with the goal of understanding the impact of global change on African woodlands. It connects researchers from various African nations, enhancing collaborative scientific research. Mobility within SEOSAW is promoted through shared data and joint research initiatives. The project has achieved significant progress in developing standardized methods for woodland surveys, though challenges persist in maintaining long-term observational networks. SEOSAW has significantly contributed to the development of research infrastructure by enhancing ecological monitoring capabilities across the continent. SEOSAW is managed communally. The scope of SEOSAW's activities is open to change as the network and its members' research interests develop. SEOSAW's main purpose is to connect researchers and their data, and to facilitate collaborative research. Anybody is welcome to become part of SEOSAW, by contributing data or expertise, or by using the SEOSAW dataset for their research.

Key output:

- Novel analyses of the determinants of ecosystem structure and function for Africa, based on a synthesis of plot data.

- Standardised methods for plot design and measurement, tailored to the socio-ecology of African woodlands.
- A long-term plan for plot remeasurement within Africa.

1.4.1.2 Regional Support Programme - Natural Resource Management and Climate Change (PRA/GRN(CC))

The Regional Support Programme focus on deepening the policy dialogue between the European Union and developing countries on climate change and intensify support to target countries and implement priority adaptation and mitigation measures. It supports the implementation of the Global Climate Change Alliance (GCCA).

1.4.1.3 The Global Climate Change Alliance

Change Alliance Plus (GCCA+) GCCA+ is the second phase of an initiative of an initiative of the same name launched by the European Commission (EC) 2007 with a view to strengthening dialogue and cooperation in the field of climate change climate change between the European Union (EU) and the most vulnerable developing vulnerable developing countries.

1.4.2 Western Africa

1.4.2.1 Food System Resilience Program (FSRP)

The FSRP is a regional initiative in West Africa aimed at strengthening food system resilience in the face of climate change. Since its inception, it has facilitated collaboration among regional institutions, driving scientific research focused on food security. The program supports regional mobility and capacity building by fostering partnerships and sharing expertise. Despite facing challenges in coordinating efforts across multiple stakeholders, FSRP has improved food system resilience, contributing to sustainable land management practices and strengthening regional research infrastructure.

1.4.2.2 SERVIR West Africa

The main objective of the ‘SERVIR AFRIQUE DE L'OUEST’ project is to support regional institutions in improving their capacity to apply geo-spatial and analytical techniques, to the region's resilience to the impacts of climate change and to ensure sustainable land management and reduce greenhouse gas emissions.

1.4.2.3 The project, "Intégration des mesures d'adaptation au changement climatique dans la gestion concertée du Complexe Transfrontalier W-Arly-Pendjari (WAP) - (ADAPTWAP)

The main objective of the Adapt WAP project is to strengthen the resilience of ecosystems and improve the livelihoods of populations within the WAP Complex in relation to climate change through climate change by setting up a Multi-Environment Early Warning Multi-Hazard Early Warning System (EWS) and the implementation of concrete adaptation measures.

1.4.3 Central Africa

1.4.3.1 Central African Forests Commission (COMIFAC)

COMIFAC, headquartered in Central Africa, was established to foster regional cooperation in forest management and climate change adaptation. The commission collaborates with regional and international partners to coordinate projects aimed at sustainable forest management and combating illegal logging. Its work has led to the establishment of transboundary protected areas, although challenges such as illegal logging persist. COMIFAC's contribution to research infrastructure includes the development of monitoring systems and improved data collection, essential for forest conservation and climate change adaptation efforts.

1.4.3.2 Central African Forest Initiative (CAFI)

Established in 2015 at the margins of the UN General Assembly by a coalition of donors and partner countries to reduce forest loss and poverty, CAFI is both a Trust Fund that supports direct investments on the ground and a high-level political negotiation platform. Our climate and development objectives are attained through the implementation of ambitious national investment frameworks. Such socio-economic transformation comes from measures that properly address both direct drivers of deforestation (such as agriculture, wood energy, forestry and mining) and underlying drivers (such as lack of land use planning and insecure land tenure, poor governance and rapid population growth). CAFI operates in countries such as Democratic Republic of Congo, Gabon, Republic of Congo, Cameroon, Central African Republic & Equatorial Guinea. Launched during the 2015 United Nations General Assembly, the Central African Forest Initiative (CAFI) is a collaborative partnership that gathers the United Nations Development Programme (UNDP), the United Nations' Food and Agriculture Organization (FAO), the World Bank, six Central African partner countries and a coalition of donors. Its aim is to support governments in the region to implement reforms and enhance investments to halt drivers of tropical deforestation. Focusing on Central African high-forest cover countries, the Initiative supports country-level efforts for reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+) and low emission development investments to mitigate climate change and reduce poverty.

1.4.3.3 Congo Basin Forest Partnership (CBFP)

The Congo Basin Forest Partnership (CBFP) was launched by former United States Secretary of State, Colin Powell, and the Central African Heads of State at the 2002 World Summit on Sustainable Development in Johannesburg as a response to Resolution 54/214 of the United Nations General Assembly which urged the international community to support efforts towards conservation and sustainable management of Congo Basin forests, outlined in the Yaoundé Declaration adopted by the Heads of State in Yaoundé in 1999.

The Congo Basin Forest Partnership is a member of the partnerships of the UN Commission on Sustainable Development. As a "Type II" multi-stakeholder partnership, the CBFP allows member organizations to cooperate on a voluntary basis. The CBFP currently counts 128 members including 10 Central African countries and nearly a hundred partners concerned with Congo Basin forest ecosystems including: ECCAS, COMIFAC, financial partners, Congo Basin civil society, international NGOs, multilateral organisations, research and training institutions, and private sector actors.

1.4.3.4 Indigenous Women's Forum

This forum highlights the role of indigenous communities, particularly women, in conserving the Congo Basin. It advocates for sustainable agriculture and agroforestry, ensuring that environmental conservation efforts are inclusive and community-driven.

1.4.4 Eastern Africa

1.4.4.1 African Centre for Technology Studies (ACTS)

ACTS, based in Nairobi, Kenya, focuses on environmental and climate-related research. Since its inception, it has developed a strong network by collaborating with national and international organizations. The centre supports research on climate change adaptation and water resource management, with mobility facilitated through international research exchanges. ACTS has made significant contributions to policy recommendations for climate adaptation, though securing long-term funding remains a challenge. The centre has enhanced research infrastructure by improving observational capabilities and supporting climate-related studies.

1.5 Earth System Modelling

1.5.1 Continental

1.5.1.1 Improving Model Processes for African Climate (IMPALA)

IMPALA, initiated with an ongoing timeline, brings together a consortium involving the Met Office and top UK and African institutions. This research programme aims to improve the understanding of Africa's climate to help provide high-quality information that is crucial for effective decision making across the continent.

IMPALA is a consortium of the Met Office and leading UK and African institutions including the African Centre of Meteorological Applications for Development, the Centre for Ecology and Hydrology, and the universities of Cape Town, Exeter, Leeds, Nairobi, Oxford, Reading and Yaoundé. The IMPALA research will improve understanding of African climate processes and the mechanisms of future change. The information gathered by the new research will help decision-makers reduce climate-related risks. For example, infrastructure can be re-designed to account for high temperatures and changing rainfall, while health, education and social support systems, and local planning decisions could be designed to cope with future climate conditions. African scientists will be trained on the latest climate modelling techniques and will focus on climate predictions over the next 5-40 years as this is the lifespan of many development projects being designed today.

1.5.2 Western Africa

1.5.2.1 African Monsoon Multidisciplinary Analysis-2050 (AMMA-2050)

AMMA-2050, part of the Future Climate for Africa (FCFA) program, began in 2015 and focuses on scientific knowledge enhancement and prediction of African climate, particularly in Burkina Faso and Senegal. Networking is robust, involving over 200 researchers from more than 20 countries. The project addresses critical gaps in climate understanding and effectively communicates findings to decision-makers. Mobility is supported through interdisciplinary collaborations among researchers and stakeholders. Significant advances in understanding climate variability have been made, but challenges persist in integrating findings into policy and practice. The project enhances research infrastructure by providing tools for climate-resilient decision-making and supporting climate services development.

1.5.3 Eastern Africa

1.5.3.1 Integrating Hydro-climate science into policy decisions for climate-resilient infrastructure and livelihoods in East Africa (HyCRISTAL), Kenya and Uganda

HyCRISTAL works to address uncertainty of regional climate projections and co-develop climate-change adaptation solutions that meet the region’s societal needs in both urban and rural areas. Develop new understanding of climate change and its impacts in East Africa, working with decision-makers to provide a more climate-resilient future, benefiting the poorest. ICPAC is mainly contributing within this area of work through research on drivers of extreme rainfall events over Ethiopia and South Sudan using a convection

permitting model run for the African domain. Pilot studies on urban Water Sanitation and Hygiene (WASH) and rural livelihoods that demonstrates the value of climate change information to policy. Smaller projects within HyCRISTAL (e.g., HyTPP & CI4Tea) address Lake Victoria water levels for transport infrastructure and tea production, and how climate change will impact these resources and co-develop policy proposals for adaptation.

1.5.4 Southern Africa

1.5.4.1 Council for Scientific and Industrial Research (CSIR)

The CSIR's ongoing research in South Africa is centred on Earth system model development for climate change projections. Networking is broad, involving national and international collaborations. CSIR is heavily involved in regional climate modelling and detailed climate change projections. The project supports mobility through student internships and international research exchanges. It has made significant contributions to climate and air quality modelling, but challenges such as maintaining funding and ensuring project sustainability persist. CSIR's work enhances research infrastructure by improving observational capabilities, offering high-quality data, and supporting early warning systems.

1.6 Adaptation and resilience to Climate induced Change

1.6.1 Continental

1.6.1.1 Climate Adaptation and Resilience (CLARE) Initiative

CLARE, initiated by the UK's FCDO and Canada's IDRC, started with a focus on supporting climate adaptation across Africa, Southeast Asia, and the Pacific. Networking involves collaboration with international and regional partners to bridge gaps between science and actionable climate strategies. The initiative encourages active involvement in scientific research by developing tools and supporting climate adaptation practices among governments, communities, and the private sector. Research mobility is enhanced through exchanges and collaborative projects. Key achievements include the development of new tools and the support of partner governments. Challenges are mainly in addressing the varied needs of vulnerable communities. CLARE significantly contributes to building research infrastructure by advancing climate services, tools, technologies, and capacity building for sustainable development.

