FOCUS-Africa

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Report to document the data required, and a set of guidelines, for all CS prototype development

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Summary

FOCUS-Africa is developing climate services for the Southern African Development Community (SADC) region in four different sectors: agriculture, water, energy and infrastructure. These services are being developed through eight case studies and they aim to maximize the socio-economic benefits in the five SADC countries they are based in. Close engagement with users of the case studies is essential to the co-production of the trial climate services being implemented in WP5. Likewise, it is important to learn about the socio-economic context of the proposed trial climate services, so as to be able to optimise their development and implementation. This is why a close interaction with WP6 has been pursued and maintained throughout the initial phases of WP5 (and beyond), with Task 5.1: Collate output required to develop prototypes. In this first phase of WP5 the focus has been on the collection of requirements for the planned climate services from a variety of users. Most of these users had been identified during the planning phase of FOCUS-Africa. After an initial review of the case studies, and consultation with the identified users, planning for climate services were fine-tuned, refined or revised, depending on the level of engagement of users once the project started ? in a few cases, their situation had either changed or requirements revisited, as documented in the report. Also, although user interaction had been hindered by the COVID-19 pandemic, stakeholder engagement missions starting in early 2022 have proven an excellent way to reassert the need for the planned climate services in most cases; there has also been interest from new users to benefit from the climate services developed by FOCUS-Africa. Aside from collecting and consolidating user requirements as part of the co-design phase in the co-production process, Task 5.1 has also conducted a considerable amount of work in meteorological and sector-specific (agriculture, energy, etc.) data collection as well as their initial assessment. These data analyses, which effectively started the co-development phase of co-production, has been a very useful way to strengthen the engagement with users, also as a way of demonstrating to them early delivery of useful information. A summary of these analyses is documented in this report. Another key aspect and goal of Task 5.1 has been the development of a co-production workflow for each of the case studies, covering all phases from design to delivery. The col...

Approval

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Data required, and a set of guidelines, for all Climate Service prototype development

Deliverable Report D5.1

Lead Beneficiary: WEMC
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About FOCUS-Africa

FOCUS-Africa – Full-value chain Optimised Climate User-centric Services for Southern Africa – is developing sustainable tailored climate services in the Southern African Development Community (SADC) region for four sectors: agriculture and food security, water, energy and infrastructure.

It will pilot eight case studies in five countries involving a wide range of end-uses to illustrate how the application of new climate forecasts, projections, resources from Copernicus, GFCS and other relevant products can maximise socio-economic benefits in the Southern Africa region and potentially in the whole of Africa.

Led by WMO, it gathers 14 partners across Africa and Europe jointly committed to addressing the recurring sustainability and exploitation challenge of climate services in Africa over a period of 48 months.

For more information visit: www.focus-africaproject.eu

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Executive Summary

FOCUS-Africa is developing climate services for the Southern African Development Community (SADC) region in four different sectors: agriculture, water, energy and infrastructure. These services are being developed through eight case studies and they aim to maximize the socio-economic benefits in the five SADC countries they are based in. Close engagement with users of the case studies is essential to the co-production of the trial climate services being implemented in WP5. Likewise, it is important to learn about the socio-economic context of the proposed trial climate services, so as to be able to optimise their development and implementation. This is why a close interaction with WP6 has been pursued and maintained throughout the initial phases of WP5 (and beyond), with Task 5.1: *Collate output required to develop prototypes*.

In this first phase of WP5 the focus has been on the collection of requirements for the planned climate services from a variety of users. Most of these users had been identified during the planning phase of FOCUS-Africa. After an initial review of the case studies, and consultation with the identified users, planning for climate services were fine-tuned, refined or revised, depending on the level of engagement of users once the project started – in a few cases, their situation had either changed or requirements revisited, as documented in the report. Also, although user interaction had been hindered by the COVID-19 pandemic, stakeholder engagement missions starting in early 2022 have proven an excellent way to reassert the need for the planned climate services in most cases; there has also been interest from new users to benefit from the climate services developed by FOCUS-Africa.

Aside from collecting and consolidating user requirements as part of the co-design phase in the co-production process, Task 5.1 has also conducted a considerable amount of work in meteorological and sector-specific (agriculture, energy, etc.) data collection as well as their initial assessment. These data analyses, which effectively started the co-development phase of co-production, has been a very useful way to strengthen the engagement with users, also as a way of demonstrating to them early delivery of useful information. A summary of these analyses is documented in this report.

Another key aspect and goal of Task 5.1 has been the development of a co-production workflow for each of the case studies, covering all phases from design to delivery. The collaboration with WP6 has been particularly effective in pursuing this objective. As a result, each case study now has a well developed workflow, which, although a living document, is being used to guide the development of the trial climate services. Constructing a workflow has also been a very useful exercise in trying to foresee the end point of this work, namely the delivery of the trial climate service. Indeed, this was the original motivation for considering such workflows. The workflows also highlight key stakeholders, beyond the immediate users, and possible paths for exploitation.

Three-weekly meetings were held amongst the WP5 team with additional regular meetings for individual case studies, both internally with project partners and with external non-partner users, including via in country missions. These activities have been instrumental in achieving a much clearer perspective on what users expect from climate information and its delivery. An important component of the WP5 regular meetings has also been the pursuit of cross-fertilization across CSs. This was attained for instance by taking turns in presenting case studies output, so as to share results and lessons learnt.

Overall, Task 5.1 has laid strong foundations for the co-development work in Task 5.2, which started in September 2022 (M25), thus with a 6-month overlap between these two tasks.

Keywords

Trial climate services, user requirements, co-production, co-design, co-development, co-evaluation, delivery, workflows.

Acronyms

BSC	Barcelona Supercomputing Centre
CS	Case Study
CSIR	Council for Scientific and Industrial Research of South Africa
DALRRD	Department of Agriculture, Land Reform and Rural Development (South Africa)
DARD	Department of Agriculture & Rural Development (South Africa, North West Province)
DCCMS	Malawian Department of Climate Change and Meteorological Services
DSSAT	Decision-Support System for Agro-technology Transfer
EDF	Electricité de France (EDF)
FAO	Food and Agriculture Organisation
FOCUS-Africa	Full-value chain Optimised Climate User-centric Services for Southern Africa
FGD	Focus Group Discussion
GFCS	Global Framework for Climate Services
IEA	International Energy Agency
IAT	Impact Assessment Team
IAG	Impact Assessment Grid
IIAM	Mozambique's Institute of Agricultural Research
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
MO	Met Office
RIMA	Resilience Index and Measurement Analysis
RRI	Responsible Research & Innovation
SADC	Southern African Development Community
SDG	Sustainable Development Goal
SSSA	Scuola Superiore Sant'Anna
TANESCO	Tanzania Electric Supply Company
TARI	Tanzania Agricultural Research Institute
TCS	Trial Climate Service
TMA	Tanzania Meteorological Authority
ToC	Theory of Change
UCT	The University of Cape Town
WITS	The University of Witwatersrand Johannesburg
WEMC	World Energy and Meteorology Council
WHO	World Health Organisation
WMO	World Meteorological Organisation
WRU	Water Resource Unit of Mauritius

1. Introduction

1.1 Overview of WP5 work towards the trial climate service co-production

FOCUS-Africa is developing sustainable tailored trial climate services in the Southern African Development Community (SADC) region for four sectors: agriculture and food security, water, energy and infrastructure. To achieve this, eight case studies (CSs) are being implemented in five SADC countries involving a wide range of applications to illustrate how the application of climate services can maximise socio-economic benefits in the Southern Africa region and potentially in the whole of Africa. Led by the World Meteorological Organisation (WMO), it gathers 14 partners across Africa and Europe jointly committed to addressing the recurring sustainability and exploitation challenge of Climate Services in Africa over a period of four years.

Work Package (WP) 5, which is led by the World Energy & Meteorology Council (WEMC), is responsible for co-producing a trial climate service for each of the CS. The list of CSs, their sectors and their leaders are shown in **Figure 1**. The WP5 leads of each CS, as agreed at the start of the WP5 work, are also indicated, as are the WP6 lead, given the close collaboration between these two WPs.

The objectives of WP5 are:

- To assess how the output designed for each case study can be presented as a trial service that meets users' requirements
- To produce co-designed and co-developed trial services for each case study, which have the potential to be operated in near real time
- To determine, document and share development and trial services approaches within the FOCUS Africa consortium and with external stakeholders

Specifically, WP5 begun in February 2022 and will continue until the end of the project, namely August 2024. Note that while the originally planned start month was M19 of the project (i.e. March 2022), this was moved forward by a month to allow a little more time for the work of WP5, also accounting for the delays caused by the lack of direct interaction due to COVID. In particular, the additional time was mainly dedicated to strengthening the co-design of the trial climate service thorough user engagement activities. Co-design is in fact a key element of the co-production process.

This report, deliverable 5.1, focuses on the first phase of WP5, and is aligned with Task 5.1, *Collate output required to develop prototype*, which runs from February 2022 to February 2023. This task gathered the output from relevant WPs (especially WPs 3 and 4) as a basis for the development of the case study trial climate services, and through regular interactions with stakeholders. Work has also been regularly shared amongst all CS partners to ensure best practice is adopted, and possible commonalities are exploited, across trial climate services, at every stage of the co-production process.

Co-production is typically broken down into[1]: i) co-design, ii) co-development, iii) delivery and iv) co-evaluation. These phases (or steps) broadly follow the time sequence (i to iv) as presented, so usually co-development follows co-design, at least in the first co-production iteration. Ensuing iterations do not necessarily follow this precise sequence. The purpose then becomes a continuous refinement of the climate service, to meet user requirements, and this could be done by even going back to the co-design phase if it is found that for instance the indicators and other products are not easily exploitable.

In co-production is also very important to clearly identify the 'actors' that contribute to the trial climate service. Accordingly, three main roles have been defined within WP5: 'Users' (the most important actor), 'Researcher' and 'Service developer/provider'. The three actors are indicated in **Figure 2** for each of the CS, noting that the same organisation can play different roles.

[1] An additional phase could be added at the beginning, namely co-exploration (or pre-feasibility study) but in FOCUS-Africa this was done at the project proposal level, and partly refined in the first part of the project.

Case Study	1	2	3	4	5	6	7	8
Country	South Africa	Malawi	Mozambique	Tanzania	Tanzania	Tanzania	Malawi	Mauritius
Sector	Food Security	Food Security	Food Security	Food Security	Infrastructure	Energy	Energy	Water & Food Security
Leader	CSIR, Trevor Lumsden	BSC, Dragana Bojovic	SSSA, Matteo Dell'Acqua	BSC, Dragana Bojovic	MO, Kate Dart and Erasmo Buonomo	MO, Kate Dart and Elisabeth Thompson	EDF, Hiba Omrani and WEMC, Alberto Troccoli	CSIR, Mohau Mateyisi
WP5/ CS Lead	Land Bank, Nehru Pillay	Amigo, Marcello Petitta	SSSA, Robel Takele	WEMC, Alberto Troccoli	Amigo, Marcello Petitta	WEMC, Penny Boorman	WEMC, Penny Boorman	WEMC, Kristian Nielsen
WP6/IAT Lead	BSC, Ilaria Vigo	LGI, Sam Whittlesey	LGI, Yasmina Dkhissi	LGI, Sam Whittlesey	LGI, Adéola Jaiyeola	LGI, Adéola Jaiyeola	BSC, Sara Octenjak	BSC, Ilaria Vigo

Figure 1: FOCUS-Africa Case Studies with focus on WP5, highlighting also link to WP6

Case Study	1	2	3	4	5	6	7	8
Country	South Africa	Malawi	Mozambique	Tanzania	Tanzania	Tanzania	Malawi	Mauritius
Sector	Food Security	Food Security	Food Security	Food Security	Infrastructure	Energy	Energy	Water & Food Security
Users	Land Bank	Local farmers' association (NASFAM)	INAM, smallholder farmers in Mogovolas	Tanzania Agricultural Research Institute	Ministry of Water / ACET / IET	TANESCO (and TotalEnergies)	EDF	Water Resource Unit
Research actor	WITS	BSC, WEMC	SSSA, IIAM	BSC, WEMC	MO, UCT	MO	UCT, WITS	CSIR
Service developer/ provider	CSIR	DCCMS, Amigo	PLAN	TMA, Amigo	Amigo, TMA	WEMC, TMA	WEMC	MMS, WEMC

Figure 2: FOCUS-Africa Case Studies highlighting their Actors: Users, Research and Service developers/providers

The work done in Task 5.1 can be largely classified as co-design, however several elements of co-development have been performed too, as presented in this report. In any case, work in Task 5.1 also looked at mapping all phases under a workflow diagram, which is presented in this report for each of the CSs. More specifically, Task 5.1. ensured that each of the trial climate services is planned with a clear workflow pathway to allow them to eventually be tested in a non-operational environment. For this purpose, a range of requirements and settings, to reflect the climate services foci, spanning sub-seasonal to multi-decadal timescales, and for decision making applications for energy, water, food security and infrastructure sectors have been considered.

As part of the WP5 work, a diary was set up, in the form of a shared online document, which was updated throughout Task 5.1. The purpose of the diary was to capture interactions with users for the collection of their requirements, but also relevant discussions amongst CS partners, during the co-design work for each of the trial climate services. These 'diaries' have also been useful in providing a starting point for this report.

The report is organized in the following way, noting that its structure also reflects the iterative process, the discussion and development of the work done in Task 5.1. First an overview of the case studies, highlighting their overall goals, including an overarching view of the expected delivery method for each of the trial climate service, is presented. The remaining, and the bulk, of the report is structured by CS, following a presentation as uniform as possible across CSs, again to reflect the planning and co-design process, and also co-development in several instances.

2 Planning and co-design of the trial Climate Services

The work of Task 5.1 started by reviewing the original descriptions of each CS. These were refined during the course of the Task, and their current version is presented in **Table 1**. In particular, two main changes that can be observed from **Table 1** are the addition of water sector considerations in CS7, originally focused solely on energy, and similarly the inclusion of food security in CS8 (originally focused on water sector issues only; note however that there may remain inconsistencies in presentation as these changes have not fully been reflected throughout the project yet). Some minor adjustment may still be possible to reflect the morphing requirements of some users, which are expected as the trial climate services take shape as the project progresses.

While the end goal of the trial climate services was still nebulous for most, if not all, CSs at the start of Task 5.1, having a clear pathway or workflow, and trying to anticipate what the final service may look like at the end of the process, two and a half years down the line, has turned out to be a worthwhile exercise. Indeed, the process of looking ahead in the co-production 'pipeline' has helped in trying to anticipate modalities of execution, possible issues, etc.

An important component of the WP5 work is the cross-fertilization across CSs. This has been achieved by the sharing of experiences during the three-weekly WP meetings during which updates from each CS were given. Not only that, the WP5 team was encouraged to showcase new findings and developments with short presentations. Aside from providing some inspiration for other CSs, these presentations have also the objective to avoid duplication of effort. For instance, through discussions it was found that different teams were focusing on analogous methodologies for computing the onset of the rainy season. As a result of these discussions, it was agreed to distribute the work on onset computations across teams (specifically across CSs 2, 3 and 4), therefore allowing the production of a wider choice of onset indicators for users. Similarly, interactions during WP5 meetings, as well as during CS meetings, have led to the choice of using the web visualisation tool, Teal[2], as the delivery platform for a few CSs, even when the initial choice was different or unclear.

It is worth noting that the terminology used around the 'final' climate service product, to be delivered by the project, has evolved since the start of the project. What was referred to as 'prototype' climate service has now been replaced by 'trial' climate service (as used several times already). The reason for this change is because feedback from stakeholders of other climate service projects have highlighted the fact that 'prototype' conveys a sense of something that is not robust enough to be relied upon. The compromise was to then use the term 'trial', as it better demonstrates the ambition of the service to eventually become operational.

Another term we have tried to avoid is 'end-users', which although commonly found in co-production literature, can be misleading as it is not always obvious that they are the 'end' of the climate service production chain. Our preferred terminology is therefore simply 'users'.

[2] Teal is an online visualisation tool that enables users to explore climate (and other) variables for the past 70+ years, from 1950 to near real time, and projections up to 2100, as well as carbon emissions from 1960. The public version can be accessed at: https://tealtool.earth Additional custom-made restricted-access modules, which also run operationally, include seasonal climate forecast indicators on a horizon of several months ahead. The Teal tool is developed by WEMC in collaboration with Inside Climate Service srl.

Table 1: Descriptions of the overall goal of each Case Study in terms of trial Climate Service

CS No	Country	Sector	Planned Trial Climate Service
CS1	South Africa	Food security	Projections of the impact of climate change on crop and livestock production and incorporation of these projections into credit modelling to improve the characterization of long-term climate risks in credit risk assessments.
CS2	Malawi	Food security	Bias-adjusted and recalibrated high-resolution seasonal and decadal prediction; rainfall season onset and cessation dates using different techniques, cumulative rainfall; improved drought monitoring using agro-climate onset and cessation indicator.
CS3	Mozambique	Food security	Development and delivery of information concerning the agronomic onset of the rainy season; identification of climate-ready crop varieties supporting the resilience of smallholder agriculture using climate projections
CS4	Tanzania	Food security	Bias-adjusted and recalibrated high-resolution seasonal and decadal prediction; rainfall season onset and cessation dates using different techniques, cumulative rainfall; improved drought monitoring using agro-climate onset and cessation indicator.
CS5	Tanzania	Infrastructure	Bias-corrected high-resolution climate change projections; tailored non-stationary extreme value analysis (EVA) method; suitable indices from current practices in infrastructure design; climate change projections of infrastructure design indices.
CS6	Tanzania	Energy	Tailored power generation models using calibrated climate data; optimized seasonal forecast methodologies to estimate hydropower generation; high-resolution climate change projections to estimate hydropower generation and wind and solar power capacity factors.
CS7	Malawi	Energy, Water	Bias-corrected high resolution climate change projections; tailored statistical downscaling for the Mpatamanga hydropower plant (Lake Malawi and Shire river hydrological system).
CS8	Mauritius	Water & Food Security	High temporal and spatial statistically (or dynamically) downscaled seasonal rainfall forecast, verified, and optimized for different watersheds; drought forecasting and monitoring using indices specific for watersheds irrigation model input.

2.1 Expected delivery methods of the trial climate services

Another important consideration was about the way the trial climate services should be delivered. While the actual delivery is done later in the project, under Task 5.3, starting March 2023, it was very important and useful to start the conversation about delivery early on to help with information gathering from users, planning of the service, but also in terms of expectation management. Not surprisingly, there was great uncertainty about the modality of delivery at the start of the WP, not least because of minimal feedback from users who themselves did not know what to expect. This started to become clearer as the Task 5.1 work progressed as demonstrated by the current level of detail in **Table 2**.

Table 2: Climate service delivery methods by Case Study, highlighting a wide range of possible options for delivery, from simple data and graph sharing to the more sophisticated web tools.

Delivery methods						
	Demonstrator/ Web Tool	**Visualisation**	**Briefing document**	**Presentation / webinar**	**Post-processed data (relevant indicators)**	**Training (with WP7)**
CS1	Improved credit model (Restricted access)	Maps / infographics of key climate/crop variables considered in the adaptation of the credit model	Yes (TBD)	Not required	Yes: Database of climate and crop model outputs considered in the adaptation of the credit model	Understanding climate and crop model outputs considered in the adaptation of the credit model
CS2	Teal tool (tealtool.earth) displaying indicators up to province level	Maps and graphs on Teal tool	Yes, adjusted for different users, also automated on Teal tool	May be needed	Yes, all data openly available	Hands-on sessions (TBD)
CS3	Forecast agronomic onset of rainy season (R package AquaBEHER)	GUI developed and delivered to local met office (INAM). Possible integration to Teal. Maps to be delivered to farmers	Yes, adjusted for different users (INAM, farmers, extension workers)	Not required	Yes, data and methods to be provided to INAM (not in the consortium)	Yes, hands-on sessions to INAM, IIAM, WFP
CS4	Teal tool displaying indicators up to province level	Maps and graphs on Teal tool	Yes, adjusted for different users, also automated on Teal tool	May be needed	Yes, all data available	May be needed
CS5	Not required	Map, dataset	Yes (TBD)	Not required	Yes: design values	Yes (TBD)
CS6	Teal tool displaying indicators up to province level	Maps and graphs on Teal tool	Yes (TBD)	Yes (TBD)	Not required	Understanding model outputs
CS7	May be needed	Yes (TBD)	Yes (TBD)	May be needed	Yes (TBD)	Not required
CS8	Teal tool	Maps and graphs on Teal tool	Yes, adjusted for different users	Yes (TBD)	Yes (TBD)	Yes (TBD)

3 Trial climate services co-design and co-development

This section is organised by CS. Each CS presents some background, user requirements for the trial climate service (listing target climate datasets, variables, sector indicators, …), the CS workflow, the current status of the climate service development, and followed by next steps.

3.1 Case Study 1

Background

Case Study 1 involves developing climate services in the context of food security in South Africa. More specifically, CS1 aims to improve the representation of long-term climate risks in credit lending decisions in the agriculture sector. The primary beneficiary of the climate service is the Land Bank. At present, climate risks are represented in a relatively superficial manner (based on recent climate trends) and do not consider projected long-term changes in climate that will impact the sector. The projected changes have implications for long-term loans as the impacts of climate change on agricultural production are likely to be felt during the lifetime of these loans (20 – 25 years).

The proposed climate service involves developing projections of the impact of climate change on crop and livestock production and adapting the Bank's credit models to incorporate these projections to improve the characterization of long-term climate risks in credit risk assessments. The Land Bank uses credit models to assess the risk of clients defaulting on loans, and to apply appropriate pricing to loans.

The climate service is being trialled in the North West province of South Africa, a region that makes a significant contribution to agricultural production in the country. The province is already experiencing the impacts of climate change in the form of increasing droughts, while its western desert region is projected to spread eastward (Engelbrecht and Engelbrecht, 2016). Maize is the dominant crop grown in the province and has thus been selected as an indicator crop for the case study. Overall, livestock is the biggest agricultural commodity produced in the province.

