KADI

Report on optimum integration of modelling into the envisaged research infrastructure

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Executive Summary

Knowledge and Climate Services from an African Observation and Data Research Infrastructure (KADI) project, is providing concepts for developing the most advanced scientific research and science-based climate services for Africa. This is to enhance its climate research, improve and expand its observational capabilities, needed to tackle critical environmental and climate change challenges, and inform its climate action. Embedding climate modelling as a core and dynamic component of research infrastructures is essential for delivering climate services that effectively addresses user needs. Climate service pilot Task 2.1 focused on evaluating and enhancing the representation of land-surface processes within an Earth system model (ESM) over Southern Africa. Specifically, it evaluated the land-surface parameterizations in the CCAM-CABLE model. The findings indicate that the model performs well in simulating key seasonal and diurnal land-atmosphere fluxes. However, its performance varies by location, highlighting the need for validation across diverse biomes and climatic regions on the continent. While this work has a regional emphasis, future analyses incorporating Earth observation data on biomass and soil moisture across Africa will be essential for identifying hotspots of interannual carbon flux variability and understanding their drivers. In this document we provide an inventory of existing modelling infrastructure, including centres that support climate services in sub-Saharan Africa. It highlights how modelling aligns with research goals, such as seasonal prediction, climate attribution, future projections, impact studies, and ultimately decision-making. By demonstrating the role of modelling in addressing climate change and fostering interdisciplinary collaboration, it emphasizes the broader implications for climate action. The report also provides recommendations proposing mechanisms for the integration of real-time and historical observational data into modelling, to strengthen climate services provision in Africa. Some of these entails model evaluation and optimisation to identifying fit-for-purpose models tailored to specific research questions and available data; enabling the integration of diverse datasets through standardised formats and protocols for seamless sharing and model interoperability; leveraging advanced computational tools by investing in High Performance Computing (HPC) or cloud computing resources to handle complex and large-scale simulations, as well as incorporate Artificial Intelligence and Machine Learning techniques to optimize parameterisation, enhance predictions, and uncover patterns. Finally, by facilitating

collaborative infrastructure, interdisciplinary collaboration and supporting integrated assessments. This deliverable underscores KADI's commitment to building a cohesive research infrastructure by leveraging existing modelling resources, fostering international partnerships, and advancing capacity-building efforts. Through these initiatives, KADI aims to enhance climate resilience and promote sustainable development across Africa, aligning with global objectives such as the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs).

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Introduction

Climate change is a pressing global issue, affecting both human and natural ecosystems. Africa is warming faster than the global average (IPCC, 2021) making the continent particularly vulnerable to impacts of climate change. These heightened challenges require urgent, concerted, multidisciplinary efforts, focused on assessing changes in the regional and local climate that can inform appropriate mitigation and adaptation actions (Trisos et al., 2022; Gwiza & Jarbandhan 2024). Earth system models (ESMs), which employ mathematical and computational techniques to simulate the earth climate system, continue to advance our understanding of the changes in different variables. The climate system can be understood from multiple viewpoints, thus can be represented through various distinct models. A model, being an abstraction of reality, offers a particular perspective of a real-world system which is shaped by the assumptions and choices made during its development. Earth system modelling serves multiple roles; (i) as a method for organising knowledge, where data, assumptions, and understanding are systematically structured for a specific goal (Chen et al., 2008); (ii) a learning tool, in which models act as working hypotheses of how systems function, by which model evaluation becomes a form of hypothesis testing (Beven, 2006); and (iii) a boundary object, facilitating interaction among scientists, decision-makers, and stakeholders by providing a shared platform for communication and knowledge exchange (Lwanaga et al., 2021). Effective use of models requires thoughtful development to understand the model's inherent strengths and limitations; determine the most suitable configuration and tailor it to the specific application or region and evaluate the model's output by analysing biases, errors, and its performance across different spatial and temporal scales (Hewitson et al., 2004). For example, the report under Task 2.5 of this project used in situ data to validate the Earth system model (CCAM-CABLE), focusing on key processes such as net ecosystem exchange, latent heat, and sensible heat fluxes. This was carried out at six Expanded Freshwater Terrestrial Environmental Observation Network (EFTEON) eddy covariance flux tower sites in South Africa, representing diverse biomes and environmental conditions at diurnal, seasonal, and annual timescales. In addition, the study compared Earth observation-derived estimates of above-ground biomass and soil moisture with observations from these flux towers to detect potential biases at broader regional scales covered by the model. The model was found to perform well in most parts of the region.