1.6.2 Western Africa

1.6.2.1 The project, "Intégration des mesures d'adaptation au changement climatique dans la gestion concertée du Complexe Transfrontalier W-Arly-Pendjari (WAP) - (ADAPTWAP)

ADAPTWAP is a project focused on enhancing the resilience of ecosystems and livelihoods within the WAP Complex in West Africa. Initiated to address climate change impacts, the project involves collaboration with regional and international organizations. It promotes mobility by facilitating regional cooperation and capacity building. The establishment of a Multi-Environment Early Warning System is a significant achievement, although securing long-term funding remains a challenge. ADAPTWAP has strengthened research infrastructure by improving observational capabilities and supporting climate adaptation efforts.

1.6.2.2 FURIFLOOD: Current and future risks of urban and rural flooding in West Africa – An integrated analysis and eco-system-based solutions

The German African FURIFLOOD project is funded by the German Federal Ministry for Education and Research (BMBF) in response to the WASCAL Research and Action Plan 2.0 [6]. FURIFLOOD will generate scientific knowledge regarding climate drivers of current and future extreme events related to flooding in West Africa and integrates this with case studies to better understand current and future risks and impacts. Based on this understanding, the FURIFLOOD project will derive and evaluate ecosystem-based strategies to reduce current and future risk to flooding using a participatory approach. The case studies of the FURIFLOOD project will be in the tropical region of West Africa and thus complementing and building on the results of the first WASCAL research program in the Sudan Savannah zone. This approach allows to develop a regional expertise on flooding and extreme events in West Africa to be implemented at the WASCAL Competence Centre. The proactive engagement of stakeholders together with the education of future decision makers and scientist within the framework of the WASCAL Graduate Program particularly contribute to the results' uptake. Additionally, data, tools and a guidebook will be made available locally and regionally in West Africa to further encourage the use of project results.

1.6.2.3 Biodiversity and agriculture: African Centre of Excellence on Climate Change, Biodiversity and Sustainable Agriculture (WASCAL-CCBAD)

The African Centres of Excellence (ACE) project is the first large-scale regional programme financed by the World Bank in the higher education sector in Africa. It addresses the need for high-level skills as well as the requirements for innovative research initiatives to serve the continent's development priorities, through five main areas: science, technology, engineering and mathematics (STEM); agriculture; health; environment; applied social sciences and education. Since its launch in 2014, the programme has supported more than 80 centres in over 50 universities in 20 African countries [7].

In 2019, to strengthen the impact of the existing CEAs and extend the programme to more research centres, the World Bank, in collaboration with Agence Française de Développement, launched the third phase of the programme: the CEA for Development Impact project, or CEA-Impact. A total of 53 centres from 35 universities are participating in the CEA-Impact project across 11 countries (Benin, Burkina Faso, Côte d'Ivoire, Djibouti, Gambia, Ghana, Guinea, Niger, Nigeria, Senegal and Togo) to improve the quality, quantity and development impact of postgraduate education. These centres have forged strong partnerships with universities and businesses at local, regional and international level, helping to support students' research projects, offer internships and facilitate their access to the job market.

In Côte d'Ivoire, the CEA project supports the Climate Change, Biodiversity and Sustainable Agriculture (CCBAD) programme. It has set up research infrastructure through the construction of buildings, the purchase of laboratory equipment and the financing of the mobility of teachers and students. CEA-CCBAD is equipped with state-of-the-art equipment. CEA-CCBAD will be a major partner in KADI, providing support for the acquisition of measuring instruments, raising awareness of the importance of research and the development of new technologies.

Figure 14 African Centre of Excellence on Climate Change, Biodiversity and Sustainable Agriculture (WASCAL-CCBAD) of university Felix Houphouet Boigny, Côte d'Ivoire

1.6.2.4 West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), funding from the German Ministry of Education and Research (BMBF)

The Atlantic Technical University, Cabo Verde, the Master Research Programme on Climate Change & Marine Sciences (MRP-CCMS) under the Capacity Building Programme of the WASCAL

WASCAL is a wholly West African international organization with focus on academic and transdisciplinary research, building graduate-level scientific capacity and serving policy makers in West Africa with science-based advice on adaptation to climate change impacts and land use management. It cooperates with many agencies and universities in the region, providing a knowledge platform of excellence for its partners.

WASCAL is funded by the Federal Ministry of Education and Research (BMBF), Germany and its 11 West African member countries, namely: Benin, Burkina Faso, Cabo Verde, Cote d'Ivoire, Ghana, Mali, Niger,

Nigeria, Senegal, The Gambia and Togo) WASCAL's mission is to provide information and knowledge services at the local, national and regional levels to West African member countries to cope with the adverse impacts of climate change. We do this through capacity building support to young West African scholars in fields of climate, natural and social sciences and by strengthening the regional universities deliver climate and environmental services in member countries.

The master's Research Programme on Climate Change & Marine Sciences of the Atlantic Technical University is implemented in close cooperation with the GEOMAR Helmholtz Centre for Ocean Research Kiel, the University of Kiel and the Thünen Institute, as German partner institutions and with the National Institute for Fishery Development (INDP) as the Cabo Verdean partner institution. This consortium is well suited to provide needed scientific and academic skills in climate, marine sciences and management both on an international and on a regional level in West Africa, in a climate change context. The proposed Master Research Programme will adequately prepare West African students for subsequent post-graduate studies or professional careers as managers or experts in industry, consultancy, governmental agencies etc.

1.6.2.5 AdaptCoop: Strengthening the resilience of cocoa cooperatives to climate change in Côte d'Ivoire

AdaptCoop is an applied research project that aims to sustainably increase the resilience of cocoa cooperatives and member families to the impacts of climate change in Côte d'Ivoire.

cocoa cooperatives and their member families in the face of the impacts of climate change in Côte d'Ivoire. The specific objectives of the project are as follows:

- Increase knowledge and build capacity in climate scenarios in West Africa, particularly in Côte d'Ivoire.
- To consolidate and develop Côte d'Ivoire's expertise in interpreting climate scenarios for the cocoa value chain and inform national policies in this area.
- Strengthen the capacity of cooperatives and cocoa producers to adapt to climate change and develop a tool to help them do so. producers and develop a gender-sensitive decision-support tool for cocoa cooperatives to help cooperatives to adapt to climate change.
- Strengthen the capacity of Ivorian cocoa cooperatives and their member families in terms of planning, accessing, adopting and applying innovative solutions for adapting to climate change, including gender-sensitive solutions.
- Integrate gender equality considerations into decision-making processes within Ivorian cocoa cooperatives to adapt to climate change and contribute to better climate change and contribute to improving women's access to the resources they need to adapt to climate change.

Lasting three years, with an extension of a few months, the project was implemented by SOCODEVI, Ouranos and the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), more

specifically its Côte d'Ivoire branch CEA-CCBAD (African Centre of Excellence on Climate Change, Biodiversity and Sustainable Agriculture) at the Université Félix Houphouët-Boigny, in collaboration with the Agence Nationale d'Appui au Développement Rural (ANADER) and the Centre National de Recherche Agronomique (CNRA). The final year of the project has seen all the expected deliverables finalised and the achievement of the specific objectives documented. The activities carried out have made it possible to continue efforts to promote and capacity-building, in particular through a self-assessment by the participants, a visit by from CEA-CCBAD researchers and a three-month internship at Ouranos for a doctoral student, the expertise put forward by the CEA-CCBAD, the CNRA and other implementing partners. Concrete support strategies for the adaptation practices of cocoa producers and cocoa cooperatives have been implemented, while integrating a perspective of integrating a gender equality perspective to recognise the specific realities of women and to propose and women's specific realities and to propose, then implement, ways of doing things that can help to correct the inequalities they face and to value their role in adapting to climate change [8].

1.6.2.6 AEMET Regional Training Centre

In the 70th Executive Council of the WMO (2018) AEMET was designated as a WMO Regional Training Centre (RTC) in Spain. In this new RTC, AEMET cooperates to complement the global offering of training in Meteorology and Climatology in Spanish-speaking countries and in those countries with historical and geographic links, such as those in western Africa. Thus, Spain joins the currently 26 RTC network of WMO to complement the training offered at the world level. Among these activities highlight the monitoring and training activities of AERONET-NASA operators in North Africa (Egypt, Tunisia and Argelia) as well as recurrent training on sun photometry to other African institutions.

1.6.3 Northern Africa

1.6.3.1 Global Climate Change Alliance Plus (GCCA+)

GCCA+ began in 2007 as an initiative by the European Commission to foster cooperation on climate change between the EU and vulnerable countries, including those in Northern Africa. The project has established a strong network by collaborating with international and regional organizations. It supports scientific research focused on climate adaptation and mitigation, with mobility facilitated through international collaboration. The initiative has implemented significant climate resilience measures, although coordinating among diverse stakeholders remains challenging. GCCA+ has bolstered research infrastructure in Africa by enhancing observational capabilities and supporting sustainable development efforts.

1.6.4 Eastern Africa

1.6.4.1 African Centre for Technology Studies (ACTS)

Based in Nairobi, Kenya, ACTS works on various environmental and climate-related projects. It focuses on policy-relevant research, including climate change adaptation and water resource management.

1.6.4.2 The Eastern Africa Climate Smart Agriculture Platform (EACSAP)

EACSAP promotes agricultural productivity, adaptation, and resilience to climate change through technological innovation and sustainable practices.

1.6.5 Southern Africa

1.6.5.1 Council for Scientific and Industrial Research (CSIR)

The CSIR's ongoing research in South Africa is centred on Earth system model development for climate change projections. Networking is broad, involving national and international collaborations. CSIR is heavily involved in regional climate modelling and detailed climate change projections. The project supports mobility through student internships and international research exchanges. It has made significant contributions to climate and air quality modelling, but challenges such as maintaining funding and ensuring project sustainability persist. CSIR's work enhances data and infrastructure by improving observational capabilities, offering high-quality data, and supporting early warning systems.

1.6.5.2 Long-Term Adaptation Scenarios Flagship Research Programme (LTAS)

LTAS, linked to South Africa's National Climate Change Response, started with a focus on adaptation research and scenario planning across various sectors, including agriculture and biodiversity. Networking is established through collaboration with entities like the DFFE and SANBI. The project involves extensive scientific research across multiple sectors and facilitates research mobility through exchanges and partnerships. LTAS has developed adaptation scenarios and strategies, although integrating diverse data sources and maintaining continuous stakeholder engagement pose challenges. The program supports research infrastructure by advancing climate services, early warning systems, and climate-resilient policymaking.