Farmers are also important stakeholders in the case study as changes in climate not only have the potential to impact their production, but as long-term climate risks are factored into lending decisions, their access to finance (and interest rate pricing) may also be impacted. The information produced in the case study also has the potential to benefit relevant government departments (DALRRD, DARD) who may be able to apply the information in their long-term planning and policy development for the province. As they work with the farmers in the province and provide extension services, they have the means to efficiently disseminate information on climate change to the farming community.

The climate service users in the case study, and their information requirements for the climate service, are summarized in **Table 3**. The users and their requirements are subject to ongoing consultations and may be refined as the case study progresses.

Table 3: Climate service users in Case Study 1 and their information requirements

User	Information Requirements
Land Bank	Climate risk variables that can be used to predict default, thus allowing for improved representation of climate risk in credit modelling and lending decisions
Farmers	Projections of the impact of climate change on crop and livestock production presented in a suitable format (e.g., as infographics)
DALRRD, DARD	Projections of the impact of climate change on crop and livestock production presented in a suitable format (e.g., as a summary report for decision-makers)

The following sections present the data requirements and a proposed workflow for CS1. The current status of the development of the climate service is also summarized. Finally, the next steps in the development process are identified.

Data requirements and workflow

The information requirements of the users will be met by combining climate data/ projections with crop and livestock models. The outputs of these models will be used to provide climate risk data and indicators that can be used to improve the representation of climate risks in the Land Bank's credit models and processes. The outputs of the climate, crop and livestock simulations will also be analyzed to assess changes in key relevant variables and indicators of interest to farmers and government officials. These analyses will then be presented to those users in a format suitable to their needs (e.g., infographics, reports).

Projections of the impact of climate change on crop production will be assessed by combining climate projections with a crop simulation model. Projected impacts of climate change on livestock production will be assessed by evaluating changes in a livestock stress index, the inputs of which will be derived from climate projections.

The credit models used by the Land Bank are statistical in a nature and consider economic risks and a range of other factors (including climate risks). To adapt the models to consider a new risk, or to enhance the representation of an existing risk, a process to test the relevant new variable/s is required to assess whether they result in improved model predictions of loan defaults. This is done for an historical period and utilizes available credit data for that time to assess whether the predictions improve.

Information about the data required by the various models used in the case study is detailed in **Table 4**. Some information presented in the table (e.g., time periods of interest) may be refined subsequent to this report in response to ongoing consultations with relevant stakeholders.

A workflow of the various activities and steps in the development of the climate service is presented in **Figure 3**. The users of the climate service are central to the case study and are represented in the middle of the workflow diagram. Their inputs to the climate service development are indicated with blue arrows. Activities of the core CS1 team are indicated in black. In some contexts, users are also responsible for core technical activities (for example, the Land Bank performs credit modelling and associated testing). The processes of assessing user needs, design of the service, modelling, disseminating the information, and testing of the service are represented from left to right in the top half of the diagram. Running in parallel to these activities are analyses of the socioeconomic context, the impact of the climate service, scalability and replicability of the service and potential for broader exploitation (all represented in the lower half of the diagram). Feedback loops to the design phase of the climate service are also represented to allow for refinements to the design to be made.

Current status of the trial climate service co-production

Thus far, work has been done on assessing user needs, collecting information on existing climate services, design of the service, and gathering of data required for the service. These activities are ongoing and involve consultation with relevant stakeholders. The Land Bank, as technical contributors to the climate service development, are consulted on a regular basis in CS1 team meetings. The third stakeholder workshop in Pretoria gave the opportunity to consult with government departments (DALRRD and DARD) and a small group of North West farmers, who act as mentors to other local farmers. A mission trip to the North West province is being planned in the near future for further consultations with farming organizations and government officials.

Table 4: Information about the data required for the various models used in Case Study 1

Model	Model Resolution and Time-step	Proposed Time Periods of Interest	Input Data Requirements	Sources of Input Data	Relevant Model Output Variables / Indicators
Crop	Resolution: 10 km grid or other soil database mapping unit (model outputs to be aggregated to a suitable scale for decision-making, e.g., district) Time-step: daily	1991-2020 (baseline) 2026-2055 (future)	Climate (daily): - rainfall - max & min temp - max & min RH - wind speed - solar radiation Soils (key inputs): - texture & depth - hydraulic properties - root growth - nitrogen & pH Management: - planting & harvest details - cultivar details - irrigation - fertilizers	Climate: - observed (QCD[1]) - modelled (CORDEX-CORE) Soils: - QCD[1], SAACA[2] or SoilGrids[3] Management: - representative management scenarios derived from literature and stakeholder consultation	- yield - water requirement - soil moisture - seasonal shifts - heat units
Livestock Stress Index	Resolution: - climate model grid resolution Time-step: - daily	1991-2020 (baseline) 2026-2055 (future)	Climate (daily): - max & min temp - max & min RH	Climate: - observed (QCD[1]) - modelled (CMIP6, CORDEX-CORE)	Temperature-Humidity Index (THI)
Credit	Resolution: - flexible Time-step: - flexible	2011-2020 (baseline test period) 20-year loan period (future)	Climate, crop and livestock model output variables (listed above) will be tested as candidate input variables (after aggregating the data to a suitable temporal and spatial scale) Economic and other variables currently used in the credit model	Climate, crop and livestock model simulations sourced / produced in the case study Standard data sources used by the Land Bank	Probability of default

[1]QCD: Quinary Catchments Database (Schulze et al., 2010)

[2]SAACA: South African Atlas of Climatology and Agrohydrology (Schulze, 2008)

[3]SoilGrids: Soil profiles for crop modelling derived from the SoilGrids database by Han et al. (2015)

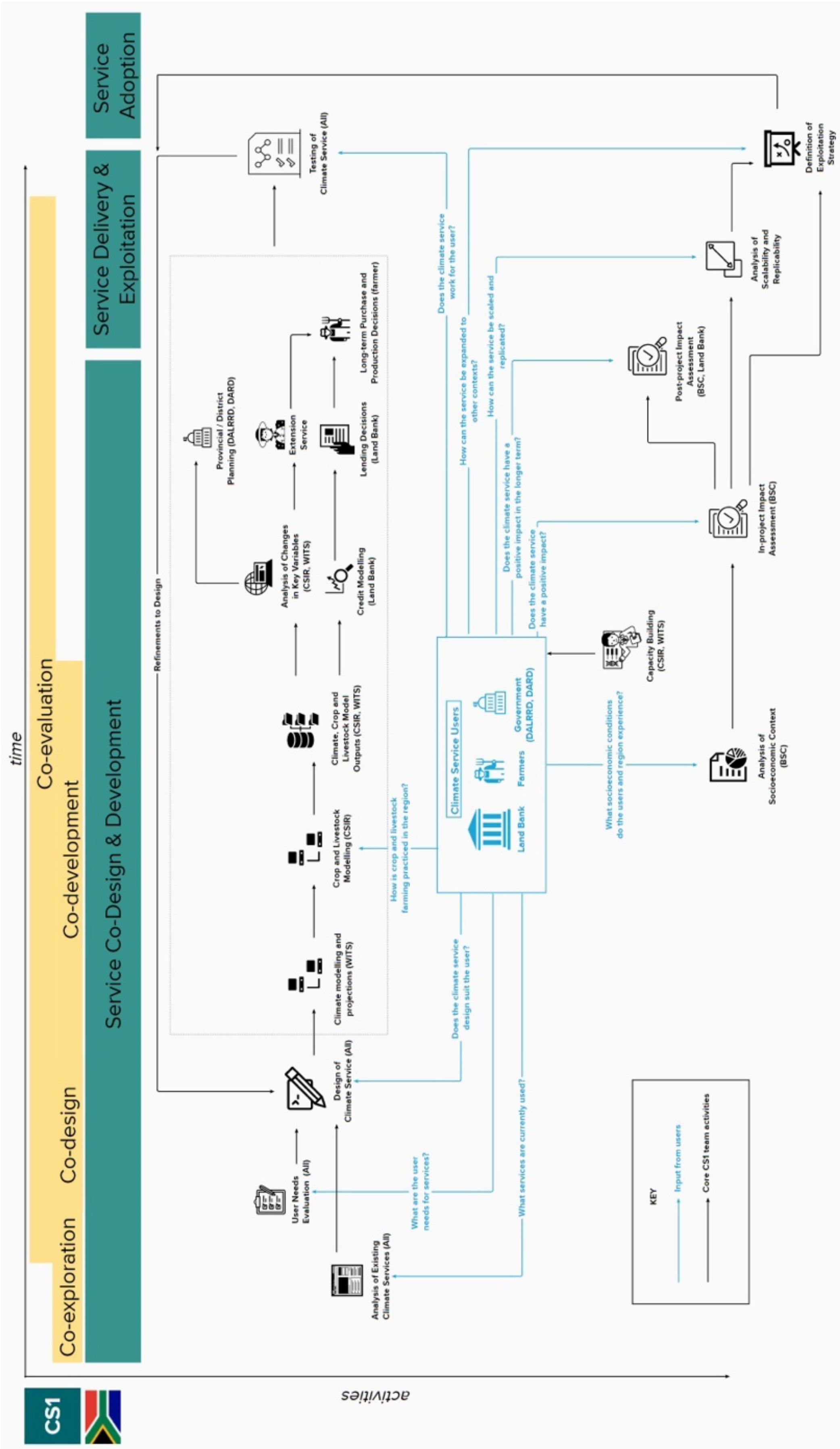

Figure 3: Workflow of the climate service development for Case Study 1

The Wits team provided historical (CRU) data for basic climate variables (rainfall and temperature) to the Land Bank to allow for testing of these variables as predictors of the probability of default. The data were provided at a monthly and seasonal time step for the province as a whole. They were also provided on a monthly time step for a 0.5-degree grid over the province. **Figure 4** shows the mean annual precipitation over the province according to the CRU data provided to the Land Bank (on a 0.5-degree grid). Testing of these climate variables as predictors revealed that both rainfall and temperature showed statistical significance in predicting default at provincial-level. On a district-level, the statistical significance was slightly stronger in the centrally located districts (Dr Kenneth Kaunda, Ngaka Modiri Molema) than in the western (Dr Ruth Segomotsi Mompati) and eastern (Bojanala) districts (**Figure 5**).

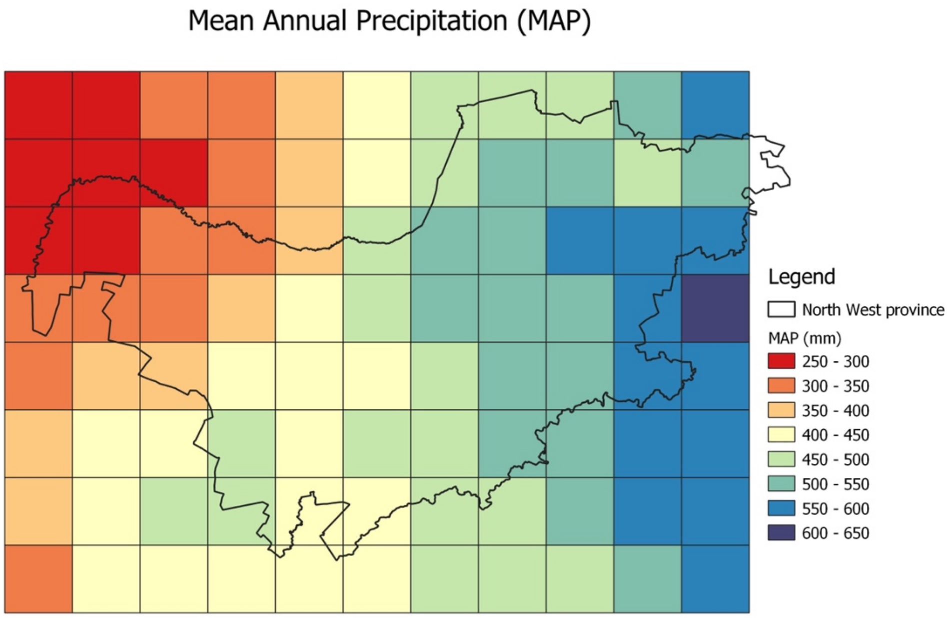

Figure 4: Mean annual precipitation (MAP) over the North West province as derived from CRU data provided to the Land Bank

Figure 5: District municipalities in the North West province of South Africa

Output variables from the crop and livestock models will also be assessed for inclusion as predictors in the credit model once these data become available. The process to test new variables needs to consider and minimize possible correlations between candidate input variables.

Discussions have been held with the Wits team regarding the climate projection data that are available for the climate service. These are listed in **Table 4**. Perspectives on the projections and the patterns of change represented in them (as derived from Work Package 3 and 4 activities) were shared with the case study. The requirements for projections for the case study have been communicated to the Wits team.

A strategy for how the crop model will be set up and run has been developed. This includes consideration of factors such as the scale at which the model will be run, the sources of input data, the time periods of interest etc. The representation of crop management (e.g., planting and harvest details, irrigation, fertilizer) will be scenario-based (e.g., well vs moderately resourced management scenarios) and will be informed by literature and stakeholder consultation. The outputs of the crop model will be aggregated to a suitable spatial scale for the credit modelling and other applications (e.g., planning, policy) identified in the case study.

Soils data have been gathered from various sources and are currently being evaluated for their suitability of use in the crop modelling. Factors such as the variables available in the datasets, the scale of the data, how data were measured or estimated, and their consistency with expected trends in soil properties in the region are being considered in the evaluation.

In summary, the development of the climate service is progressing as planned.

Next steps

The next steps in the development of the climate service include completing the configuration of the crop model for historical conditions, and the testing of the outputs as predictors of default in the credit model. Completing the crop model configuration will involve selecting a soils dataset from those evaluated, developing management inputs and formatting climate data for application in the model.

There will also be further engagement with stakeholders in the North West province to refine the design of the climate service ahead of Deliverable 5.2 (Plan for co-designed and co-developed climate services).

3.2 Case Study 2

Background

The climate service produced in Case Study 2 (CS2) is directed at smallholder farmers, mainly through the National Smallholder Farmers' Association of Malawi (NASFAM), using the Phalombe and Zomba districts as benchmarks for innovation.

Calls and discussion between BSC and DCCMS early in the project helped the CS2 team understand past and ongoing activities in Malawi related to climate services. This dialogue also increased project partners' understanding of the local socio-economic setting and complemented findings from the literature review done in the beginning of the project. A dedicated exercise that BSC conducted with DCCMS helped identify the key CS2 stakeholders in Malawi and initiated communication with them through a short survey sent via email. This activity enabled BSC to do an initial stakeholder analysis, as preparation for subsequent engagement.

The main research partner, JRC, needed to leave the project at the end of 2021. JRC presented the planned and accomplished technical aspects of the climate service to the rest of the CS2 team. The main accomplishment was the update of the ASAP platform with seasonal forecasts.

Following JRC's departure, the lead scientific role in CS2 was shifted from JRC to WEMC. Consequently, the CS2 team was rethinking the climate service and adapted it based on the new conditions, on what was learned in the project so far and the new capacities provided by WEMC. The team also started discussions on ensuring the sustainability of the service after the project. Once the climate service was redesigned into its current form, the frequency of the CS2 team meetings has increased and interaction with DCCMS was continued.

The service is composed of a bias-adjusted seasonal forecast downscaled to district level and updated monthly; a forecast of the rain season onset and cessation; and a multi-annual forecast. In addition, the collaboration with CS3 will result in the provision of the forecast for an agro-meteorological onset and cessation of the rainy seasons.

As international travel became possible again in 2022, preparations for the study mission to Malawi began. The team established a link with the National Smallholder Farmers' Association of Malawi (NASFAM) and initiated collaboration with them online. NASFAM's participation was crucial for the organization of focus group discussions with farmers and extension officers, which helped to further refine user needs and gain a deeper understanding of the socio-economic situation they operate in.

In October 2022, the CS2 team conducted the study visit, collaborating closely with DCCMS staff while in the country. Two focus group discussions were held with farmers and extension officers, one in Zomba and one in Phalombe. Several interviews were done with national stakeholders who are key in the food security domain: Ministry of Agriculture (Dept. of Agricultural Planning, Dept. of Crop Development, Dept. of Agricultural Research Services), Food and Agriculture Organisation (FAO) Malawi office, the Lilongwe University of Agriculture and Natural Resources, World Food Programme (WFP), Famine Early Warning Systems Network (FEWSNET), NASFAM and Farm Radio Trust (see also **Figure 6**).

Data requirements and workflow

The user requirements collected through online and 'on the field' elicitation meetings are summarized in **Table 5**. As it can be seen the list of desirable output and tools that constitute CS2 trial climate services are extensive. As such, a selection will have to be made based on current developments and capabilities of the teams involved, also considering that the primary users of CS2 are NASFAM, but also DCCMS.

Table 5: Information about the user requirements for the trial climate service in Case Study 2

User	User requirements	Sector indicators	Input
Primary users: Farmers in Zomba and Phalombe (through NASFAM)	1. Onset and cessation of the rainy season 2. Total amount of rain in a season 3. Time and length of dry spells in a season (All downscaled to district level) 4. Cyclone prediction	1. Improved agricultural planning (e.g., timing of sowing and harvest) 2. Easier determination of which crop/variety to plant 3. More efficient decision making (planting early/late maturing crops; changing from conventional to pit farming to conserve humidity...) 4. Effective preparation for cyclone impact such as floods	Climate data from ground stations, satellite-based (e.g. CHIRPS) and reanalyses (e.g. ERA5Ag)
NASFAM (National Smallholder Farmers' Association of Malawi)	5. Multi-annual prediction of precipitation, temperature, drought index (1-5 years)	Improved strategic planning (e.g., increasing production of a certain crop) and easier price negotiation for farmers and off-takers	Gridded observation data Crop yield monthly data
Other users: Ministry of Agriculture - Department of Planning Department of Agricultural Research Services Lilongwe University of Agriculture and Natural Resources	5. Multi-annual prediction of precipitation, temperature, drought index (1-5 years)	Improved strategic planning (5–10 year time horizon is used by the Ministry and 1-5 year by the Dept. Of Agricultural Research Services)	
FEWSNET	Regularly updated forecast with a higher spatial resolution (1, 2, 3 and 4 above)	More reliable food security early warnings	
WFP	1. Onset and cessation of the rainy season 2. Total amount of rain in a season or number of rainy days in a season 3. A pest index	Improved triggers for anticipatory action on food security (with a better integration of seasonal forecast in the trigger definition) Improved preparation for the fall armyworm invasion	

The workflow for the development of CS2 climate services is summarized in **Figure 7**. With the end of co-exploration phase, the scientific co-design and co-development of the service began, and will continue as the work progresses into service delivery and exploitation, thanks to a process of continuous feedback. The service adoption phase begins with the end of the project and includes stakeholders who have embedded the service in their processes either as users, producers or intermediaries of climate information.

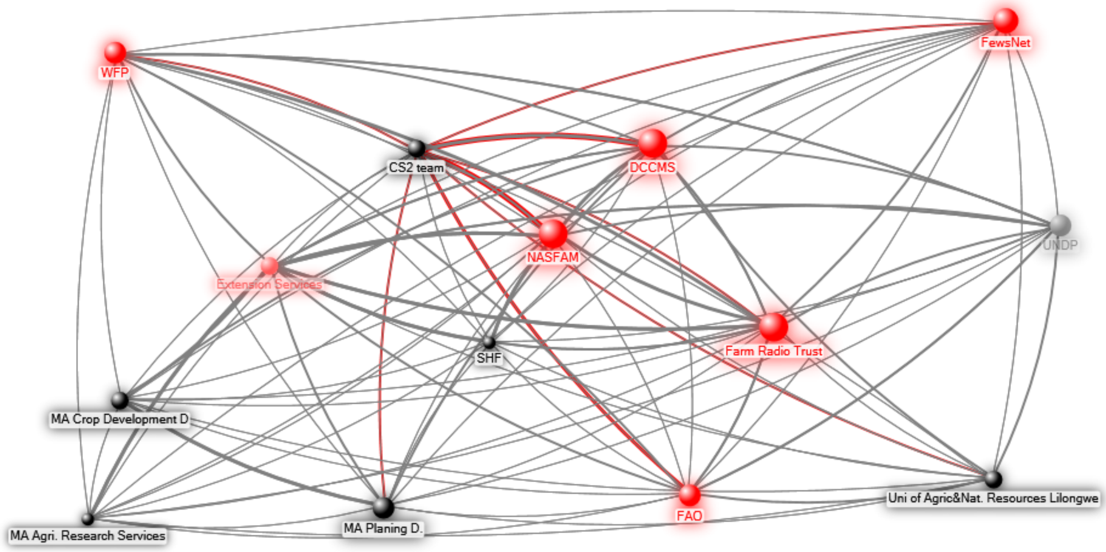

Figure 6: CS2 stakeholder network in Malawi. Red nodes represent stakeholders who are active in the National Agricultural Content Development Committee (NACDC), a committee that decides which messages are communicated to agricultural stakeholders based on climatic and other information. The red lines link the CS2 team to fellow users who expressed interest in using (a part of) the CS2 trial climate service.

Current status of the trial climate service co-production

Based on the findings about user needs from the discussions and interviews with the stakeholders in Malawi, recommendations for the CS2 trial climate service were developed. Climate information that the farmers and extension officers are mainly interested in includes: forecast of the total amount of rain in a season, the dates of the onset and cessation of the rainy season, and the timing and length of dry spells in a season. Forecasts of cyclones and other extreme weather events are also needed for better preparation and planning. Cumulated rainfall for October-November-December (OND) season is computed and Onset dates for the OND season are identified. For Onset calculations, four different computation methodologies are employed. The first method considers the method used by the national meteorological service (DCCMS), while the next two methods focus on cumulative rainfall anomaly to calculate onset. These three methods only consider precipitation data, which is processed in different ways. The last method instead, in addition to precipitation, takes into consideration also other agricultural-relevant variables such as soil moisture. Major drivers of the OND monsoon season are also identified.

Data retrieval and processing necessary to compute the required indicators. Data are mainly from satellite-based (CHIRPS) and from reanalysis (ERA5). Some results from initial investigations about data quality and their suitability for the computation of onset, cessation and rainfall amounts are presented in the following.

