KADI

Building a Needs-Based Climate Services Research Infrastructure in Africa

Deliverable 1.1. HORIZON-INFRA-2021-DEV-01-02

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KADI

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Executive Summary

The project 'Knowledge and climate services from an African observation and Data research Infrastructure' (KADI) is an interdisciplinary African-European project developing a design of a pan-African climate research infrastructure (RI) using climate services (CSs) as a guiding principle. Work Package 1 (WP1) focuses on identifying the CS needs in Africa through two aims. The first aim is to gain a comprehensive understanding of CS needs across Africa through a systematic literature that spans different sectors and spatial scales. The second is to validate and improve the CS needs through engagement with key actors. This first deliverable focuses on the first aim and covers the following topics:

- investigate existing RIs to identify their core elements and innovative approaches to providing impactful products, solutions, and outputs,
- establish a clear understanding of the state of CSs and its key components in the African context,
- articulate critical needs and gaps of CSs across Africa,
- identify additional core elements of RI to assist in developing need-based CSs in Africa,
- address the CSs needs of each pilot through the lens of the identified innovative approaches, and
- show concrete examples of CSs using the pilot sectors to identify CS needs at different scales.

RIs and CSs can tend to focus on "hard" infrastructure that provides high quality data but struggle to show impact to stakeholders, actors and the community. Recent efforts have focused on the development of "softer" scientific infrastructures, prioritising user spaces. Users of various CSs, both hard and soft infrastructures, including those that embrace social and cultural dimensions, the consideration of the roles of formal and informal institutional spaces, various sources and requirements of data and information (including local, tacit and indigenous knowledge) and economic infrastructural services for effective decision making. Key elements and principles of engagement in these 'soft' infrastructures include relational engagements, trust building approaches and understandings, mutual respect and humility, appreciation of different world views and values, and the ethics of CSs. KADI is working to follow such an approach. As such, through this review, the description of the key elements has been expanded to include these considerations (Figure ES1). In this figure, those in green are the elements that are typical in an RI and those in blue are those added in this review to cover additional elements for a needs-based RI to support CSs.

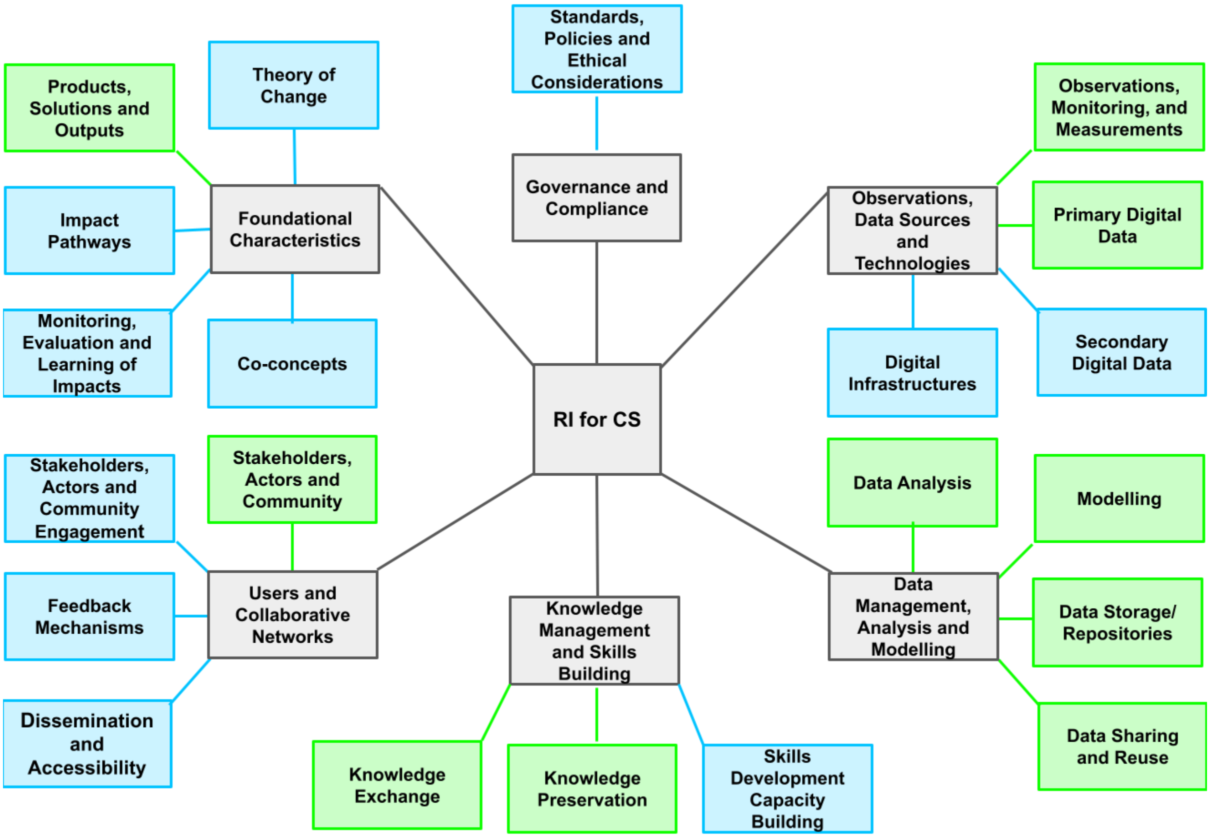

Figure ES1. Key elements of a CS RI. The green boxes indicate those elements that are typical in an RI and the blue boxes indicate those elements that are added through this review.

Applying a bottom-up approach that focused on the pilot sectors (i.e., WP2 pilots), the CS needs and relationships to these RI elements were identified for all the pilot sectors. This assessment is initial as it only includes input from the literature review and internal KADI team members. Interestingly, while all pilots could identify examples across the selected RI elements assessed, most focused on data as a CS. This assessment also provided an opportunity to test the approach to omit the more contextual RI elements to avoid repetition and identify concrete examples.

The next steps of WP1 activities include expanding the sectors and actors through literature review and engagement. The engagement plan for 2024 will be split into two phases (ES2). The first will focus on targeted workshops that will focus on the pilot domains, CS needs, and the observational network design. This phase will conclude with a larger meeting with stakeholders identified in the initial workshops and expanding to include additional sectors. The second phase will have additional focused workshops and hybrid sessions including both online and in-person options. This phase will also include a large workshop in the form of the KADI annual meeting in 2024 and will present the key activities of the KADI project to that point including the draft blueprint for the observational network for Africa. These engagements with the stakeholders and actors throughout the two phases will aid in identifying the feedback loop for WP1's proposed framework and will continue to aid in identifying missing actors and sectors that need to be included.

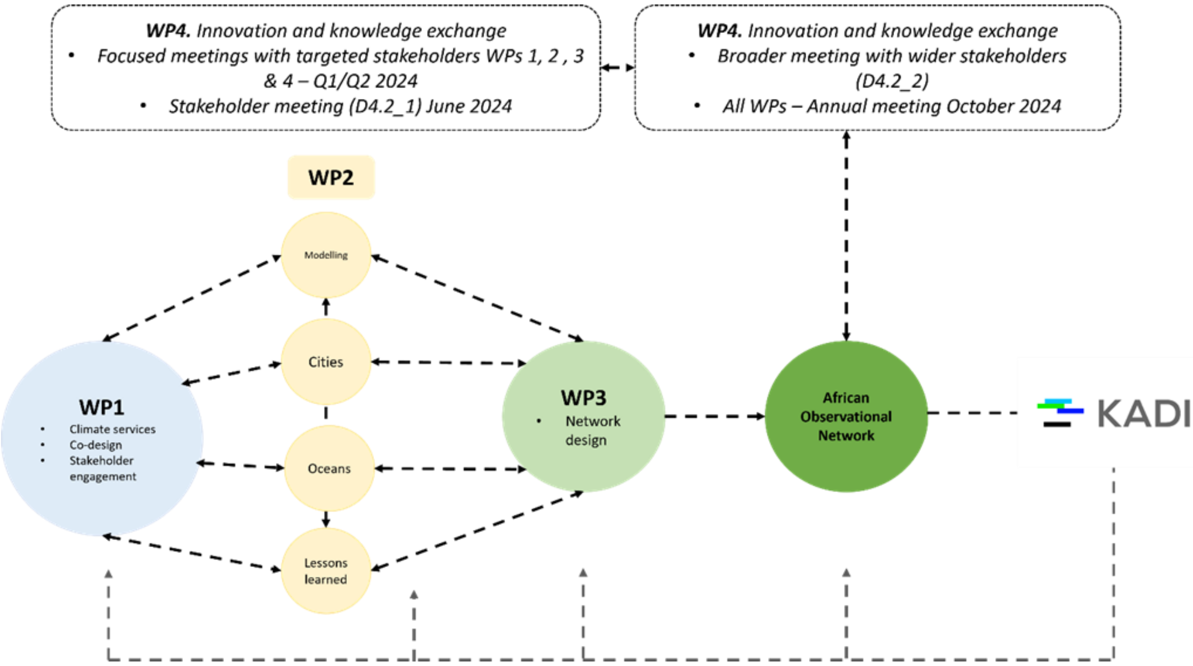

Figure ES2. Schematic of the planned WP1, WP2 and WP3 stakeholder and actor engagement.

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Introduction

The project ‘Knowledge and climate services from an African observation and Data research Infrastructure’ (KADI) aims to provide concepts for developing the best available science and science-based services in Africa that are needed to sharpen our common action on climate change. KADI is an interdisciplinary African-European project developing a design of a pan-African climate research infrastructure (RI) using climate services (CSs) as a guiding principle. The proposed design for the RI will aim for effective solutions for Africa and, thus, will not simply copy but adapt and further develop the solutions and in turn, also inform from an African perspective those that have been found for European research infrastructures. These developments will be driven by the CS needs that will inform science and modelling needs.

Work Package 1 (WP1) focuses specifically on these needs through the following aims,

- Identify, analyse and characterise CS needs via systematic literature and service review at multiple scales and contexts in Africa.
- Then, via collaborative and participatory engagement of key actors and organisations, gain new user understanding of users’ needs and then through ongoing engagements validate these services and improve their potential data and infrastructure designs.

This report is the first deliverable from WP1 and describes the current state of the literature review towards addressing the first aim. This deliverable does not yet completely address this first aim as it is the first draft. This deliverable will be expanded, validated and finalised in 2024 (final version due October 2024) through input from internal team members, external actors (as noted in the second aim) and a broadened literature review that will include more sectors. The next steps for this work are described in the last section.

The specific task that this deliverable is addressing is WP1 Task 1.1. (as taken from the proposal).

“This task will begin by identifying key sectors and stakeholders in need of climate services across Africa (where available and appropriate), as well as observation and modelling capacity and infrastructure (e.g., GHG, SLCP), responding to these requirements through a systematic literature and climate service review (using scientific and applied literature, web sites, policy papers, strategy papers etc.)”

Such a CS needs approach to developing an RI is new and thus has led to the expansion of the defining characteristics of RI. This deliverable assesses the current characteristics of RIs and those that would be needed to support and provide CSs. WP1 has taken a bottom-up and emergent approach towards “identifying key sectors and stakeholders in needs”, through a focused review and assessment of the needs of the sectors and stakeholders covered in the pilots in WP2. WP2 contains four pilots that have been used to test the concepts developed by providing experience to co-design the requirements of CSs. Briefly, the four pilots in the project are,

1. Earth System Modelling
    a. Focuses on evaluation and improvements of parameterisations of land-surface characteristics and land-atmosphere fluxes in an Earth Systems Model.
2. Coastal Biogeochemistry
    a. Quantifying key components of the coastal carbon cycle that are relevant to the regulation of climate change, and focuses on carbon cycling and other greenhouse gas measurements.
3. Cities
    a. Local climate solutions for rapidly growing cities with case studies in three African cities,

   i. Abidjan, Côte d'Ivoire:
   ii. Nairobi, Kenya:
   iii. Dar es Salaam, Tanzania:

4. Long-term climate and atmospheric composition observations
   a. Assess the value and derive lessons-learned of the existing long-term climate and atmospheric composition observations provided by national meteorological services, using Kenyan Meteorological Department as a case study.