1.6.5.3 Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL)

SASSCAL is a collaborative initiative that addresses climate change and adaptive land management in southern Africa. It aims to improve the understanding of climate change impacts and develop adaptive strategies.

1.6.5.4 African Climate and Development Initiative (ACDI) at the University of Cape Town

ACDI focuses on climate research and its intersection with sustainable development. It aims to address climate change through research, education, and policy advocacy.

1.6.5.5 Coordination, Capacity Development and Knowledge Exchange Unit (CCKE)

The main aim of the CCKE Unit Impact Strategy is to create enabling environments to realise a central hypothesis of the FCFA's Theory of Change, namely that improved scientific understanding of African climate variability and change with enhanced medium---term climate prediction leads to improved decision---making when coupled with strengthened user knowledge, skills and tailored climate products. Therefore, ensuring effective uptake of research will be critical to achieving FCFA's intended impacts.

1.6.5.6 University of Pretoria - Centre for Environmental Studies (CFES)

CFES offers multidisciplinary graduate training in environmental sciences, focusing on sustainable development, conservation, and natural resource management (University of Pretoria).

1.6.5.7 Council for Scientific and Industrial Research (CSIR)

The CSIR is a prominent research organization involved in a wide range of environmental and climate research projects. They work on sustainable development, climate resilience, and environmental protection.

1.7 Marine and Coastal observations

1.7.1 Western Africa

1.7.1.1 West Africa Coastal Areas Management Program (WACA)

Coastal erosion and flooding in West Africa severely threaten people's communities, livelihoods, safety and investments. About 56% of West Africa's GDP is generated in coastal provinces, where one-third of the population resides. Stronger storms and rising seas are wiping out homes, roads and buildings that have served as landmarks for generations. Some beaches are deeply mined for sand, protective mangroves are deforested, and people are increasingly vulnerable to the impact of climate change. Some residents have no choice but to move away—a trend that is breaking up communities and changing the social fabric for future generations.

Rapid and often unplanned urbanization has devastated the natural landscape that once served as a buffer for erosion and flooding. These developments disproportionately affect the poorest and most marginalized and will intensify due to climate change. While countries have started to contain erosion and flooding, there is an urgent need for partners to mobilize financing through coordinated regional action. Collaboration at the

policy and technical levels helps countries to manage erosion hotspots, and to maintain the livelihoods that a healthy coastal ecosystem provides to people and economies [9].

The Knowledge Pillar of the WACA Platform is critical to identify needs and priorities for coastal resilience investments and to facilitate countries' access to the best global expertise and knowledge. It is currently coordinated by the World Bank. Various knowledge products will be produced to guide intervention strategies in natural capital, nature-based and sustainable infrastructure solutions, new or updated WACA Multi-Sector Investment Plans, and migration and gender aspects. The Platform is developing long-term partnerships among countries, regional institutions, and global partners to enhance the effectiveness and sustainability of initiatives and investments. Knowledge exchanges remain a key tool to enhance knowledge transfer. Currently coordinated by the World Bank, the Knowledge Pillar is being implemented with multiple partners through several initiatives, including:

The African Centre of Excellence for Coastal Resilience, or ACE CoR hosted by the University of Cape Coast, the WACA ACE CoR is leading the development of a network of academic and training institutions that will provide the courses, training, and cutting-edge research needed for long-term development of regional expertise for resilient coastal management.

The West Africa Coastal Observatory: currently facilitated by the Centre de Suivi Ecologique and the International Union for Conservation of Nature building on the West Africa Coastal Management Scheme, the Observatory will produce a "State of the West Africa Coast Report" that will highlight biophysical and socioeconomic trends and indicate the actions needed to maintain healthy and productive coastal areas.

On Knowledge and Training the Platform is facilitating knowledge exchanges between countries within West Africa, and with countries beyond. The intent is to stimulate interest in new solutions and lessons from other countries, and at the same time apply these approaches to WACA countries' multi-sector investment plans, local solutions, and new project designs.

1.7.1.2 Centre de Recherches Océanologiques (CRO)

The Centre de Recherches Océanologiques (CRO) is an international initiative dedicated to the research and study of the oceans [10]. Its main objective is to better understand the oceans, their ecosystems and their importance for the planet. The CRO conducts in-depth research in various fields of oceanography, such as marine biology, seawater chemistry, marine geology, ocean meteorology and the study of ocean currents.

CRO researchers collaborate with scientists from around the world to collect oceanographic data, carry out field and laboratory studies, and develop advanced research models and tools. They study marine biodiversity, interactions between marine organisms, the effects of climate change on the oceans, marine pollution and other related topics.

CRO's main missions include collecting oceanographic data using research vessels, ocean buoys and automatic sensors, analysing samples taken from the ocean, monitoring seawater quality and studying ocean phenomena such as tides, waves and currents.

In addition to its research activities, the CRO also plays an important role in educating and raising public awareness of the importance of the oceans. It organises conferences, workshops and exhibitions to share scientific knowledge and promote the preservation of marine ecosystems.

1.7.1.3 West Africa Coastal Areas Resilience Investment Project

The development objective of Coastal Areas Resilience Investment Project is to strengthen the resilience of targeted communities and areas in coastal Western Africa. This project has four components. 1) The first component, Strengthening Regional Integration, Strengthening Regional Integration, aims to play a strategic role in the implementation of the regional component. 2) The second component, Strengthening the Policy and Institutional Framework, aims to will help countries develop the adequate policy framework and the necessary tools for the development and or operationalization of their coastal management strategies and plans, both at the national and regional levels. 3) The third component, Strengthening National Physical and Social Investments, aims to finance coastal investments, or sub-projects, to protect vulnerable areas from coastal erosion and flooding, to support pollution control and waste management operations, and to promote climate-resilient coastal development. 4) The fourth component, National Coordination, aims to ensure that the project is implemented in accordance with the Project appraisal document (PAD) and the country-specific project description and that the West Africa coastal areas (WACA) Multi-sectoral investment plan (MSIPs) or an agreed alternative national strategy or plan continues to form the basis for coordinated support from technical and financial partners to address the most pressing needs for management of the coastal zone.

1.7.1.4 West Africa Coastal Areas Resilience Investment Project for Climate Change Adaptation (WACA ResIP-CCA)

With one third of West Africa's population and source of 42 percent of its GDP, coastal areas are the region's socio-economic nexus. Population growth and associated anthropogenic stressors have imposed enormous pressure on coastal resources.

Moreover, the region is among the World's hotspots for climate change impacts. Many coastal African countries are vulnerable to sea-level rise, flooding and increased erosion, which pose immediate and long-term risks to livelihoods, assets and natural resources. The project will strengthen the resilience of the most vulnerable coastal communities and areas against the climate change risks in five countries of West Africa. It will mainstream climate risks and the associated resilience measures in policies and plans at the national level and implement structural resilience measures against the sea level rise (SLR), extreme events and flooding at the local level. The project will be housed within West Africa Coastal Areas (WACA) Program and will use its implementation arrangements.

1.7.1.5 Associated young team IVOARE-UP (ocean-atmosphere interactions and variability linked to upwelling)

Understanding the interrelationship between coastal upwelling and climatic and biogeochemical parameters in the Gulf of Guinea is one of the top priorities for West African countries, particularly Côte d'Ivoire.

Indeed, the Ivorian-Ghanaian upwelling plays a key role in the regional climate, primary production, local fishing and therefore the economies of neighbouring countries. This subject of study is in line with sustainable development objectives 14 and 13, which focus on the conservation and sustainable use of oceans, seas and marine resources, with a view to achieving sustainable development and combating climate change and its consequences for the region. JEAI IVOARE-UP proposes to observe, analyse and better understand regional ocean-atmosphere interactions and spatio-temporal variability linked to this coastal upwelling. In particular, the aim is to study the interrelationship of coastal upwelling with climate modes and extremes, biogeochemical parameters and primary production in the Gulf of Guinea.

This JEAI is based on a team of Ivorian researchers from distinct but complementary scientific disciplines (physical oceanographers, atmospheric physicists, climatologists, biogeochemists, chemists and a computer scientist managing marine data and information). Their expertise will be reinforced by researchers and engineers from LEGOS, LOPS, LOCEAN and US IMAGO.

The studies proposed as part of this JEAI are grouped into three themes:

- In-situ observations and measurements.
- Interannual dynamics of coastal upwelling and ocean-atmosphere coupling in the Gulf of Guinea.
- Coastal upwelling and its interrelations with biogeochemical parameters and primary production in the Gulf of Guinea.

The scientific activities are aimed at training students, organising or participating in international scientific conferences, and promoting and transferring skills. One of the aims of these activities will be to set up a new research team specialising in oceanography, ocean-atmosphere coupling and physics-biogeochemistry. They will create synergy between the partners and strengthen national, regional and international collaboration.

The added value of this JEAI lies in the fact that it is a springboard for:

local measurement campaigns, during the period and in the Ivorian coastal upwelling zone,

high-resolution regional coupled ocean-atmosphere modelling. The simulations will serve as tools for studies of air-sea coupling on different spatio-temporal scales and for climate studies on a regional scale.

1.7.1.6 AMMA's advances in ocean-atmosphere interactions

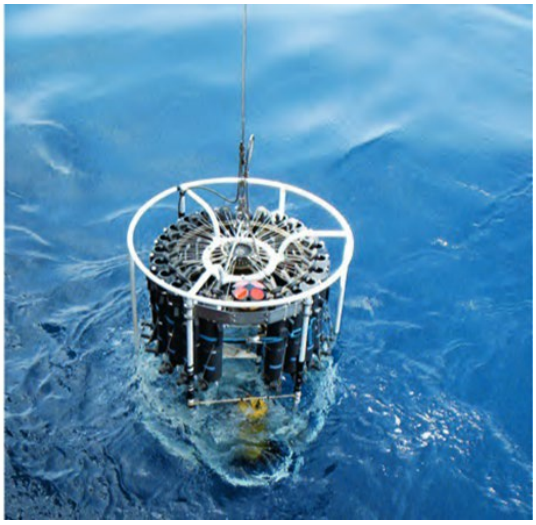

Figure 15 Launch of the CTD (Conductivity Temperature-Depth) to measure temperature, salinity, fluorescence and nutrient salts in the ocean [11]

The results gathered since the AMMA/EGEE campaigns of 2005-2007 in the field of air-sea interactions are presented. They show the key role of the Atlantic cold tongue (ACT) in the eastern equatorial Atlantic on the West African monsoon. The strengthening of south-easterlies, associated with the Saint-Helena anticyclone, promotes the preconditioning of the thermocline along the equator and the development of the ACT. The equatorial front on its northern boundary, modifies the surface heat fluxes that affect the circulation in the lower atmosphere. This circulation helps to push moisture northward, toward the West African sub-continent, and impacts the monsoon jump.