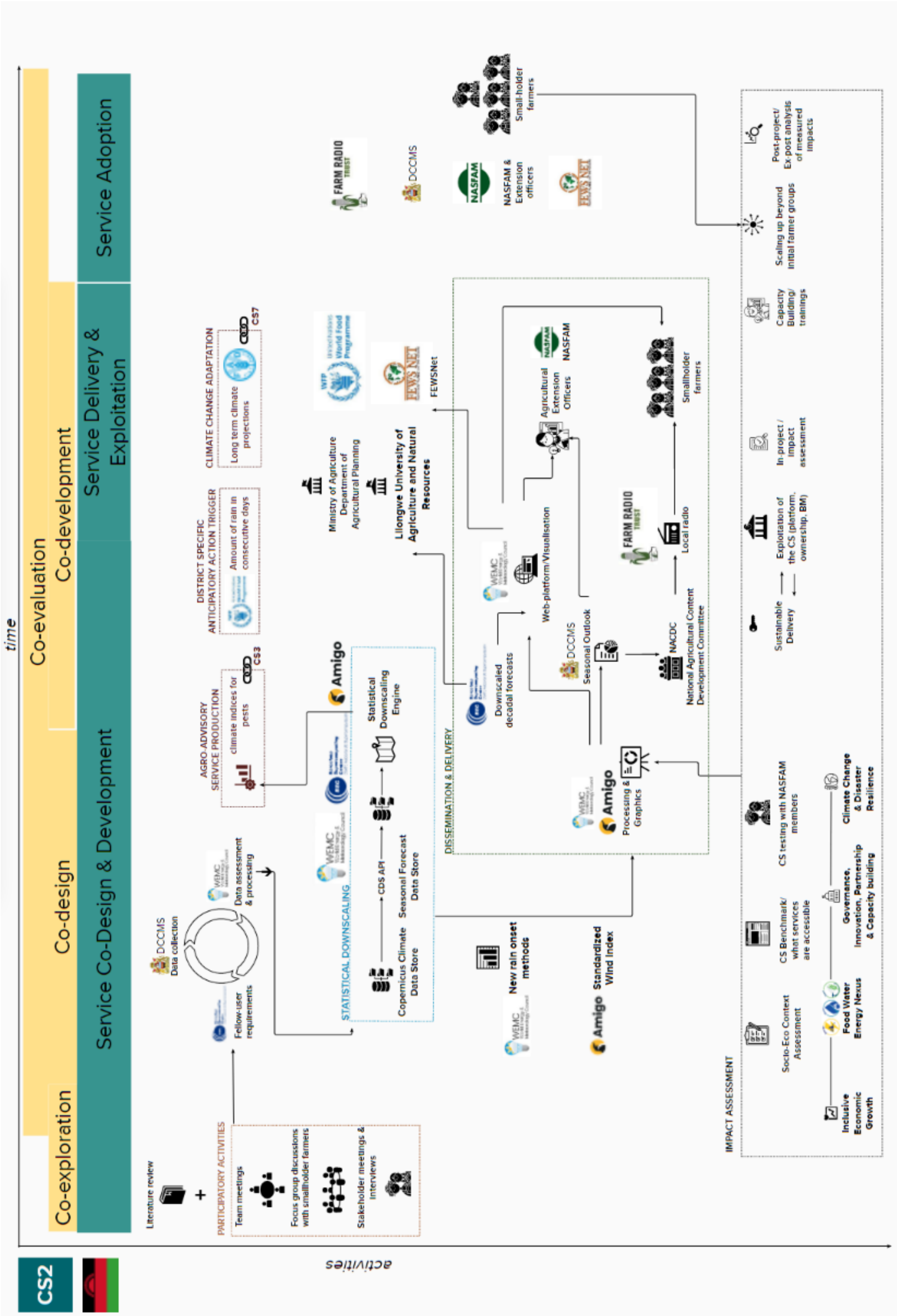

Figure 7: Workflow of the climate service development for Case Study 2

Analyses using various observational and reanalyses products indicated that high-resolution CHIRPS data is strongly correlated with station precipitation data. Also, mainly in terms of temperature, ERA5 Land was found to show higher correspondence with station data than other available datasets (cf. also CS4 and CS6 results). Therefore, subsequent analyses over Malawi were performed using these two datasets, CHIRPS for precipitation and ERA5 Land for temperature (but also for precipitation).

Results using ERA5 Land and CHIRPS data were presented for monthly average of the total rainfall pattern over Kasungu –Malawi, an area of study for case study 2. The datasets captured the climatological unimodal pattern of rainfall well over Kasungu (**Figure 8**). Variation is shown unimodal with six months of monsoon season, while rainfall peaks in January-February. The rainy season mainly starts in October and continues till May. Rain is essentially nominal from May up to October. Results are consistent with previous studies too which also identified similar unimodal pattern of rainfall variation in Malawi (Warnatzsch and Reay, 2019).

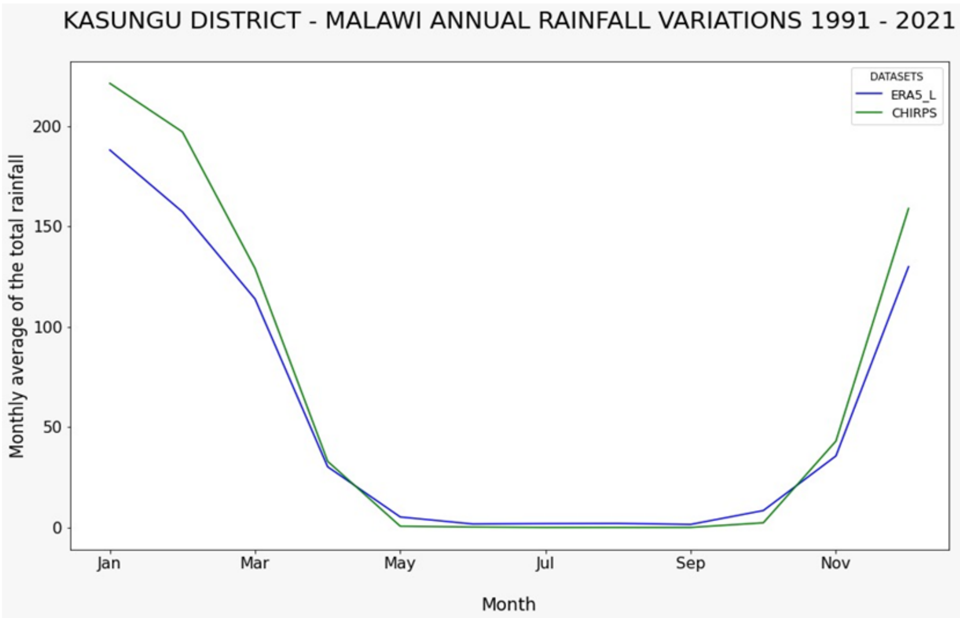

Figure 8: Analyses using ERA5 Land and CHRIPS data on annual rainfall variation in Kasungu district, Malawi.

An analysis considering the spatial pattern of annual mean precipitation shows that high amounts of rainfall are located in areas along Lake Malawi and the southeast part of Malawi (**Figure 9** left). The eastern part receives more rainfall than the western part of the country, as it can be seen in analysis of the spatial map (**Figure 9**, left) using ERA5 Land data from 1991 to 2020. This is also consistent with a previous study done by Tadeyo et al. (2020, **Figure 9**, right).

The analyses from ERA5 Land data also identified that the main rainy season of Malawi is from November to April and the dry season is from May to October (**Figure 10**). This assessment is in agreement with the work of Ngongodo et al. (2011).

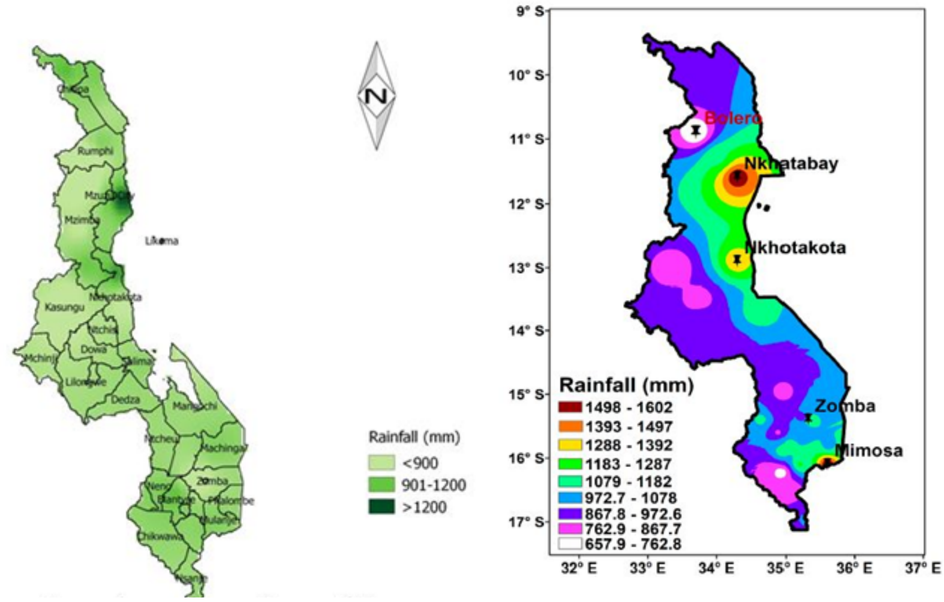

Figure 9: Annual average rainfall in Malawi (1991-2020).

Figure 10: Climatogical rainfall in Malawi by month of the year (1991-2020).

Two drivers of Monsoon viz. El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are identified and both independently indicate very strong positive connections with monsoon October-November-December (OND) rain in regions of Malawi, and especially its northern regions. A strong significant correlation is present not only in the OND season with zero seasonal lag but the signal is also present even from June onwards. A compositing technique that can additionally identify strong correlations even when opposite ENSO and IOD signals act as confounding factors is also tested. Results of precipitation anomaly in OND using compositing, when IOD and ENSO are both negative (positive) in July-August-September (JAS) indicate a decrease (increase) in rainfall in that region. This confirms that the northern part of Malawi is mostly affected and the variation is more pronounced in December (**Figure 11**). Such results have implications for regional planning purposes in optimizing agricultural and energy outputs.

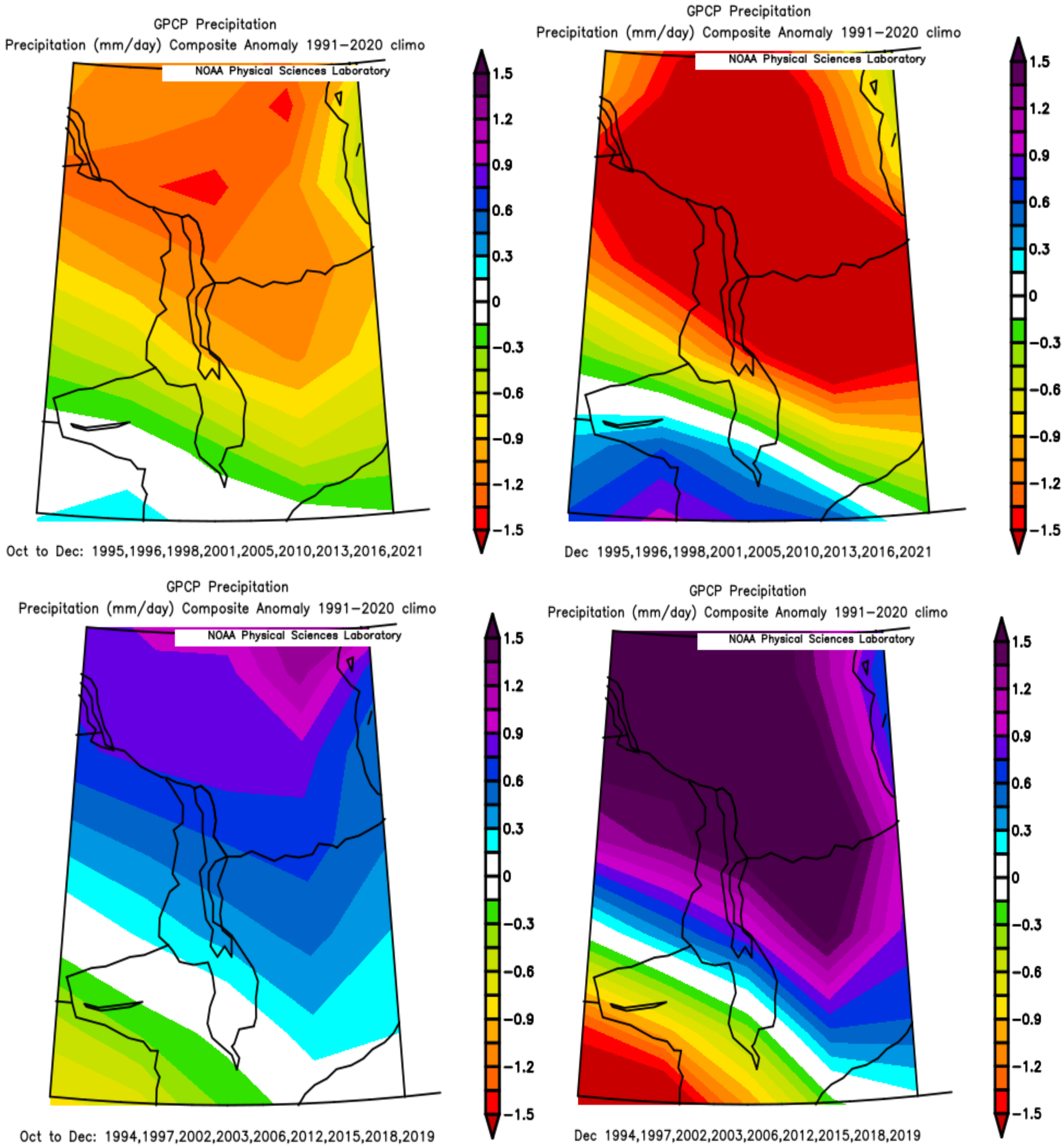

Figure 11: Rainfall variation (OND) in Malawi when IOD and ENSO are in the same phase in JAS using GPCC. Top (bottom): IOD and ENSO both negative (positive). A deficit (excess) in rain is noticed on the top (bottom) panels. Left: variation over OND; right: December only. The northern part of Malawi is mostly affected and the variation is more pronounced in December (right).

A station in Malawi, Kasungu, is considered to study the variation of total accumulated rainfall, with the aim to compute the onset of the rainy season. Rain prior to September is practically nominal. The onset day of rain is explored as it is an important parameter for agricultural crop planting. Distribution of accumulated rain (mm) and Onset days of monsoon are presented in a form of boxplots (**Figure 12**). Onset based on a technique that followed cumulative rainfall (Zampieri et al., 2022) is shown alongside the DCCMS technique. Uncertainty is reduced in pink or blue (when IOD and ENSO are both negative or positive in JAS, respectively) compared to Case 6 (overall climatology). In the top panel of **Figure 12** the uncertainty range for pink is the smallest. Late onset is identified when ENSO and IOD both negative in JAS compared to years when both were positive (**Figure 12** middle and bottom panels).

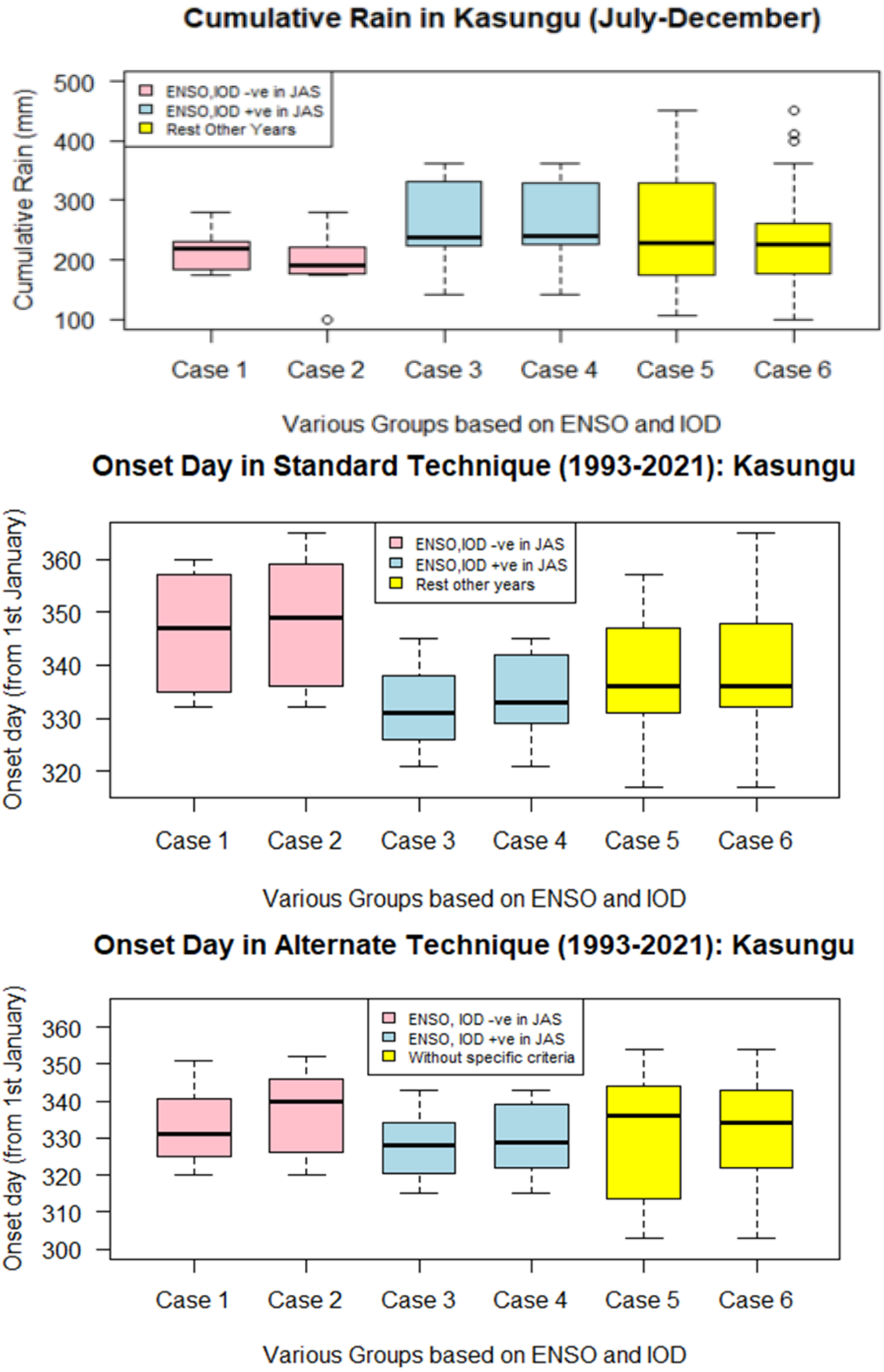

Figure 12: Distribution of rainfall and rainy season onset days for OND in Kasungu. Top: accumulated rain; middle: onset based on the DCCMS technique; and bottom) onset based on a technique based on cumulative rainfall (Zampieri et al., 2022). Various cases based on ENSO and IOD phases are shown. Case 1: both negative in JAS and OND; Case 2: both negative in JAS; Case 3: both positive in JAS and OND; Case 4: both positive in JAS; Case 5: opposite phase; Case 6: all years together.

Based on these assessments, the main conclusions are the following:

1. A unimodal pattern of rainfall variation is identified in Malawi using CHIRPS and ERA5 Land. The rainy season covers six months that peaks in January-February. The main rainy season of Malawi is from November to April and the dry season is from May to October.

2. Two drivers for OND Monsoon are identified for South East Africa, that include Malawi too. A very strong significant positive correlation is detected for both ENSO and IOD in regions covering Malawi
3. A striking precipitation anomaly during OND is noticed in Malawi when IOD and ENSO both are of same sign in JAS. A deficit (excess) in rainfall is noticed in OND when both are in negative (positive) phase in JAS.
4. IOD and ENSO phases in JAS are good indicators for onset too. Late (early) onset happens when both of those indicators are negative (positive); this has been verified even using different techniques to compute the onset.
5. The uncertainty range in prediction of cumulative rainfall and onset date can be improved based on IOD and ENSO phase in JAS.

Next steps

Following the analysis of the recommendations collected during the study trip to Malawi, a plan for the development of the trial climate service is underway. A preliminary CS2 trial climate service is to be developed and shared with national stakeholders who expressed interest in some elements of the service, possibly during the stakeholder workshop in Mozambique that will take place in May 2023. After the initial demonstration, the team will conduct a co-assessment of the draft trial climate service with stakeholders.

The CS2 team has already developed several methods for onset and cessation predictions that can be included in future seasonal outlooks and is collaborating with CS3 to develop a forecast of the agronomic onset of the season. The team also developed the Standardized Wind Index (SWI), that is similar to the standardized precipitation index (SPI), but can be used to determine the intensity of a cyclone, and is more standard than the Storm Severity Index.

In addition to continuing the development of the main indicators (onset and cessation of the rainy season, total amount of rain in a season, time and length of dry spells in a season and cyclone prediction), additional development based on the in country user consultation may be also considered. In particular, different stakeholders also expressed the need for improvement of the seasonal outlook, wanting to receive it earlier in the year (July/August instead of September/October), and desiring updates of the forecast throughout the season. This will likely be addressed in CS2 by updating the seasonal forecast every month and making the updates available on the platform. The team also plans to have a discussion with ACMAD and ICPAC about harmonizing different ways of providing seasonal forecasts: using model outputs and the current practice of consensus-based forecasting coordinated by SARCOF.

In conversation with Farm Radio Trust, a suggestion made by the interviewee was to have more posters of the seasonal outlook available for each district, to display them at more visible locations, such as the marketplace. In the future, they hope to have one single app or digital source for everything that a farmer in Malawi may need, from forecasts and agricultural advice to connecting with a buyer of their produce.

Several stakeholders, mostly in the domain of research and national planning, expressed the wish to receive decadal forecasts, focusing on time scales from 1 to 10 years in advance. Having such information would help them improve their strategic planning. The CS2 team envisages developing a part of the service on a multi-annual time scale as well to address this need. A few interviewees also showed interest in longer term climate projections, which are already being developed for Malawi as a part of CS7. The projections would allow them to see whether a trend is appearing in the shift in the start and/or end of the rainy season, as well as a long-term warming trend. It would also help plan national action on adaptation to climate change.