This report, through the lenses of climate modelling, explores avenues for integrating climate modelling into the envisaged Pan-Africa climate service Research infrastructure (RI) designed to improve climate services delivery on the continent. With the observed rapid warming over the continent (IPCC, 2021), there is an increasing need for climate services to support a diverse range of climate sensitive sectors which employ more than 66% of the African workforce (Trisos et al., 2019; Akinsanola et al. 2025; Amakrane et al. 2023). Fit-for-purpose Africa Earth system models are crucial for analysing and simulating present-day climate and projecting future changes that support long-term climate planning, decision making and the deployment of appropriate climate action (Meque et al. 2021; Achour et al. 2025). Advances in the understanding of physical processes in different regions of the continent, model development and application of modelling output, though limited, is increasing in Africa. However, modelling efforts and the effective use of outputs to support decision making are still impeded by data limitations, inadequate infrastructure and modelling capacity and limited funding (Lamptey et al. 2024). Global cooperation and partnerships continue to play a critical role in ensuring these efforts are sustained (Timlin et al. 2024). This report provides recommendations on integrating modelling into the envisaged infrastructure to strengthen provision of climate services in Africa. It also reviews model providers, current collaborations, and suggests ways to improve collaboration for sustained long-term modelling services.

PART I

Modelling centres and infrastructure that support provision of climate services in Africa

1.1 Modelling Centres

Africa is making notable progress in earth system modelling through a variety of initiatives designed to enhance scientific understanding and develop/tweak models tailored to the continent's unique requirements (Gwiza & Jarbandhan, 2024). This section provides an overview of existing modelling infrastructures in Africa that continue to support and advance the understanding of climate system changes and their impacts on human and natural systems.

1. **South African Council for Scientific and Industrial Research (CSIR) climate and air quality modelling**

The climate and air quality modelling initiative at CSIR applies modelling expertise to simulate emissions, ambient (outdoor) air quality concentrations, and resultant impacts. Leaning on collaborative efforts of researchers in the Climate Services Research Group, the team also examines the connections between air quality and climate change, as well as conducting integrated vulnerability assessments. They make use of publicly available and open-source data. The CSIR also hosts Alliance for Collaboration on Climate and Earth Systems Science (ACCESS) and the Climate Services Research Group which are platforms for research and services that also conduct climate modelling.

2. **Climate System Analysis Group (CSAG)**

CSAG, based at University of Cape Town, is considered one of the top international climate research centres in Africa, with expertise in both the physical and social aspects of climate. It has experience in generating climate trends and projections, engaging with society with a rich history of capacity development.

3. **Southern African Development Community Climate Services Centre (SADC-CSC)**

The SADC Climate Services Centre offers regional services for monitoring and predicting extreme climate conditions. It develops and distributes meteorological, environmental, and hydro-meteorological products to support disaster risk management, helping member states better prepare for weather and climate-related hazards while promoting natural resource conservation. Established in 1990 as the Drought Monitoring Centre, it is one of four such centres across Africa and the only one serving the SADC region. As part of the SADC programme, it operates under the Infrastructure and Services (I&S) Directorate in the same location (co-located) with Botswana Meteorological Services. The Centre also provides climate prediction training for personnel in National Meteorological and Hydrological Services (NMHSs) and next user in weather-sensitive sectors such as agriculture, health, energy, water resource management, and transport, enhancing their ability to apply climate products and services effectively.

In fulfilling its mandate of promoting Regional Integration and Poverty Eradication, Meteorological Services in the Southern African Development Community deliver a range of services and operate specialised centres aimed at providing governments, businesses, and citizens with access to essential operational services and regional information. These services and centres are established in areas where regional access to information is most critical or where gaps previously existed in delivering such information at the regional scale.

4. **Global Change Institute (GCI)**

GCI is at the forefront of innovative climate modelling downscaling efforts over the southern African region, specializing in the development of high-resolution climate projections. The institute is not only renowned for its innovative scientific research but also for its expertise in transdisciplinary approaches towards climate action. By working closely with those directly affected by climate change, the GCI ensures that its research is both responsive to real-world needs and effectively translated into action, fostering meaningful engagement and impact.

5. **African Centre of Meteorological Applications for Development (ACMAD)**

ACMAD aims to understand the atmospheric and climatic processes over Africa, collect, analyse and disseminate meteorological and hydrological information, provide a meteorological watch and early warning system over Africa and promote the training of African scientists and technicians in the application of meteorology for development.