1.7.1.7 The Ocean Country Partnership Programme (OCPP), Cape Coast, Ghana

The Ocean Country Partnership Programme (OCPP) is a UK Government-led development programme under the Blue Planet Fund, delivered by Centre for Environment, Fisheries and Aquaculture Science (Cefas), the Joint Nature Conservation Committee (JNCC) and the Marine Management Organisation (MMO) on behalf of the Department for Environment, Food and Rural Affairs (Defra) [12].

***Marine pollution*:** The OCPP will support countries to be equipped with the skills and expertise needed to tackle, reduce and mitigate marine pollution through the development of science-led policy.

By improving our understanding of the impacts of pollution, as well as identifying and supporting effective responses, we will make sure that communities are better equipped to prevent and manage marine pollution. This will improve health and livelihoods.

Sustainable seafood: The OCPP will support the development of the skills and expertise needed to adopt sustainable seafood practices. This will reduce risks such as the spread of zoonotic diseases from unsustainable or unsafe activities and will support trade in safe seafood.

The programme will also help crack down on illegal, unreported and unregulated fishing by supporting the development of better management, monitoring and enforcement capabilities.

***Marine biodiversity*:** The OCPP will help countries to develop the skills and expertise needed to establish designated, well-managed and enforced marine protected areas. This work will support healthy ecosystems with thriving biodiversity and fisheries that communities rely on for food and livelihoods.

The programme aims to build these tools and by strengthening marine science expertise, develop evidence-based policy and management tools, and create educational resources for coastal communities.

1.7.2 Eastern Africa

1.7.2.1 Kenya Marine and Fisheries Research Institute (KMFRI)

KMFRI, an ongoing initiative in Kenya, focuses on sustainable management of marine and coastal resources through extensive oceanographic studies. KMFRI networks with both national and international organizations, facilitating research that spans marine biodiversity and coastal ecosystem management. KMFRI also supports mobility by providing opportunities for student internships and international research exchanges. The institute has made substantial contributions to marine research but faces challenges in securing sustainable funding for long-term projects. KMFRI strengthens research infrastructure by providing high-quality data and supporting the development of sustainable marine management practices.

1.7.2.2 Tanzania's Institute of Marine Sciences (IMS)

The IMS, part of the University of Dar es Salaam, focuses on marine and coastal ecosystem research in Tanzania, with ongoing activities that include oceanographic studies and environmental conservation. IMS networks with various national and international organizations to enhance its research capabilities. The institute is actively involved in scientific research, conducting extensive fieldwork and data collection. It encourages mobility through student internships and research exchanges. IMS has made significant contributions to understanding marine biodiversity and the effects of climate change but faces challenges such as funding sustainability. The institute contributes to research infrastructure by improving observational capabilities and supporting sustainable practices in marine management.

1.7.3 Southern Africa

1.7.3.1 South African Institute for Aquatic Biodiversity (SAIAB)

SAIAB, located in South Africa, conducts ongoing research on aquatic biodiversity, including marine and freshwater ecosystems. The institute collaborates with both national and international organizations, creating

a strong network that supports a wide range of research activities. SAIAB is involved in extensive scientific research, contributing to the understanding of environmental changes affecting aquatic life. The institute promotes mobility by offering student internships and research exchanges. While SAIAB has developed advanced research platforms and contributed significantly to aquatic biodiversity research, it faces challenges in maintaining funding and ensuring the sustainability of its projects. It enhances research infrastructure by providing access to advanced research tools, supporting the training of future aquatic managers, and expanding the capacity for aquatic biodiversity research in South Africa.

1.8 Data Infrastructures

At the global scale, the WMO Global Atmosphere Watch Program coordinates the activities of a number of GAW World Data Centres (https://community.wmo.int/en/activity-areas/gaw/research-infrastructure/world-data-centres) as well as data centres of GAW Contributing networks, through the WMO Expert Team for Atmospheric Composition Data Management (ET-ACDM, https://github.com/wmo-im/et-acdm/wiki). These data centres serve as long-term repositories for greenhouse gas, reactive gas, aerosol, ozone, UV and other data and provide services at various levels of sophistication. The official WMO global metadata repository of stations and observational information is hosted by MeteoSwiss (https://oscar.wmo.int/surface).

1.8.1 Continental

1.8.1.1 KADI (Knowledge and Climate Services from an African Observation and Data Research Infrastructure)

KADI began in September 2022 with the goal of creating a pan-African research infrastructure for climate and weather services. The project connects various African and European partners, drawing on a wide range of expertise. By focusing on the design of an all-African climate observation system and documenting existing capabilities, it plays a crucial role in scientific research. Mobility is facilitated through international collaborations and research exchanges. Although it aims to provide a comprehensive framework for climate observation, challenges include integrating diverse data sources and ensuring the system's sustainability. KADI significantly contributes to research infrastructure by improving data availability, quality, and fostering international cooperation.

1.8.1.2 Climate Data Tool (CDT)

CDT, developed by the International Research Institute for Climate and Society, is an ongoing project that supports over 20 African countries by enhancing their climate data management. It improves data availability and quality by merging national observation data with satellite and climate model reanalysis products. The tool facilitates networking between National Meteorological Services (NMS) across Africa and provides essential support for scientific research. Mobility is enhanced through training and capacity-building initiatives.

While the tool has successfully improved data management, challenges include ensuring its widespread adoption and continuous development. CDT's contribution to research infrastructure is evident in its support for climate risk assessment and the promotion of high-quality climate data.

1.8.2 Western Africa

1.8.2.1 The Côte d'Ivoire National Computing Centre (CNCI)

The Centre National de Calcul de Côte d'Ivoire (CNCCI) is one of the new research infrastructures set up to support research in Côte d'Ivoire and the sub-region. Its mission is to provide academic research with modern high-performance computing and data processing resources (Datacentre) to facilitate research work and publications, thereby enhancing the visibility and attractiveness of Côte d'Ivoire's universities. Figure 16 and Figure 17 picture the Supercomputer Architecture and Networking respectively. Several research projects are associated with the CNCCI:

The "Réseau National d'Enseignement et de Recherche - Centre de Calcul (RNER-CC)" project is a contribution from the Ivorian government and the AFD. The aim is to help develop a high-speed network to facilitate access to the computer and to meet the growing demand for High-Performance Computing (HPC) [13].

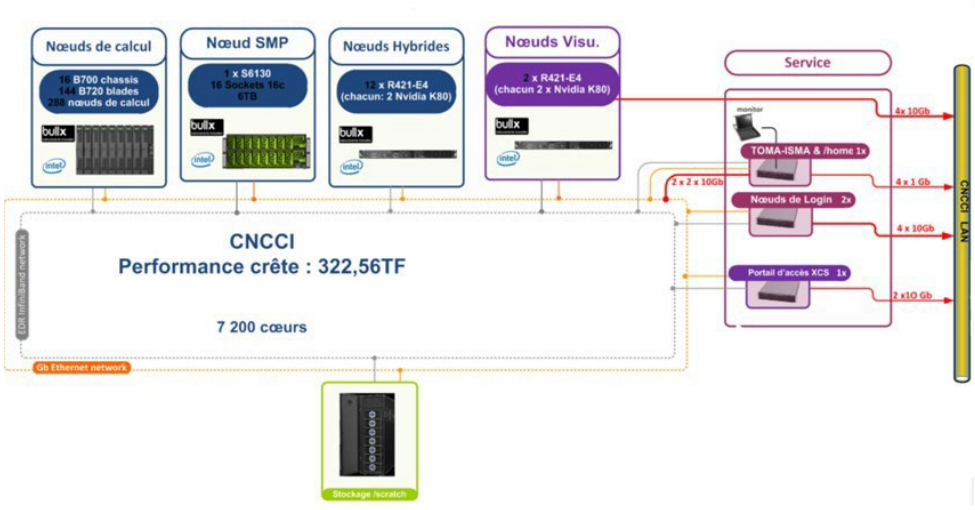

Figure 16 Supercomputer Architecture

The CNCCI offers high-performance, reliable, secure and innovative services tailored to the different uses of the teaching and research community, based on the power of the RITER network, which is at the service of the digital transformation of the MESRS in Côte d'Ivoire.

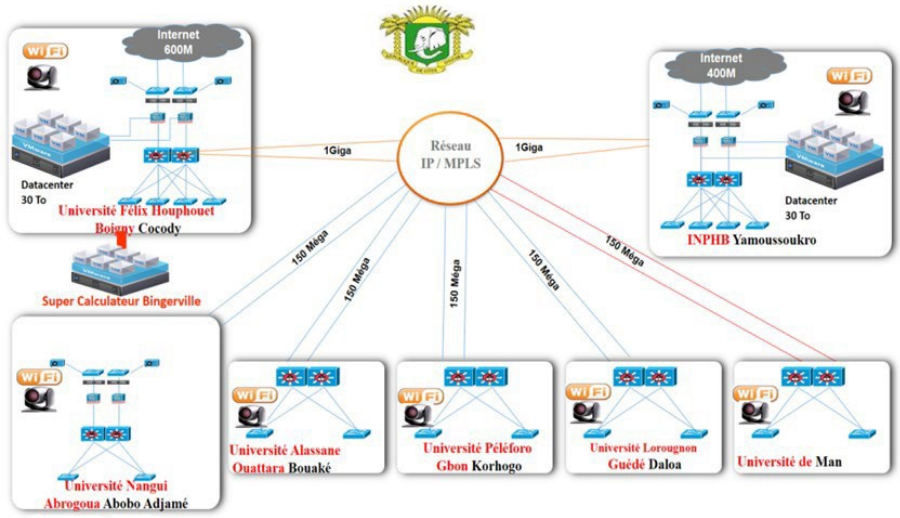

Figure 17 Networking

1.8.3 Southern Africa

1.8.3.1 SAEON

The South African Environmental Observation Network (SAEON) was established in 2002 in response to a growing recognition of the need for a coordinated and sustained environmental research observation system in South Africa. SAEON is managed as a national facility for research (however still to be declared) as provided for in section 5 of the NRF Act 23 of 1998. The SAEON uLwazi (meaning 'knowledge') node curates data and develops open data systems and applications, which are distributed on an Open Data Platform (ODP). The ODP directly supports and allows users free access to and visualisation of spatial and non-spatial data. This includes impacts of global change on human and natural environments. Open Data refers to data that is freely available, can be accessed, used and/or changed and republished by anyone. The SAEON Open Data Portal (ODP) offers the ability to store metadata and datasets in a secure environment that protects the intellectual property rights of the data providers. Metadata must accompany all datasets that

are archived or published in the SAEON ODP. To facilitate search and discovery, all metadata will be publicly accessible.