3.3 Case Study 3

Background

The climate service produced in Case Study 3 (CS3) is directed at the national met service INAM, and through INAM to smallholder farmers, focusing on the Mozambique Province of Nampula - District of Mogovolas, as benchmark for innovation. The region is dominated by semi-arid and dry sub-humid climates with hot temperatures, with an average annual temperature varying between 20 and 26 ºC. The average annual precipitation ranges from 800 to 1200 mm, while reference evapotranspiration is between 1300 and 1500mm. The high temperatures associated with high evaporation demand and the occurrence of frequent dry spells results in water deficiency, critical for agricultural production and food security. Mogovolas is among the food-insecure districts of Mozambique, and little advancement in relation to climate services provision was achieved in the area.

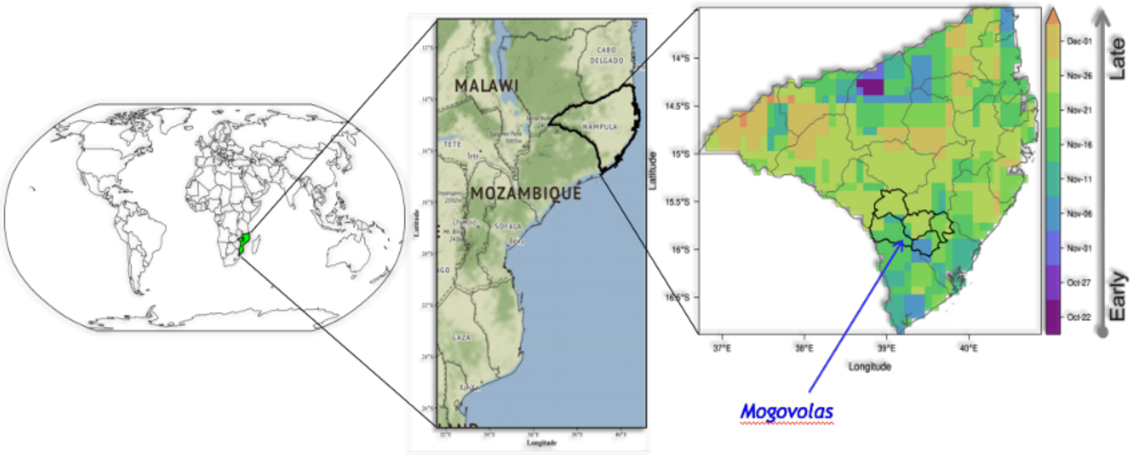

Figure 13: Location of the study site of Mogovolas District, located in northern Mozambique

The climate service produced by CS3 has a dual nature. On the one hand, the production and provision of accurate forecasts of the agronomic onset of the rainy season; on the other, crop varieties with improved traits of adaptation, and specifically rice and cowpea varieties derived from traditional varieties with high appreciation by local users. The development of the two climate services is interconnected and proceeds in parallel. The endpoint of CS3 would be to couple appropriate rice and cowpea varieties with features of the rainy season expected ahead. CS3 expects to deliver trials for the two components of the climate service in the boreal fall of 2023. The development of the trial climate service follows a co-design strategy involving farmers, national met services (INAM) and inputs from the institute of agronomic research (IIAM) and an NGO with long history in the country and in the region of Nampula (PLAN). Further inputs are being also provided by relevant stakeholders that are active in the country and were engaged during the project activities (e.g., WFP and the Ministry of Agriculture). CS3 kickstarted the development of climate services following a field mission to Mozambique in the boreal autumn of 2021, in which smallholder farmers' and local actors were involved in the identification of research priorities by means of 4 Focus Group Discussions (FGDs) involving men and women farmers in the target area, more specifically the villages of Rieque and Namachepa in the Mogovolas District. FGDs were sided by interviews with local extension workers and political and representatives of local administrative offices. The mission in 2021 also allowed an initial identification of CS3 key stakeholders. The CS3 team participated in these discussions aiming for a co-design exercise allowing to tailor climate services to end users. Through these exchanges and through this co-exploration process, it became evident that local users, both at the level of the national met service and at the level of the farmers, were eager to implement their capacity for agrometeorology and specifically forecasting of the onset of the rainy season, its duration, and its end.

This information was to be coupled with improved means of rice and cowpea cultivation in the target District for all the intended users, both at institutional and household level. These improvements include, but are not limited to, the identification of the most desirable varieties with characteristics of local adaptation.

A second field work campaign was held in September 2022, with the main aim of conducting a survey and qualitative interviews to reconstruct the status quo and identify unanswered needs for climate services. During this field campaign, a dozen key informants' interviews were organized at national and local level aimed at defining the CS stakeholders' map and better understanding the existing climate services and the extant flow of the climatic information towards users. Interviewees included representatives from the WFP, the Ministry of Agriculture at national, province and district level, INAM at national and province level, local extensionists, supporting organizations and local chiefs. A survey involving 248 households was carried out in the district of Mogovolas to better identify the current socio-economic situation in the study sites and the production, use and preferences for both climate information and cowpea/rice varieties. Interviews included questions on i) socioeconomic status, ii) agronomic practices, and iii) use of climate information. The climate service users in the case study, and their information requirements for the climate service, are summarized in **Table 6**.

Table 6: Information about the user requirements for the trial climate service in Case Study 3

Sector	Required input data	Users	User requirements	Sectors indicators
Food security/ Agriculture	• Daily climate data, including temperature and rainfall • Soil properties and root zone available water holding capacity.	*Smallholder farmers*	• Onset, cessation and duration of the rainy season (info are expected less than one month in advance, including info on the associated forecast uncertainty) • Temperature during the cropping season • Climate change in terms of rain and temperature patterns over next 5 years • Timely alert for extreme events and stressors. • Varieties resistant to drought/flood/pest and disease • Varieties with increased yield	• Improved timing of the pre-sowing/sowing activities • Improved timing of management and harvesting • Adequate selection of crop varieties (short/long productive cycle) • Adequate selection of crops/crop varieties (more resistant to drought/flood/pest and diseases) • Increased yield stability
	• Crop yield • Crop phenology	*Extensionists*	• Onset, duration and cessation of the rainy season • Timely alert for extreme events and stressors • Varieties resistant to drought/flood/pest and disease	• Improved ability to communicate actionable information to farmers (timing for pre-sowing/ sowing/harvesting activities) • Improved ability to support farmers in selecting adequate crops/crop varieties

	• Daily data (hindcasts) from seasonal forecast models. • Daily climate outputs from CMIP6 models.	*INAM – (at National and Nampula Province levels)*	• Seasonal forecasts/outlook of agroclimatic indices. • Downscaled projections of relevant agro-climate indices.	• Improved capacity for tactical/ strategic planning of the agricultural activities of the upcoming season • Improved capacity for better/informed planning and of agricultural strategies.
		Ministry of Agriculture (at national and Nampula Province level)	• Seasonal forecasts/outlook of agroclimatic indices. • Downscaled projections of relevant agro-	• Improved capacity for tactical/ strategic planning and support to agricultural activities for the upcoming season • Improved capacity for better/informed planning and development of agricultural strategies
		WFP (strong presence in climate service development for Mozambique)	• Seasonal forecasts/outlook of agroclimatic indices. • Downscaled projections of relevant agro-climate indices.	• Improved capacity for better/informed planning and development of agricultural strategies.
		IIAM (involvement in the production and release of improved crop varieties)	• Characterization of available agrobiodiversity in regard to adaptation, performance, farmers appreciation • Identification of varieties/genotypes to be prioritized for breeding and subsequent release	• Improved capacity for delivering of locally adapted and performing rice and cowpea crop varieties

Since CS3 is targeting the crop growing period (October to May) in Mozambique, we consider forecasting for about 6-month (215 days) with a lead time of one month, initialized on 1st of September. The selected variables of interest from C3S forecast systems at daily time scale are: (1) Total precipitation; (2) Minimum 2-m temperature; (3) Maximum 2-m temperature; (4) Surface solar radiation downwards; (5) 10-m wind speed; (6) Dew-point temperature. The forecast models to be implemented are summarized in **Table 7**.

The workflow for the climate services development, informed by the co-exploration phase, is summarized in **Figure 14.** With the end of co-exploration phase, the scientific co-development of the service began, including the design of an index of agronomic onset of the rainy season and associated methods and tools. The identification of rice and cowpea collections to be characterized for genomic diversity and adaptation potential to local cropping followed.

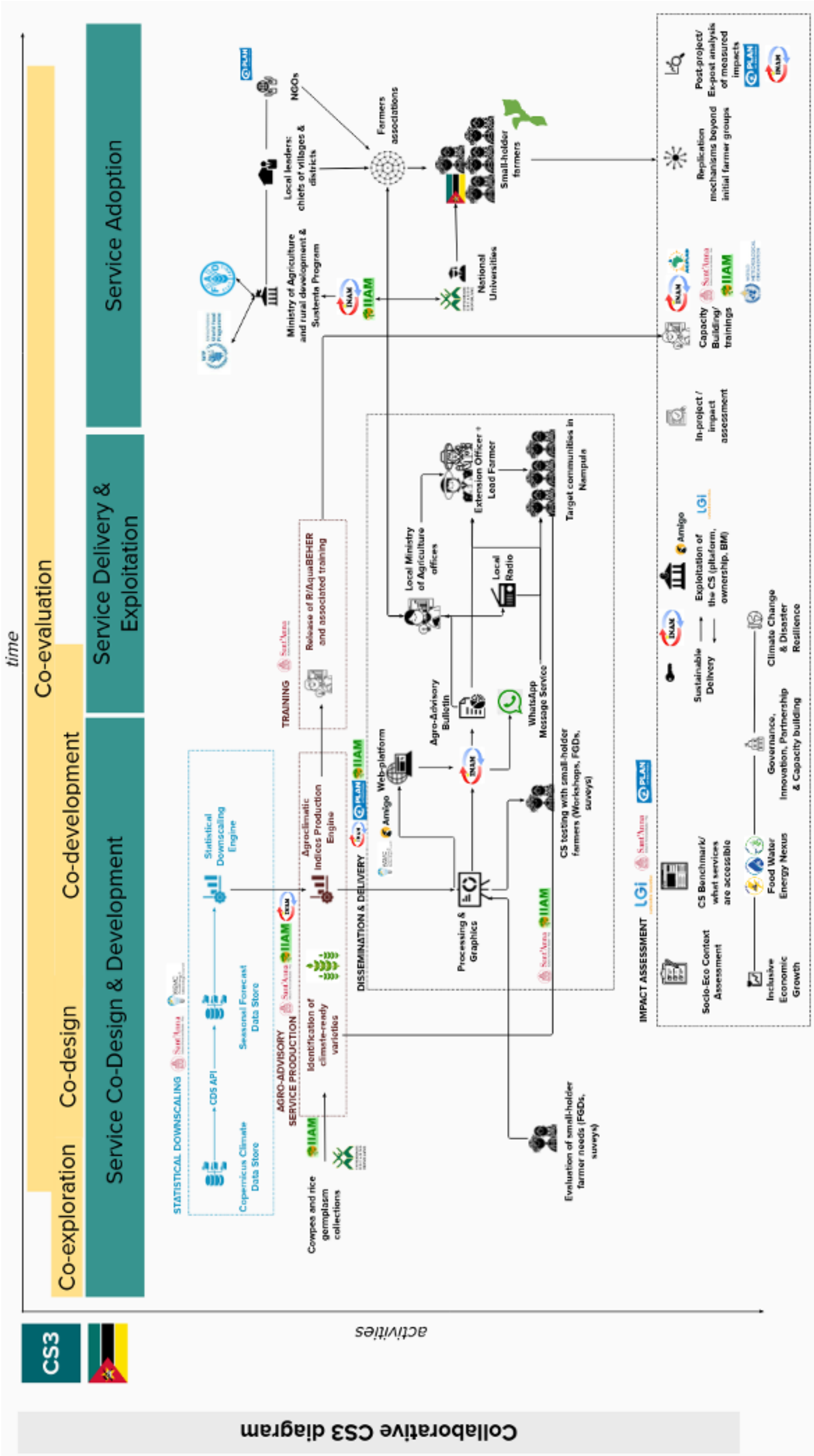

Figure 14: Workflow of the climate service development for Case Study 3

Table 7: Description of the seasonal forecast systems and climate data used in CS3

No.	Forecast Model	Time Range	Initialization	Ensemble Size
1.	ECMWF-SEAS5	215 days	1st of month	51 members
2.	CMCC-SM2	6 calendar months	1st of month	50 members
3.	Météo-France System 8	7 calendar months	1st of month	25 members

The diagram outlines the service *design*, *development*, *delivery*, *exploitation* and *adoption*, represented chronologically from left to right in the top of the diagram (*see* blue rectangles). However, these steps are operationalised using a collaborative approach among actors, researchers, government agencies, supporting actors and local communities. Therefore, the overarching process (*what we do*) is further declined based on the actors' engagement during the service production process (*how we do it*). This entails the adoption of a *co-exploration*, *co-design*, *co-development* and *co-evaluation* approach (*see* top of diagram in yellow, from left to right).

The project activities are conceptualized in 5 macro building blocks: *statistical downscaling*, *agro-advisory service production*, *training, dissemination and delivery*, and *impact assessment*. Their positioning in the diagram indicates their chronological order and the actors' engagement approach in use.

Uni- and bi-directional arrows connect the specific activities (sub-elements of the building blocks) as well as the actors of the CS3, ultimately defining the process pathways and the role played by the identified actors.

The inception of the service design phase is characterized by the co-exploration of (*from the diagram bottom to the top*): i. the socio-economic context (LGI; SSSA; PLAN); ii. CS availability (LGI; SSSA; PLAN; INAM), iii. smallholders' needs and preferences (SSSA; PLAN; smallholders) and of iv. cowpea and rice genetic resources in-situ and ex-situ (SSSA; IIAM; smallholders).

Following the shared contextual knowledge building, the co-design and co-development phases begin (*from the diagram top to the bottom*). They include the forecast/statistical downscaling to derive the agro-climatic indices (SSSA; WEMC), and the climate-ready varieties identification (SSSA, IIAM). This combination results in the agro-advisory service development.

Prior to the service delivery, graphical interfaces of the indices and cowpea/rice trial fields are developed to be tested and co-evaluated by smallholders and local actors (SSSA; IIIAM; PLAN).

The service delivery is initialised with a capacity building step (SSSA; INAM), consisting of a training on the use of the R package R/AquaBEHER (for estimating the rainy season calendar). The delivery and exploitation of the agro-climate service will follow different paths mediated by INAM: i. agro-advisory bulletins, directed to the local Ministry of Agriculture/local extensionists and from there to local radio and ultimately to farmers (or from local extensionists disseminated to famers); and ii. a whatsapp message service, directed to farmers.

Service adoption, referring to the widespread uptake and utilization beyond the target/local farmer groups, has been under construction from the kickstart of the project with extensive stakeholders networking and consultation. The upscaling is expected to build on the initial mobilization of neighbour areas, facilitated by the emerging contacts among farmers associations, local leaders, extensionists, national universities and supporting actors (e.g., FAO, WFP) and by the capillary territorial presence of INAM, IIAM and PLAN, key actors in this case study and with exhaustive expertise for replicability and fundraising. The impact assessment activity, following the entire life cycle of the project and concluding with an ex-post analysis of the project impact, is expected to provide valuable insights for replicability and upscaling.

It is worth noting that based on the flexible and feedback-sensitive approach adopted, further refinements and improvements of the diagram are expected throughout the duration of CS3.

Current status of the trial climate service co-production

Agronomic onset of the rainy season: The CS3 team attempted to develop agroclimatic indicators that characterize the crop/variety specific moisture demand/satisfaction and calendar of the rainfed growing season. The provision of seasonal forecast of those indicators is intended for use in crop production decision support. The objective seasonal forecast products of the agroclimatic indicators are issued at 1-month lead time.

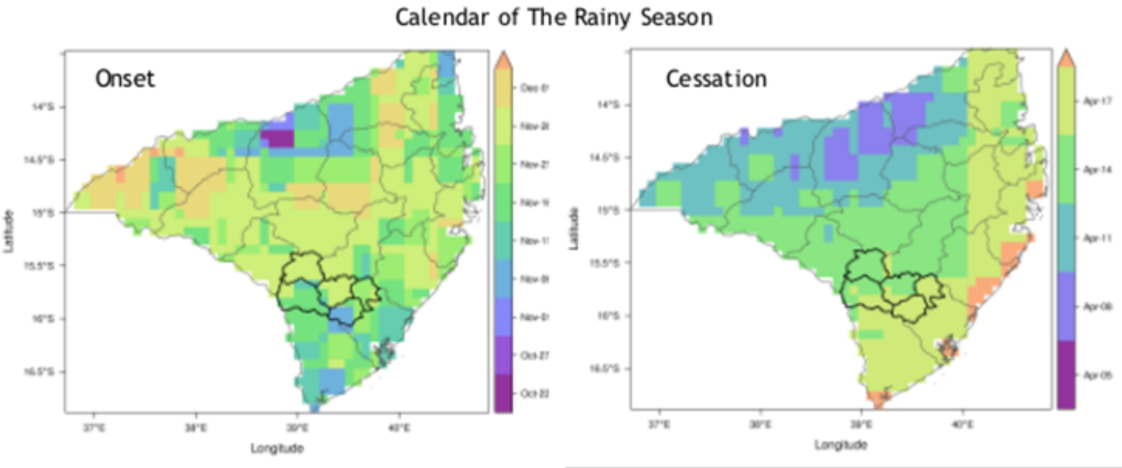

Figure 15: Example of the agroclimatic indices considered, mapped over the region of Nampula

To facilitate the usability of the derived indices, an R package called “AquaBEHER” has been developed. The package is capable of computing and integrating evapotranspiration into a daily water balance model. This will allow us to estimate daily parameters of crop and soil water balances for agricultural crops. The package can also estimate rainy season calendar (Onset, Cessation and Duration) based on an agroclimatic approach. A training workshop was conducted by SSSA on predicting rainy season characteristics and crop water balance for agricultural crops on 19 - 20, September 2022 hosted by INAM. 11 (5 female, 6 male) experts from INAM, IIAM and WFP participated. Currently, we are testing the 1st version of R/AquaBEHER. Following the interaction with INAM and IIAM experts during the September 2022 training workshop, we started the design and development of a shiny app based graphical user interface of the R package, which is currently ongoing. Using the developed R package, multi-model ensemble, hindicasts of agroclimate indices will be produced and evaluated. In parallel, we are discussing the possible integration of R/AquaBEHER to the Teal tool from WEMC. Discussions were held with the CS2 and CS4 team for the development and prediction of Agroclimatic indices over the region and a monthly meeting was set up for follow-up discussions and collaborations.

Identification of most promising cowpea and rice varieties: The team identified 350 and 450 rice and cowpea accessions for Mozambique and neighboring countries. These “core collections” are the raw materials used for the identification of most promising varities for use with farmers in Mogovolas District. In September 2022, seeds were germinated in small pots until the emergence of leaves, and DNA was extracted during the SSSA mission at IIAM laboratory facility by the IIAM and SSSA team . DNA is ongoing sequencing facility at IGA (Udine, Italy) to characterize the diversity of core collections, and results are expected in Q1 2023. Genotyping will involve ddRAD sequencing, a method which detects small genetic differences amongst alleles (single nucleotide polymorphisms, (SNP)), across the entire genome. The resulting data will be used to connect genetic agrobiodiversity to climate diversity in Mozambique in the effort of identifying genetic elements conferring adaptation to climate constrains. Rice and cowpea genotypes belonging to the "core collection" are currently grown in experimental fields in two locations in Mozambique: Nampula city (cowpea) and Chockwe (rice and cowpea) so to target different agroecologies, a first step necessary to scale up CS3 innovation beyond the piloting area of Nametil.

Next steps

Agronomic onset of the rainy season: We expect to have an advanced trial climate service by May 2023, in correspondence with the planned project workshop to be held in Mozambique. On that occasion, we will share the preliminary draft trial climate service with national and international stakeholders, possibly focusing a training module on the use of R/AquaBEHER. Immediately after the workshop, we plan to have a participatory co-assessment of the draft trial service with smallholders and other relevant local stakeholders in Nametil. In that occasion, we will showcase the service to local actors and gather feedback as per means of communication and usability of the climate service (*e.g.,* the use of maps based on probability, text, colour scales). We target the delivery of the forecasting information to farmers in the boreal fall of 2023.

Identification of most promising cowpea and rice varieties: We expect to identify molecular associations with climate variability in both rice and cowpea. Additionally, we will compute measures of genomic vulnerability of rice and cowpea cultivation based on climate projections developed in WP4. SNP data will be combined with agronomic and participatory characterization of the "core collection" cultivated in the experimental fields in the study area so to identify genetic groups most promising for cultivation in the Mogovolas District and other relevant agroecologies. In particular, two farmer-participatory variety evaluations will be organized by IIAM and SSSA between April and June 2023. We expect to have collected all the relevant information at the end of the boral summer of 2023 and be in the position to move most promising varieties closer to farmer fields, enabling a further evaluation in the target on-farm environment in combination with the provision of the forecasting information during the cropping season of 2023, that will start in November.

3.4 Case Study 4

Background

The climate service produced in Case Study 4 (CS4) is directed at smallholder farmers and the Tanzania Agricultural Research Institute (TARI), with support from the TMA. The service will be provided and tested for the Kibaha district, located in the Pwani region in the east of Tanzania (**Figure 16)**.

The CS4 team also conducted a study visit to Tanzania in May 2022 where close collaboration took place between the team and TMA staff involved in this task. Two focus group discussions were organised in Kibaha district: one with farmers and another with extension officers. In addition, two interviews were done with national stakeholders who are key in the food security domain: Mr. Mponda Malozo representing the Environment Management Unit of the Ministry of Agriculture in Tanzania, with previous valuable experience in the Tanzanian office of the Food and Agriculture Organisation (FAO), and Climate Action Network (CAN Tanzania), an NGO working on the promotion of integrated climate services.