In this project, the first pilot on Earth System Modelling is focusing on the improvement of the model through use of measurements from an RI. The other pilots are focused on how measurements in an RI can support and provide CSs. Through focusing on the sectors covered by the pilots, the team covers critical parts of the Earth system and the interfaces with societies, thus enabling a requirements-based approach to developing the desired RI. This will be expanded upon with additional sectors in the next iteration of the report.

Objectives of the Review

The objective of this review is to:

- investigate existing RIs to identify their core elements and innovative approaches to providing impactful products, solutions, and outputs,
- establish a clear understanding of the state of CSs and its key components in the African context,
- articulate critical needs and gaps of CS across Africa,
- identify additional core elements of RI to assist in developing need-based CS in Africa,
- address the CS needs of each pilot through the lens of the identified innovative approaches, and
- show concrete examples of CSs using the pilot sectors to identify CS needs at different scales.

This is the first iteration of the deliverable. All objectives are covered in this review, but will be expanded in the final version.

Overview of Climate Services in Africa

Climate change and climate variability are key challenges confronting Africa. Climate-related hazards are well known to the continent with periods of droughts, extreme heat and variable rainfall having played significant roles in African development, both in the past and more recently, under anthropogenic climate change. For example, heavy rains and flash floods devastating the KwaZulu Natal areas of South Africa and extreme droughts plaguing, among others, Kenya and Somalia. In addition, Africa has exhibited a warming trend more rapid than the global average bringing with it within a range of impacts and consequences (Pörtner et al., 2022; WMO, 2022). Africa also has to deal with the other dimensions of climate impacts, namely vulnerability. Vulnerability and exposure to climate phenomena can compound disaster risks (Dodman et al., 2022; Pörtner et al., 2022) notably in rural areas but increasingly in urban areas, where large numbers of people, driven by livelihood needs, are moving (Dodman et al., 2022).

Climate projections (e.g., climate parameters such as rainfall and temperature, as well as extreme events) have been and are continuing to be developed with potential use for Africa. Such information, together with a range of other products and engagements (e.g., services) requires some form of co-ordination and effective implementation that KADI hopes to contribute.

The need for an effective suite of services that can enable both people and ecosystems to enhance their ability to withstand climate shocks and stresses is therefore very clear and has been for some time (Goddard, 2016).Similarly, the term ‘end’ user is also not necessarily appropriate. In some contexts, for example, it is often used to describe value ’chains’ of science-based information moving to users, waiting at the ’end’ of the information chain, rather than being co-created with users at the very outset of the information process. In this overview of services, two aspects of CSs will be focused on with relevance for the KADI project:

- CSs with respect to climate change adaptation (e.g., managing risks coupled to variations in rainfall, temperature etc.) and,
- Climate change mitigation in terms of greenhouse gas emission reductions (energy and CSs) from human and natural systems (e.g., industrial and local economic activities and land use changes) including carbon dioxide removal from the atmosphere by enhanced uptake of natural systems.

These two aspects will be viewed in the wider focus of KADI which is focusing on RIs for enhanced capacities to respond to climate challenges and provide effective services. Infrastructures in the wider field of climate change adaptation and mitigation are very broad, and include physical infrastructures for protection and management of climate-related hazards (e.g., sea wall protection; enhanced building infrastructures; irrigation, drainage and engineering infrastructures etc). This brief overview focuses on the ‘science’ infrastructures required to enhance adaptation to climate risks and challenges (e.g., enhanced monitoring and forecasting of key resources; enhanced detection and monitoring of greenhouse gas emissions). These we can think of as the so-called ‘hard’ infrastructures that are often termed as an RI which will be further discussed below with Figure 4). However, coupled to these types of infrastructure are the so-called ‘softer’ infrastructures namely institutional, organisational and social, cultural and relational infrastructures that will also feature in this deliverable. These ’softer’ infrastructures are not normally included in an RI design; however, as noted in the next section, inclusion will be critical for an RI that will effectively support CSs in Africa.

Background to Global and African Climate Services

The World Meteorological Organization (WMO) has created and implemented the Global Framework for Climate Services (GFCS) that has grown rapidly (Lugen, 2020; Vaughan & Dessai, 2014). The GFCS identifies the CS priority areas to be the following:

- Agriculture and food security,
- disaster risk reduction,
- energy and
- health (WMO, 2024).

Various providers of CSs include the national meteorological services, universities, national research centres, private consultants, and various actors with business expertise.

According to the latest assessments, the state of CSs through GFCS in Africa is variable with some areas better off than others (Figure 1). More than half of the WMO members provide a form of service (about 60%) across a range of infrastructural services e.g., data services, climate monitoring, climate analysis and diagnostics and climate prediction (WMO, 2022). Very few members, however, provide climate projections (estimated 30% of Members) (WMO, 2022).

Various meteorological entities provide services (e.g., African Centre for Meteorological Applications for Development, ACMAD). Detailed cases where more participatory and transdisciplinary approaches have been undertaken include cases from the FRACTAL (Future Resilience for African Cities and Land) and

UMFULA (Uncertainty Reduction in Models for Understanding Development Applications) projects as well as an overview review of CSs in Africa (Vogel et al., 2019; FCFA 2021). WMO and WHO both provide excellent source materials that explain and show the breadth of such services (e.g., rainfall, temperature). More detailed interrogation of the infrastructural linkages relating to KADI focal issues e.g., greenhouse gases, land surface emissions and pollution related infrastructures still require more comprehensive investigation (e.g., WMO (2023b)).

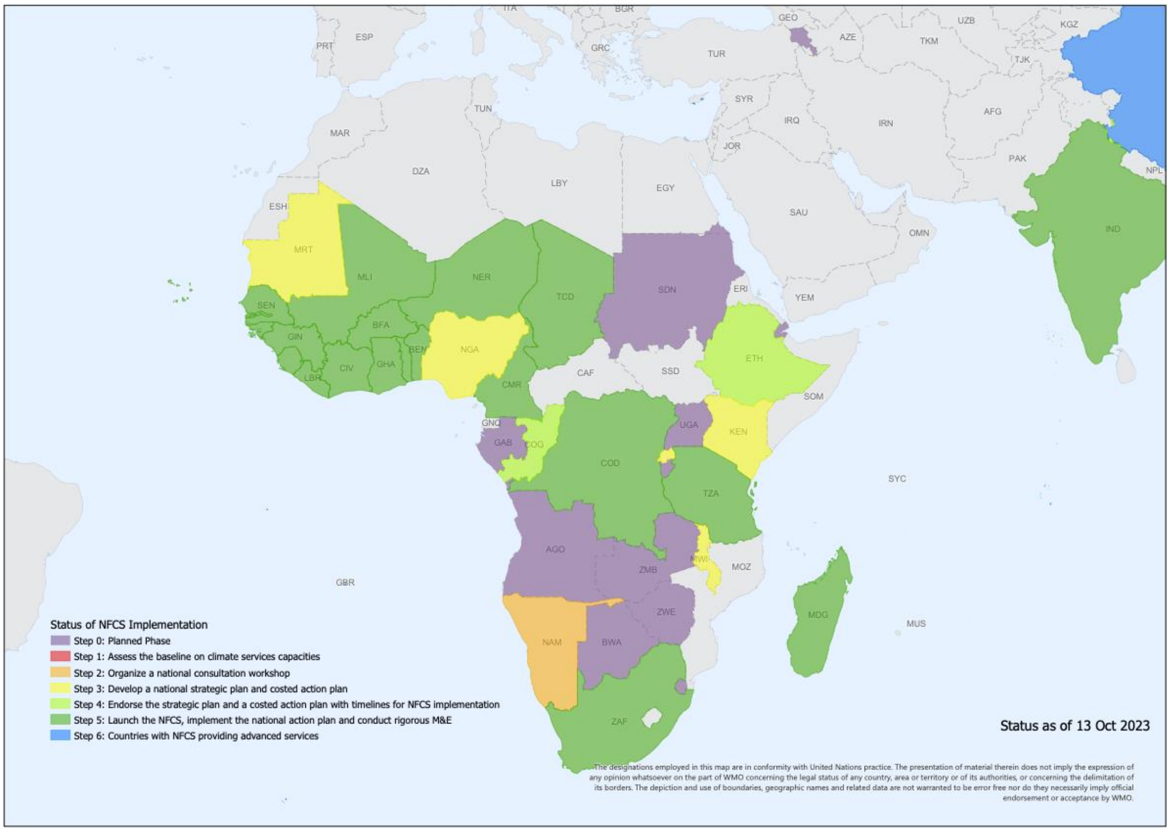

Figure 1. Status of National Framework for Climate Services (NFSC) implementation October 2023 (WMO, 2023).

After this short introduction to services in the African climate context, attention now turns to examine types of infrastructures, linked both to climate change adaptation and mitigation.

1) Climate services with respect to climate adaptation e.g., managing risks coupled to climate variability and change.

Hard infrastructures and technical climate services

The need for more detailed and systemic assessments of greenhouse gas emissions, given growing urbanization along with land use and land cover change in Africa, is creating serious avenues for CSs or what may be termed 'hard infrastructures' (Merbold et al., 2021). Nickless et al. (2020 proposed an African network of about 60 atmospheric greenhouse gas monitoring stations largely based on existing infrastructures. Merbold et al. (2021) provided a blueprint design study inventory of existing atmospheric, terrestrial and oceanic observations and the spatial disaggregation of locations that will enable the reduction in the uncertainty in climate forcing in Africa and globally. Assessments of the various institutional requirements, partnerships and understanding of land tenure and other socio-political dimensions that factor into the siting of new climate and other infrastructures in Africa are also described by Merbold et al. (2021) and López-Ballesteros et al. (2020).

Greenhouse gas emissions, including agricultural practices in Africa, opens up another interesting set of issues, in particular those concerning livestock systems and livelihood practices. Greenhouse gas emissions, for example, from livestock and soil organic carbon storage in livestock systems require detailed assessment of science infrastructures that are pertinent to the work being considered in KADI (Graham et al., 2022).

Other infrastructural services that may be termed 'hard' are those requiring and utilising long-term environmental observations (e.g., in-situ and remote sensing infrastructures as noted in Figure 1). Goddard (2016) noted:

"[…] *compared to Germany, the entire continent of Africa has less than 10% the number of rain gauges reporting to global data centres. And the number of these gauges worldwide is decreasing, especially in African countries. Such gaps in observational records severely limit their value."*

and

"What is clear is that climate ***services require more than just climate science****. To work, they depend on a solid understanding of how climate fits into the broader decision context, as well as the political will to foster multidisciplinary re-search and practice" (Goddard, 2016., 1367, italics added).*

2) Moving climate services science into action – what 'soft' infrastructures are needed?

Apart from the many efforts in science and services described above there have also been growing efforts in what may be termed the 'softer' science infrastructure focusing on 'user' 'people spaces. Users of various CSs, both hard and soft infrastructures, include those that embrace social and cultural dimensions, the consideration of the roles of formal and informal institutional spaces, various sources and requirements of data and information (including local, tacit and indigenous knowledges) and economic infrastructural services for effective decision making (Tall et al., 2014; Tall et al., 2013; Vincent et al., 2017; Vogel et al., 2019; Webber & Donner, 2017; West et al., 2018).