6. **Intergovernmental Authority on Development Climate (IGAD) Prediction and Applications Centre (ICPAC)**

ICPAC, headquartered in Nairobi Kenya, is a World Meteorological Organisation-accredited climate centre that delivers climate services to 11 East African states. It works to strengthen capacities in severe weather early warning systems, numerical weather prediction, computing and power storage, data collection and sharing across the member states. Its efforts focus on building resilience in a region heavily impacted by climate change and extreme weather events.

7. Regional Centre for Training and Application in Agro-Meteorology and Operational Hydrology (AGRHYMET)

Established in 1974, the AGRHYMET Regional Centre is a specialized institute of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS), comprising nine member states: Burkina Faso, Cape Verde, Chad, The Gambia, Guinea-Bissau, Mali, Mauritania, Niger, and Senegal. Headquartered in Niamey, Niger, AGRHYMET operates as an interstate public institute with legal status and financial autonomy. Its primary objectives are to enhance food security, boost agricultural production in CILSS member states, and improve natural resource management across the Sahel region.

8. National Hydrological and Meteorological Centres (NHMCs)

At least every country in Africa runs a national meteorological service that provides climate services at the state level. Some meteorological Centres have developed a National Framework on Climate Services, a tool that will guide Centres in engaging and coordinating actors and stakeholders along the national climate services value chain in developing and enhancing existing and planned management and operational systems and processes. These include observation networks, monitoring systems, user interface platforms, research, modelling and prediction, climate services information systems, and capacity building. These are indispensable ingredients for the successful co-design, co-development and delivery of climate information and services to the end user.

Table 1. A summary of the existing climate modelling centres in Africa including the modelling centre, the location, scale and services provided.

Modelling centre	Location	Scale	Services
South African Council for Scientific and Industrial Research (CSIR) climate and air quality modeling group	South Africa	Regional and national	Climate modelling, seasonal forecasting, regional downscaling, chemical transport modelling, emissions modeling and inventories and air quality management
Climate System Analysis Group (CSAG)	South Africa	Continental	Climate Modelling, Capacity building, online platforms, bespoke climate information and climate service research
Regional Specialised Meteorological Centre (RSMC)	South Africa	Regional	Numerical weather prediction products including weather forecasts and warnings, nowcasting and Meteo France Application of Research to Operations at Mesoscale (AROME) model outputs
Global Change Institute (GCI)	South Africa	Global	Climate projections
African Centre of Meteorological Applications for Development (ACMAD)	Niger	Continental	Weather and climate products
Intergovernmental Authority on	Kenya	Regional	Climate forecasting, disaster risk

Development Climate (IGAD) Prediction and Applications Centre (ICPAC)			management, water resources, climate information dissemination, agriculture and food security, environmental monitoring, capacity development and climate change
Regional Centre for Training and Application in Agro-Meteorology and Operational Hydrology (AGRHYMET)	Niger	Regional	Weather forecast and climate models and scenarios
Southern African Development Community (SADC) Climate Services Centre	South Africa	Regional	Disaster risk management using meteorological, environmental and hydro-meteorological products
National Hydrological and Meteorological Services	All countries	National	Climate modelling, seasonal forecasting, regional downscaling, Numerical weather prediction products including short and medium range weather forecasts and warnings, nowcasting

1.2 High-performance computational facilities in Africa

High-performance computational facilities are a key component of the delivery of these services. They improve the accuracy of the simulation of earth system complex processes. The use of these supercomputers has revolutionised climate modelling speed and storage demand. Africa host a few of such facilities, which could be leveraged by the envisioned CS RI:

9.1 National Integrated Cyberinfrastructure System (NICIS) Centre for High Performance Computing (CHPC)

The NICIS CHPC in South Africa provides advanced computing support to both the research community and industry across South Africa and the African continent. It offers access to high performance computing hardware, specialised software, and expert technical support for running domain-specific applications. One of its key resources is the Lengau (meaning "Cheetah" in Setswana) CPU cluster, which was launched in 2016, boasts more than 30,000 CPU cores and 3 petabytes of data storage and is ranked among the world's top 500 supercomputers. To assist SKA (Square Kilometre Array) partner countries, the CHPC has provided training and computational infrastructure to Botswana, Madagascar, Namibia, Zambia, Ghana, Mozambique, Kenya, and Mauritius. Additionally, institutions such as the University of Venda, Sol Plaatje University, University of Fort Hare, University of the Witwatersrand, Hartbeesthoek Radio Astronomy Observatory, and Stellenbosch University have received both training and equipment to support small-scale data processing.

9.2 University of CapeTown's High Performance Computing (UCT HPC)

The UCT HPC facility offers researchers a centralized, reliable, and scalable computing environment. By consolidating computing resources, UCT HPC provides an economical and environmentally friendly solution for computational research needs (UCT, 2025).