Based on the outcomes about user needs from the discussions and interviews with the stakeholders in Tanzania, recommendations for the CS4 trial climate service were developed. Climate information that the farmers and extension officers are mainly interested in includes: forecast of the total amount of rain in a season, the dates of the onset and cessation of the rainy season, and the timing and length of dry spells in a season. All information that is communicated should be downscaled to district level.

The collaboration and discussions with TMA complemented the findings from the stakeholder elicitations and literature review conducted during the first year of the project. These findings also helped understand the socio-economic circumstances in the country, existing climate services and user needs with respect to climate information. The CS4 aspects, originally planned in the project, were also reconsidered after JRC had left the project and WEMC became the new CS4 scientific lead. Discussions on assuring the sustainability of the service after the project ends also prompted new considerations for CS4 climate service. New elements have been proposed which are currently under development.

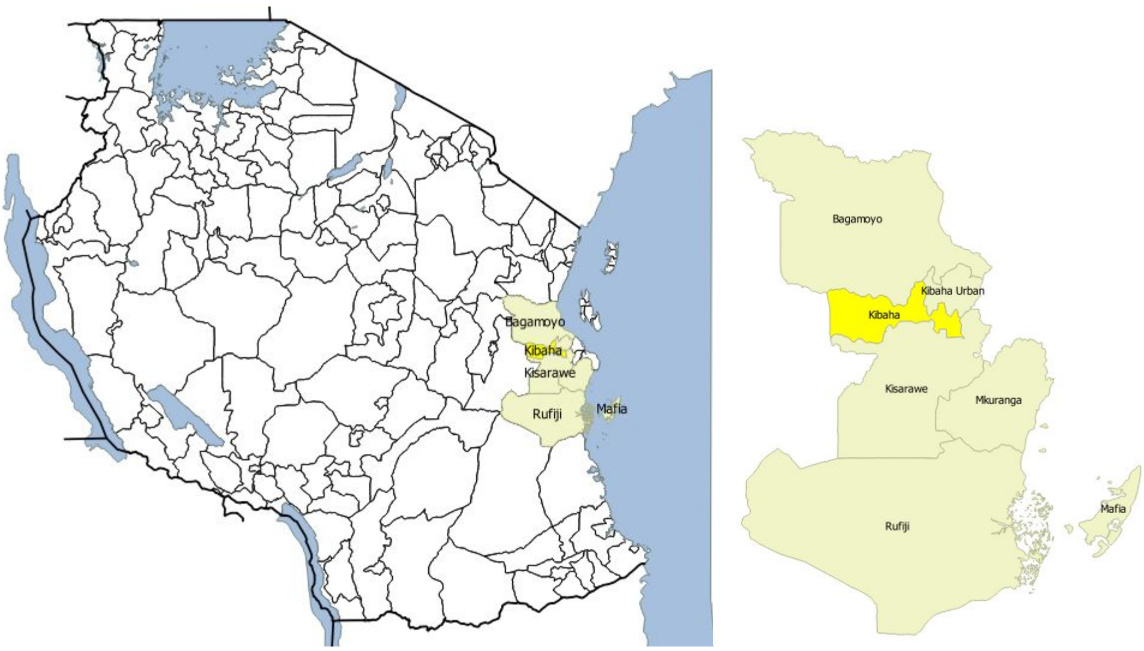

Figure 16: Districts in Tanzania (left), with Kibaha district highlighted in yellow, and expanded on the right.

Farmers and extension officers also expressed the need for improvement of the seasonal outlook, wanting to receive it earlier in the year to have more time for preparation activities, and desiring updates of the forecast throughout the season. This will be addressed in CS4 by updating the seasonal forecast every month and making the updates available on the platform. New visualisation opportunities are also being discussed within the team and will be addressed with TMA, to assure the clarity of communication of the forecasts.

Data requirements and workflow

The service is composed of a bias-adjusted seasonal forecast downscaled to district level and updated monthly; a forecast of the rain season onset and cessation; and a multi-annual forecast. In addition, the collaboration with CS3, as well as CS2, will result in the provision of the forecast for the agronomic onset of the season. The summary of user requirements is presented in **Table 8**.

The workflow for the development of CS4 climate services is summarized in **Figure 17**. With the end of co-exploration phase, the scientific co-design and co-development of the service began, and will continue as the work progresses into service delivery and exploitation, thanks to a process with continuous feedback. The service adoption phase begins with the end of the project and includes stakeholders who have embedded the service in their processes either as users, producers or intermediaries of climate information.

Table 8: Information about the user requirements for the trial climate service in Case Study 4

User	User requirements	Sector indicators	Input
Primary users: Farmers in Kibaha	1. Onset and cessation of the rainy season 2. Total amount of rain in a season 3. Timing and length of consecutive dry and wet days in a season (All downscaled to district level)	1. Improved agricultural planning (e.g., timing of sowing and harvest) 2. Easier determination of which crop/variety to plant 3. More efficient decision making (planting early/late maturing crops; changing from conventional to pit farming to conserve humidity...)	Climate data, gridded.
TARI Kibaha	4. Multi-annual prediction of precipitation, temperature, drought index (1-5 years) 5. A pest index	Improved strategic planning	Gridded observation data Crop yield monthly data
Other users identified during field trip (government, int. organizations): Ministry of Agriculture & FAO	4. Multi-annual prediction of precipitation, temperature, drought index (1-5 years)	Improved strategic planning	

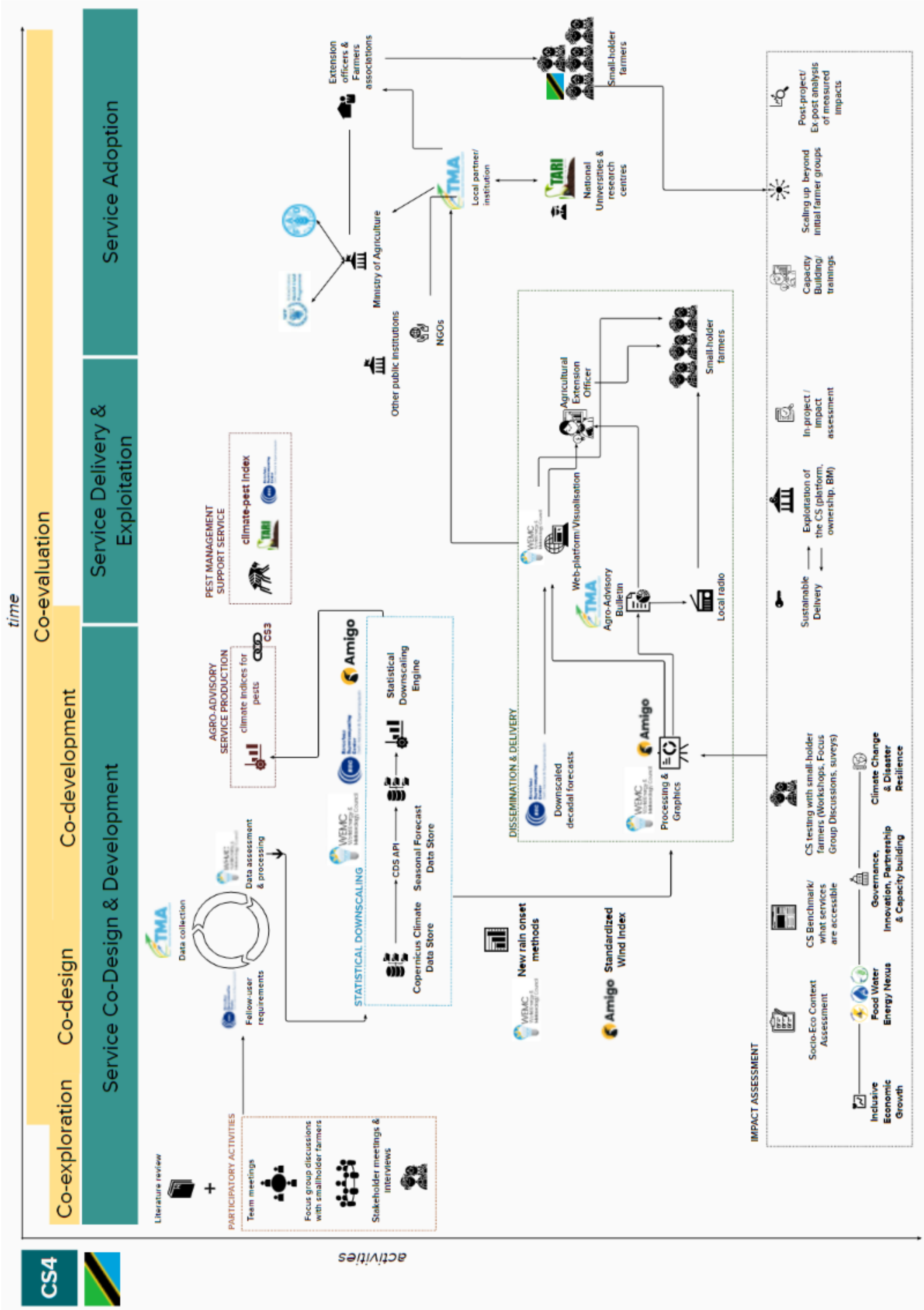

Figure 17: Workflow of the climate service development for Case Study 4

Current status of the trial climate service co-production

This case study aims to develop climate services for the agricultural sector in Tanzania, and tailor them to the local farmers' and TARI's needs especially for the Kibaha district. To this end, a comprehensive assessment of the available data and tools have been performed, with the objective of improving the detection and assessment of rainy season, droughts and other weather extremes, and crop climate vulnerability and also of supporting adaptation measures. Specific activities have been:

1. Comparison of meteorological data from different datasets
2. Identification of important drivers of South-East African monsoon (OND) rainfall
3. Computation of the Onset for monsoon (OND) rainfall in Kibaha using different methodologies, and their comparison.

<u>Comparison of meteorological data from different datasets</u>

Five datasets from different sources – CHIRPS, MSWEP, ERA5, ERA5 Land and MERRA2 – were considered and compared with local station observations for Kibaha. Their main features (such as spatial and temporal resolution) are shown in **Table 9**.

Table 9: Characteristics of rainfall data used for the CS4 indicators

Dataset	Temporal Resolution	Spatial Resolution	Type	Source
Station Observation	Daily	Pointwise	Instruments	TMA
CHIRPS	Daily	0.05^{0} X 0.05^{0}	Satellite-based	
MSWEP	Daily	0.1^{0} X 0.1^{0}	Satellite-based	
ERA5	Daily	0.25^{0} X 0.25^{0}	Reanalysis	ECMWF
ERA5-Land	Daily	0.1^{0} X 0.1^{0}	Reanalysis	ECMWF
MERRA-2	Daily	0.5^{0} X 0.625^{0}	Reanalysis	NASA

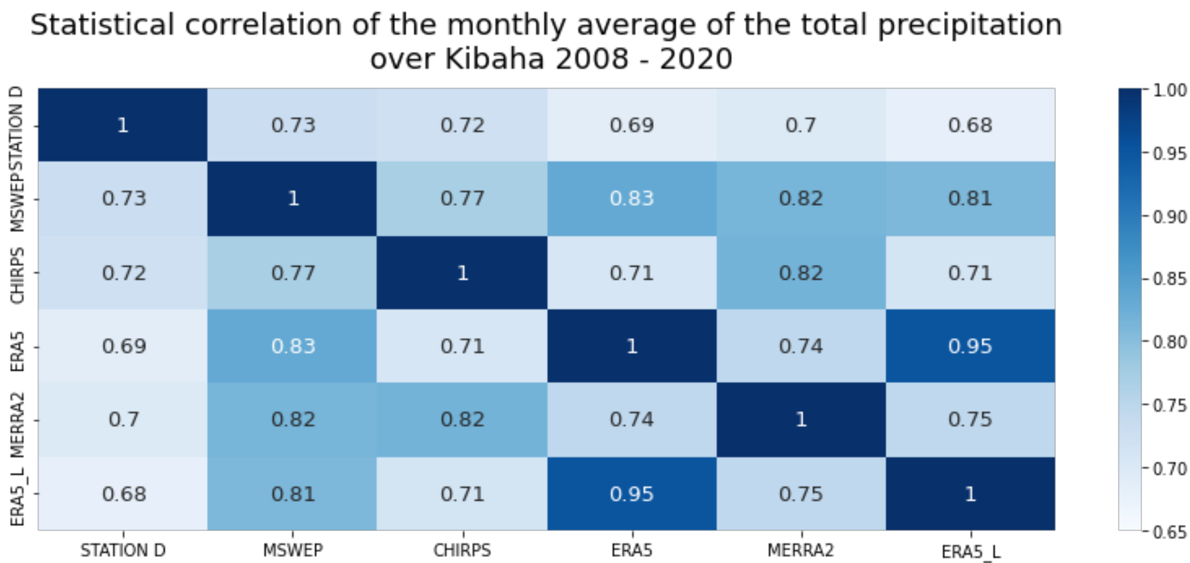

Figure 18: Correlation between the five rainfall datasets considered at the monthly resolution for the period 2008-2020, after removing the annual cycle.

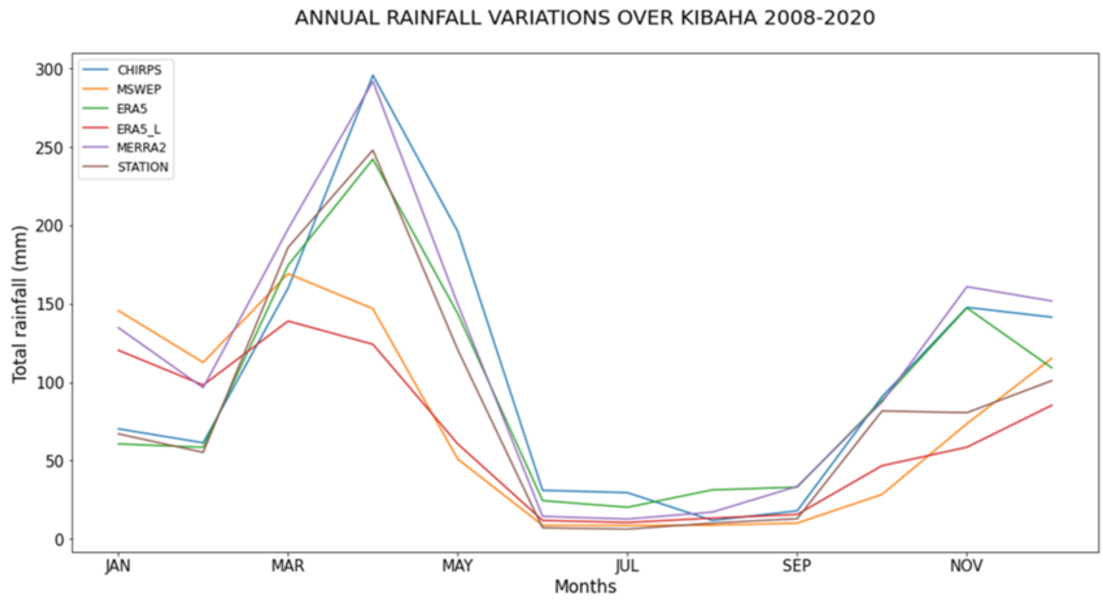

Figure 19: Climatological annual cycle of rainfall in Kibaha using different data sources, including station observations, for the period 2008-2020

From the statistical correlation for the five datasets against station observation, as well as between each other, it was found that CHIRPS and MSWEP have a strong correlation with station observation data of 0.72 and 0.73 respectively (**Figure 18**). The five datasets were also used to assess the rainfall behaviour over Kibaha. All the datasets captured the bimodal pattern of rainfall of Kibaha, which has two rainy seasons: MAM (March, April and May) and OND (October, November and December).

As a result of our analyses, the CHIRPS dataset[3] version 2 (Funk et al., 2015) is chosen as the main reference dataset of rainfall for our subsequent analysis., even though MSWEP could similarly be used. Both are generated by combining satellite observations with surface station data. CHIRPS has two different spatial resolutions too (0.05^0x0.05^0 and 0.25^0x0.25^0) that can easily be incorporated based on user needs and computational power. Various studies opted that data for onset determination in the region and found it more suitable compared to other data sources (Dunning et al., 2016; Zampieri et al., 2022).

An assessment of rainfall over the whole of the Kibaha district indicated that rainfall increases towards the South Western part, which receives an annual rainfall of between 1900 mm to 2000 mm, whereas the North Eastern parts receive less than 1800 mm. When broken down into seasons, in OND rainfall is 900-1000 mm in the SW compared to 800 m in the NE, and in MAM, it is 1000 m and less than 950 mm respectively.

<u>Identifying important drivers of South-East African monsoon for the OND rainfall.</u>

Similarly to CS2, but possibly even more so for Tanzania, monsoon rainfall plays a crucial part in Africa's socio-economic structure and its year-to-year variability has profound implications for agricultural, energy, and other societal sectors. October-November-December (OND) is the rainy season for most of Tanzania, and beyond. Such drivers could be different in early or extended boreal winter, due to the relative positioning of the Intertropical convergence zone, which passes through this region - hence the location and season is the focus here.

Two drivers of Monsoon viz. El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are identified and both independently indicate very strong positive connections with monsoon OND rain.

[3] https://www.chc.ucsb.edu/data/chirps

Not only is a strong significant correlation present in the OND season with zero seasonal lag but the signal is also present even a few months ahead. This has been tested using various data sources and covering even earlier as well as later time periods too. Analyses using regression suggest similar findings and hence may also be used for prediction purposes. To further strengthen results, a compositing technique is applied that can additionally identify strong signals even when opposite signals act as confounding factors.

Results of precipitation anomaly for OND for compositing, when IOD and ENSO are both negative in July-August-September (JAS) indicate a decrease in rainfall in that region. In the last thirty years, a total of 9 years matched the criteria and all showed a deficit in rainfall; more recently, that criteria is again noticed in 2022 (JAS). On the other hand, excess rain in OND is noted when both drivers are positive in JAS (**Figure 20** and **Table 10**). Looking at composites by month, rather than season, for the OND months, indicates that signals transmit from the northern part of SE Africa to the southern part from month October to December (not shown).

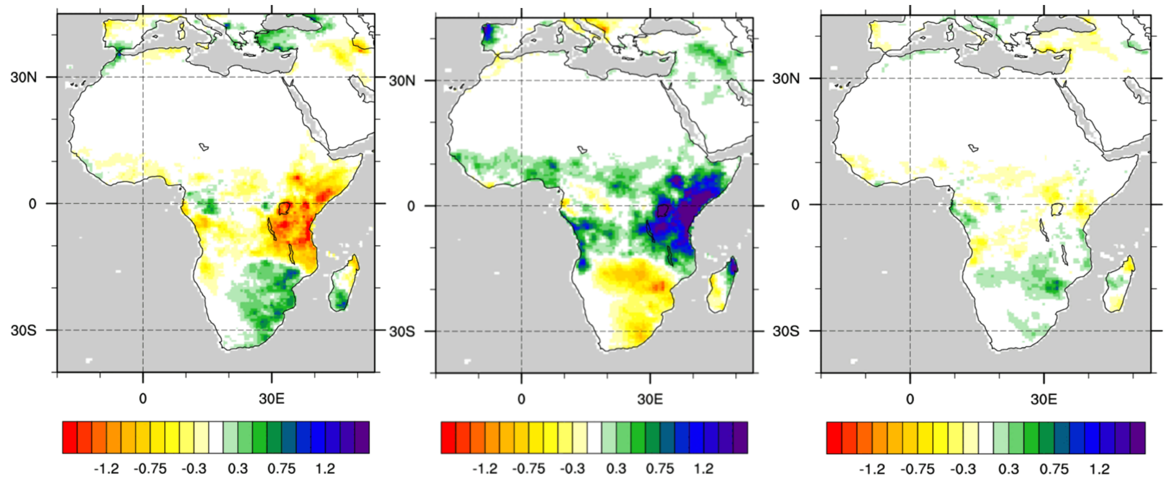

Figure 20: Precipitation composite anomaly (OND) using CHIRPS data for Case 1, when ENSO, IOD both negative in JAS and OND (left); b) Case 3, when ENSO, IOD both positive in JAS and OND (middle); and c) Case 5, when ENSO and IOD in opposite phase during JAS (right).

Table 10: Various cases based on IOD and ENSO phases in JAS and OND

Cases	Criteria	Years	Rain (OND) in SE Africa	Onset dates
1	IOD and ENSO both negative in JAS and OND	1995, 1996, 1998, 2001, 2005, 2010, 2016	Deficient, more dry spells	Late
2	IOD and ENSO both negative in JAS	1995, 1996, 1998, 2001, 2005, 2010, 2016, 2013, 2021	Deficient, more dry spells	Late
3	IOD, ENSO both positive in JAS and OND	1994, 1997, 2002, 2006, 2015, 2018, 2019	Excess, more wet days	Early
4	IOD, ENSO both positive in JAS	1994, 1997, 2002, 2006, 2015, 2018, 2019, 2012, 2003	Excess, more wet days	Early
5	Rest other years (ENSO and IOD in opposite phase in JAS)	1993,1999, 2000, 2004, 2007, 2008, 2009, 2011, 2014, 2017, 2020	Not identified	Not identified
6	All years together	1993-2021	Normal range	Normal range

Such knowledge of time progression of signal is very useful for regional agricultural (and other sectors) planning purposes. For this reason, it is important to look at the larger scale circulation. Indeed, the Walker circulation seems to play a major part in transporting signals in both phases, by modulating the precipitation in SE Africa during OND. When IOD and ENSO are in the same phase (both positive or both negative in JAS), two opposite signed signals are located in the SE African sector respectively (**Figure 21**). Locations of updrafts and downdrafts for the Walker circulation are easily identified. Here Case 2 and Case 4 situations are shown, when IOD and ENSO were either both negative or both positive in JAS. Deficit in rains (OND) in SE Africa is clearly distinct when the sign for both is negative, while excess rain when that is positive. Signals are similar using Case 1 instead of Case 2 or Case 3 instead of Case 4.