Rather than adopting a linear, value chain of climate-science-infrastructures-to-service model and approach, additional articulations of climate-science-to-services are being adopted, tested and implemented (e.g., Figure 2). Various cycles of information, data gathering, dialoguing, sharing of information needs and requirements are enabled and practiced as ongoing activities. Repeated feedbacks, learning cycles and loops, rather than once-off 'science data' capturing that is then thrown over the walls of the laboratory to 'end' (*sic*) users, are employed. As noted above, the cases from the FRACTAL and UMFULA engagements contain useful approaches, methods and results of a more co-created science involving science engagements *with* society approaches in Africa (Vogel et al., 2019; FCFA 2021).

Key elements and principles of engagement in these 'soft' but critical approaches include relational engagements, trust building approaches and understandings, mutual respect and humility, appreciation of different world views and values, and the ethics of CSs (Adams et al., 2015). KADI is working to follow such an approach and as detailed in the following sections, to include these 'softer' infrastructures.

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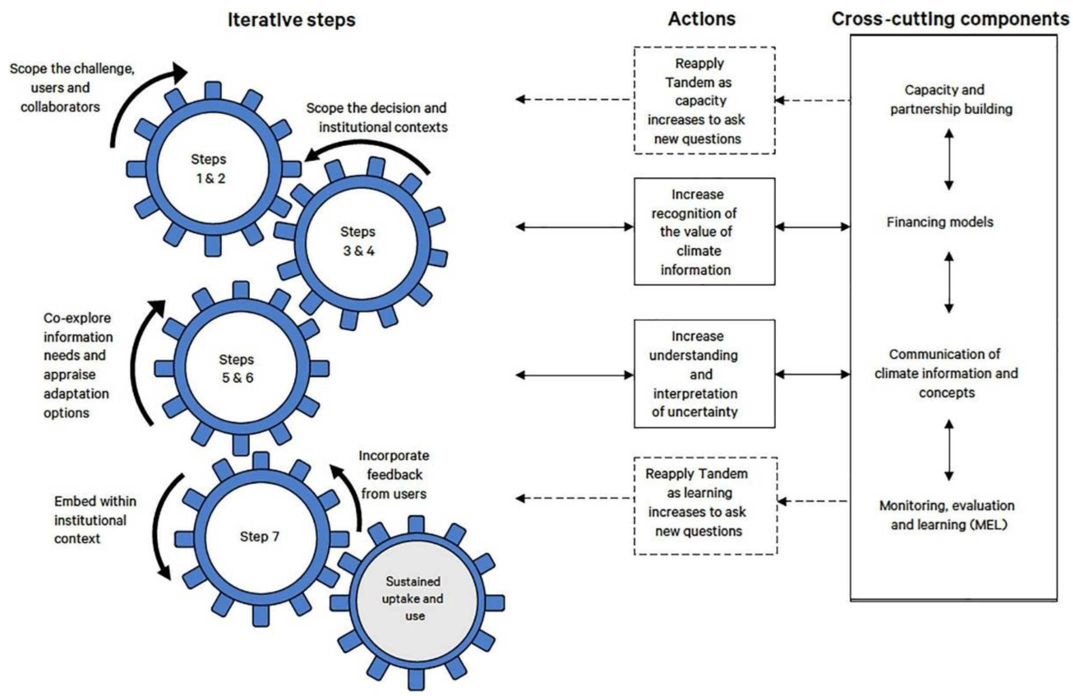

Figure 2: Suggested alternative and additional science to (with) services approach (Vogel et al., 2019). Copyright permission outstanding.

Addressing Key Needs in Climate Services in Africa

Much attention, both globally and very locally (e.g., at the city, local village and household, ward level), is now being given to climate change and climate variability in Africa. Enhanced understanding of climate hazards, monitoring and data systems, exposure and vulnerability assessments are all urgently needed. At the same time, the need for a more 'honest' appraisal of what it will take to ensure that science, including social and other approaches, will be of use in everyday and longer-term decision-making contexts is no longer optional but an urgent necessity. The overview provided here has illustrated some of the global and local types of science infrastructures that may be required *in, for and with* Africa(ns) in support of CSs. KADI is working to add value to such efforts enabling a safe and thriving Africa for the environment and people.

Taking this overview into account, the following sections unpack the needed characteristics of an Africa-based RI that will support CSs.

Methods of Review

Literature review

This following section describes the methodology used to conduct the literature review. First, definitions of research infrastructures (RIs) were found from traditional RI that were focused on hard infrastructures. Next, self-identified RIs across the globe were put into categories based on the data collection methods used and the offerings provided. These steps were done to determine gaps and innovative approaches, including soft infrastructures, that a needs-based RI should encompass. CS examples were included to contextualize the hard and soft elements of RI.

Defining and Categorising Research Infrastructures

The European Union defines an RI as "the physical and digital tools that researchers use to conduct innovative research and provide unique infrastructures, such as laboratory equipment, data repositories, and knowledge-based resources" (EU, 2013). RI have been defined throughout the literature and the key elements are summarised in Figure 3 (ESFRI, 2018; OECD & Europe, 2020; Ramoutar-Prieschl & Hachigonta, 2020; Wood et al., 2013).

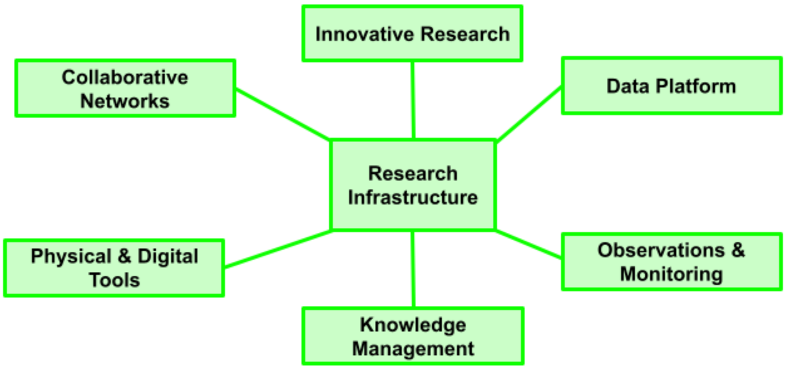

Figure 3. Key elements of a traditional RI identified based on the literature review.

For this report, RIs were investigated to identify their core characteristics. Only RIs that self-identified as an RI were included in this report. Other long-term measurement stations that did not identify as an RI were beyond the scope of this review for this iteration, but will be investigated for further iterations and in WP3 that focuses on RI design.

Identified RIs were grouped and classified into different types:

- In-situ: Measurements taken directly at the location of interest
- Remote Sensing & Satellite: Observation and measurements taken from a distance using airborne, ground based and satellite platforms
- Modelling: Data from computational models and the supporting digital infrastructure
- Digital: Large collections of secondary data

Examples of each type of RIs are included in Table 1 and Figure 4 shows the distributions of RIs found from this review across categories. The full list can be seen in Appendix A.

Table 1. Example RI and measurements/offerings for each RI type

Type	Example RI	Example measurements/ offerings	Links
In-situ	In-service Aircraft for a Global Observation System (IAGOS)	Global observations of atmospheric composition from commercial aircraft	https://www.iagos.org/
Remote Sensing & Satellite	Atmospheric dynamics Research InfraStructure in Europe (ARISE)	Atmospheric boundary-layer wind and turbulence	http://arise-project.eu/
Modelling	Partnership for Advanced Computing Europe (PRACE)	Supercomputing	https://prace-ri.eu/
Digital	European Brain Research Infrastructures (EBRAINS)	Neuroscience data	https://www.ebrains.eu/

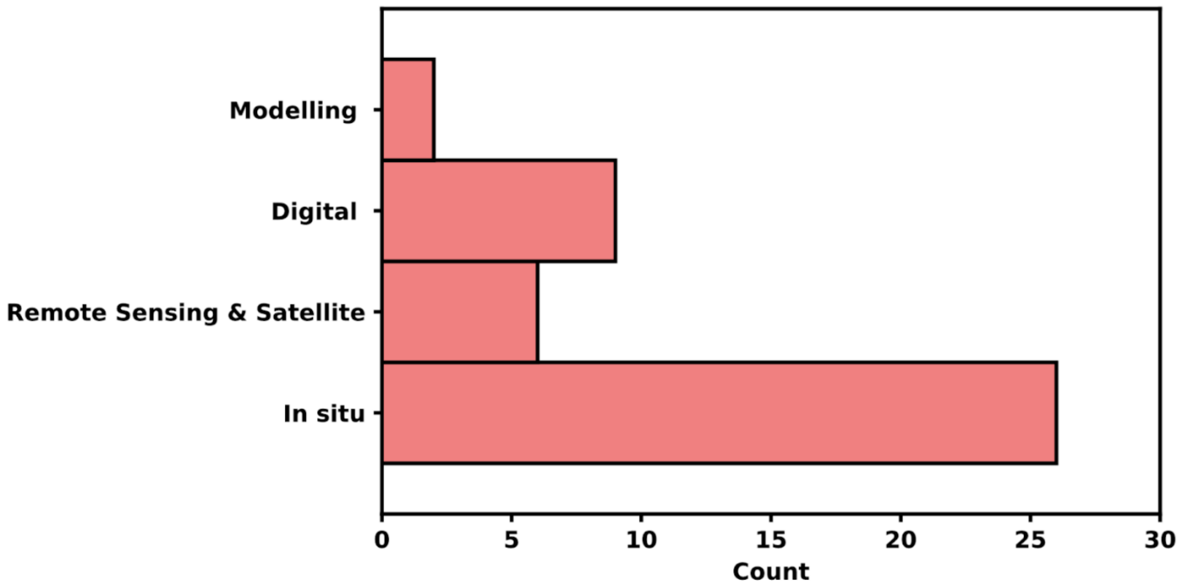

Figure 4. Number of RI by type globally (based on literature review).

As can be seen in Figure 4, in-situ RI are the most common globally. All of the RIs identified in Africa were located in South Africa. Additional qualitative elements were identified to assist in developing a RI that provides need-based climate solutions in Africa.

Key Concepts and Elements of a Research Infrastructures Supporting Climate Services

Existing RIs and literature present a variety of critical elements for the RI to be operational and impactful (e.g., Figure 3). However, as discussed above, there are additional elements needed for a more nuanced and holistic approach to the design of RI for CSs. Additionally, RIs operating in LMICs (low- and middle-income countries) have different requirements to their design when compared to the Global North. These requirements stem, for example, from data scarcity, culture, the decision-making context, power dynamics, and the reality that climate change impacts are already visible in many countries.

From the review, we have identified elements that are critical to achieve a needs-based RI design that has an impact on the society when adapting to and coping with changing climate, and when building resilience against climate risks. These are described in Table 2. The typical (green in Table 2) and added elements (blue in Table 2) stem from the review of academic literature, not only concentrating on RI, but also contextual literature of CSs that operate in Africa, and best practices identified. They are also identified via discussions with experts that are KADI project partners, and with the KADI pilot stakeholders. Many of these added elements can be seen as the “softer side” of the RI coin, where the importance of, for example impact, collaboration and learning, are highlighted.

Table 2. Key elements of a needs-based RI to support CSs. This table lists elements that are typically found in RI (coloured as green). Elements that are coloured as blue are added elements which are important for RI that have impact on the society.