The SEAON uLwazi node has 5 team with a total of 13 specialist staff members and curates over 3580 datasets, with a mirrored storage capacity of 300TB. This includes a number of large projects such as 1) the South African Risk and Vulnerability Atlas, 2) the South African Bioenergy Atlas, 3)the Marine Information Management System (MIMS), 4) the National Climate Change Response Database, 5 National Climate Change Information System (NCCIS), 6) the SEACRIFOG inventory tool and the 7) the South African Carbon Sinks Atlas.

1.9 Carbon Accounting

1.9.1 Continental

1.9.1.1 The Africa Carbon Markets Initiative (ACMI)

Launched in 2020, the Africa Carbon Markets Initiative (ACMI) aims to expand carbon credit production across Africa, enhance job creation, and unlock significant revenue streams. ACMI encompasses multiple African countries such as Nigeria, Togo, Malawi, and Gabon. It fosters networking among these nations and international partners to promote the development of carbon markets. The initiative supports research into carbon credit production and market development while facilitating global collaboration. ACMI has set ambitious goals to produce 300 million carbon credits annually by 2030 and 1.5 billion by 2050. However, it faces challenges related to equitable revenue distribution and transparency. By enhancing carbon market infrastructure and supporting climate mitigation, ACMI plays a crucial role in building research infrastructure for sustainable development.

1.9.2 Western Africa

1.9.2.1 West African Alliance on Carbon Markets and Climate Finance

The West African Alliance on Carbon Markets and Climate Finance (https://westafricanall.wpenginepowered.com/our-activities/), established in 2019, aims to boost West African countries' capacity for participating in international carbon markets and accessing climate finance. This alliance works with national and international organizations to build capacity, develop policies, and facilitate market participation. It enables research exchanges and collaborative projects, enhancing regional collaboration. Achievements include improved capacity for market participation and climate finance access, while challenges involve ensuring effective implementation and coordination among member countries. The alliance contributes to research infrastructure by supporting carbon market development and promoting climate finance access in the region.

1.9.3 Southern Africa

1.9.3.1 South African Carbon Sink Atlas

Initiated in 2015, the South African Carbon Sinks Atlas provides detailed data on carbon sinks across South Africa, aiding climate change mitigation efforts. This project collaborates with various national and international organizations, focusing on mapping and analyzing carbon sinks. It offers opportunities for student internships and international research exchanges. Achievements include the development of comprehensive carbon sink maps that support climate policy and mitigation strategies. Challenges include securing long-term funding and maintaining the sustainability of research projects. The atlas enhances data availability and quality, supports climate mitigation efforts, and promotes sustainable land management in Southern Africa.

1.9.3.2 The African Carbon Asset Development (ACAD)

Facility was originally established in 2009 at the height of Clean Development Mechanism (CDM) project development to address the widespread concern that CDM evaded the African continent. As the market shifted away from CDM and into other concepts like Programmes of Activity, NAMAs and micro finance. ACAD supported local projects and financial institutions in about half of all countries on the African continent, pursuing its goals through training, seed funding and developing methodologies that stimulate market development. ACAD can contribute to training and research over universities and support the mobility in African continent. reinforce the link between higher education and finance institutions over the continent.

1.9.3.3 South Africa’s Tax

South Africa’s Carbon Tax (COAS), South Africa was the first country in Africa to introduce a carbon tax in 2019 The carbon tax is seen as a key tool to help achieve its Nationally Determined Contributions to the Paris Agreement, which it updated to commit to reducing its GHG emission to 350-420MtCO2e by 2030 and reach carbon neutrality by 2050.

This fund can also support the training and research on climate change and air quality management in the southern Africa region.

1.10 Adaptation/Resilience to Climate Extremes

1.10.1 Continental

1.10.1.1 MedCOF

Launched following the Scoping Meeting in June 2013 at the State Meteorological Agency of Spain (AEMET), the Mediterranean Climate Outlook Forum (MedCOF, http://medcof.aemet.es/) generates consensus seasonal forecasts for the Mediterranean region and Northern African region. The forum reflects the World Meteorological Organization's (WMO) desire to increase the availability of user-friendly climate service. Its purpose is to improve climate scientists' understanding of the information needs of different user groups and thus able to produce more usable and salient climate information. The aim of MedCOF is to strengthen the collaboration between the Regional Associations I and VI in developing capacities for the Climate Services Information System within the Global Framework for Climate Services (GFCS). MedCOF brings together all the member countries of the South-Eastern Europe Climate Outlook Forum (SEECOF) and those of the forum of Prévisions Climatiques Saisonnières en Afrique du Nord (PRESANORD) and France, Italy, Jordan, Lebanon, Malta, Mauritania, Portugal, Spain and Syria. The first forum was conducted in November 2013 by the Republic Hydro-meteorological Service of Serbia in Belgrade. Since then, the forum has been conducted twice per year through teleconference in May-June and in an assembly in November. The forum stands for an opportunity to member countries to exchange information on the last and current knowledge of climate conditions. Besides, it promotes training and operational activities on seasonal timescales. In particular, the MEDSCOPE project—in which AEMET and other active institutions in MedCOF participate—part of the European initiative ERA4CS, substantially contributes to MedCOF by supporting training tasks and the development of specific tools for the Mediterranean region. The following countries are currently participating in MedCOF:

- PRESANORD: Algeria, Egypt, Libya, Morocco, Tunisia
- MIDDLE EAST: Jordan, Lebanon, Syria
- WEST EUROPE : France, Italy, Malta, Portugal, Spain
- SEECOF: Albania, Armenia, Azerbaijan, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Georgia, Greece, Hungary, Israel, Macedonia, Moldova, Montenegro, Romania, Serbia, Slovenia, Turkey, Ukraine

1.10.1.2 Future Resilience for African Cities and Lands (FRACTAL), Botswana, Malawi, Mozambique, Namibia, South Africa, Zimbabwe and Zambia

This initiative is a trans-disciplinary group of researchers from partner organisations around the world. FRACTAL aims to advance scientific knowledge about regional climate responses to human activities. Together with a broad range of stakeholders, researchers are working to co-produce relevant knowledge that will support resilient development pathways and enable decision-makers to better integrate pertinent climate knowledge into their resource management decisions and urban development planning.

FRACTAL was initiated in June 2015 as a four year project. A funded extension phase was completed in mid-2021. It is coordinated by the Climate Systems Analysis Group at the University of Cape Town. It is part of the multi-consortia Future Climate for Africa (FCFA) programme – jointly funded by the UK's Department for International Development (DFID) and the Natural Environment Research Council (NERC).

1.10.2 Western Africa

1.10.2.1 EVIdENCE: Extreme rainfall events, vulnerability to flooding and water contamination

Many cities in Africa, which are undergoing rapid demographic and spatial expansion, are experiencing an upsurge in flooding caused by extreme rainfall. While the primary cause could be an increase in extreme rainfall linked to climate change, rapid and poorly planned urbanisation is exacerbating the phenomenon. Abidjan, a city of 6 million people, is no exception. Every year, the rains cause material damage and loss of life.

The impact of rainfall hazards is heightened in areas of the city where rainwater drainage networks are deficient or missing. The functionality of the network is closely linked to the uses made of it by the population and to the management of solid waste and wastewater by the local authorities. The poorest populations are generally the most vulnerable, often occupying areas of the city that have been left vacant because of the risks involved (gullies, low-lying flood areas, steep slopes).

In addition to flooding, floods generated by intense rainfall affect the environment in the absence of sanitation. Rainfall erodes and washes away the urban fabric, generating large flows of solid waste and contaminants that can alter groundwater and surface water resources.

The aim of this project is to help reduce the risks associated with extreme rainfall, which has an impact on the living conditions of urban populations. Two risks will be examined: the risk of flooding and the health risk posed by massive flows of contaminants during flooding [14].

1.10.3 Eastern Africa

1.10.3.1 Intergovernmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAC) EAST AFRICA

ICPAC provides climate information, early warning services, and climate change adaptation strategies across eight East African countries. It focuses on mitigating climate-related security risks and enhancing the adaptive capacity of the region.1.11.5.2 UMFULA (Uncertainty reduction in Models for Understanding Development Applications), Malawi and Tanzania

UMFULA (‘river’ in Zulu) is an international research project led by the Grantham Research Institute that aims to address critical knowledge gaps in the understanding of the region’s climate and communicate effectively climate information to decision-makers; both are crucial to enable climate resilient development in Central and Southern Africa.

1.10.3.2 Future Climate for Africa (FCFA)

As the final curtains come down on the FCFA programme, the impacts and outcomes of the programme will live on for many years. FCFA was one of the largest single investments in African climate science to date, and delivered considerable advances in understanding what drives the climate across the continent and what the future of climate change might look like. While the progress made within the programme life span was considerable, there are still several research gaps which limit our ability to understand Africa's climate. and how it may change.

In a new brief outlining the value of continued investments in science for Africa, we highlight the scientific achievements made within FCFA and why there is need for further investment in this regard. One of the key ingredients to the success of FCFA's achievements was the collaborative nature of the programme. Working within large research consortia on a shared goal to improve the understanding of Africa's climate allowed researchers to "hunt in packs". This approach meant researchers could pool knowledge and resources, share learning and emerging results to rapidly build off each other's' progress.