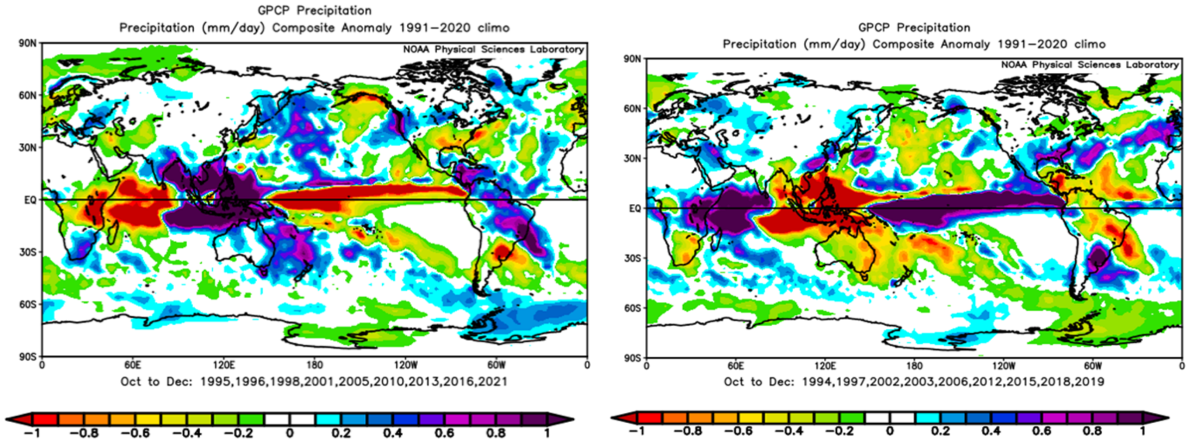

Figure 21: Composite of precipitation anomaly (mm/day) in GPCP data. Cases when IOD and ENSO are both negative (left) (positive; right) in JAS.

<u>Prediction for 2022 Monsoon (OND) and Validation in recent months (Oct-Nov 2022)</u>

By September 2022, we knew we were in Case 1 situation where IOD and ENSO were both negative in JAS (that eventually continued to OND). This knowledge can be used for early warning purposes, based on an analysis of historical data. More specifically, in 2022 ENSO and IOD were both strongly negative since JAS and were unlikely to change phase till December, as also indicated by global dynamical seasonal forecast models. Hence it was possible to attempt a prediction for OND even in the season of JAS. Based on this information a strong deficit in rainfall (and a late onset, as discussed below) had been anticipated. Ahead of the 2022 (OND) monsoon season, a bulletin[4] was circulated within the project consortium and relevant stakeholders (e.g. SARCOF) and a blog[5] was published as a way to provide an early warning about the upcoming very dry season.

<u>Onset of monsoon OND rainy season in Kibaha</u>

Different methodologies exist for the computation of the onset (and cessation) of the rainy season. For CS4, as for CS2, four methods will be adopted. However, here a thorough comparison between two of these methods to gain a good understanding of the way onset is detected by different approaches. The sensitivity of these methods is also assessed using the different rainfall datasets presented above.

4 https://wemcouncil.sharepoint.com/:b:/s/WorldEnergyMeteorologyCoucil/EfyHXNDleGVPpJKoccG1iz0BAegllGOy65iT_2f1rttmIw?e=hjLpa4

5 https://www.wemcouncil.org/wp/tech-blog-important-drivers-of-southeast-african-monsoon-variability-is-early-monsoon-onset-prediction-and-planning-possible

The first method is the one commonly used by the Tanzania Meteorological Authority (TMA). According to this method, hereafter referred to as Standard Technique (ST), the onset of rains is calculated as the first occasion during the OND (or MAM) season when a) 20 mm or more rainfall is received in four consecutive days, b) with at least two wet days and c) no dry spell of 10 days or more within the following 30 days. A wet day is defined when there is 1 mm or more rainfall in the day, while during dry spells days record less than 1mm of daily rainfall. It is instructive to assess how ST varies depending on the dataset used (**Figure 22**). Large variations in onset day are present amongst these data sources, with differences often as large as a few tens of days, and up to about sixty days in 2016, as highlighted in **Figure 22**. This is a year when IOD and ENSO were both negative in JAS and OND (see **Table 10**). The difference in onset day for 2016 is particularly pronounced between the station data (late onset) and the CHIRPS dataset (near normal onset).

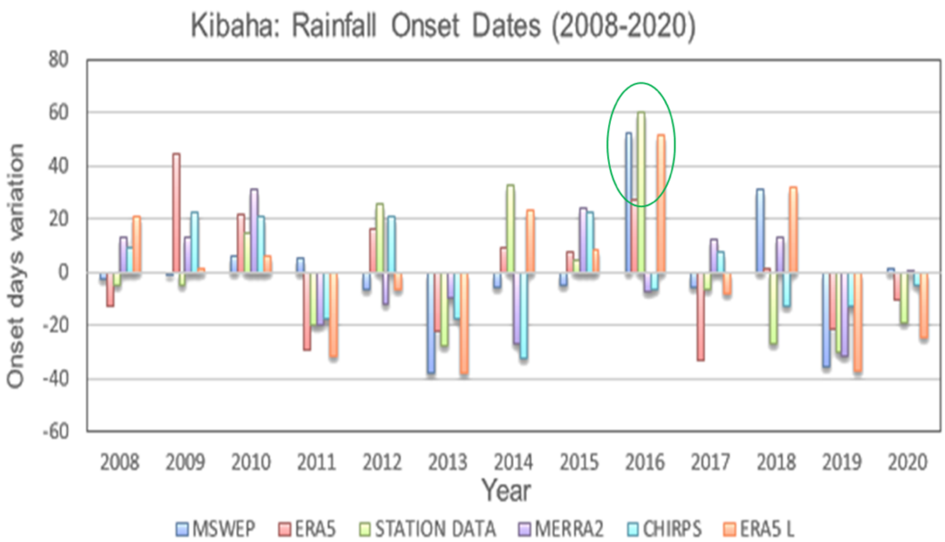

Figure 22: Comparison of OND Onset using Standard Technique (ST) calculated from different datasets (see legend) at one location Kibaha, Tanzania. Year 2016 is highlighted, due the large variations amongst the datasets.

The second methodology is instead based on accumulated rainfall only, which therefore reduces the number of thresholds in its definition to only one (Zampieri et al. 2022). The approach is described in in a form of schematics in **Figure 23** (left). A change in cumulative rainfall from the annual average (Y axis, right), shown in blue, is plotted over time (days since 1st July in X axis). The time when the accumulated rainfall stops decreasing is defined as the Onset date (green circle), while the reverse behaviour is the Cessation date (red circle).

In the particular case shown, for 2017, the onset matches that computed using the Standard Technique. However, in general some discrepancy between two techniques usually arises, especially in rain deficit years as they are often associated with prolonged dry spells. Year 2013 for instance is a Case 2 situation and accompanied by frequent dry spells (**Figure 23**, right). Those situations often happen when IOD and ENSO are in negative phase in JAS (Case 2). In **Table 11** shows that for 2013 there are around 50 days difference between the two techniques. The onset using ST can be identified at around 100 days. ST using various data sources show a consistent result, but it does not account for consistent dry spells after the first two spikes in precipitation. If there are dry spells after the onset is publicly announced there could be severe consequences for crops. In this sense, AT can overcome such shortcoming – in this case the onset with ST occurs 50 days later than with ST. Instead, in years with abundant rain the two techniques usually yield consistent onset dates. For completeness, there are also cases when the onset is not identified in given years, when they are especially dry.

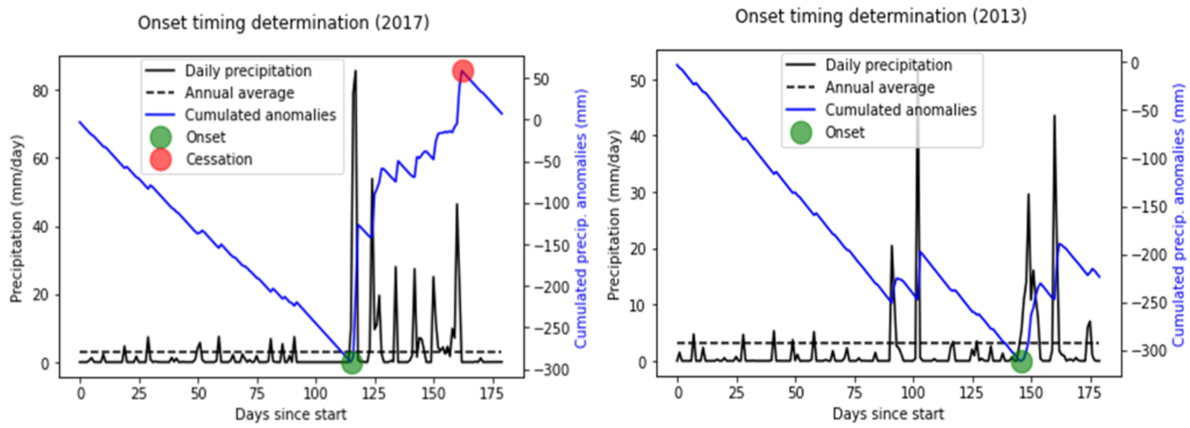

Figure 23: Two examples of the computation of the onset and cessation dates for the OND monsoon in Kibaha using the alternate technique based on cumulative rainfall, based on CHIRPS data. Left: for 2017; in this case the onset is 23rd October and the cessation is 9th December. 2017 was a normal year. Right: for 2013.

Table 11: Comparison of Onset days based on two methods, Standard Technique (ST, using several dataset) and Alternate Technique (AT, using CHIRPS data).

Year	CHIRPS (using AT)	Date (for AT)	Station Data	CHIRPS	MSWEP	ERA5	MERRA2	ERA5 Land
2008	299	26th Oct	301	301	311	285	299	336
2009	340	6th Dec	301	314	313	342	299	316
2010	339	5th Dec	320	313	320	319	317	321
2011	309	5th Nov	286	274	319	268	266	283
2012	328	24th Nov	331	313	307	314	274	308
2013	327	23rd Nov	278	274	276	275	276	277
2014	303	30th Oct	338	259	308	307	259	338
2015	302	29th Oct	310	314	309	305	310	323
2016	360	26th Dec	366	285	366	325	279	366
2017	296	23rd Oct	299	299	308	264	298	307
2018	319	15th Nov	279	279	345	299	299	347
2019	275	2nd Oct	276	279	278	276	254	278
2020	285	12th Oct	287	287	315	287	286	290
Average (Std. Dev.)	314 (23)	10th Nov	306 (26)	292 (18)	313 (23)	297 (23)	286 (19)	315 (27)

Figure 24 shows the long term trend for cumulative rain and onset date (using the Alternate Technique) for the OND season in Kibaha. Accumulated rain increases over the ca. 30 year period, while for onset date shows a decreasing trend. A strong significant negative correlation is also present between onset date and cumulative rainfall, with rain deficit years usually associated with late onset and vice versa for excess rain years.

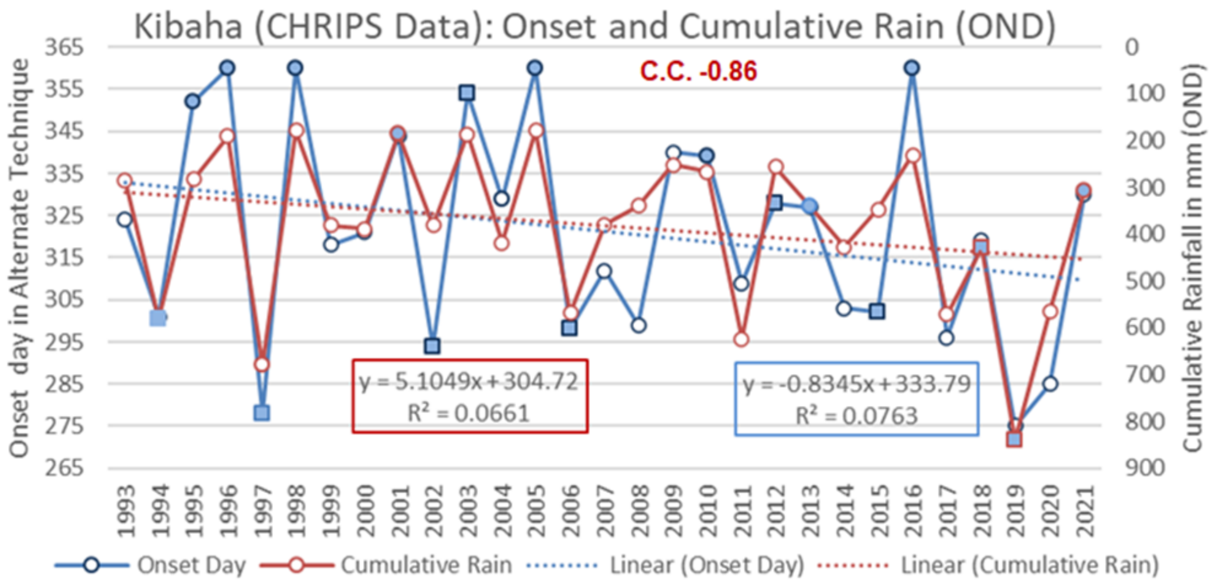

Figure 24: Cumulative rain and onset day for the OND season in Kibaha using CHIRPS data and AT technique. Trends for both indicators are shown. A strong correlation (-0.86) is also noted between the two. Note the reverse order in the y-axis for cumulative rain.

A more systematic comparison between OND onset using ST and AT, as well as cumulative rain in Kibaha using CHIRPS data for 1993 to 2021 is shown in **Figure 25**. This analysis is stratified according to ENSO and IOD phases. For Kibaha, a total of around 216 mm cumulative rain is expected from July to December (with one standard deviation [s.d.] of 44mm), which is only 56% of the long-term mean. Interestingly, when IOD and ENSO are both positive in JAS and OND, the amount of total rain is more than doubled (546mm) with a s.d. of 210 mm. Normal cumulative rain is 381 mm with s.d. of 169 mm.

Normal onset day as identified by AT is 16th November (day 321 starting from 1st January, with a s.d. of 26 days); while with ST, it is 31st October (day 305, s.d. of 23 days). Both methods in general yield a late onset for rainfall deficit years, while early onset in years of excess rainfall. In years when IOD and ENSO are both negative in JAS, and this continues till OND season, the average onset day based on the cumulative rainfall's approach of AT is around 19th December (day 354, with a s.d. of 9 days). Thus, considering these different factors, our analysis of AT indicates a very late onset in 2022. Onset days based on the ST also suggest a late onset in 2022 (around 9th November, day of the year 314, with a s.d. of 25 days). Thus, in situations when both IOD and ENSO are negative, a large deviation in onset day between the two methods is expected.

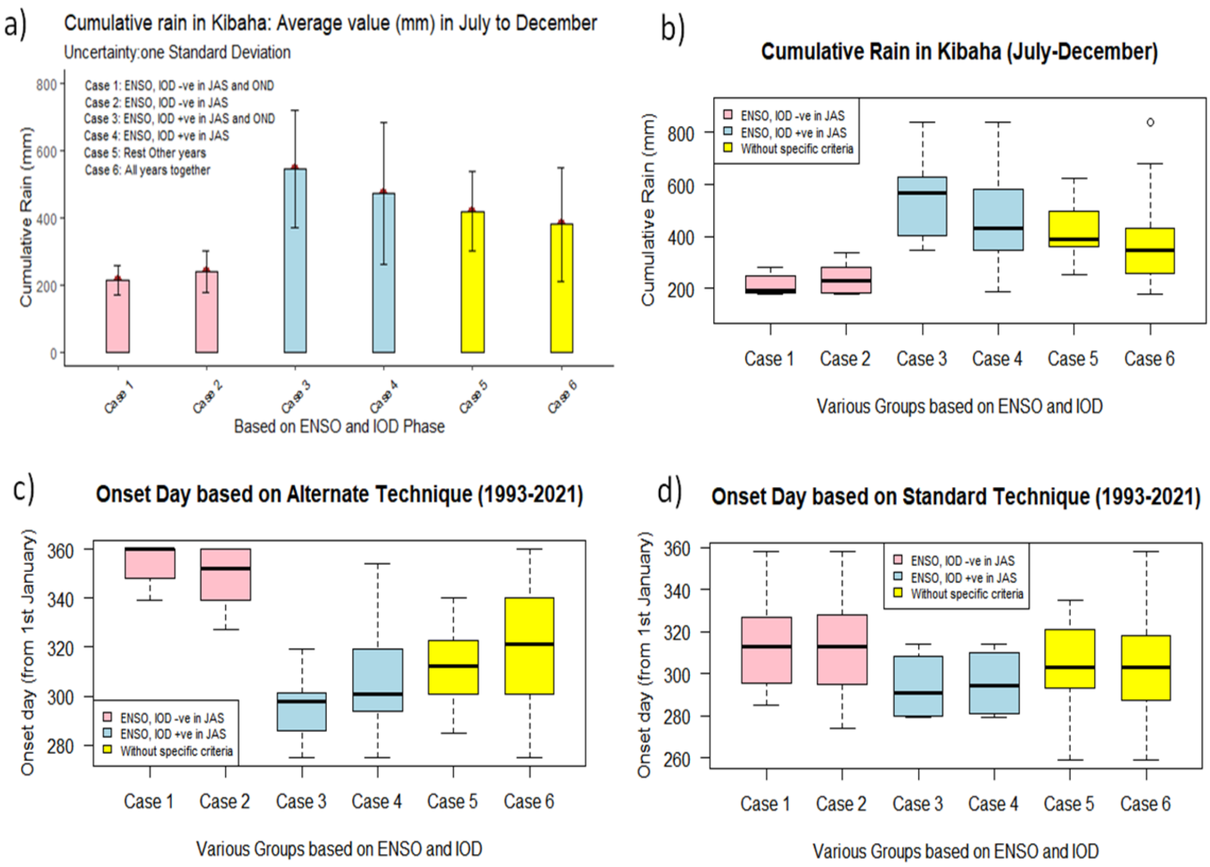

Figure 25: Cumulative rain (mm) and onset of OND monsoon in Kibaha using CHIRPS data for 1993 to 2021, divided into ENSO and IOD phases. Top for cumulative rain: a) average from July to December with uncertainly range marked; b) boxplot showing variations of cumulative rainfall and median values. Bottom for onset days using the Alternate Technique (c) that focuses on cumulative rainfall; d) based on the current technique used by TMA.

Summary and Next steps

Cumulated rainfall and onset dates for October-November-December (OND) season have been computed for Kibaha. Four different techniques are being considered for the onset calculations, even though for simplicity only two of them have been discussed here. Results with the other two methods are consistent with the two presented. The first method considers the TMA approach, while the next two focus on cumulative rainfall anomaly to calculate onset. The last method uses additional climate variables to detect a more agricultural oriented onset. Major drivers of the OND monsoon season are also identified. IOD and ENSO phases were shown to play a strong role in rainfall variability as well as variation of onset dates. The CS4 team has already developed several methods for onset and cessation predictions that can be included in future seasonal outlooks and is collaborating with CS3 to develop a forecast of the agronomic onset of the season. The team also developed the Standardized Wind Index (SWI), that is similar to the standardized precipitation index (SPI) but can be used to determine the intensity of a cyclone and is more standard than the Storm Severity Index.

Representatives of TARI Kibaha expressed the wish to develop a pest-climate index, to help manage pests better under the changing climate conditions. The main crop that the TARI Kibaha center is working on is cassava so any crop related developments in FOCUS Africa for Tanzania should include cassava, in addition to maize. The crop-relevant indicators (rainfall onset, etc.) could also be applied to other provinces and possibly other crops (**Figure 26**).

TARI would also like to receive decadal forecasts, focusing on time scales from 1 to 5 years in advance. Having such information would help them improve their strategic planning. The CS4 team envisages developing a part of the service on a multi-annual time scale to address this need.

Following the analysis of the recommendations collected during the study trip to Tanzania, a plan for the development of the trial climate service is underway. A preliminary CS4 trial climate service is to be developed and shared with national stakeholders, possibly during the stakeholder workshop in Mozambique that will take place in May 2023. After an initial demonstration, the team will conduct a co-assessment of the draft trial climate service with stakeholders.

A discussion with TARI about pest-climatic indices is still pending and WEMC will reinitiate and facilitate it in the coming months. The team also plans to have a discussion with ACMAD and ICPAC about harmonizing different ways of providing seasonal forecasts: using model outputs and the current practice of consensus-based forecasting coordinated by SARCOF.

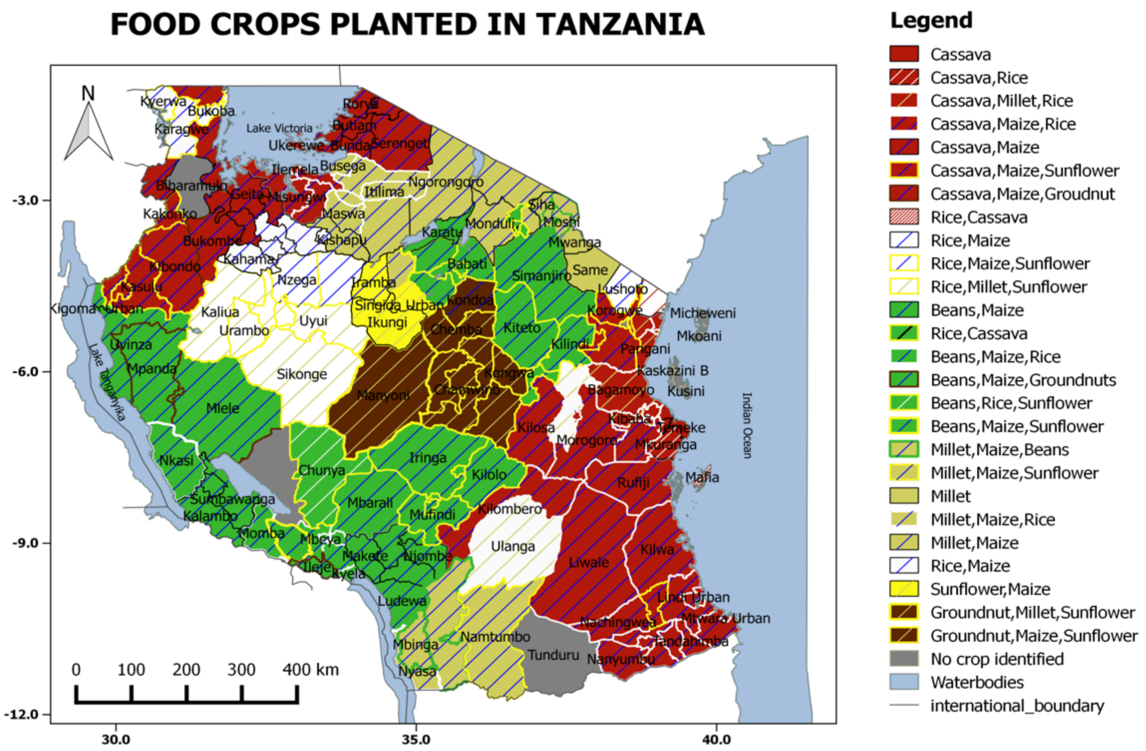

Figure 26: Provinces in Tanzania (left), with Kibaha province highlighted in yellow, and expanded on the right.