RI element	Description and examples related to CSs	References and links
Foundational characteristics		
Theory of Change	Articulates the intended positive, meaningful and sustainable changes that are expected to happen when the RI products, solutions or outputs are used in the society by stakeholders, or in the research community. It communicates the logic between the RI's activities, outputs, short-term outcomes and long-term impacts. **CS example:** Climate information is used for preventing and controlling malaria outbreaks in Ethiopia. Malaria outbreaks occur seasonally, and climate information is needed to predict the outbreaks. Theory of change: Successful usage of climate information helps design malaria interventions, such as allocation of staff, health equipment and medicine, community-level capacity building and urban planning on all decision-making levels. To achieve this goal, Ethiopia has implemented projects and strategies for decades to improve climate observation infrastructures, facilitate health experts' collaboration in data and knowledge sharing and technical support, and organise training for communities and professionals at various levels.	Shumake- Guillemot J. And L. Fernandez-Montoya (eds.; 2019). Climate services for health: improving public health decision-making in a new climate. Geneva: World Health Organization and World Meteorological Organization. *https://library.wmo.int/idurl/4/41941* Pages 36-39
Products, solutions and outputs	RIs deliver key outputs in diverse forms, such as innovative research results and publications, new methods and data processing pathways, training materials, data/information dashboards, projections and models. Successfully adopted scientific research and other RI activities generate solutions, products and outputs that directly respond to the intended users' needs, and thus are able to support knowledge-based decision-making and further actions that lead to true impacts. This element is coloured as an element that is typically found in RIs, but it can be claimed that direct provision of services is more rarely an element of an RI. **CS examples:** CSs can be anything between climate information dashboards, portals and map services, early warning systems, workshops and methodologies, climate change projections and related products, handbooks and guidelines, insurance products, information for adaptation	Climate information dashboard Kenya expert tool, read more here; Climate Observer Early warning system Husika, read more here Workshop methodologies PICSA Climate projections and related products Climate Impact Map Handbooks and manuals Co-production manual

RI element	Description and examples related to CSs	References and links
	and mitigation strategies, research publications, tools, impactful stories, virtual labs, and beyond.	Insurance products New initiative by the African Development Bank
Impact pathways	More specified steps that highlight the causal relationships between RI's activities, outputs, outcomes and impacts: what practical things must take place for the RI to achieve its intended impacts? Impact pathways can be used as a roadmap for the RI activities and they help overcome the barriers from the information or solutions ending up in use, and turning into benefits. **CS examples:** Impact goal: "Improved public health on respiratory diseases caused by air pollution" Example of an impact pathway: 1. Co-design with professionals in health and urban planning, as well as with communities of what a useful and useable air quality index should look like and how it should be disseminated 2. Ground-based measurements of air pollution particles 3. Data analysis and processing for creating an air quality index based 4. Validating the air quality index model with stakeholders, and improving it based on feedback 5. Disseminating the air quality index and related information via appropriate channels and format 6. Training of different sectors and the communities on the usage of the product 7. Stakeholders equipped with knowledge and tools to address air quality problems **(short-term outcome)** 8. Concrete actions made based on the new knowledge, such as reducing pollution levels, making infrastructure changes to prevent aerosol spreading, allocating health sector resources, and aware communities are able to protect themselves from poor air quality **(mid-term outcomes)** 9. Improved public health on respiratory diseases **(long-term impact)**	Air quality, climate change and public health – how C3S and CAMS can protect European cities. ECMF (accessed 2.2.2024) https://stories.ecmwf.int/air-quality-climate-change-and-public-health/index.html
Monitoring, evaluating and learning (MEL) of impacts	Monitoring and evaluation systematically examines the performance, progress, and impact of research infrastructures (Gomez et al. 2018 / EU InRoad). MEL activities in current RIs generally focus on operations and scientific impact. However, these need to be expanded to include an ongoing process that assesses how well services are adopted by intended beneficiaries and the value produced by research outcomes. Learning involves iterative actions, adjustments, and improvements based on M&E results (Visman et al. 2022). **CS examples:** In the climate adaptation, mitigation, and resilience field, it is important to remember that measurable and identifiable impact can take time, and thus process-based MEL strategies that evaluate long-term structural changes are as vital as short-term indicator-based strategies.	Salamanca A., and Biskupska, N. (2021). Monitoring, evaluation and learning to build better climate services: A framework for inclusion, accountability and iterative improvement in tandem. SEI Discussion Brief. Stockholm Environment Institute. https://www.sei.org/publications/monitoring-evaluation_climate-services-in-tandem/
Co-concepts	Co-design, co-production, co-creation, and other collaborative concepts may be integrated into the planning, development, execution, maintenance, and dissemination of	A manual for co-production in African weather and climate services

RI element	Description and examples related to CSs	References and links
	RIs and their products, solutions and outputs. These concepts humbly and genuinely include respect of working with society and of recognition of various knowledge domains, and the expertise of multiple actors from different backgrounds. Methodologies of implementing co-concepts are vast and case specific. **CS examples:** Co-concepts are integral to successful CSs, fostering sustainable uptake of them and leading to true impact in the society (Dilling & Lemos 2011).	https://futureclimateafrica.org/coproduction-manual/ Case-studies https://futureclimateafrica.org/coproduction-manual/book/text/06-case-studies.html
Observations, data sources and technologies		
Observations, measurements, and monitoring	Key activities for collecting data and information that supports research, analysis and decision-making. Observations refer to collection of data or information of a phenomenon by using instruments, sensors, other equipment or human observers. Monitoring refers to continuous observations and measurements that can reveal changes and trends in the monitored phenomenon. **CS example:** Climate observations are gathered from the atmosphere, oceans, or land-systems using various in situ and ex-situ instruments (including citizen science), observations and monitoring stations/networks as well as remote sensing systems.	Integrated Carbon Observation System (ICOS) https://www.icos-cp.eu/ Aerosol, Clouds and Trace Gases Research Infrastructure ACTRIS https://www.actris.eu/t Global Atmosphere Watch Programme (GAW) https://gcos.wmo.int/ Network for the Detection of Atmospheric Composition Change (NDACC) https://ndacc.larc.nasa.gov/ Global Basic Observing Network (GBON) https://community.wmo.int/en/activity-areas/wigos/gbon
Primary digital data	Primary data that is collected and/or managed by the RI. It is directly related to the theme/sector where the RI operates in. **CS example:** Climate-related data, such as digital records of measured climatic conditions (e.g., temperature, precipitation, wind, particles) with a specific temporal scale and location.	Copernicus Climate Data Store (CDS) https://cds.climate.copernicus.eu/#!/home
Secondary digital data	Secondary or supportive data that helps the RI to tie its primary data to context. Can be obtained by the RI itself, or re-used or refined from other data providers. **CS example:** Contextual data of demographics, infrastructure and environment is combined with climate data to create meaningful CS solutions for specific contexts and purposes. This spatial data enables the design of location-specific CSs that reveal the specific characteristics of given locations e.g., in terms of its vulnerability against climate risks.	The U.S. Climate Vulnerability Index https://map.climatevulnerabilityindex.org/map Greenbook https://greenbook.co.za/
Digital infrastructures	Digital infrastructures are integral to modern research practices. RI's digital infrastructures enable other RI activities, such as analysis and modelling, and data storage	New Machine Learning-Based Model Boosting Africa's Preparedness and

RI element	Description and examples related to CSs	References and links
	and sharing. Digital infrastructures vary based on the RI activities and RI's needs, and can be anything from computing resources to high-speed networks, cloud environments, AI and visualisation tools, cybersecurity measures and digital collaboration platforms. **CS example:** For most cases, CSs utilise digital infrastructures for data management and sharing, digital data platforms with possible user interfaces, and data visualisation, models and simulations. Additional digital technologies can be utilised in performing these activities, such as using AI for analysing big climate data, or cloud environments for data storage. All these digital activities require sufficient computing power and network connections.	Response to Climate Change https://www.globalissues.org/news/2023/07/20/34305
Data management, analysis and modelling		
Data analysis	Systematic examination and interpretation of raw data to produce meaningful insights, identify patterns and draw conclusions, i.e., information that can be transferred to knowledge. Analysis methods vary between disciplines, and can include e.g., statistical analysis, data mining, machine learning methods, etc. **CS example:** Modelling of in-situ and ex-situ observations and measurements into local, regional and global models of weather/climate information. This includes climate projections, short-term and long-term models, downscaled and regional models, and more.	
Modelling	Process of creating and using models to simulate, represent, or analyse complex systems, phenomena, or processes. Models are simplified representations of real-world phenomena, and modelling involves developing these representations to gain insights, make predictions, or test hypotheses about the behaviour or characteristics of the studied system. Modelling methods are vast and they are often discipline-specific. **CS example:** Most obvious example for modelling in the context of CSs is using climate model output for areas where true observations are scarce, or production of projections of the future climate. Modelling produces useful climate information for decision-making, and simultaneously contributes to the science of developing the climate models for different purposes. Climate modelling services are also an increasing business opportunity where companies provide different modelling services for clients, such as near-term forecasts for disease outbreaks, crime hotspots, energy trends, or infrastructure failures.	ICPAC seasonal climate forecasts https://www.icpac.net/seasonal-forecast/ https://eco-act.com/
Data storage/repositories	Data repositories, or archives, play a crucial role in managing, storing, accessing, and disseminating datasets generated by RI activities (Roadmap 2021: Part 2 Landscape analysis). They promote data reuse and contribute significantly to the advancement of science. These repositories may incorporate various technologies such as APIs or automated quality control processes. Modern RIs are encouraged to integrate FAIR (Findable, Accessible, Interoperable, and Reusable) data principles to their data repository infrastructure to enable the philosophy of openness and transparency.	ESFRI Strategy Report on Research Infrastructures Roadmap 2021 https://roadmap2021.esfri.eu/

RI element	Description and examples related to CSs	References and links
	CS example: FAIR data can support the development of localized and tailored products and services that rely on data from RIs (e.g., locally created apps from open air quality data to provide information to communities).	
Data sharing and reuse	RIs might share openly the data they collect, or products of it. Sharing requires an interface or another technology, such as an API that is accessible for the further data users. As for the Data storage / repositories element, FAIR principles are relevant also for data sharing practices of an RI. FAIR data principles stress the discoverability and usability of the data and meta-data, meaning that the data is shared in a format usable by others, and it can be found, understood, and accessed without closed systems and too complicated interfaces (Wilkinson et al., 2016). RIs should also articulate their data sharing processes which can be anything from automated processes of quality control and sharing to community-based activities. Openly sharing the RI data or data products is an integral part of advancing open science and transparency, but it also ensures smart use of resources that have been allocated for collecting and processing the data. **CS example:** As already touched in the element of "Products, solutions and outcomes", different means for data sharing, such as data platforms may be seen as a product of an RI. However, due to their integral role in the domain of RIs for CSs, they are presented as their own element. For example, the Climate Risk Database (CRD) is the data management and sharing user-interface platform of Tanzania Resilience Academy that is built on an open-source Geonode technology. CRD is the final location where data collected via other Resilience Academy activities, such as students' mass-industrial placement for critical geospatial data collection, is stored and shared openly for anyone to use. CRD also facilitates a data management protocol where a community of experts quality control the shared data, and organise data sharing events like Data Parties.	Climate Risk Database https://geonode.resilienceacademy.ac.tz/
Knowledge management and skills building		
Knowledge exchange	One of the core activities of RI's is to facilitate multi-directional knowledge exchange flow between researchers, policy-makers, industries, businesses, and citizens. Successful knowledge exchange fosters innovation and concrete actions "on the ground", enhances the RIs performance, and creates a culture of openness and collaboration. Knowledge exchange may take different forms, such as possibilities for dialogue in conferences, workshops, and on online platforms, via training, outreach, and participatory approaches, or by creating policy recommendations and ensuring space for discussion and feedback.	
Knowledge preservation	RIs may enforce systematic and intentional efforts to safeguard and maintain the outputs, data, methodologies and intellectual contributions generated through the RI activities. This element plays a critical role in ensuring the longevity, accessibility, and usability of the resources, and thereby contributing to the continuity of scientific progress, advancement of knowledge, and reliability for climate actions.	