9.3 Morocco's National centre for Scientific and Technical Research

The National Center for Scientific and Technical Research (CNRST) in Morocco is a public institution focused on promoting scientific research. It functions to develop research infrastructure, fund scientific projects, and foster innovation. Its key functions include research and technological development, scientific information dissemination, and infrastructure strengthening by supporting national research facilities and collaborations. CNRST also facilitates international cooperation, allowing Moroccan researchers to participate in global scientific efforts. Its initiatives contribute to economic, social, and technological advancements, enhancing Morocco's position in scientific research.

1.3 Support for an African Earth System Model

Climate modelling in Africa has been beneficial in the prediction of extreme events, assessing climate change impacts, and informing policy decisions. Regional assessments of climate extremes in Coupled Model Intercomparison Project Phase 6 (CMIP6) models under shared socio-economic pathways in different regions of Africa, however, overestimates precipitation wet days and underestimate very wet days (Deepa et al., 2024). These have been linked to biases in model resolutions, convective parameterisation schemes in models, choice of reference data sets, atmospheric-land model interactions and other factors (Deepa et al., 2024).

An evaluation of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal Cubic Atmospheric Model (CCAM) concerning its effectiveness in simulating high-impact weather events, particularly focusing on rainfall predictions in southern Africa found that CCAM generally captures the spatial patterns of rainfall well, but underestimates the maximum rainfall of two heavy events by over 100 mm (Bopape et al., 2024). The simulations also struggle with pinpointing heavy rainfall inland and along the northeast coast.

For decades, Africa has relied on numerical weather and climate models developed and evaluated in the global north for operational forecasting and analysis of climate trends and projections and for policy development (Maisha et al 2025). These models are typically optimised for the regions where they were created, which can result in biases and limitations when applied in other areas. An assessment aimed at improving the performance of the CCAM over southern Africa, which is crucial for accurate simulations of weather and climate over the region, shows that the CCAM can reproduce the spatial and temporal distribution of a range of weather and climate events over the region. The model however depicts shortcomings, i.e. it underpredicts extreme events (Maisha et al 2025). Climate modelling predictions are however being used extensively across the continent to inform adaptation decision making, planning and strategy development for major crops (Adebayo, 2025). Its success in these areas has been important in reducing climate change impact in Africa's rainfed agricultural sector irrespective of its shortcomings.

ESMs are global climate models with the added capability to explicitly represent biogeochemical processes that interact with the physical climate and so alter its response to forcing such as that associated with human-caused emissions of greenhouse gases. This is a more holistic modelling approach that takes into consideration the interconnectedness of the earth system components such as the atmosphere, oceans, land surfaces, biosphere, cryosphere, and human interactions. Its emphases are on identifying the interactions and evolution of the subunits of the earth systems over time (Hamidi, 2022). In this section, we highlight an initiative that focuses on evaluating and improving the parameterizations of land-surface attributes in an Earth System Model that plays a central role in providing climate services in Africa.

1. Conformal Cubic Atmospheric model (CCAM)

CCAM is a variable-resolution global atmospheric model (Thevakaran et al., 2016), that was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in the 1990s (Bopape et al., 2022; Engelbrecht et al., 2011; Mcgregor, 2001; Thevakaran et al., 2016). Since CCAM is a variable resolution model, it can be run with a high resolution over a particular region of interest (Engelbrecht et al., 2011). Severe studies have applied CCAM to generate high resolution projections of climate change over southern Africa (e.g. Bopape et al., 2022; Engelbrecht et al., 2011). CCAM was developed in Australia and is an open-source model.

2. Community Atmosphere Biosphere Land Exchange (CABLE)

CCAM has a dynamic land-surface component called CABLE (CSIRO Atmosphere Biosphere Land Exchange). CABLE is a dynamic land surface model that calculates fluxes of momentum, energy, water and carbon between the land surface and the atmosphere (Kowalczyk et al., 2006). This model can be applied as a stand-alone model for a single location or globally, or as part of an atmospheric model (Haverd et al., 2018; Kowalczyk et al., 2006). The first version of CABLE which was developed in 2003 by Australian researchers included the two-leaf canopy model, the canopy turbulence model and the multilayer soil/snow model was coupled with CCAM (Kowalczyk et al., 2006). The model consists of a biophysics core, the CASA-CNP "biogeochemistry" module, the POP module for wood demography and disturbance-mediated landscape heterogeneity, and a completely new module for land use and land management (Haverd et al., 2018). The model is coupled to the Met Office Unified Model (UM) and provides the land surface component of the Earth system models ACCESS-ESM1-5 and ACCESS-CM2. The CABLE code has a long history of use and development and has been available to the wider research community from 2006. The CABLE community includes around 100 researchers from more than 30 organisations. CABLE is open source. Registration is required to access the CABLE code repository.