3.5 Case Study 5

Background

The infrastructure sector in Tanzania has been identified as a suitable case study to produce users'-relevant climate change information. The case study started with a focus on the ongoing Standard Gauge Railway (SGR) project, with the contribution of COWI, the engineering company responsible for the design of the first section of the railway (Dar es Salaam – Morogoro). The initial discussion identified potential hazards from changes in temperature and precipitation in the future climate, highlighting a series of climate-related risks which would be worth investigating. The natural context for this activity would be an assessment of existing design values for infrastructure planning. For the SGR project, extreme peak discharge indices were identified as the main targets for the initial phase of this activity and a useful starting point for a climate service case study. In addition, an initial engagement with the Institute of Engineers Tanzania (IET) also highlighted increased risks due to changing temperature and expected increase in heatwave. The initial planning of this case study involved estimates for peak discharges and relevant heatwave indices with COWI and IET as potential users.

During the stakeholder engagement mission in Tanzania (9th-13th May 2022), the CS 5 team, together with TMA, visited Prof. Pius Yanda at the Institute of Resource Assessment (IRA) of the University of Dar es Salaam (UDSM) to discuss climate services for infrastructure in Tanzania. Prof. Yanda provided useful recommendations about the use climate change information in the context of the planning and construction of the SGR. He also provided an example of Jangwani bridge in Dar es Salaam Tanzania that was built without considering climate change and now during rainy periods the bridge is flooded, with severe effects to transportations and communications.

Table 12: Information about the user requirements for the trial climate service in Case Study 5

User	User requirements	Sector indicators	Input
Primary users: Infrastructure planners and designers	1. Changes in peak discharges for different return periods for river catchments 2. Changes in heatwaves indices relevant for structural damages and health and safety risks.	Prolonged lifetime of structures when climate change adaptation has been considered.	Gridded climate data for target adaptation scenarios, including estimates of projection uncertainty
Construction management	Estimates number of wet days on seasonal base for present and future climate	Cost-saving estimates	Gridded climate data for target adaptation scenarios, including estimates of projection uncertainty
Other potential users: Governmental Institutions	Climate change projections of main meteorological variables and commonly used climatic indices	Improved strategic planning	Gridded climate data for target adaptation scenarios, including estimates of projection uncertainty

Current status of the trial climate service co-production

With the withdrawal of COWI from this project, there has been a considerable effort by TMA to find alternative users. On hydrological extremes, the Ministry of Water has relevant expertise in flood modelling capabilities, an ongoing collaboration with TMA and has shown an interest in discussing the possibility of getting involved in this project. The current discussion with the Ministry of Water, led by TMA, is aimed at understanding whether current flood modelling capabilities can be adapted to study climate change by using rainfall from climate model projection. In addition, TMA has also included the Association of Consulting Engineers Tanzania (ACET) as a potential case study end user. Their interest is also in changes in peak discharge at all time scales, already an issue in the current planning which could potentially exacerbated in the future climate, with impacts on transport and urban infrastructures coming from very intense, short-lived extremes (e.g., flash floods in urban areas) or less intense, more widespread events leading to river floods in bigger catchments. There has also been a discussion on the potential usefulness of wet day forecasts in current practices in construction works.

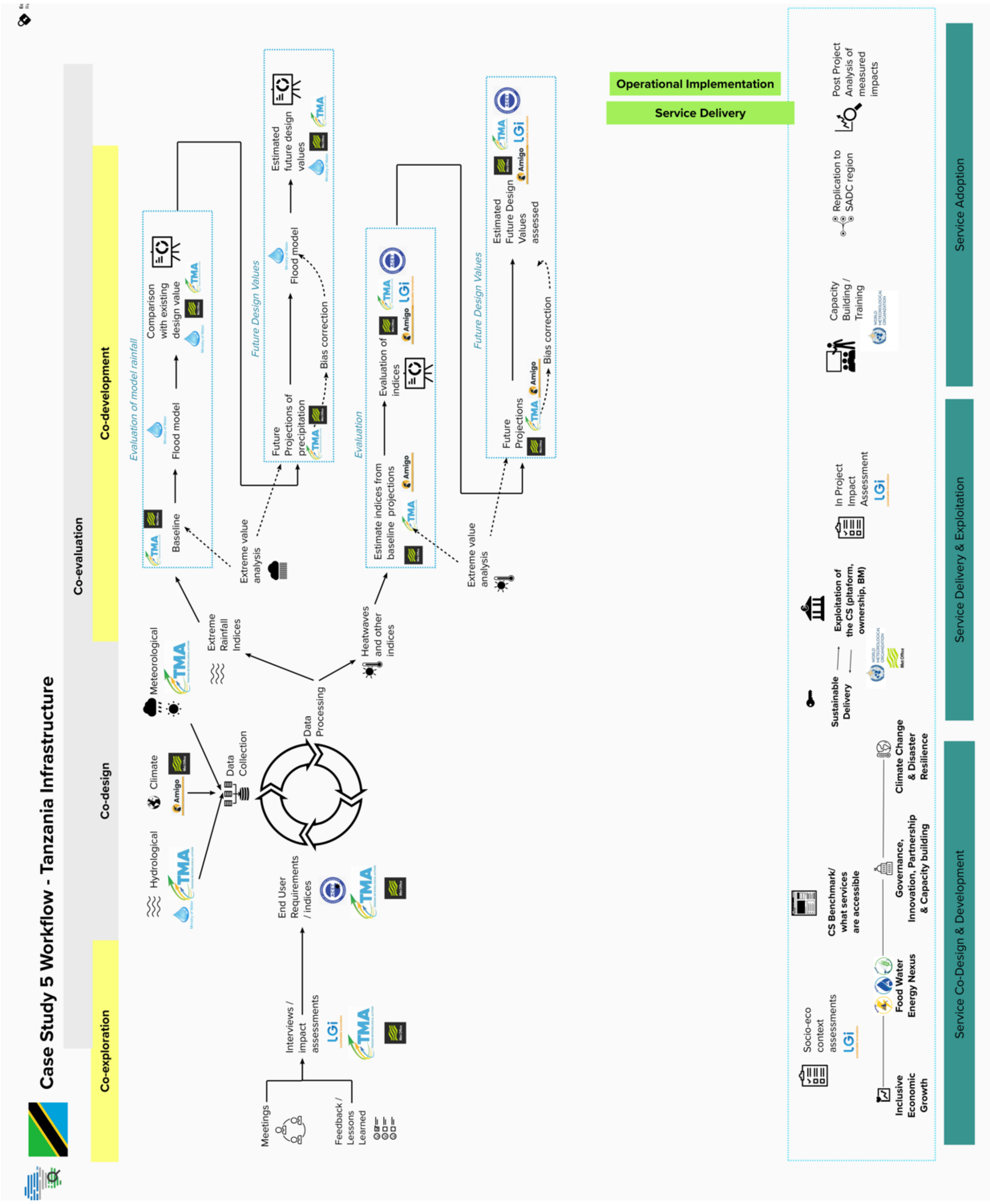

Figure 27: Expected workflow of the climate service development for Case Study 5

It is not clear whether these risks have already been captured in suitable indices from current practices in infrastructure design, ongoing discussions with potential users will be helpful to understand this issue and in defining suitable indices for risks not yet standardised which will be able to capture the changing hazard under climate change. For this purpose, the CS5 team is currently planning a mission to Tanzania, with the hope of resolving this issue and potentially involving the Ministry of Water and ACET as an integral part of this case study.

Next steps

At the present stage, the existing CS5 workflow assumes the active involvement of these users, in a two-step engagement which involves evaluation of indices from climate projections under the historical scenario, which will help to understand climate model skill and potentially highlight the need of bias correction, and a second step which will produce climate projections of these indices in a format suitable for users needs (e.g., climate change factors, bias-corrected time series for impact studies, etc.). Both these steps rely on the expertise in Tanzanian climate and the availability of local observational dataset from TMA. The second mission to Tanzania is aimed at discussing their engagement. Since it cannot be ruled out the possibility of their limited involvement in this case study, a backup plan will have to be discussed between FOCUS-Africa, with the crucial support of TMA, to adapt relevant meteorological indices to the study of the design and maintenance of infrastructure in Tanzania.

In addition, TMA have shown an interest in getting more detailed information on existing climate projections of standard meteorological variables: as this information is available from the climate projection activities in WP3 and WP4, there is also the possibility of extracting relevant information from these WPs. The CS5 team has also started a discussion on users' training, prompted by the discussion with ACET, potentially linked with other case studies in the region and with the climate projection work in WP3 and WP4.

3.6 Case Study 6

Background

The focus of this case study is the development of a trial climate service for hydropower generation and for the estimation of the potential of future wind and solar resource. The main user is the government-controlled energy company known as Tanzania Electric Supply Company Limited (TANESCO). However, discussions with another user, TotalEnergies, have been held too (see **Table 13**).

Tanzania heavily relies on hydropower, which is projected to be increasingly exposed to large climate fluctuations. The electricity produced is used in various activities, including industrial operations, hospitals, domestic uses, schools, offices, sports and entertainment, etc. Production and supply of electricity in Tanzania is under TANESCO, which owns six operating hydroelectric power plants (Nyumba ya Mungu, New Pangani, Hale, Mtera, Kidatu and Kihansi) and is responsible for electricity generation and supply over the country. In addition to those six hydroelectric power plants, TANESCO owned other power plants currently under construction, including the Julius Nyerere Hydroelectric power plant, which is expected to produce more electricity than all six operating hydroelectric power plants combined.

Hydroelectric power is greatly affected by climate variability and change, significantly the increase in periods of droughts and heavy rains that affect the production and supply of electricity, respectively. For instance, prolonged severe droughts have been the primary cause of the reduction of water for hydroelectric production; power cuts have been common in the country (Magreth, 2019). Furthermore, the impacts of climate variability and change on hydroelectric power resulted in Tanzania reducing its dependence on hydroelectric power from 96% in 2003 to 34% in 2015 (USAID-IRRP, 2019).

While hydropower is currently the largest source of renewable electricity in Tanzania, solar and wind power are projected to provide significant generation capacity to support the country economic development. There are significant climate challenges, however, with developing additional renewable energy capacity:

- Annual and inter-annual variability of the climate can lead to energy shortages, and limitation in generation capacity
- The current energy mix has a significant dependency on reservoir fed hydropower
- Droughts (i.e. 2006, 2011) reduce the availability of water in reservoirs and increase the pressure on using available water for agriculture and sanitation
- Climate change may increase the frequency of climate conditions that impact power generation, livelihoods, health and wellbeing

Through a series of elicitation meetings, including a face-to-face meeting during the mission in Dar Es Salaam in May 2022, the CS 6 team was able to collect the information regarding the specifics of the trial climate service, including the data required to produce the tools constituting the service. Some of the questions that were asked as part of the elicitation process are:

- What are TANESCOs existing tools or hydrological models used to manage hydropower production in Tanzania?
- Who are the TANESCO staff responsible to use these tools and communicate weather/climate/hydro information to the hydropower assets managers?
- What type of weather/climate data (in-situ observations, forecasts) are currently used in these tools or communicated directly to asset managers?
- What is the source of the required weather data (TMA, public domain)?
- What challenges are experienced by TANESCO with the current use of weather/climate data and internal hydrological tools/models?

- What are TANESCO's desired improvements for these data and tools?
- How does climate variability affect TANESCO's renewable power generation and development plans?
- In terms of climate services for renewables development planning, what are TANESCO's plans in terms of investment in future hydro, wind, solar power?

Based on the information collected, the practical targets of the CS 6 trial climate service thus are (see also **Table 14**):

- Co-production, with climate service user TANESCO (and TotalEnergies) and climate services providers WEMC and TMA, for development planning, assets' operation and associated hydropower production forecast tools
- Climate services for renewables development planning to:
    - Identify and analyse historical datasets to produce reliable climatology maps and long-term statistics
    - Analyse most recent future climate projections and evaluate the potential impact on renewable energy production
- Climate services for support of renewables' assets operations to:
    - Develop site- and area-specific seasonal predictions of rainfall, including onset, cessation and duration of rainfall for hydropower
    - Develop a statistical model for hydropower production for the TANESCO plants for which local data are available
    - Incorporate seasonal forecast data into the hydropower statistical model to predict the generation of reservoir-fed and run-of-river hydropower stations up to a few months ahead
    - Incorporate climate projections data into the hydropower statistical model to estimate impacts on reservoir-fed and run-of-river hydropower stations

Table 13: Climate service users in Case Study 6 and their information requirements

User	Information Requirements
TANESCO	Estimation of climate-driven variability in hydropower generation and an estimation of wind and solar power resources based on historical and projection climate data.
TotalEnergies	Estimation of wind and solar power resources based on historical and projection climate data to support their long term plans. However, their planning is still at preliminary stages (as of May 2022); the feasibility of a trial climate service for this application would need to be further discussed

Data requirements and workflow

TANESCO explained their goals. Namely, they want to improve the way they manage hydropower generation, by making use of climate data in a systematic and quantitative way. Indeed, currently TANESCO does not have a hydropower model that accounts for climate variables, and water resources are managed based on bulletins which provide large scale (therefore not specific to individual power plants) seasonal climate outlooks. TANESCO also highlighted some of the challenges they face in terms of hydropower data. Collection of data is normally done manually and sometimes this leads to delay in data transfer (ideally, they would need automatic gauging stations for collection of data); delays are exacerbated also by occasionally faulty data loggers. However, there are sufficient data to train hydropower generation models for each of the plants, and TANESCO was eventually able to make these data available for exclusive use by the project.

Table 14: Information about the data required for the Case Study 6 trial climate service

Model	Spatial and temporal Resolutions	Time Periods of Interest	Input Data Requirements	Sources of Input Data	Relevant Model Output Variables / Indicators
Hydropower generation	Space: Catchment area (climate data, from observations, satellite and model output to be aggregated at catchment level prior to computation of power output) Time-step: monthly, and possibly weekly	2012-2021 (based on available observed data, to build a baseline) Predictions a few months ahead Projections over next decades (e.g. 2040-2080)	Climate (daily, but used as monthly, or weekly, averages): - rainfall - air temperature Hydropower plant: - inflow - river discharge - reservoir level - water spill	Climate (see also **Table 16**): - observed station TMA's propriety data - satellite derived (e.g. CHIRPS) - reanalyses - climate models for seasonal forecasts - climate models for projections Hydropower plant: - TANESCO's propriety data	- Hydropower generation, including capacity factor for future (decades) estimates - Onset, cessation, and accumulated precipitation of rainy seasons
Simple conversion models of climate data into Wind and Solar Power Capacity Factors	Space: - Under assessment (e.g. based on ERA5 grid) Time-step: - Monthly - Daily for selected output (for extreme analysis assessment)	1991-2020 (baseline) 2030-2070 (future)	Climate (monthly, and daily): - air temperature - 10m wind speed (to be converted to higher elevations) - downward solar radiation	Climate: - ERA5 reanalysis - modelled (CMIP6, possibly CORDEX-CORE)	Wind and Solar Power Capacity Factors

For completeness, and as mentioned above, another user, TotalEnergies, was also consulted for the possible development of an additional trial climate service related to the assessment of wind and solar power resource potential. However, as little information on requirements for such a trial climate service has been provided thus far, no work could be performed, and all the project team effort was therefore placed on the trial climate service for TANESCO. Nonetheless, we agreed with TotalEnergies that updates on their status will be provided later in the project to ascertain whether there is still scope for the co-production of a service within the lifetime of FOCUS-Africa.

Thus, to address the CS 6 targets, the team aims to implement a hydropower model that will support hydroelectric power generation considering climate variability, change, and projection scenarios. This hydropower model requires input climate data (rainfall and temperature), and ideally water inflow, as predictors. The predictand is hydropower generation data. The Tanzania Meteorological Authority (TMA) is the custodian of climate data in Tanzania and owns around 48 synoptic and agro-meteorological stations and more than 2000 rainfall stations. Furthermore, most of those stations are operating manually and are scattered around the country. However, some automatic weather stations have been installed but their record duration is not sufficiently long for climate studies. In the study area (catchment area of each hydroelectric power plant), there are a few meteorological stations (**see Table 15**). As some of them present considerable gaps, satellite-based or reanalysis datasets have been used as the main input for the development of our models. More specifically, following an extensive assessment of these data against the available station observations, satellite-based data have been used for precipitation and reanalysis data for air temperature. Hydropower related data for the six hydropower plants were provided by TANESCO. These data include: water inflow, river discharge, reservoir level, water spill (**see also Table 14**). Even in this case there are numerous gaps (see data assessment below), but their overall quality is sufficient to train the statistical hydropower model.

As for other variables (mainly wind speed and solar radiation), which are needed for the estimation of wind and solar power resource potential, the reference will be ERA5 reanalysis data.

Table 15: List of meteorological stations used and their corresponding hydropower plant

<table>
<tr><th>Met Station name</th><th>Longitude</th><th>Latitude</th><th>Hydropower plants</th></tr>
<tr><td>Dodoma</td><td>35.767</td><td>-6.167</td><td rowspan="3">Mtera
Kidatu</td></tr>
<tr><td>Singida</td><td>34.717</td><td>-4.8</td></tr>
<tr><td>Iringa</td><td>35.767</td><td>-7.633</td></tr>
<tr><td>Igeri</td><td>34.667</td><td>-9.667</td><td>Kihansi</td></tr>
<tr><td>Moshi</td><td>37.333</td><td>-3.35</td><td rowspan="3">Nyumba ya Mungu</td></tr>
<tr><td>KIA</td><td>37.067</td><td>-3.417</td></tr>
<tr><td>Arusha</td><td>36.633</td><td>-3.367</td></tr>
<tr><td>Same</td><td>37.733</td><td>-4.083</td><td rowspan="2">Hale
New Pangani</td></tr>
<tr><td>Handeni</td><td>38.033</td><td>-5.433</td></tr>
</table>

Table 16: List of satellite and reanalysis datasets and their main characteristics

Data Source	Data Type	Spatial Resolution	Temporal Resolution	Data Availability	Coverage
CHIRPS	Satellite-based	0.05^0 x 0.05^0	daily	1981 to present	Quasi-Global
MSWEP	Satellite-based	0.1^0 x 0.1^0	3 Hourly	1979 to present	Global
GPCC	Satellite-based	0.25^0 x 0.25^0	Monthly	1891 to present	Global
TAMSAT	Satellite-based	0.25^0 x 0.25^0	Daily	1983 to present	Africa
CHIRTS	Satellite-based	0.05^0 x 0.05^0	Daily	1983 to 2016	Quasi-Global
ERA5	Reanalysis	0.25^0 x 0.25^0	Hourly	1979 to present	Global
ERA5-Land	Reanalysis	0.1^0 x 0.1^0	Hourly	1979 to present	Global
MERRA-2	Reanalysis	0.5^0 x 0.625^0	Daily	1980 to present	Global

The preparation of input data for the hydropower model was a co-design activity. This was achieved through regular interactions, particularly between WEMC, TMA and TANESCO. The results of each step, from the data collection to their assessment were shared in a monthly technical meeting via Microsoft Teams, bringing together the service developers and providers (WEMC and TMA), the research partners (MO) and the climate service user (TANESCO), and are described in some detail in **Figure 28**.

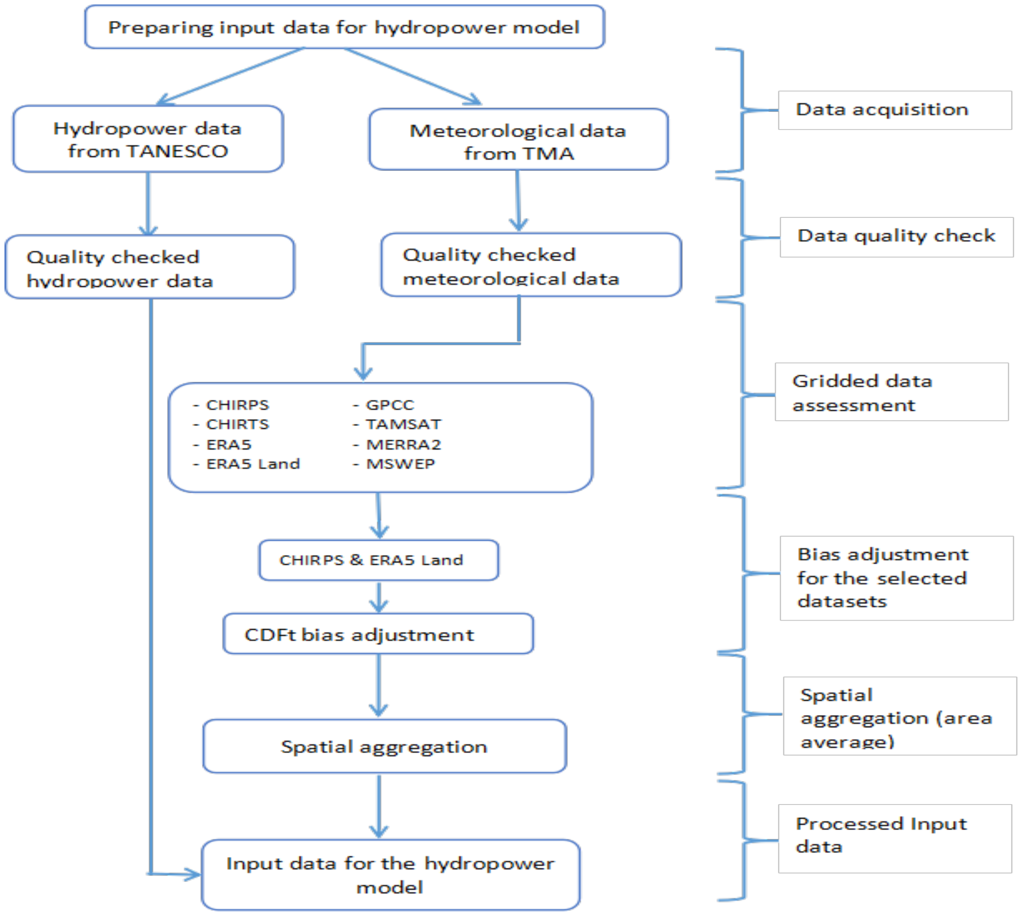

Figure 28: Workflow for the processing of the data for the hydropower model

The workflow in **Figure 28** is part of the overall CS6 workflow representing the various co-production activities of the trial climate service, from co-exploration to delivery (**Figure 29**). The main user of the climate service, TANESCO, is central to the case study development. Accordingly, their inputs to the climate service development are indicated in all the activities. The processes of assessing user requirements, design of the service, co-development, co-evaluation and delivery of the service are represented from left to right in the top half of the diagram. Included in the workflow are also activities related to the socioeconomic context (as conducted in WP6), the impact of the climate service, scalability and replicability of the service and potential for broader exploitation (all represented in the lower half of the diagram). Feedback loops to the design phase of the climate service are also represented to allow for refinements to the design to be made.