RI element	Description and examples related to CSs	References and links
Skill development/capacity building	RIs may provide training events, materials and campaigns for different stakeholders, and in different stages of the infrastructure design. For example, the RI can facilitate operators (e.g., WMO ETPR) and researchers' training and skill development, and also provide capacity-building to the RI users, institutions and stakeholders. **CS examples:** RI for CSs may provide climate-related skill development materials for the public as one of the service products; training events to increase knowledge and skills of how to access and use climate data, models and tools (C3S User Learning services); methodologies for citizen science-based climate or contextual data collection that includes data collection training at the beginning (Resilience Academy methodology).	CS3 User Learning services https://climate.copernicus.eu/user-learning-services Resilience Academy methodology https://resilienceacademy.ac.tz/student-interns/ WMO Education and Training Programme (WMO ETPR) https://wmo.int/activities/education-and-training-programme GAWTEC https://www.gawtec.de/
Users and collaborative networks		
Stakeholder, actors and community	RIs define their most important existing and potential stakeholders, actors and community members who have different roles in the infrastructure, such as giving the need and demand for the services, producing, and maintaining some of the infrastructure elements, and/or benefiting from the products and solutions. Iterative stakeholder mapping is a possible methodology for scoping existing and potential stakeholders throughout the RI lifetime. New stakeholders might appear via different RI activities along the road, and some might opt out. Inviting an active community around the RI ecosystem builds trust, enables multi-way communication, helps to understand the shifting needs of the benefiting actors, and fosters sustainable implementation of the RI products, solutions, and outputs in the society.	
Stakeholder, actors and community engagement	(See also: co-concepts) Engaging the stakeholders, actors, and community to the RI activities in all stages of its lifecycle from planning to development, implementation, MEL and feedback is important for all RIs. Engagement is designed to ensure that the perspectives, needs, and concerns of the individuals and groups affected by or involved in the RI are considered and incorporated into decision-making processes. Means of engagement are various, such as inclusive decision-making, two- and multi-way communication, capacity building, collaborative designing, and feedback loops. Effective engagement enhances the legitimacy, social acceptance, and overall success of RIs by fostering a sense of ownership, inclusivity, and shared responsibility among those directly affected or involved.	
Feedback mechanisms	Systematic processes and channels established to collect, analyse, and respond to input, comments, evaluations, and suggestions from various stakeholders involved in or affected by the RI. These mechanisms are essential for maintaining transparency, accountability, and continuous improvement throughout the lifecycle of the RI. Collection of input must be followed by responsive action, communication of changes, and continuous improvement. Feedback mechanisms can vary, and can take a form of surveys, interviews, focus group discussions, workshops, and one-on-one communication.	
Dissemination and accessibility	Dissemination activities are for sharing the RI products, solutions, and outputs widely available for various	

RI element	Description and examples related to CSs	References and links
	stakeholders. Scientific publications, reports, stories, social media posts, direct contacting etc. reach different audiences. Ensuring accessibility involves open access publications and data, user-friendly interfaces, and addressing barriers like language, geographical restrictions, and technical complexity.	
Governance and compliance		
Standards, policies and ethical considerations	A set of principles, guidelines, and practices that govern the planning, development, operation, and dissemination of RI activities, with good ethical practices. These elements might materialise, for example, when defining products and solutions' ownership, how data is collected, managed and shared, or when ethical reviews are needed. **CS example:** Commonly agreed ethical guidelines for CSs have been proposed, and their development by the CS community is on-going (see e.g., Pacchetti et al. 2022; Adams et al. 2015). It is important that all CS-related activities – such as designing an RI - follow ethical guidelines and contribute to their development when needed. Multiple CS elements might follow global, regional, or national standards, such as the observation methods, data models, climate projections and data sharing practices.	Pacchetti et al. 2022 https://doi.org/10.1175/BAMS-D-21-0137.1 Adams et al. 2015 http://dx.doi.org/10.13140/RG.2.1.1029.0645

The elements described above are summarized in Figure 5 below. The grey boxes are the categories from above, with the elements per category coloured in green (existing) and blue (added) elements of an RI. This highlights the broadened needs from an RI to support and provide CSs.

This approach was tested with the pilot sectors to begin to understand the CS and infrastructural needs per pilot area, as well as the applicability of these elements across sectors and spatial scales. The pilots and their CS needs are described briefly below, and then they are summarized per RI element.

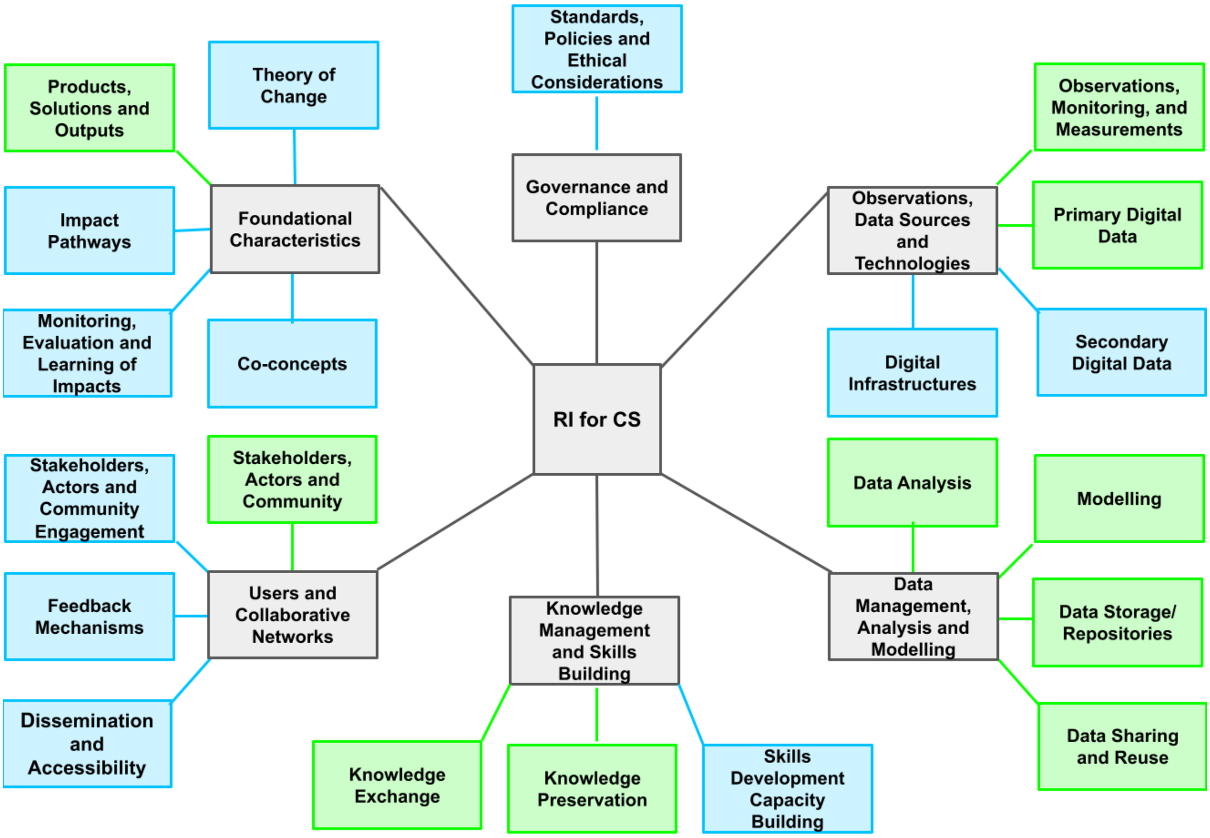

Figure 5. Key elements of a CS RI. The colouring is the same as in Table 2, with green boxes indicating those elements that are typical in an RI and the blue boxes indicating those elements that are added through this review.

Climate Service Needs Per Pilot

As described above, a bottom-up approach was used in this review that focused on the sectors covered by the KADI pilots. The CS needs of each pilot is addressed based on the sector the pilot represents, the spatial scale, the geographical context, and the needs of the identified stakeholders and actors that will be using the services. This is based on literature review and the expertise of the KADI team working on the respective pilots.

Urban

CS needs in an urban African context vary greatly between sectors, spatial scale, and who the actor using the service is. For example, citizens' and drainage infrastructure planners' needs can be very different. Citizens benefit more from services that they can utilise in their everyday life, whereas drainage infrastructure planners might appreciate services that they can use when a strategic planning process is starting. Planning processes require evidence on the current and future state of precipitation risks, topography, river sedimentation, waste management infrastructure, soil condensation and more.

The most common service modes that are considered as CSs are relevant for urban contexts, too. Weather and climate forecasts are useful when preparing for climate risks, such as droughts, floods and sea level rise. Small-scale urban agriculture is a source of living for many households and even communities in the cities, and thus climate information that is tied to crop and seed performance aid the farmers in selecting the cultivated crops according to forecasted rainy seasons and temperature.

One of the most important aspects for urban CSs to consider is that the cities in the Global South tend to develop fast. Urban intrusion grows the city from its edges towards the countryside, and urban densification uses free space from the centre parts in more and more effective ways. With other contextual issues the cities might face, it can be difficult to efficiently integrate climate adaptation and mitigation into current decision-making strategies since all energy goes to managing land ownership, drainage-, water- and waste infrastructure issues of the fast-developing city. Although, it is very widely known that climate change and its already visible impacts in the Global South exacerbate these other internal problems.

As the internal problems are not overarching to all cities in the Global South or Africa, the CSs tailored for urban contexts must be context aware. What works in Johannesburg might not work exactly as such in Addis Ababa. This notion is examined below where the three KADI CS city pilots are looked through the lenses of 'climate service needs'.

The geographic context helps us understand CS needs. Although all of the pilot cities (Abidjan, Nairobi and Dar es Salaam) experience similar climate risks, their management can require different approaches based on the decision-making atmosphere, citizens' desires, available resources, and so on. The geographical context of the pilots and reasoning behind the CS pilot are presented as they highlight the CS needs per city.

Abidjan, the economic capital of Côte d'Ivoire, is experiencing high levels of anthropogenic activity due to a growing urban population. Pollutants including $PM_{2.5}$, which have a proven impact on health, have concentration levels higher than those measured in major European cities. They are mainly emitted by combustion sources such as the burning of fossil fuels and biomass, waste burning and industry. Studies highlighted those residential sources account for more than 50% of $PM_{2.5}$ emissions. This source of PM is increasing due to the growing demand for domestic energy, which is closely linked to the demography.

Despite the known impacts of air pollution and the immediate perception of the population, Abidjan city has neither a real air quality measurement network, nor a forecasting system to manage pollution episodes in real time. However, this service must also enable us to identify the pollution source**s** to support decision making in emission reduction strategies. The main objective of this pilot is the production of air quality indicator maps, based on severity scales defined jointly and therefore understood by all.

Nairobi is the metropolitan capital of Kenya with a population of about 5 million people spread across the city in suburbs and in informal settlements. Nearly half the population of Nairobi live in informal settlements which make up about 1% of the land in the city. This makes for extremely cramped living conditions and very low access to necessary services. Nairobi is prone to urban flooding and flash floods during the rainfall seasons and the nature of the informal settlements make it a literal hotspot for heat stress during the hotter months of the year which is about 4-5 months each year.