3. CCAM inline ocean model

CCAM employs an in-line Boussinesq ocean model with z-* coordinate (Thatcher et al 2015). CSIRO decided to use a common grid for both the atmosphere and ocean, then combine the boundary layer turbulent mixing into a single parameterisation. This approach allows for an implicit solution to the coupling (i.e. solving a large tridiagonal matrix) and can be cost-effective to update at every time-step. However, it does not allow the atmosphere and ocean grids to be independently optimised (e.g. along coasts). Simulation speed is still satisfactory (e.g. 8 sim years per day at 12.5 km) despite an inhomogeneous distribution of ocean points across computing nodes.

4. GCI ocean model (WPOM-Wits Planetary Ocean Model)

WPOM is a quasi-elastic (nonhydrostatic) ocean model with pressure-based sigma coordinate (Engelbrecht et al., 2006). WPOM is formulated on the equi-angular gnomonic cubic-grid and employs a split-explicit solution procedure. WPOM can run independently of CCAM and can be optimised along coastal areas. A key line of work is coupling WPOM and CCAM on the same equi-angular gnomonic-cubic grid.

PART II

Recommendations for the optimum integration of modelling into the envisaged research infrastructure

To effectively meet Africa's modelling requirements, modelling efforts need to be aligned to the continent's specific challenges and needs related to climate change (Tamoffo et al. 2024). These involve creating models that account for diverse climatic and ecological zones, socio-economic vulnerabilities, and local weather patterns. Fit-for-purpose modelling requires a robust data collection system, advanced computational tools, and the active inclusion of local scientists in research and decision-making processes. It also demands practical applications, such as integrating model outputs into policy frameworks, disaster preparedness strategies, and sustainable development planning. Partnership and collaborative efforts between African researchers and their international counterparts have been quite instrumental. Nonetheless, obstacles such as limited access to data, inadequate computational resources, and insufficient capacity-building for local scientists persist. This section provides recommendations on integrating modelling into the envisaged infrastructure to strengthen provision of climate services in Africa.

2.1 Data integration and observational systems

To ensure the effective integration of modelling into CS research infrastructure in Africa, data management must be prioritised through robust strategies for storage, access, interoperability, and quality assurance. All data products generated or utilised within the modelling infrastructure should be securely archived in a centralised, long-term repository. Leveraging best practices from existing long-standing observational stations,such as those that contribute to both global data centers and national databases which can provide a model for efficient and reliable data management. Long-term observations of the main climate essential variables are clearly scarce on the African continent, improving their spatial and temporal coverage is unequivocally needed (see recommendations from Task 3.1). Combining in situ measurements with satellite products are particularly important for documenting key local climatic parameters (i.e. precipitation, vegetation and land-use) and their change over time. Satellite observations are becoming progressively available for an increasing number of atmospheric species. As an example, aerosol optical depth is a relevant proxy of the aerosol atmospheric load that are been derived from historical sensors (i.e. Advanced Very High Resolution Radiometer [AVHRR], Meteosat) while the most recent sensors also provide aerosol optical properties and indications of the aerosol's vertical profiles such as the Moderate Resolution Imaging Spectroradiometer (MODIS). Africa is among the most important sources of desert dust and biomass burning aerosol in the world, satellite aerosol products allow a long-term survey of their sources and regional transport (Nyayapathi et al., 2025). Other spaceborne sensors to detect key reactive gases that impact the atmospheric composition have a biogeochemical interest such as ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2) and more recently ammonia (NH_3). These satellite observations can be tested and evaluated against the in-situ measurements and then used to evaluate regional and global models. Finally, in-situ and satellite products can be assimilated to improve the forecasting capabilities of the models and the quality of the re-analysis. As an example, satellite-derived concentrations of methane (CH_4) (Thermal and Near Infrared Sensor for Carbon Observation [TANSO]; Infrared Atmospheric Sounding Interferometer [IASI]) and carbon dioxide (CO_2) (TANSO) are assimilated to constrain the global simulations of the European Atmosphere Monitoring service (Copernicus Atmosphere Monitoring Service [CAMS]). The CAMS re-analysis are based on the assimilation of numerous satellite products such as Aerosol Optical depth (MODIS), O_3 columnar content and vertical profiles (Ozone Monitoring Instrument (OMI), Solar Backscatter Ultraviolet (SBUV-2), Scanning Imaging Absorption Spectrometer For Atmospheric Cartography (SCIAMACHY), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), Global Ozone Monitoring Experiment-2 (GOME-2), CO concentration, Measurements of Pollution in the Troposphere (MOPITT) provided by different International agencies (National Aeronautics and Space Administration [NASA], European Space Agency [ESA], Japan Aerospace Exploration Agency [JAXA]). Satellite products can also be used directly to map emissions of atmospheric species as proposed by the Emission Observatory project (Lolongo et al., 2024) for CH_4, nitrogen oxides (NO_x) and SO_2. Such maps can be used to improve emission inventories in global and regional models of atmospheric composition, which is critical to correctly simulate the concentrations of short-lived species. They can also be used directly to monitor sources of atmospheric pollutants in urban areas and to identify and monitor sources associated with industrial activities (mining, power plants, oil and gas) in order to reduce and mitigate these emissions.