Priority research gaps for future research:

Despite the significant progress made within the climate science space, there are still significant research gaps inhibiting our understanding of Africa's climate. It's important for future research to catalyse off advances made from FCFA, to further improve the understanding of Africa's climate. Some key gaps still exist in understanding the water cycle, including the degree of future change, high impact events such as hail and fog, feedback between land surface temperatures and soil moisture; as well as understanding the impact of atmospheric aerosols. A key area of FCFA's progress was improving understanding of model biases and errors of key climate processes in Africa. High resolution convection permitting models (such as CP4-Africa) should be prioritised to further examine model representation of large-scale weather features across Africa. This will help provide further insights into how well models are capturing large scale processes (such as mega storm or cloud bands) which drive the climate over Africa. But beyond fostering collaboration between climate scientists, FCFA supported interdisciplinarity and trans disciplinarity between a range of experts, decision makers and stakeholders to produce relevant climate information [15].

1.10.4 Southern Africa

1.10.4.1 Long-Term Adaptation Scenarios Flagship Research Programme (LTAS)

This program responds to the South African National Climate Change Response White Paper by conducting climate change adaptation research and scenario planning. It is led by the Department of Forestry, Fisheries, and the Environment (DFFE) in collaboration with the South African National Biodiversity Institute (SANBI) and supported by the Gesellschaft für Internationale Zusammenarbeit (GIZ). The research encompasses various sectors, including agriculture, forestry, biodiversity, human health, and marine fisheries.

1.10.4.2 Climate Change Resilience through South Africa's Water Reuse Programme (WRP)

This project aims to address water scarcity by transforming the wastewater system into a resource-efficient one. It involves creating a national water reuse program to mitigate the effects of climate change on water resources. The project is supported by the Green Climate Fund (GCF) and aims to stimulate economic growth while ensuring water security for the future.

1.10.4.3 Green Fund

Managed by the DFFE, the Green Fund supports the transition to a low-carbon, resource-efficient, and climate-resilient development path. The fund facilitates projects that deliver economic, environmental, and social benefits, promoting sustainable development across South Africa.

KADI

Part II: Recommendations to scientific institutions and programmes contributing to the delivery of Climate Services in Africa

2.1 Universities and research institutions

Universities and research institutions will be key for scientific support as well as usage of research infrastructure. Many of them have already been listed as important stakeholders in KADI Deliverable 5.1. This section provides a list from the scientific usage point of view (Table 1 and Table 2). This is a prerequisite for improving the scientific usage of the data. Scientific analysis of the data is an important step in the value chain from observations to political impact through climate services.

KADI

Table 1: List of Universities and their Research Institutes with Climate Science and Teaching

University name	Country	Institute	Teaching
University Felix Houphouet Boigny (UFHB)	Côte d'Ivoire	Laboratoire des Sciences de la Matière, de l'Environnement et de l'Energie Solaire (LASMES)	MSc and PhD programs related to renewable energy, solar energy, and environmental science
University Cheick Anta Diop (UCAD)	Senegal	Sciences et Technologies Sciences Economiques et de Gestion	PhD in Science and Technology, majoring in Engineering Sciences, specialising in Climate, Atmospheric and Ocean Sciences Professional degree in economics, specialising in agricultural statistics, evaluation of climate change policies
University Abdou Moumouni (UAM)	Niger	Faculty of Science and Technology	Atmospheric physics and climate
University Ki Zerbo	Burkina Faso	Doctoral School in Computer Science and Climate Change (ED-ICC)	Computing and climate change
University of Nairobi	Kenya	Institute for Climate Change and Adaptation (ICCA)	MSc and PhD programs in Climate Change Adaptation and Mitigation
University of Rwanda	Rwanda	College of Science and Technology (CST)	MSc in Atmospheric and Climate Sciences

University of Cape Town	South Africa	African Climate and Development Initiative (ACDI)	MSc in Climate Change and Sustainable Development
North West University	South Africa	Centre for Environmental Management and Unit for Environmental Sciences and Management	MSc in Environmental Sciences with specializations in Climate Change, Environmental Management, and Sustainability
University of Pretoria	South Africa	Centre for Environmental Studies	MSc in Environmental Management with a focus on Climate Change
University of Kwazulu-Natal	South Africa	Centre for Environmental Management	MSc in Climate Change and Environmental Management
University of Witwatersrand	South Africa	Global Change Institute (GCI)	MSc in Climate Change and Sustainable Development; Research programs in Earth Sciences and Climate Change
University of Dar es Salaam	Tanzania	Centre for Climate Change Studies (CCCS)	MSc in Climate Change and Sustainable Development
University of Ibadan	Nigeria	Centre for Sustainable Development (CESDEV)	MSc in Environmental and Climate Change Science
University of Lagos	Nigeria	Centre for Climate Change and Environmental Research	MSc in Climate Change and Environmental Management

Federal University of Technology, Akure (FUTA)	Nigeria	School of earth and mineral science (SEMS)	Meteorology Marine Science and Technology Remote Sensing and GIS
University of Addis Ababa	Ethiopia	Institute of Climate and Society	MSc in Climate Change and Development
University of Ghana	Ghana	Institute for Environment and Sanitation Studies (IESS)	MSc in Climate Change and Sustainable Development
Kwame Nkruma University of Science and Technology, Kumasi	Ghana	Department of Meteorology and Climate Science	Msc and PhD in Meteorology and Climate Science
University of Cape Coast (UCC)	Ghana	Department of Physics Department of Fisheries & Aquatic Science	B.Sc Meteorology and Atmospheric Physics Msc. and Ph.D Oceanography and Limnology
University of Botswana	Botswana	Okavango Research Institute (ORI), Centre for Scientific Research, Indigenous Knowledge, and Innovation (CesrIKi)	MSc and research programs focusing on Climate Change, Ecosystem Dynamics, and Water Management
University of Cape Verde	Cape Verde	International Centre for Climate Research and Applications (CIICLAA)	MSc in Climate, Natural Resources and Risks

Université des Sciences et de la Technologie Houari Boumediene (USTHB)	Algeria	Laboratory of Environmental Science and Technology (LEST)	MSc in Environmental Science and Climate
University of Tlemcen	Algeria	Pan African University Institute of Water and Energy Sciences (PAUWES)	MSc in Climate Change (Technical and Policy tracks)
University of Algiers	Algeria	Faculty of Earth Sciences, Geography, and Territorial Planning	MSc in Climate and Environmental Sciences
University of Oran	Algeria	Faculty of Earth Sciences	MSc in Climate Change and Environmental Management
Cadi Ayyad University	Morocco	Faculty of Sciences and Techniques	MSc in Climate Change and Sustainable Development
Mohammed V University	Morroco	Faculty of Sciences	MSc in Climate and Environmental Sciences
University of Carthage	Tunisia	National Institute of Marine Sciences and Technologies	MSc in Climate Change and Marine Sciences
University of Tunis El Manar	Tunisia	Faculty of Sciences of Tunis	MSc in Environmental Sciences with a focus on Climate Change
Makerere University	Uganda	College of Agricultural and Environmental Sciences	MSc in Climate Science and Environmental Management
University of Yaoundé I	Cameroon	Laboratory for Environmental Research and Climate Change	MSc in Environmental and Climate Change Science

University of Kinshasa	Democratic Republic of the Congo	Centre for Climate Change and Environmental Studies	MSc in Climate Change and Environmental Management
University of Bangui	Central African Republic	Institute of Environmental Sciences	MSc in Climate Change and Sustainable Development
Cairo University	Egypt	Institute of Environmental Studies and Research	MSc in Environmental Studies and Climate Change
Alexandria University	Egypt	Institute of Graduate Studies and Research	MSc in Environmental Studies and Climate Change

Table 2: Research projects and institutions supporting climate science in Africa.

Project/Institution	Networking	Involvement in research/ Mobility within the project	Achievements and challenges	Contribution of the project to RI building
WASCAL	BMBF; ECOWAS; universities Strong networking system across West Africa	Trains west African researchers; WASCAL has trained more than 200 PhD; Build many infrastructures over West Africa; Reinforcement of research capacities. Transdisciplinary research project.	Mobilities of researchers Germany-Africa across West Africa	Provides courses. Designing common curricula for training courses.
SASSCAL	BMBF; South and East Africa	Transdisciplinary Projects Support for higher education and research	Mobilities Germany-Africa across south and east Africa	Provides courses. Designing common curricula for training courses;

Africa Higher Education Centre of Excellence (ACE)	Association of African Universities (AAU). ACE I: 22 Centres of Excellence in nine (9) countries across West and Central Africa ACE II: East and Southern Africa with 24 centres across 8 countries	Support Higher Education institutions in specializing in Science, Technology, Engineering and Mathematics (STEM), Environment, Agriculture, applied Social Science / Education and Health.	Half-yearly reviews during workshops attended by all the centres, enabling experiences to be shared and shortcomings to be corrected.	Benefit from the ACE network & apos;s infrastructure assets
International joint laboratories (LMI)	Gather research institutes and NMHS, Researchers from North and South West and Central Africa (24); Latin America and the Caribbean (17); Asia (12); Mediterranean (9); Eastern and Southern Africa and the Indian Ocean: 4	Transdisciplinary subjects involving different research teams. Supporting the strengthening, empowerment and international influence of higher education and research systems in countries in the Mediterranean and inter-tropical zone	Research development; training and innovation activities, based on joint projects using a common platform; Shared governance between the partners (North-South). A long-term partnership	Benefit from intercontinental networking Benefit from the various scientific achievements of the LMI
Partnership for skills in Applied Sciences, Engineering and Technology (PASET)	More than 25 African countries, as well as representatives of Brazil, China, India, Japan and Korea have participated in PASET's various activities.	Strengthen institutional capacity for quality and sustainable doctoral training, Research and innovation in transformative technologies in sub-Saharan Africa. Regional Scholarship to support research and Innovation Fund (RSIF); PhD scholarships and fosters partnerships between African and international universities. promotes mobility by facilitating internships and collaborative research projects.	Establishment of the RSIF, funded numerous PhD students and research projects. Development of a critical mass of skilled professionals in applied sciences and technology. Limited funding and resources to expand research infrastructure.	Enhancing the capacity of universities and research centres, promoting regional collaboration, and supporting the development of high-quality research programs in applied sciences and technology.