The communities living in the various informal settlements have low access to the services necessary to support their well-being. These include lower health services access, overcrowded schools, proper governance, electricity access in most cases, and the high rates of unemployment. The population in these settlements is also rapidly growing due to increased rural to urban migration in search of employment. Stakeholders include various research organisations carrying out work in the settlements, social enterprises seeking to improve well-being as well as various government agencies working to provide and improve public services.

Dar es Salaam is particularly vulnerable to climate risks due to rapid and largely uncontrolled urban growth with weak land use planning, little information to assess vulnerability and risk, and a widening infrastructure gap. It has been estimated that 50-80% (Magembe-Mushi & Lupala, 2015; Team, 2020) of the city's inhabitants live in unplanned and weakly built areas in terms of urban infrastructures such as housing, transportation, and urban vegetation. The most pressing climate risks that affect Dar es Salaam are regularly occurring flash floods, heat stress, and air and water pollution. Flash floods, their causes, effects, and vulnerability patterns in Dar es Salaam are rather well understood, and both national and city governments take measures to protect lives and livelihoods that are affected by the floods. Heat stress and air pollution on the other hand are less represented in research and policy making, and there are little to no data of these climate risks available for informed decision-making.

Due to the knowledge gap regarding heat stress and air pollution and their cascading effects – together with flash floods – on individual citizens and larger communities, there is also little recorded knowledge on the communities' needs for CSs that would be beneficial for their use in adapting to these challenges. Thus, this city pilot first scopes these needs via participatory mapping and interviews in selected communities in the city that are vulnerable to the three mentioned climate risks and consequential effects. The communities are thus brought to co-create the concept for a local-scale CS where missing digital climate data is collected via citizen science methods and community-based approaches.

Marine Biogeochemistry

The Coastal Southern African Biogeochemistry pilot partnered with a pre-established RI (Shallow Marine and Coastal Research Infrastructure (SMCRI; SMCRI, 2022)) in South Africa to serve as a test case that can be applied to other coastal areas in Africa. This KADI pilot focuses on quantifying key components of the coastal carbon cycle that are relevant to the regulation of climate change, and focuses on carbon cycling and other greenhouse gas measurements.

This pilot will be able to address needs such as quantifying carbon sequestration, coastal GHG flux, ocean acidification, and the productivity of oceans. Through this focus CSs needs of sectors such as fisheries, aquaculture, oil and gas, shipping, mining, and coastal development can be addressed.

Ocean carbon sequestration is referring to the ocean's role in the natural process of capturing and storing atmospheric CO_2 (Brodeur et al., 2022).The primary data needed to characterise this process are measurements of dissolved organic carbon and carbon isotopes from water samples to determine the carbon efflux from monitoring sites (Zhou et al., 2021). Ocean acidification is the process of the oceans becoming more acidic of atmospheric carbon dioxide (NOAA, 2024). Primary data of pH, total alkalinity and pCO_2 can provide the data needed to determine the acidity of the ocean. The process of ocean production is when phytoplankton use sunlight to create food in the form of organic matter for themselves and other ocean creatures. Additionally, they play a role in chemical processes within the ocean and absorb CO_2 from the atmosphere (Sigman & Hain, 2012). Measurements of phytoplankton and zooplankton diversity and biomass are primary data needed to determine ocean production. All the primary data can be combined with secondary data such as geospatial data to find the locations that will be most impacted by these processes. A data platform can be utilised to provide real-time monitoring of these ocean processes to relevant stakeholders.

As noted above, such a coastal biogeochemical RI has key sectors that are impacted by fluctuations in these aspects of the marine coastal environment due to climate change. These sectors include fisheries, aquaculture, oil and gas, shipping, mining, and coastal development (SMCRI, 2022). Fisheries encompass both the location where fish are harvested and the industry involved in their capture (NOAA, 2023). Related to this is aquaculture, which refers to the cultivation of various fish and other aquatic organisms (NOAA, 2023). These stakeholders could benefit from the location-specific CSs. Additionally, this RI aims to validate a range of sensors that could be used in data scarce regions across the continent. This pilot will need to collect primary data from a range of sensors in order to make recommendations.

Long-term observations - Lessons Learned and Links to Climate Services

WMO in its GFCS defines CSs as "Climate information prepared and delivered to meet users' needs." At the core of this provision–of climate information are long-term meteorological and atmospheric composition observations. The key components of the GFCS are;

- Climate observations and monitoring,
- Climate research, modelling and prediction,
- CSs information system,
- Engagement between users and providers of CSs, and
- Capacity development.

The GFCS is implemented through national meteorological and hydrological services (NMHSs) in collaboration with various partners including governments, universities and research institutions, donor projects, and development partners. The NMHSs play the key role of gathering observations that form the foundation of CSs and are central to the CS information system. They are also key to the development and implementation of systems and processes for generation of climate products as well as facilitation of interaction with and among users and stakeholders.

The role of the national meteorological (met) services in supporting the development of an African RI cannot be overstated. As the generators and custodians of crucial long-term climate data, they play a key role in supporting researchers, generation of new information as well as validation of research, data and studies. The met services in turn stand to benefit from established RI through identification of needs, priority areas for research as well as existing gaps. The interaction of the met services with RI also provides credible ground for co-production of CSs with collaboration in research including the non-physical sciences such as social and human sciences to support decision making for the benefit of society.

In Africa, the provision and delivery of context-relevant CSs is hampered by many challenges (Vogel et al., 2019) including insufficient or sparse observational networks as outlined in the 2021 State of the climate in Africa report by WMO (WMO, 2021). They report that there remain significant gaps in the observation of certain variables over Africa, particularly precipitation, but also the basic variables defined in the WMO Global Basic Observing Network (GBON). Table 3 highlights the mandatory measurements from the GBON requirements (taken from WMO, 2023c).

Table 3: Mandatory measurements from GBON requirements. Note that there are additional measurements listed in GBON, this table has only highlighted those that are mandatory (taken from WMO, 2023c).

	Horizontal resolution	Vertical resolution	Observing cycle	Variables to be observed (as applicable) *
Surface land stations	200 km	n/a	1 hr	SLP, T, H, W, P, SD
Upper air stations operated from land	500 km	100 m	2/24 hr	T, H, W
Surface marine stations in EEZs**	500 km	n/a	1 hr	SLP, SST
Upper air stations in EEZs**	1000 km	100 m	2/24 h	T, H, W

* Atmospheric pressure (SLP), air temperature (T), humidity (H), horizontal wind (W), precipitation (P), snow depth (SD), sea surface temperature (SST)

** Exclusive Economic Zones (EEZ)

The KADI project is working to highlight the advances in observational capabilities including lessons learnt from over 25 years of observations in Kenya. While these operation observations are not defined as a RI, the experiences with long-term atmospheric measurements (which will be a goal of the recommend RI from KADI) and links to supporting CSs are invaluable. In addition, these observations include those of the Global Atmospheric Watch (GAW) station on Mt Kenya. GAW focuses on long-term atmospheric composition measurements in order to understand trends, as well as the interactions between the Earth system (i.e., atmosphere-terrestrial-ocean linkages and feedbacks). Figure 6 below displays the GAW global stations. The assessment here focuses on the Mt Kenya site that provides a regional view of atmospheric composition (https://community.wmo.int/en/activity-areas/gaw).

Figure 6: GAW Global Stations (taken from: https://community.wmo.int/en/activity-areas/gaw/research-infrastructure/gaw-stations).

Earth System Model Development

Earth System Model development requires, access to quality-controlled observations, for the purpose of model verification, and subsequent model improvement. The provision of these data is a CS. The observational networks required for model development processes include weather stations, flux towers, upper air soundings and oceanic-based observations. Largely unexplored for Africa, is the use of flux tower data to verify Earth System Model representations of land-atmosphere fluxes, including carbon fluxes. Project KADI is playing a major role in this respect, by providing access to flux tower networks for the purposed of model verification.

Example Services for Each Pilot

The section above has highlighted the CS needs that are the focus of the pilots. In order to develop an RI that will support and provide such CS, it is critical to all elements of an RI. This has been mapped below per pilot/pilot sector (Table 4). Through the next phase of WP1, the team will work with stakeholders to discuss CS needs and will work to articulate the needed elements for these needs as done per pilot below.

Table 4 shows an effort by all the pilot teams to assess what could be needed across all RI elements (as possible) for each pilot sector to support and produce CSs. The different sectors and spatial scales are represented by the KADI pilots. The contents for each concrete example show the differences in terms of their demand and need levels. It is planned that this framework will guide the analysis of the further work in WP1 (i.e., information from stakeholders and literature review) as it ties the CSs needs to the needed elements of an RI.

Table 4. Examples of CSs organised by the relevant RI elements at different spatial scales as explored in the various pilots.

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
Products, solutions and outputs	**Disaster risk management**: Community-based adaptation in an informal settlement improved flood risk management led by the community in Cape Town, South Africa (Fox et al., 2023). **Climate adaptation management:** Participatory mapping in an informal settlement empowered the community to lead climate adaptation strategies in Durban, South Africa (Mazeka et al., 2019).		GAW: Africa is a continent with a serious shortage of air quality information. Measurements in cities (like Nairobi) can provide useful information to the public with respect to health-relevant conditions. Measurements at remote locations (like the Mount Kenya station) profit from small local impact, and, thus, are usually representative for a large spatial area. The large representativeness provides excellent conditions for measurement-model comparisons and trends in background conditions. Retrieving global patterns of atmospheric composition's variability and trends with a rather small number of background stations is one of key goals of the GAW programme (WMO, 2014). National Observations: stakeholder survey is being conducted to collect feedback on current products and services provided, as well as to inform future service development.	Earth System Models have become the main tools to project future climate change, thereby informing on climate change adaptation and exploring the consequences of different mitigation scenarios. Earth System Model simulations can also, through inverse modelling, inform on the optimal design of observational networks. Note that the Earth System Model applied and developed in project KADI is uniquely African based.
Observations, measurements, and monitoring	**Citizen science:** An opportunity in African cities with large digitally skilled young populations is a possibility for "citizen sensors" where communities contribute to data collection by using their mobile phones and participatory online platforms. -The UrbanBetter project #Citysens4CleanAir in Cape Town, South Africa leveraged the participation of young people to co-design and lead a clean air campaign that collected air quality data. Participants wore low-cost sensors during community running events and shared the	Observation of Essential Ocean Variables (EOVs), Essential Biodiversity Variables (EBVs) and Essential Climate Variables (ECVs) at fixed and discreet stations around the coast of South Africa. Fixed stations will include the deployment of near real-time MetOcean observations moorings in Algoa Bay and St Helena Bay. Discreet stations have been sampled in Algoa Bay since 2010 and EOVs	GAW: Installation and station characteristic of the Mount Kenya station is documented in Henne et al., (2008a) and Henne et al., (2008b). National Observations: The national observing capabilities of Kenya, including the KMD and other infrastructure are being documented in a structured manner in the WMO's reference metadata portal (www.oscar.wmo.int/surface).	Earth System Model simulations can be used as inputs to inverse modelling, thereby informing on the optimal design of observational networks.