To overcome the lack of in-situ measurements that meets international standards, there is an increase in the deployment of low-cost sensors for greenhouse gases (GHG), reactive gases and aerosol as an alternative, the lower precision of the sensors are being compensated by a high number of observations (e.g. Peltier et al., 2020). It requires standardisation and intercomparison protocols of the different sensors but also numeric infrastructure to store, analyse and share the data so that they can be used to validate models or to be assimilated. Rules of distribution and use should also be carefully established for seamless sharing among African countries and diverse types of users. Optimum integration of modelling into the proposed African CS RI design would require progressively upgrading the skills and capabilities of African modelling scientists and modelling centres.

2.2 Designing of modelling frameworks

While the model itself can be a key outcome of a modelling project, much of its value lies in the process of developing and evaluating it. A model's purpose goes beyond its technical function to include how it is managed and the specific problem or project context it serves. Developing a model that is "fit-for-purpose" involves making strategic choices to ensure the model is useful (addressing the needs of the next user), dependable (obtaining an adequate level of certainty or trust), and practical (within practical constraints of the work it handles). Key decisions in modelling include selecting appropriate spatial and temporal scales, identifying relevant system features and processes, choosing the model type, be it process-based, statistical, or hybrid, and determining evaluation methods (Hamilton et al., 2022). For example, the KADI Task 2.1 assessed the performance of the CCAM-CABLE ESM in simulating land-surface and land-atmosphere fluxes across Southern Africa. The evaluation revealed systematic biases, including underestimation of CO_2 uptake across three EFTEON sites—Benfontein Savanna (BSV), Benfontein Nama-Karoo (BNK), and Jonkershoek (JHK)—throughout the year. Model skill was also found to vary by ecological zone, with better performance for sensible heat fluxes (H) in semi-arid regions compared to wetter sites. This underscores the importance of site-specific and biome-specific validation to improve model robustness. To support long-term use and relevance, modelling infrastructures should embrace:

Scalability: Models should be able to accommodate growing data volumes, expanding domains, and increasing computational complexity.

Interdisciplinarity: Integrating models from different fields (e.g. climate, hydrology, ecology, economics) allows for holistic assessments of risk and resilience.

Modularity and Flexibility: Systems should be designed to allow modular, plug-and-play integration of new tools, datasets, and models as user needs and scientific priorities evolve.

Adaptability: The modelling architecture must support updates, refinement, or substitution of models without disrupting the entire system.

Such an approach ensures models not only serve today's needs but can evolve to support future research and decision-making priorities.

2.3 Innovative data storage and handling capabilities

Climate model datasets are extensive, and managing their storage presents considerable challenges in Africa. While it is important to harness and develop modelling capabilities in Africa, there is a need to extensively develop and improve the back-end issues relating to data storage infrastructure, skills requirements and access. All data should adhere to the FAIR principles: Findable, Accessible, Interoperable, and Reusable, with comprehensive metadata accompanying every dataset to ensure transparency and usability. The RI should also plan adequate data storage capacity estimated at 25–30 TB per year based on the expected data output volume from both observational and modelling sources. Sharing these datasets is complex, the envisioned unified RI design could necessitate a data platform where researchers can download data or perform analysis on the server and then download only the analysed outputs. To foster ethical and transparent data use, the infrastructure should operate under a clearly defined licensing framework. This license should grant users permission to share and adapt datasets within specified terms, including proper citation of data sources and notification to providers when data contribute to publications. Data should remain strictly non-commercial. This could be achieved by leveraging existing infrastructure, regional collaborations, partnerships or cloud-based solutions.