African NMHS SODEXAM/ SAWS (South African Weather Service)	National, regional and international collaboration WMO; CSIR	Provide climate data for research; student internships; Collaboration with research institutes and universities; Actively involved in research initiatives.	Development of forecasting products over the continent; Enhancement of decision-making and planning in key socioeconomic sectors. Low coverage of stations; Data not freely available;	Partnership with NMHS and providing meteorological data in designing RI; Meteorological Prevision; Early Warning system; Climate Modeling; Design climate services; Plays a crucial role in the RI building.
LAMTO	Collaborations: Many north-south; national and international institutions, including the Universities (UFHB, UNA), ENS in Paris Etc.	Host research programs and measurement units (weather; chemistry; environment). Research on tropical savanna ecosystems and seismology; student internships. Several PhDs carried out	Savanna ecosystems study, theses and scientific publications. Maintain a 100-hectare savanna area protected from bushfires since 1962 for research purposes. Limited funding and the need.	Ecological, physico-chemical and geophysical data, supporting biodiversity conservation, and contributing to the development of sustainable practices in Côte d'Ivoire. Installation of new measurement tools for the RI;
African Centre of Meteorological Applications for Development (ACMAD)	Regional climate centres (RCC) Global level, Regional level, National level (NMHS)	Capacity Building; research methods and tools development; Strengthening Africa's contribution to global weather and climate programs; Establishes and shares databases	Enables NMHS to benefit from funded programs through continental projects with NMHS as the main target group. Limited funding and resources, which impact the ability to expand observational networks	Enables provision of weather/climate monitoring, forecasts and regional early warning on drought, tropical cyclones and other extreme weather/climate events

			and improve forecasting accuracy.	
HPC (Côte d'Ivoire ; South Africa ; Sénégal, etc.)	Regional integration tools in scientific research domains (ECOWAS, CEMAC)	Research support tools. Contribute to students training; Capacity building on climate modeling; Facilitate the networking;	HPCs contribute to human capital development HPCs outside South Africa most of them do not work properly; electricity; Support the innovation within the IR	Data Storage; Computing system within the RI;

2.2 Integrating Programs

2.2.1 Interdisciplinary Policy-Oriented Research on Africa (IPORA)

The IPORA (2002-2030) analyses the multidimensional and systemic aspects of the new challenges facing African societies, by creating a new, more interdisciplinary type of research network. The project brings together four universities: the University of Bordeaux (France), the Félix Houphouët-Boigny University of Abidjan (Côte d'Ivoire), Addis Ababa University (Ethiopia) and the International University of Rabat (Morocco), with the support of Sciences Po Bordeaux, Inserm, IRD and the University of Bordeaux Montaigne.

2.2.2 National Climate Change Management System Support Program

This program, started in 2018, aims to strengthen institutional capacities for climate data management and the integration of climate considerations into national policies. It is cofinanced by the United Nations Development Programme (UNDP). This program targets specific countries in Africa, including Ghana, Kenya, Mozambique, Uganda, and Zambia. These countries are part of the initiative to enhance their ability to manage and utilize climate data effectively.

2.2.3 National Climate Change Program (NCCP)

The NCCP has been ongoing since 2018, targeting specific countries in Africa, including Ghana, Kenya, Mozambique, Uganda, and Zambia. It coordinates national efforts in data collection and research on climate impacts, in collaboration with various ministries and institutions. It includes activities to raise awareness and build local capacity to respond to climate challenges.

2.2.4 National Framework of Climate Services (NFCS)

NFCS, initiated by WMO has been ongoing since 2018. It supports the Paris Agreement, which aims to strengthen the global response to the threat of climate change, by ensuring the availability of science-based research and systematic observations for decision-making. NFCSs help countries who are part of the Paris agreement prepare, maintain and communicate their Nationally Determined Contributions (NDCs). NFCSs also complement National Adaptation Plans (NAPs) by providing climate services that help in assessing climate vulnerabilities, identifying adaptation options, developing products that help improve the understanding of climate and its impacts, and enhancing the adaptation planning and implementing capacity of climate-sensitive sectors. The NFCS helps countries, including Mauritania, Mali, Niger, Senegal, Gambia, Chad, Guinea-Bissau, Guinea, Burkina Faso, Benin, Nigeria, Sierra Leone, Ethiopia, Côte d'Ivoire, Liberia, Togo, Cameroon, Congo, Rwanda, Tanzania, Malawi, Madagascar, and South Africa, prepare, maintain, and communicate their Nationally Determined Contributions (NDCs).

2.2.5 Research Program on Climate Change and Sustainable Development in Africa (CCDA)

This program, ongoing since 2006, aims to promote research on climate change and its impacts in Africa through collaborative research projects, training and scientific co-publications.

2.2.6 RIAS Project (Strengthening African Institutions in Science and Technology for Climate Change Adaptation)

The RIAS project ran from 2020 to 2022, aim to build the capacity of African institutions, including those in Côte d'Ivoire, to better understand climate impacts and develop adaptation strategies, through the development of regional climate models specific to West Africa and the training of local researchers in the use of these models.

2.2.7 CORDEX Program (Coordinated Regional Climate Downscaling Experiment)

The CORDEX Program has been ongoing since 2009, focusing on downscaling global climate models for West Africa, to provide high-resolution climate projections for regions around the world, including West Africa. Developments and validation studies of regional climate models are underway at the National Computing Centre to better understand climate change on a local scale.

2.2.8 PRECIS project (Providing Regional Climates for Impacts Studies)

Initiated by the UKMO, PRECIS project (ongoing since 2002) uses the PRECIS regional model to generate detailed climate scenarios tailored to the needs of African Regions, facilitating the assessment of climate change impacts at the local scale.

2.2.9 National program for the fight against Climate Change (PNLCC)

The PNLCC has been ongoing since 2018, coordinating national efforts to mitigate greenhouse gas emissions and adapt to the impacts of climate change. More specifically, it aims to improve the integration of mitigation strategies into sectoral policies and increase funding for adaptation projects, and to oversee the inventory of greenhouse gases (GHGs) and data for adaptation in vulnerable sectors (agriculture, water, health), as well as institutional capacity building.

2.2.10 REDD+ Project (Reducing Emissions from Deforestation and Forest Degradation)

REDD+ (2021-2025) in African countries aims to reduce emissions by promoting sustainable forest management through remote sensing forest monitoring, forest inventories and reforestation programs.

2.2.11 WACA Program (West Africa Coastal Areas Management Program)

The WACA Program has been ongoing since 2015, aiming to improve the resilience of coastal ecosystems and communities to the impacts of climate change. Priority activities include mangrove protection and restoration, sustainable coastal resource management, and monitoring ecosystem changes along coastal zones.

2.2.12 PANA Project (National Adaptation Action Plan)

The PANA Project has been ongoing since 2001, targeting Least Developed Countries (LDCs) globally, with specific implementations in African countries.
It aims to:

- Integrating climate change concerns into ecosystem and biodiversity management.
- Develop and implement national adaptation plans to cope with the effects of climate change.
- Assess the impacts of climate change on critical ecosystems, such as forests and wetlands, and develop adaptation strategies to protect biodiversity.
- Identify climate vulnerabilities, assess adaptation needs, and develop policies and projects to strengthen community resilience.

2.2.13 African Cities Adaptation to Climate Change Project (VACC)

This project which began in 2018, focuses on adapting urban infrastructures and improving the resilience of urban communities to the impacts of climate change. Abidjan is one of the pilot cities benefiting from this program, in partnership with organizations such as UNDP and UN-Habitat.

2.2.14 Agriculture Adaptation and Food Security (AASR) program

The VACC project has been ongoing since 2018, aiming to improve the resilience of African agriculture to climate change and develop drought-resistant crop varieties, sustainable water management and improved early warning systems.

2.2.15 National Climate Change Management Program

The National Climate Change Management Program has been ongoing since 2018, targeting specific African countries such as Kenya, Ethiopia, Uganda, Tanzania, Rwanda, Ghana, Nigeria, and South Africa to implement concrete actions to mitigate the impacts of climate change and adapt agricultural infrastructures and practices, draw up management plans, collect data on greenhouse gas emissions, and promote agroforestry and sustainable agricultural practices.

2.2.16 Integrated Coastal Zone Management Support Project (PAGIZC)

The PAGIZC project has been ongoing since 2018, aiming to manage coastal zones sustainably to minimize the impact of climate change and protect marine and coastal ecosystems, monitor coastal ecosystems, contribute to sustainable urban planning and restore mangroves.

2.2.17 Sustainable Land Management and Adaptation to Climate Change Project (PGDT-ACC)

The PGDT-ACC project has been ongoing since 2018, promoting sustainable agricultural practices in response to climate change in African countries through:

- Studies on land degradation and sustainable management, reforestation initiatives, and adoption of resilient agricultural practices.
- Resilient agricultural practices, reforestation, and community education on climate adaptation.

2.2.18 Forest and Biodiversity Sector Development Program (ProDEF)

The ProDEF program has been ongoing since 2018, aiming to strengthen the sustainable management of forests and biodiversity to mitigate the effects of climate change in African countries. The main activities concern forest conservation, reforestation and natural resource management.

2.2.19 Climate Change Agriculture and Food Security (CCAFS)

The CCAFS program ran from 2010 to 2021, addressing the challenge of global warming and declining food security on agricultural practices, policies and measures through a strategic collaboration between CGIAR and Future Earth. It focused on climate-smart agriculture in African regions. CCAFS contributed to catalyze positive change for climate-smart agriculture and played a major role to bring to scale the practices, technologies and institutions that enable agriculture to meet triple goals of food security, adaptation and mitigation. The CCAFS-Climate data portal provides global and regional future high-resolution climate datasets that serve as a basis for assessing the climate change impacts and adaptation in a variety of fields including biodiversity, agricultural and livestock production, and ecosystem services and hydrology.

2.3 Conclusion and Recommendations

Science is essential in the fight against climate change. Indeed, the significant contribution made by research and education institutions around the world has enabled significant progress to be made. Science is the basis for the various innovations. The African continent, one of the most vulnerable to the effects of climate change, has few renowned universities and research institutions. Where they exist, most are not included in global university rankings. Training and knowledge exchange is key to success on building research infrastructure in Africa. The potential of data is highly untapped. This should be streamlined and mainstreamed. Africa's

greatest human resource, the youth, are digitally skilled. Systematically integrating teaching strategies into education that enables the youth to master the interface between digital skills and technology's potential to address societies' pressing needs is critical. In terms of scientific research and training, Africa faces enormous challenges, including inadequate facilities for researchers and trainers, limited training frameworks, data availability, low density of measurement networks and standardisation of training. This highlights the need to restructure research in Africa to fill these gaps. The development of a research infrastructure could make it possible to address the challenges of climate and environmental data management, strengthen networking, increase knowledge sharing and build the capacity of stakeholders. The creation of research infrastructure will enable countries to respond to/address the various climate challenges, develop appropriate adaptation measures and help them achieve their global climate objectives. To achieve its objectives, the KADI project builds on the achievements of previous projects and initiatives.