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
	data with the public on an interactive platform (Oni, 2022). **Weather stations**-(TAHMO) **Citizen Weather Stations (CWS)** (Meier et al. 2017) **Participatory observations** (Citizen Sensing) **Social media observations** by citizens (Fohinger et al. 2015) **City scale weather stations and loggers** (TURCLIM) **Hyperlocal/high density observation network** (Scott et al. 2017)	linked to carbon will be included from 2024. In addition, GHG CO_2, CH_4, N_2O) fluxes will be measured from the soil/water/vegetation in key coastal habitats at discreet stations to better understand flux in these habitats.	Eddy Covariance towers are currently collecting continuous information on CO_2/H_2O exchange over different land use types - located in the savanna biome. These systems include rangeland (wildlife/livestock), large scale no-till agriculture, small-scale agriculture and shrubland.	
Primary digital data	**Africa Data Hub Climate Provider:** A provider of climate data at African cities and towns (https://www.africadatahub.org/).	Two near-real time moorings will collect hourly data on: water column pCO_2, temperature, salinity, pressure/depth, pH, DO, NO_3, Chl-a, turbidity & surface met climate. Discreet data from 8 stations have been collected in Algoa Bay since 2010 and include: water column temp, DO, salinity, pressure, depth, pH, Chl-a, turbidity, NO_3, NO_2, PO_4, $Si(OH)_4$, phytoplankton community and biomass, and zooplankton community and biomass. In addition, hourly in-situ temperature, current direction and strength and swell	GAW: The Mount Kenya station is one of the currently 30 global (i.e., flagship) stations of WMO's Global Atmosphere Watch network. National Observations: The Eddy Covariance stations have been registered in OSCAR and are run by international research centres or foreign universities. Data are made publicly available.	The African-based Earth System Model is generating detailed simulations of climate (Big Data) within project KADI, of value for inverse modelling and research on African climate processes, climate variability and anthropogenically-induced trends in climate.

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
		data have been collected at >20 stations since 2008.		
Secondary digital data	**Building footprints:** A review of building footprint data shows data products that provide building footprints for urban areas in countries across Africa. The data providers include Ecopia, Google, Microsoft, and OpenStreetMap (Chamberlain et al., 2023). **Population distribution:** Africapolis is an inventory of official urban population across all African countries (https://africapolis.org/). **Vegetation cover:** NOAA Advance Very High-Resolution Radiometer (AVHRR) images can be used to calculate the normalized difference vegetation index (NDVI) to determine the influence of vegetation on urban climate in Gaborone, Botswana (Jonsson, 2004).	Access to South African Weather Services (SAWS) data from coastal weather stations Ocean colour remotely sensed data products to fill the gaps between the fixed and discreet stations. Access to streamflow data from the Department of Water and Sanitation (DWS) to better understand freshwater inflow into estuaries. Access to tide gauge data from SANHO (https://www.sanho.co.za/) and DWS.	Measurements, supported by meteorological models to learn about the history of the sampled air masses, can provide information about the spatial distribution of emissions (Kirago et al., 2023, Henne et al., 2008a, 2008b).	Not applicable.
Digital infrastructures	**Urban flood prediction:** A nowcasting model developed using machine learning and satellite observation that started in urban areas in Ghana. The output is available online at https://rainsat.net/ (Lugt et al., 2021).	All SAEON data adheres to the FAIR principles and are available free and open on our observations database and data portals.	GAW: Final data are usually made available with a delay of several months. Near-real-time data release is not established but is foreseen in planned activities like WMO's Global Greenhouse Gas Watch (https://wmo.int/activities/global-greenhouse-gas-watch-g3w).	The KADI climate model simulations will be stored on a Wits Global Change Institute data server for several years, in support of ongoing research efforts on African climate processes and related observational structures.
Data sharing and reuse	**Climate Risk Database:** The Tanzania Resilience Academy aims to provide digital services and skills to address urban climate risks in Dar es Salaam, Tanzania. As mentioned previously, the Climate Risk	All data adhere to FAIR principles and can be accessed at the Observations Database https://observations.saeon.ac.za/	GAW: Data are freely available in various global data repositories. Terms of use are provided by the data centres along with the downloaded data.	Climate model simulations generated as part of project KADI will be freely available for research purposes, via

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
	Database is the data management and sharing user-interface platform of Tanzania Resilience Academy that is built on using open-source Geonode technology (https://geonode.resilienceacademy.ac.tz/).	also discoverable via the SAEON Data Portal https://catalogue.saeon.ac.za/		the Wits Global Change Institute data servers.
Data analysis	**Future Resilience for African Cities and Lands (FRACTAL) Climate Information Portal (CIP):** FRACTAL aims to equip design-makers in Southern African cities with decision-making tools informed by local climate data. The CIP tool web interface displays climate data and future projections (https://cip.csag.uct.ac.za/webclient2/app/).	Data produced by the pilot will be analysed by scientists and collaborators linked to the pilot from both Europe and Africa. The data will also be made available in raw and processed formats to allow free access to any other scientist interested in the data.	GAW: Data analysis of atmospheric data mainly focusses on detection and interpretation of variability and trends. In the future, observations will increasingly use for timely generation of elaborated products (like monthly national emissions as planned within WMO's Global Greenhouse Gas Watch) programme.	Within project KADI, analysis of the Earth System Model simulations is focussed on the improved understanding of land-atmosphere fluxes, and the improvement of the representation of land-surface features within the model.
Modelling	**Uncertainty reduction in Models for Understanding Development Applications (UMFULA):** UMFULA aims to improve climate information decision-making in cities in Tanzania and Malawi. UFLAMA is focused on reducing uncertainties in climate models by using a process-based model evaluation (Rouhaud, 2016). **African Monsoon Multidisciplinary Analysis 2020 (AMMA-2050):** AMMA-2050 aims to use participatory modelling to aid in climate adaptation management. A high-resolution model of hydrological simulation to support flood risks management using Ouagadougou, Burkina Faso as a city pilot (Visman, 2020).	The coastal biogeochemistry pilot will rely on external collaborators for modelling and integration with other components of the earth system. We have two partners in mind that worked on the global assessment of coastal fluxes and "model inversions" of coastal fluxes based on DIC and deltaC in the ocean.	GAW: Open and free tools exist for calculation of backward-trajectories to determine the origin of air masses and to establish source-receptor relationships. Examples are HYSPLIT (https://www.arl.noaa.gov/hysplit/) or FLEXTRA (https://projects.nilu.no/ccc/trajectories/). tools	The African Earth System Model, of which the land-surface component is being further developed in the project, is the only model of its kind based in the African continent, The key service provided by the modelling system, is its projections of future climate change.
Data storage / repositories	**South African Population Research Infrastructure Network (SAPRIN) data repository:** SAPRIN collects population-based health and demographic data in	SAEON data repositories can be found here: Observations Database https://observations.saeon.ac.za/	GAW: Data are made freely available in public global data repositories such as World Data Centre for Greenhouse Gases (https://gaw.kishou.go.jp/) and	The climate model simulations generated as part of project KADI are freely available for research

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
	urban and rural areas in South Africa. The data is open access and available through a data repository (SAPRIN).	also discoverable via the SAEON Data Portal https://catalogue.saeon.ac.za/	the World Data Centre for Reactive Gases (https://www.gaw-wdcrg.org/).	purposes, via the Wits Global Change Institute data servers
Knowledge exchange	**FRACTAL weADAPT**: A climate adaptation community led online networking tool (SEI, 2024).	Knowledge gained through the project will be shared with the European and African community through workshops, presentations at conferences, reports, popular articles and targeted meetings.	KMD hosts the Institute for Meteorological Training and Research (IMTR), which is a WMO Regional Training Centre (WMO - RTC) in Nairobi.	The Earth System Model simulations, and new insights gained in terms of land-atmosphere fluxes will be shared with the scientific community through the usual methods of scientific papers and conference proceedings.
Skill development / capacity building	**Resilience Academy methodology:** The Resilience Academy builds capacity through student interns who receive data collection training, and conduct data collection campaigns in city-scale.	The coastal biogeochemistry pilot will conduct two training workshops in Africa, i.e., one in March 2024 and the second likely early in 2025. The aim of the training workshop is to build capacity in coastal GHG observations in Africa.	Being an active member in the Global atmosphere Watch community, KMD staff can profit from training activities within the programme, like the GAW Training and Education Centre (https://www.gawtec.de/) and other events of WMO’s Global Campus (https://learningevents.wmo.int/#/).	Project KADI is contributing to the in-house training of regional climate modellers working within the project, primarily within the Wits Global Change Institute.
Stakeholders, actors and community engagement	**Developing Risk Awareness though Joint Action (DARAJA):** DARAJA aims to develop a co-designed city scale forecasting and early warning service for weather and climate adaptation to increase accessibility of these services (Sen, 2020). Stakeholders, actors and engaged communities for city-scale CSs are often – the citizens, – citizen communities, – urban planners, – officials from environmental, meteorological and disaster risk management offices, – media representatives, – academics and researchers,	The coastal biogeochemistry pilot will co-design the establishment of a coastal GHG observation network with all the actors in this discipline/field. Engagement will take the form of open and targeted workshops online and in person. National (South Africa) and Africa-wide engagements will take place concurrently.	<u>National Observations</u>: A comprehensive stakeholder screening was performed as part of the KADI project.	The stakeholders to climate change projections are extremely broad, stretching across all sectors and all spheres of government, national and international. The African-based Earth System Model serves, first and foremost, African societies and the environment.

	Local	Regional		Continental
RI element	**City pilots**	**Coastal biogeochemistry pilot**	**Long-term observations pilot**	**Earth system modelling pilot**
	– education institutes, – relevant local NGOs, and – decision-making bodies.			
Feedback mechanisms	**DARAJA Evaluations:** DARAJA gets feedback from stakeholders through activities such as small-scale weekly surveys.	Feedback from the actors following regular workshops and online meetings will be incorporated in the design of the observation network. Feedback will be continuous through the establishment of a Community of Practice working group that will be regularly consulted.	National Observations: Following the stakeholder screening, a stakeholder survey was prepared and distributed; responses are currently evaluated.	For the Earth System Model development process in KADI, the main feedback loop is between model development on the one side, and observational networks on the other side, via the process of model verification.
Dissemination and accessibility	**AMMA-2050 science communication:** A Theatre Forum was developed to communicate climate change impacts across different stakeholders, actors, and community members.	All data will be disseminated via databases mentioned above. In addition, data will be shared with other large RI's and global networks, e.g., ICOS, GERI, ILTER (DEIMS database) to increase access and impact of data. Access to the Ri will be open and free.	See 'Data sharing' and 'Data storage' above.	See 'Data sharing' and 'Data storage' above.

Table 4 above highlights how all the pilots are beginning to work across the selected elements of an RI. These selected elements from Table 2 omit more contextual elements to avoid repeating and identify clear examples of CS needs of each pilot. Many of the examples from the pilots are focused on provision of data, which is a CS. In the discussions with actors in the engagements that will follow (described below) the team will work to understand what additional services are needed across the pilots.

Summary and Next Steps

There is a large variety and breadth of the linkage between long-term measurements and modelling output to CSs in Africa. This has had, a particular focus on physical (i.e.,” hard”) infrastructure, yet does not generally consider the” softer” infrastructures that provide additional information and contexts. In addition, the linkages are often seen as one-directional, with scientific information providing a service. These approaches have left gaps in CSs (e.g., how they are developed, how they are implemented, how their impact is assessed). As this review has shown, the development of an African-based RI to support and provide CSs must broaden the scope of what is considered key elements of an RI as well as the approach to CSs, with a focus on co-development.

This review has developed a new approach to the key elements of an RI that will be needed to support CSs. Using a bottom-up approach of focusing on the KADI pilot sectors, this innovative approach has been tested and refined towards addressing the CS needs of each pilot. This is an initial assessment as it is based on internal input as the first test of the approach. The next steps, as described below, will focus actor engagement to refine and/or broaden (as needed) the CS needs and link to an RI within the pilot sectors as well as in additional sectors.