2.3.1 Advanced computational tools: Artificial intelligence and machine learning techniques

Leverage, improve and expand available high computational infrastructures on the continent, such as high performance computing facilities and cloud-based platforms, to facilitate advanced modelling simulations. Also enable collaboration and partnerships to increase access to data, modelling skills to operate the high computational infrastructures, funding and open sources climate modelling computational tools (Meque et al., 2021). The high performance computational facilities in Africa mentioned in the previous section of this report would be good starting points for integrating advanced computational tools in the envisaged Research Infrastructure design. Additionally, Artificial intelligence and machine learning techniques could be incorporated to optimise parameterisation, enhance predictions, and uncover patterns/schemes.

2.4 Collaboration networks

A functional collaborative network framework is needed to enable a unified approach to addressing Africa's unique climate modelling requirements, taking advantage of the scientific advances in the field. Collaborative networks on the continent will support RI data sharing, governance and funding mechanisms. Initiatives fostering partnerships for knowledge sharing, capacity building, and joint research, with a common goal to improve and develop climate modelling in and for Africa, to inform decision making for effective climate action are therefore emerging. These networks are leaning on their interdisciplinary skills, pulling their resources together, synergising their knowledge base for the integrated evaluation and development of viable climate models, for local Africa context simulations. Available networks have been joining forces to enhance climate modelling in Africa, for the purpose of delivering enhanced climate information for decision-making and policy development on the continent. Mbuvha et al. (2024), advocates for a Pan-African climate model development and capacity building that leverages on AI to develop context-aware modelling solutions tailored to the continent's specific needs and challenges. Initiatives fostering partnerships for knowledge sharing, capacity building, and joint research in climate modelling in Africa include:

African Climate Development Initiative (ACDI)

ACDI is an interdisciplinary African climate development initiative with multi-national and scaled representation. They are anchored in South Africa, but extended via collaboration to southern Africa, the wider African continent, and various international partners. They lead innovative research, guiding Africa towards low-carbon, equitable, and climate-resilient societies.

Future Climate for Africa (FCFA)

FCFA is focused on creating new climate science for Africa and ensuring the impact of its intervention reflects on human development. The FCFA's IMPALA project aims to enhance climate models for better simulation of Africa's climate. These developments are expected to improve the representation of African climate processes in models.

Insights from the FCFA programme on Africa's climate processes have been integrated into the 7th iteration (GA7) of the Met Office Unified Model (MetUM), enhancing global models' accuracy. Further advancements are being included in the iteration (GA8). The initiative currently has five programs running across Africa namely AMMA-2050 – Burkina Faso and Senegal, UMFULA – Malawi and Tanzania, HyCRISTAL – Kenya and Uganda, FRACTAL – Botswana, Malawi, Mozambique, Namibia, South Africa, Zimbabwe and Zambia, IMPALA – Pan-Africa.

International Centre for Theoretical Physics (ICTP)

ICTP is a unique institution that explores fundamental scientific questions at the highest level, promotes active engagement with scientists in developing countries, and advances international cooperation through science.

Improving Model Processes for African Climate (IMPALA)

The initiative is part of the Future Climate for Africa (FCFA) program. It focuses on developing high resolution climate models to better capture convective storms and local weather on the continent. These improved models benefit sectors like agriculture, water resources, and health.

Climate Model Evaluation Hub for Africa

LaunchPAD is the first phase of the Climate Model Evaluation Hub for Africa, builds on the IMPALA project's work under the Future Climate for Africa (FCFA) programme. Includes researchers from Oxford University, the Met Office, and universities in Ghana, South Africa, Kenya, and Cameroon. It aims to enhance understanding of climate models in African regions and provide better information to policymakers.

Global Change Institute (GCI)

The GCI is a multidisciplinary research institute dedicated to addressing global change, climate change, and sustainability challenges. It aims to promote informed action for adaptation and innovation in the rapidly changing southern African region.

African Monsoon Multidisciplinary Analysis (AMMA)

This is a collaboration initiative that includes experts from academia, regional climate centres, and National Meteorological and Hydrological Services from southern, eastern, western, and central Africa. This is one of the main international programs on climate and environment in Africa. The program integrates weather and climate science to enhance the understanding and predictability of monsoon systems over Africa. This improvement in forecast reliability has been supporting forward planning in response to monsoon on the continent.

German Academic Exchange Service (DAAD) climapAfrica

The DAAD climapAfrica program aims to improve technical expertise in climate research in Africa, a region significantly affected by climate change. It also encourages collaboration between scientists and practitioners. The climate change and modelling working group component of the program seeks to examine environmental responses to climate change, past, present, and future, using various modelling methods. This goal is supported by engagement with peers across Africa to share interests and further develop skills.