The various research programmes inventoried on the African continent show, on the one hand, the scientific community's willingness to work together to standardise efforts with a view to obtaining convincing results. On the other hand, the multi-disciplinary nature of the programmes means that different aspects can be considered simultaneously to be more effective. Many of these programmes have enabled obtaining measurement tools, data acquisition, reinforcement of the networking across the continent. However, despite that efforts some need to be done. Hence the ambition of the KADI programme which is to build a comprehensive concept for an African research infrastructure. By identifying the key players to operate the research infrastructure, search for sustainable funding, and build a solid strategy for implementation.

The creation of research infrastructure will enable countries to respond to/address the various climate challenges, develop appropriate adaptation measures and help them achieve their global climate objectives. To achieve its objectives, the KADI programme will need to build on the achievements of previous programmes, hence the following recommendations:

2.3.1 Improving data collection and analysis methodologies

One of the key challenges in climate research is ensuring the accuracy and reliability of data. To improve the methodologies used in data collection and analysis, it is essential to invest in real-time data collection systems, with a focus on integrating remote sensing technologies and geographic information systems (GIS). These tools, supported by in-situ observations for small-scale information, ground-truthing and validation, will enhance the precision of climate observations. Moreover, standardizing data collection protocols at an international level will ensure the comparability of data, making it more useful for cross-border research and global climate assessments. Beyond technology, human capacity must also be developed by training researchers and technicians in critical areas such as climate modelling, remote sensing, and data management, which are essential for accurate analysis and interpretation of climate data.

2.3.2 Partnerships for climate research and development

Collaboration plays a pivotal role in the advancement of climate research. Establishing robust partnerships between national institutions and international research organizations, including non-governmental organizations (NGOs), will facilitate the exchange of knowledge, resources, and expertise. These

collaborations are particularly valuable in regional projects, where data and resource sharing across borders can provide a more comprehensive understanding of climate dynamics. Additionally, fostering collaboration between stakeholders, including the beneficiaries of climate services, ensures that the outcomes of research are directly applicable to community needs. Such co-production of knowledge is crucial for ensuring that research findings lead to practical, actionable solutions.

2.3.3 Connect with international training opportunities

Organisations of the UN family like WMO, the United Nations Institute for Training and Research (UNITAR), the United Nations Environment Program (UNEP), the UN Climate Change Learning Partnership (UN CC:Learn) and the United Nations Framework Convention on Climate Change as well as international organizations/initiatives focussing on atmospheric and climate related topics such as European Commission's Copernicus service, EUMETSAT or NASA do offer a wide range of training opportunities, which are often open to professionals world-wide. Progress in an all-African RI could profit from a wide participation of local professionals in those training events. Trainees could range from operators, data managers, data analysts, to the management level, responsible for strategic decisions and the allocation of funds.

2.3.4 Institutional capacity building

For climate policies to be effective, national institutions must possess the capacity to collect, manage, and analyze climate-related data, particularly regarding greenhouse gas (GHG) emissions. Strengthening the institutional infrastructure involves not only technological investment but also the continuous professional development of individuals working in climate-sensitive sectors. Creating education programs that target these professionals can guide industries towards adopting low-carbon development strategies. International and regional collaborations are also essential for the transfer of knowledge and technology, allowing national institutions to stay at the forefront of climate science and policy development.

2.3.5 Sustainable financing for climate research

Climate research requires consistent and diversified funding sources to remain effective. To this end, national institutions must be equipped to secure financing from global climate funds, such as the Green Climate Fund, and develop the necessary expertise in proposal writing and project management. At the same time, local initiatives should be encouraged and supported through subsidies or national funding programs. Expanding financial avenues to include public-private partnerships and access to international climate funds will ensure the sustainability of research projects. This diversified funding approach not only stabilizes financial support but also increases resilience against economic challenges that may impact climate research in the long term.

2.3.6 Integrating climate data into planning and policy

The inclusion of climate data in both urban and rural planning is essential for mitigating the risks posed by climate change. Governments need to incorporate future climate projections into infrastructure planning to bolster resilience against extreme weather events and other climate-related challenges. This requires a

concerted effort to bridge the gap between research and policymaking. Climate research findings should inform national development strategies, helping to guide decision-making processes across sectors such as agriculture, energy, and industry. Such integration ensures that development strategies are sustainable and responsive to evolving climate conditions.

2.3.7 Improving Research Infrastructures (RI)

Modernizing research infrastructures is crucial for fostering innovation and advancing climate science. Investment in cutting-edge environmental monitoring equipment and upgrading research laboratories will enable researchers to conduct high-quality studies that contribute to climate resilience. Equally important is the promotion of green technologies and nature-based solutions that can help mitigate climate change impacts. Encouraging technological innovation not only drives scientific progress but also enables the development of practical tools and strategies for adaptation and mitigation. A strong infrastructure base will facilitate ongoing research and ensure that climate studies remain at the forefront of scientific discovery.

2.3.8 Awareness and community involvement

The success of climate initiatives depends heavily on the engagement of local communities. By involving communities directly in research projects and emissions reduction programs, researchers can ensure that these initiatives are both effective and sustainable. Community participation provides valuable local insights and encourages long-term commitment to climate adaptation strategies. Additionally, involving communities in the decision-making process fosters a sense of ownership and accountability, which is key to the lasting success of climate initiatives.

2.3.9 Integrating research findings into public policy

Research findings should serve as the foundation for public policy related to climate change. The incorporation of scientific evidence into policy planning ensures that climate strategies are both data-driven and effective. This requires a multidisciplinary approach, where research from various fields, including agriculture, energy, and industry, informs policymaking. Such integration promotes a holistic approach to climate governance, ensuring that policies are comprehensive and that they address the interconnected nature of climate challenges. By grounding policy decisions in research, governments can develop more robust strategies for mitigation and adaptation.

2.3.10 Networking and collaboration between African climate scientists

To address the diverse and complex challenges posed by climate change, it is crucial for African climate scientists to adopt transdisciplinary approaches. Networking and collaboration within Africa and between African and global research institutions can greatly enhance the capacity for climate research on the continent. Various programs, such as FRACTAL, CEA, WASCAL, and SASSCAL, have already established frameworks for collaboration between African and international institutions, yet much of this collaboration remains focused on North-South partnerships. There is a pressing need to strengthen intra-African networks

to ensure that researchers across the continent can collaborate more effectively. This will help build a solid foundation for the development of a pan-African research infrastructure.

2.3.11 Developing common curricula for climate studies

A unified approach to climate education across African universities is essential for developing a highly skilled workforce capable of addressing the continent's climate challenges. By designing common curricula, African universities can ensure that their graduates possess the necessary expertise to contribute to climate resilience and sustainable development. Programs such as WASCAL and SASSCAL have already demonstrated the potential for regional collaboration in climate education, offering master's and PhD programs in various climate-related fields. Expanding such initiatives across the continent will standardize education, facilitate student and faculty mobility, and enhance the overall quality of climate research in Africa.

2.3.12 E-learning for climate studies

The rise of e-learning during the COVID-19 pandemic has highlighted its potential for expanding access to education and research opportunities. E-learning offers numerous advantages, including cost savings and flexibility, which make it an ideal tool for fostering collaboration across Africa. However, technical challenges, such as poor internet connectivity, must be addressed to ensure that e-learning can be fully utilized. Incorporating e-learning into the development of pan-African research infrastructures will facilitate remote training, meetings, and data sharing, enabling researchers from across the continent to engage in collaborative projects without the need for extensive travel

2.3.13 Exchange programs for researchers and university teachers

Exchange programs play a pivotal role in fostering collaboration and knowledge sharing between African institutions. By facilitating the movement of researchers and educators across institutions, these programs allow for the exchange of ideas, methodologies, and best practices. Programs such as PASET and WASCAL provide valuable opportunities for doctoral students and researchers to gain experience in diverse academic and research environments. Expanding these exchange programs will strengthen research networks across Africa, promoting the development of a cohesive climate research community and enhancing the continent's capacity to address climate change.

2.3.14 Additional recommendations

- Strengthen connections between the global observation infrastructures, such as World Meteorological Organization Global Atmospheric Watch and the observations done in Africa. This allows comparability and harmonization of techniques and data. This will elevate the visibility of Africa as a global contributor for climate relevant observations.
- Support connections between thematic observation networks, such as Integrated Carbon Observation System (ICOS) and Aerosols, Clouds and TRace gases Research Infrastructure

(ACTRIS) and similar measurement activities in Africa to ensure comparability of methodologies, data and data interpretation.

- Support co-location of thematic observations and infrastructures, when possible. For example, climate parameters, ecosystem observations and parameters important for air quality. This would support multidisciplinary science and education as well as data driven decision making to tackle interconnected grand challenges.
- Support provision of open and harmonized data streams into local, regional, continental and global data platforms while ensuring the data ownership to the local data providers. This will increase level of science and expand possibilities for innovation.
- Support development of a (cross-RI) access programme where especially physical access would be provided to facilities for north-south and south-north direction, supported by global (IMF?) or EU considering the specific financial and administrator needs for such an access program.
- Create a framework for exchanges between the various international programmes and the structures responsible for higher education with a view to achieving the objective of harmonising training curricula all over the continent.
- Sub-regional organisations such as ECOWAS, CEMAC, the Francophonie, the Commonwealth, the African Union, etc. should support programmes to standardise higher education curricula.
- Technical and financial partners, such as the World Bank, the European Union, the IMF, IDRC, AFD, IRD, etc., should also be involved.
- Extend programmes such as WASCAL, SASSCAL, LMI, CEA, etc. to all the African sub-regional blocs to strengthen the mobility of students, researchers and teachers in Africa.
- Strengthen South-South and North-South mobility through federative and transdisciplinary projects.
- Encourage programmes or areas of programmes that focus on gender equality. One example is the WAfriCLP programme, which promotes female leadership in Africa.
- Train stakeholders in the use of e-learning technologies to facilitate their use by the community,
- Improve Internet connection in universities and make them free for users.

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