Upcoming Stakeholder Engagement Plans

A focus of the next steps is on engaging with actors to discuss CS needs that can be addressed by an RI. Furthermore, continuing the literature review and incorporating insights from stakeholder engagements will help expand beyond the pilots to include additional sectors. The engagement plans for 2024 (Figure 7) will focus on leveraging proposed WP1 and WP4 stakeholder meetings by coordinating with WP2 and WP3. The first phase (left hand side of Figure 7) will occur in Q1 and Q2 of 2024 and will engage stakeholders in key project activities that will support the development of the theoretical observational network (WP3). This will be done through targeted workshops that will focus on discussions of CSs, pilot domain areas and observational networks. This will also include a larger meeting in June 2024.

The second phase (right hand side of Figure 7) will include the annual meeting in 2024 and will provide an opportunity for a large workshop to present the key activities of the KADI project to that point and the development of the draft blueprint for the observational network for Africa. This will build on the targeted workshops in the first phase by showing participants what has been done and what still needs to be done. The number and range of actors will be expanded at each engagement, though the initial actors will continue to be involved throughout. These workshops will be a feedback loop for WP1’s proposed framework, helping to identify how other actors and sectors can be involved. Offering additional focused workshops and hybrid sessions (combining online and in-person options) is expected to boost participation in this phase.

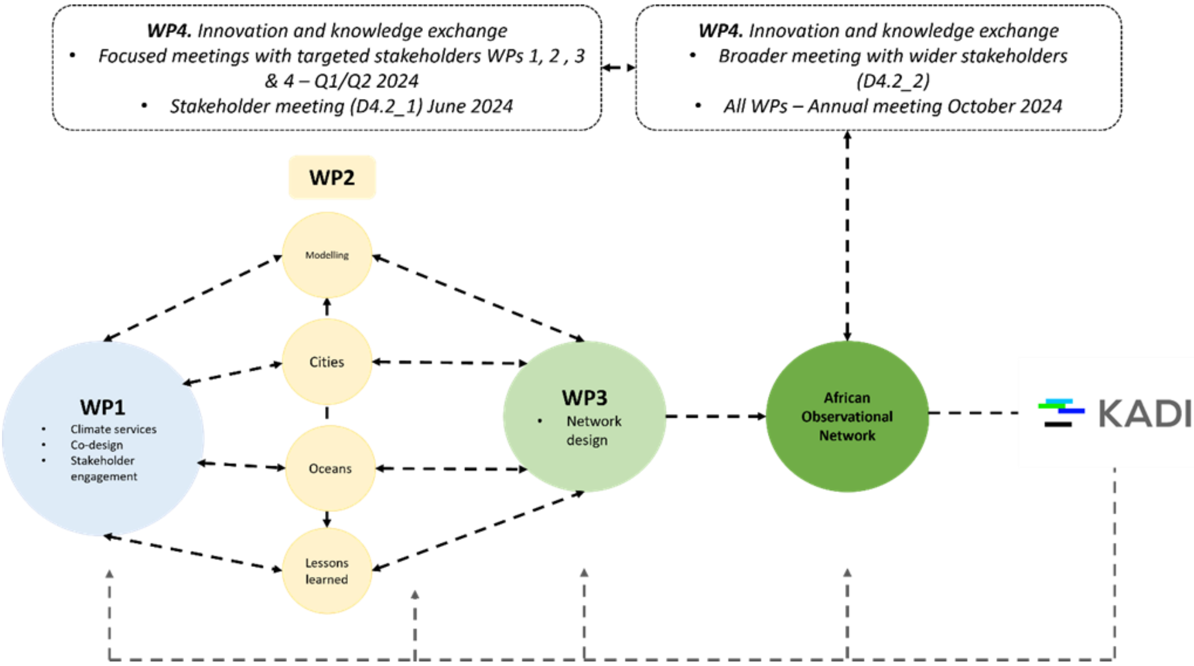

Figure 7. Schematic of the planned WP1, WP2 and WP3 stakeholder and actor engagement.

In addition to this actor engagement, the literature review will continue to broaden to consider additional sectors past those of the pilot sectors. It is anticipated that key stakeholders from these additional sectors will be part of the actor and stakeholder engagement meetings from Q2 of 2024.

Ethical clearance has been granted to the University of Pretoria for all stakeholder engagement activities under WP1 (reference number: NAS084/2023). See Appendix B at the end of this document..

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KADI

Appendices

Appendix A

Table 1. List of identified RIs across the globe.

RI Name	Link	Geographical Location (Asia, Africa, Europe, North America, South America, Australia/Oceania)	Type (In situ, Modelling, Remote Sensing & Satellite, Digital)
The African Group on Earth Observations (AfriGEO)	https://www.earthobservations.org/afrigeo.php#	Africa	Remote Sensing & Satellite
Nuclear medicine research facility (NuMeRi)	https://sanumeri.co.za/	Africa	In situ
South African Centre for Digital Langauge Resources (SADiLar)	https://sadilar.org/index.php/en/	Africa	Digital
Natural Science Collections Facility (NSCF)	https://nscf.org.za/	Africa	Digital
Distributed PLatfrom in OMICS (DIPLOMICS)	https://www.diplomics.org.za/	Africa	In situ
South African Polar Research Infrastructure (SAPRI)	https://www.sanap.ac.za/	Africa	In situ
South Africa Nano-Micro Manufacturing Association (SANMMA)	https://www.sanmma.org.za/	Africa	In situ
Solar research facility	https://www.csir.co.za/csir-solar-photovoltaic-power-plant-research-facilities-support-increased-use-renewable-energy-sa	Africa	In situ
Material characterisation facility	https://www.csir.co.za/dsi-csir-national-centre-nanostructured-materials-characterisation-facility	Africa	In situ

Biogeochemistry Research Infrastructure Platform (BIOGRIP)	https://www.biogrip.ac.za/	Africa	In situ
South African Environmental Observation Network (SAEON)	https://www.saeon.ac.za/	Africa	-
Expanded terrestrial and freshwater environment observation network (EFTEON)	https://efteon.saeon.ac.za/about-efteon/	Africa	In situ
South African Population Research Infrastructure Network (SAPRIN)	https://saprin.mrc.ac.za/	Africa	Digital
Shallow marine and coastal research infrastructure (SMCRI)	https://smcri.saeon.ac.za/	Africa	In situ
Biodiversity Biobanks South Africa (BBSA)	https://bbsa.org.za/	Africa	Digital
Integrated Carbon Observation System (ICOS)	https://www.icos-cp.eu/	Europe	In situ
RI-Urbans	https://riurbans.eu/	Europe	In situ
In-service Aircraft for a Global Observation System (IAGOS)	https://www.iagos.org/	Europe	In situ
European Research Infrastructure Consortium (EUROARGO)	https://www.euro-argo.eu/	Europe	In situ

The Aerosol, Cloud and Trace Gases Research Infrastructure (ACTRIS)	https://www.actris.eu/	Europe	Remote Sensing & Satellite
Integrate European Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER)	https://elter-ri.eu/	Europe	In situ
Environmental Research Infrastructures (ENVRI)	https://envri.eu/research-infrastructures/	Europe	-
Atmospheric dynamics Research InfraStructure in Europe (ARISE)	http://arise-project.eu	Europe	Remote Sensing & Satellite
European Facility for Airborne Research (EUFRAR)	https://www.eufar.net/	Europe	Remote Sensing & Satellite
HEMERA RI	https://www.hemera-h2020.eu/	Europe	In situ
Analysis and Experimentation and Ecosystems (AnaEE)	https://www.anaee.eu/	Europe	
Distributed System of Scientific Collections (DISSCO)	https://www.dissco.eu/	Europe	Digital
European Infrastructure for Multi-scale Plan Phenomics and Simulation (EMPHASIS)	https://emphasis.plant-phenotyping.eu/	Europe	Digital
INTERACT	https://eu-interact.org/	Europe	In situ
EUROFLEETS+	https://www.eurofleets.eu/	Europe	In situ

Gliders for Research, Ocean, Observation & Management Research Infrastructure (GROOM RI)	https://www.groom-ri.eu/	Europe	In situ
Joint European Research Infrastructure of Coastal Observatories Research Infrastructure (JERICO-RI)	https://www.jerico-ri.eu/	Europe	In situ
SeaDataNet	https://www.seadatanet.org/	Europe	Digital
European Plate Observing System (EPOS)	https://www.epos-eu.org/	Europe	Remote Sensing & Satellite
European Global Ocean Observing System (EuroGOOS)	https://eurogoos.eu/	Europe	In situ
Infrastructure for the European Network for Earth System Modeling (IS-ENES3)	https://is.enes.org/	Europe	Modelling
Svalbard integrated Earth observing system (SIOS)	https://www.sios-svalbard.org/	Europe	In situ
Network of Leading Ecosystem Scale Experimental AQUAtic MesoCOSM Facilities (AQUACOSM-PLUS)	https://www.aquacosm.eu/	Europe	In situ

International Centre for Advanced Studies on River-Sea Systems (DANUBIUS-RI)	https://www.danubius-ri.eu/projects.html	Europe	In situ
European Marine Biological Resource Centre (EMBRC)	https://www.embrc.eu/	Europe	In situ
e-Infrastructure for Biodiversity and Ecosystem Research (LIFEWATCH)	https://www.lifewatch.eu/	Europe	Digital
European Multidisciplinary Seafloor and water column Observatory (EMSO)	https://emso.eu/	Europe	In situ
INFRAFRONTIER		Europe	Modelling
European Incoherent Scatter Scientific Association (EISCAT 3D)	www.eiscat3d.se	Europe	Remote Sensing & Satellite
National Ecological Observatory Network (NEON)	https://www.neonscience.org/	North America	In situ
Centro de Referência em Informação Ambiental (CRIA)	https://www.cria.org.br/	South America	Digital

Appendix B

Ethical Clearance for Work Package 1

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee
E-mail: ethics.nas@up.ac.za

19 February 2024

ETHICS SUBMISSION: LETTER OF APPROVAL

Prof RM Garland
Department of Geography Geoinformatics and Meteorology
Faculty of Natural and Agricultural Science
University of Pretoria

Reference number: NAS084/2023
Project title: Knowledge and climate services from an African observation and Data research Infrastructure (KADI)

Dear Prof RM Garland,

We are pleased to inform you that your submission conforms to the requirements of the Faculty of Natural and Agricultural Sciences Research Ethics Committee.

Please note the following about your ethics approval:

- Please use your reference number (NAS084/2023) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.
- Please note that ethical approval is granted for the duration of the research (e.g. Honours studies: 1 year, Masters studies: two years, and PhD studies: three years) and should be extended when the approval period lapses.
- The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.
- **If Applications using GM permits:** If the GM permit expires before the end of the study, please make an amendment to the application with the new GM permit before the old one expires
- **If Applications using Animals:** NAS ethics recommendation does not imply that Animal Ethics Committee (AEC) approval is granted. The application has been pre-screened and recommended for review by the AEC. Research may not proceed until AEC approval is granted.

Please take note of the reviewers comments:

This project is accepted based on the requirements of Work Package 1 to which UP is the lead investigating institution.

Interactions and participation in work packages (2-4) will require updated to this ethics application that better outlines any investigations and/or analysis that UP intends to undertake as part of the KADI project.

As indicated in the project proposal:

7) Establish a Memorandum of Understanding (MoU) among all partners documenting their role on data handling, data sharing and data access.

Post approval submissions including application for ethics extension and amendments to the approved application should be submitted online via the Ethics work centre.

We wish you the best with your research.

UNIVERSITEIT VAN PRETORIA
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YUNIBESITHI YA PRETORIA

Yours sincerely,

Prof VJ Maharaj
Chairperson: NAS Ethics Committee