Coordinated downscaling experiment (CORDEX) framework under the World Climate Research Programme (WRCP)

The flagship pilot study aims to understand regional climate change in southeastern Africa by analysing regional phenomena and circulations using observational data and climate model outputs. Existing African modelling collaboration networks could therefore be leveraged to be expanded and integrated into the envisaged RI design. This is to better understand and enhance capabilities to reasonably predict climate change impacts on the continent, reduce impacts, inform decision making for effective climate actions, and support resilience efforts. Suggested approach for the development of a collaborative framework for the optimum integration of climate modelling into the envisaged research infrastructure includes:

2.5 Climate modelling skills development, enhancement and capacity building

A dedicated data management portal should be developed as part of the RI, offering tools for data access, visualization, and analysis. Interactive platforms such as Jupyter Notebooks or other graphical user interfaces (GUIs) would enhance usability for researchers and stakeholders. Processed data should be organized by modelling themes to streamline discovery and application.. The Infrastructure should incorporate a digital infrastructure that is tailored to handle the specific types of data it generates and receives. This infrastructure must include tools and systems capable of processing raw data through to the stage where it is standardized and ready for dissemination. To accommodate future data growth, storage capacity should always exceed the projected data volume. Oversight and management of the digital infrastructure should be entrusted to a single institution, designated through consensus by the consortium of stakeholders and RI developers. Due to the cost associated with the lengthy time frame required to acquire the specialised skill sets needed in the field, Africa is trailing behind the rest of the world (Lamptey et al. 2025). Sustained investments dedicated to training and capacity building are required to build required modelling capacity on the continent, needed to support the climate modelling component of the envisioned CS RI. Examples of capacity building include:

- **Enhance training programs:** Foster local expertise to maintain and improve models for climate scientists and modellers in Africa.

- **Train researchers:** Train early career and established researchers in model use, analysis, interpretation and limitations.
- **Documentation and Guidelines:** Provide comprehensive documentation for models and workflows.
- **Tools:** Develop dashboards and visualisations to make model outputs accessible to non-expert stakeholders.

2.6 Stakeholder identification and engagement

To effectively integrate climate modelling into the envisaged research infrastructure, there is a need to identify and take stock of the climate modelling activities, model providers, available capacities, and public and private research institutions involved with climate modelling on the continent, which can be enhanced, expanded or replicated to support CS.

2.7 Building on existing climate modelling initiatives

There are currently a number of climate modelling initiatives (such as Future Climate for Africa [FCFA] programme, GCI) on the continent that have made significant strides in providing climate modelling products, which could be leveraged, improved on and integrated into the proposed RI design. Forming alliances with international organisations with advanced modelling technologies and infrastructure will assist African model providers to improve the accuracy and reliability of their climate predictions over Africa. Highlighting the need for these types of partnership in the RI design will ensure its efficiency and sustainability.

2.8 Developing policies and regulatory support for climate modelling in Africa

Standardized data protocols across all modelling centres are essential to ensure consistency in format, storage, and access. A centralised structure similar to established atmospheric and carbon observation RIs featuring centralized data quality control facilities and distributed data centres would serve the African context well. This will provide the necessary national imperatives to support the integration of climate modelling in national, regional and continental planning processes.

Conclusions

The KADI project represents a critical effort to enhance climate research and services across Africa by integrating environment and climate modelling into decision-making processes. These modelling tools are essential for understanding climate variability and change, projecting future changes, and guiding adaptation strategies that support sustainable development. An assessment of modelling infrastructure across the continent reveals a concentration of functional modelling centres in Southern Africa. The report also evaluates the current application of Earth system modelling, its effectiveness, and the limitations of existing approaches. A central recommendation is the integration of diverse observational data sources to improve model validation and development. The use of advanced computational tools—such as artificial intelligence and machine learning—is also encouraged, alongside fostering collaboration between existing initiatives, expanding modelling expertise, and engaging stakeholders. In the short- to medium-term, leveraging outputs from international and regional modelling efforts (e.g., CMIP and CORDEX-Africa) remains a practical strategy. These platforms support both evaluation of current models and focused research on climate impacts, while building capacity among African scientists. In the longer term, Africa should aim to develop unified, region-specific datasets and models led by African institutions to meet its climate service needs. Ultimately, embedding Earth system modelling into climate services is essential for effective mitigation, adaptation, and policy planning. Establishing a Pan-African climate services research infrastructure—backed by interdisciplinary collaboration, robust data integration, and institutional support—will be key to building long-term climate resilience and addressing future challenges on the continent.

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