Current status of the trial climate service co-production

Six hydropower plants were used in this study (see **Table 17**). While in Tanzania there are a total of 13 hydropower plants and 76 catchment areas suitable for establishing new small hydropower plants (Mdee et al. 2018), the six used were the main ones with the longest records for analysis. The hydropower plants used in this study were also used in other studies (Kichonge, 2018) describing Tanzania's hydropower. The Tanzania hydrological system is categorized into nine hydrological basins (Pangani, Wami/Ruvu, Rufiji, Ruvuma, Lake Nyasa, Internal drainage, lake Victoria, Lake Tanganyika, and lake Rukwa basin). The six selected hydropower plants are located in two large basins. Three (Pangani, Hale and Nyumba ya Mungu) are located in the Pangani basin while the other three (Mtera, Kidatu and Kihansi) are located in the Rufiji basin (**Figure 30**).

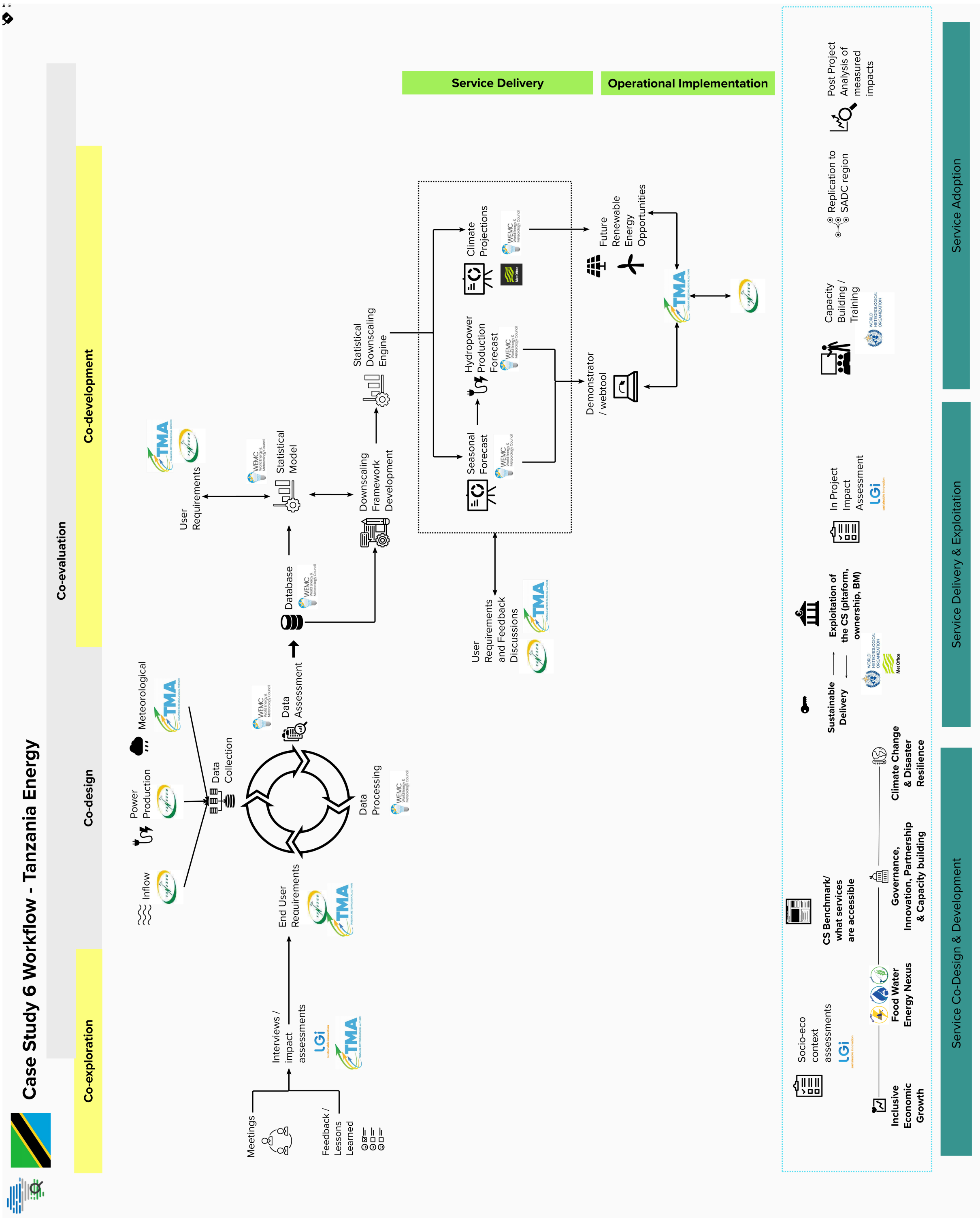

Figure 29: Workflow of the climate service development for Case Study 6

Within the six selected hydropower plants, only two are run-of-river (Hale and Kihansi), while the remaining are reservoir based. They also differ in installed capacities and their annual contribution to Tanzania's electricity generation (**Table 17**, see also World Bank, 2018). Kidatu has the highest installed capacity (204 MW), while Nyumba ya Mungu has the lowest installed capacity (8 MW). The largest annual contribution is given by the Kihansi plant, with its 793.49 GWh, given its relatively high performance (50% efficiency factor). In contrast, Nyumba ya Mungu has the lowest contribution of 21.53GW to Tanzania's annual electricity generation.

Table 17: Main characteristics of hydropower plants (see also their locations in Figure 30)

Hydropower plant	Generation type	Latitude	Longitude	Installed capacity (MW)	Annual generation (GWh)	Plant factor/ performance (%)
Kidatu (KDT)	Reservoir	-7.637	36.887	204	558.34	31
Kihansi (KHI)	Run-of River	-8.575	35.851	180	793.49	50
Mtera (MTR)	Reservoir	-7.136	35.987	80	166.68	24
New Pangani (NPF)	Reservoir	-5.349	38.650	68	137.2	23
Hale (HAL)	Run-of River	-5.298	38.604	21	36.11	20
Nyumba ya mungu (NPY)	Reservoir	-3.826	37.469	8	21.53	31

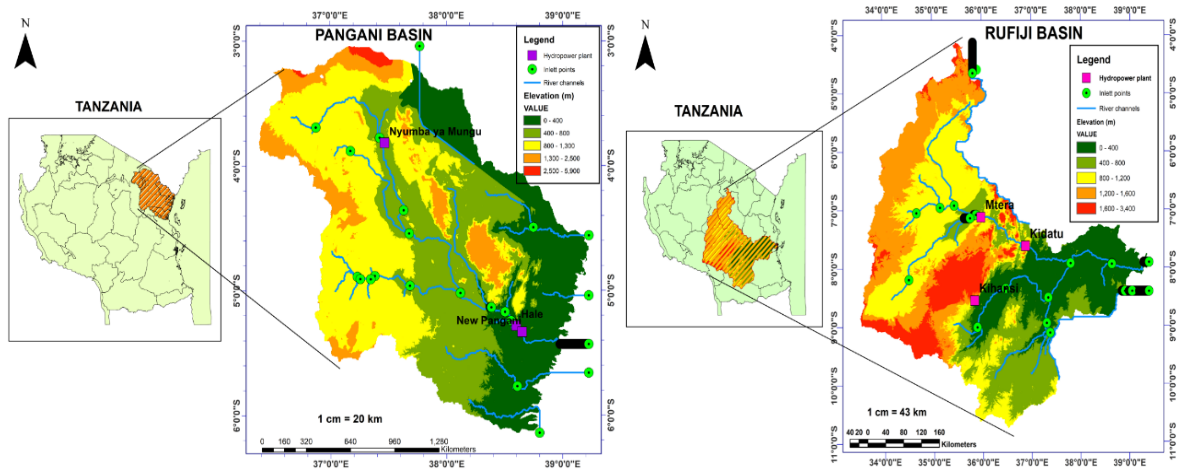

Figure 30: Location of hydropower plants in their respective basin: Pangani basin (left), Rufiji basin (right).

In view of the preparation of the hydropower model, it is critical to assess the available climate and hydropower data to be used for the training of the model. The data required for the model's training are hydropower generation data and climate data (precipitation and temperature). The hydropower generation data were obtained from TANESCO (hydropower plants owner), while the *in situ* precipitation and temperature data were obtained from the TMA (Meteorological station owner). The hydropower generation data for six hydropower plants over a period of 12 years (2010 to 2021) were used in this study. The precipitation and temperature data are essential in the hydropower model since they are the main predictors of hydropower generation. Not only do the data at the time of the production are needed, also their aggregated values over a period of up to one year is considered to account for effects such as water accumulation. As a result several monthly (or weekly) accumulated data lags are used, which are therefore used as additional predictors to the hydropower model. Through watershed delineation, nine meteorological stations were found to be the best representatives of precipitation and temperature that influenced the amount of water in the catchment area of each hydropower plant (**Figure 30**). A period of 14 years (2008 to 2021) of precipitation and temperature data from 9 meteorological stations were used in this study (**Table 15**).

Seven gridded datasets were assessed in this work to select the best representatives of precipitation and temperature station data, by comparing them with the TMA's station data. Those datasets are CHIRTS, CHIRPS, MSWEP, GPCC, TANSAT, ERA5, ERA5 Land and MERRA2 (see **Table 16**). The same datasets are also used in various studies, including Parsons D. et al. (2022), Berck H., et al. (2019), which we used to cross check our results. CHIRTS and CHIRPS have a higher spatial resolution (0.05^0 x 0.05^0) than the other datasets considered.

To compare the gridded data with station measurements, the data from the nearest grid point to each station were extracted from each gridded dataset. The precipitation, minimum and maximum temperature used were at monthly temporal resolution and the three metrics used for the assessment are the standard measures, namely Bias, Pearson correlation, and Root Mean Square Error (RMSE).

Figure 31 shows the annual precipitation, minimum, and maximum temperature cycle. For the stations located in the Pangani basin (Arusha, KIA, Moshi, Same and Handeni). Their precipitation peaks in April, while the highest maximum temperature is observed to be higher in February. Stations in the Rufiji basin (Igeri, Dodoma, Singida, and Iringa), most of their precipitation peaks in December except for Igeri, for which the the peak is in March, and Iringa (in January). Also, the minimum temperature of all meteorological stations was observed to be lower in June, July, and August. In addition, all stations in the Pangani basins exhibit bimodal rainfall seasons; one which typically starts within the October to December (OND) season, and the other which starts in March to May (MAM). Instead, stations in the Rufiji basin exhibit unimodal rainfall season, which typically starts around November and ends in April of the following year (NDJFMA), as described in **Figure 31**.

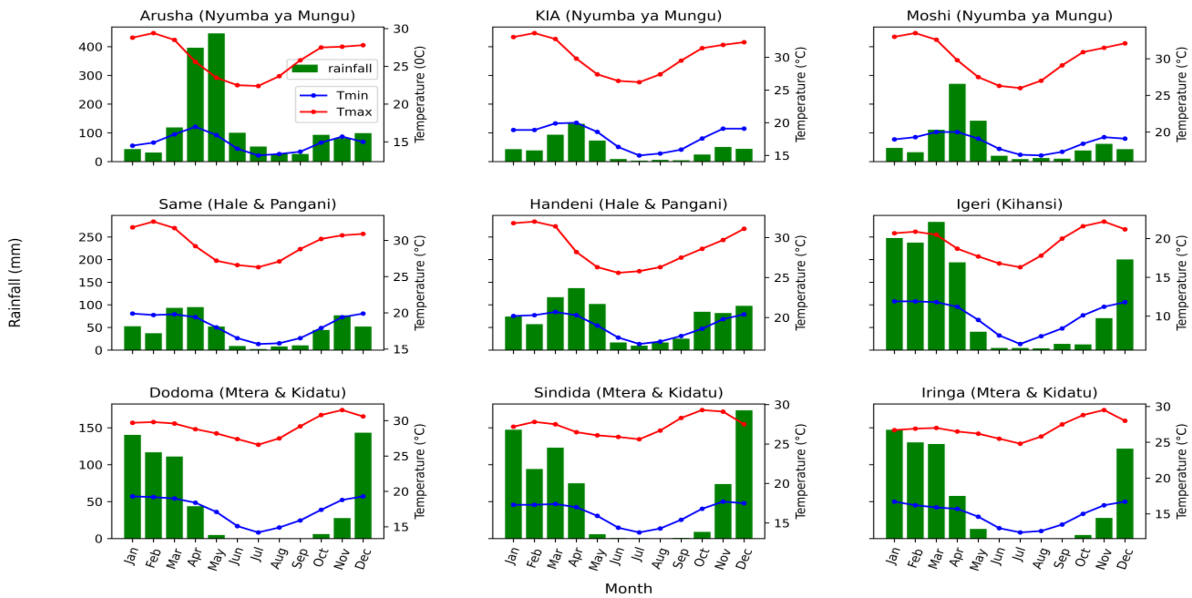

Figure 31: Annual cycle of Rainfall, minimum and maximum temperature from the period of 14 years (2008 to 2021).

Comparison of precipitation gridded data to station measurements were made by considering the Pearson correlation, bias, and the Root Mean Square Error (RMSE) as described in **Table 18, 19, and 20**, respectively. MSWEP and CHIRPS datasets for all meteorological stations used in the study were found to have a higher correlation ($r >= 0.77$) than other datasets. The higher performance of CHIRPS and MSWEP was also captured in other studies (e.g. Berck et al., 2019). In addition, four datasets were observed to have the lowest correlation in Moshi meteorological station, and this includes MSWEP, ERA5, ERA5 Land and TAMSAT, with a correlation of 0.78, 0.55, 0.49 and 0.52, respectively which is comparatively lower to that of other stations.

The results from the RMSE show that the MSWEP dataset had the lowest values compared to other datasets. The MSWEP dominates in seven meteorological stations out of 9. The lowest RMSE of MSWEP was also captured in the study of Berck et al. (2019). In addition, the CHIRPS was found to have the second lowest RMSE, after MSWEP. On the other hand, ERA5 and ERA5 Land were found to have a higher RMSE (RMSE >100), especially for the KIA, Moshi, and Igeri meteorological stations. Considering the overall performance, and also the fact that CHIRPS has a higher resolution than MSWEP (0.05^0 x 0.05^0 vs 0.1^0 x 0.1^0) which can in principle be exploited, CHIRPS was selected as our reference dataset for precipitation for ensuing studies.

The comparison of minimum and maximum temperature gridded data to station measurement was done as for precipitation by considering the Pearson correlation, Bias, and RMSE (see **Table 21, 22, and 23**, respectively). The ERA5 had a higher correlation in many stations, 7 out of 9 (r >= 0.82) followed by the ERA5 Land, which dominates 4 stations out of 9 (r >= 0.75). On the other hand, CHIRTS was found to have a higher correlation for maximum temperature, performing best in six stations out of 9 (r >= 0.91), followed by ERA5, with the same number of stations of 6 out of 9 (r >= 0.88). The best performance of CHIRTS at maximum temperature and lower at minimum temperature was also captured in Parsons et al. (2022).

Despite ERA5 Land having a lower correlation in comparison to ERA5 and CHIRTS in both minimum and maximum temperature, it has the lowest RMSE in minimum temperature in comparison to other datasets, in 5 stations out of 9. CHIRTS continue to be the best performer in maximum temperature with the lowest RMSE that dominates in 5 stations out of 9 (RMSE <= 0.96).

Overall, while CHIRTS was the best performer in maximum it showed poor results in minimum temperature compared to the other available datasets. ERA5 Land was observed to have a lower RMSE, especially at minimum temperature and in some of the stations at maximum temperature. Considering also that CHIRTS production stopped in 2016, ERA5 Land was selected to represent the temperature data of station measurements for our work.

Next Steps

The hydropower statistical model will be developed using the precipitation data from CHIRPS and the temperature data from ERA5 Land as predictors of the model. Other predictors will also be considered, including water inflow data, as provided by TANESCO. The hydropower model will then be used in conjunction with seasonal climate forecasts to produce outlooks of power generation a few months ahead. Similarly, the model will be applied to climate projections to provide an assessment of future resource variability and extremes in hydropower generation.

Work will also start on the assessment of the wind and solar power resources over the next decades, exploring downscaled projection data especially from CMIP6 models. This assessment will also include the evaluation of changes in trends, variability and possibly on extremes.

Discussions with TANESCO around delivery methods for the trial climate service will look at various options (data transfer only, visualization on a web platform, bulletins, etc.) and eventually agree on the most suitable approach. Training will always be part of the delivery.

Table 18: Pearson correlation of precipitation between seven gridded datasets and the station data at nine locations

Station	CHIRPS	MSWEP	ERA5	ERA5 Land	GPCC	TAMSAT	MERRA2
Arusha	0.81	0.80	0.76	0.77	**0.82**	0.58	0.71
KIA	**0.86**	0.83	0.63	0.67	0.82	0.76	0.80
Moshi	**0.81**	0.78	0.55	0.49	0.79	0.52	0.68
Handeni	0.77	0.78	**0.79**	0.78	0.57	0.61	0.72
Same	0.80	**0.83**	0.66	0.71	0.70	0.69	0.60
Igeri	**0.89**	0.88	0.87	0.87	0.88	0.81	0.81
Dodoma	0.90	0.87	0.84	0.83	**0.98**	0.87	0.93
Singida	0.89	**0.92**	0.89	0.90	0.89	0.87	0.80
Iringa	0.92	0.93	0.87	0.90	**0.95**	0.89	0.88

Table 19: As in Table 18 but for precipitation bias (mm).

Station	CHIRPS	MSWEP	ERA5	ERA5 Land	GPCC	TAMSAT	MERRA2
Arusha	1.23	0.99	1.14	1.03	1.20	**0.83**	1.07
KIA	1.04	1.34	3.03	2.55	1.91	**0.94**	1.72
Moshi	1.42	1.22	1.90	2.60	1.44	**0.98**	0.90
Handeni	1.26	1.20	1.64	1.48	1.18	**0.67**	1.94
Same	1.30	1.28	0.91	1.07	1.01	**0.80**	1.58
Igeri	**0.80**	0.92	1.47	1.47	0.89	0.83	1.35
Dodoma	1.13	1.01	0.89	**0.84**	1.03	1.08	1.34
Singida	1.02	0.95	**0.91**	0.95	1.02	0.98	1.32
Iringa	1.00	1.03	1.02	1.17	1.13	**0.98**	1.70

Table 20: As in Table 18 but for precipitation RMSE (mm/month).

Station	CHIRPS	MSWEP	ERA5	ERA5 Land	GPCC	TAMSAT	MERRA2
Arusha	65.17	**51.50**	55.89	54.36	53.14	76.25	61.48
KIA	**30.26**	37.99	131.51	102.02	66.93	39.42	54.43
Moshi	72.37	**61.75**	115.65	120.78	66.78	89.51	71.10
Handeni	50.69	**40.96**	59.13	51.39	72.76	53.56	98.57
Same	45.01	**39.03**	49.79	46.84	47.02	48.81	64.43
Igeri	62.55	**60.76**	115.85	112.45	61.05	76.61	113.93
Dodoma	32.40	34.71	38.79	40.32	**15.54**	35.15	34.48
Singida	34.82	**29.99**	35.19	33.43	34.12	36.59	52.01
Iringa	26.78	**26.14**	34.26	33.32	25.80	32.31	69.17

Table 21: Minimum and maximum temperature correlation between gridded datasets and the station data at nine locations.

	Minimum temperature				Maximum temperature			
Station	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**
Arusha	0.75	**0.82**	0.75	0.64	**0.98**	**0.98**	**0.98**	0.91
KIA	**0.92**	**0.92**	0.91	0.89	**0.99**	0.88	0.96	0.90
Moshi	0.83	**0.88**	0.85	0.81	**0.95**	**0.95**	0.94	0.88
Handeni	0.93	0.98	**0.97**	0.94	**0.97**	**0.97**	**0.97**	0.83
Same	0.96	**0.97**	**0.97**	0.96	0.97	**0.98**	0.96	0.90
Igeri	0.91	**0.93**	**0.93**	0.92	0.96	**0.97**	0.94	0.82
Dodoma	0.97	**0.99**	0.98	0.97	**0.97**	0.94	0.89	0.72
Singida	0.93	0.98	0.98	0.98	**0.91**	0.90	0.86	0.86
Iringa	0.94	**0.95**	**0.95**	0.94	0.92	**0.96**	0.92	0.75

Table 22: As in Table 21 but for Temperature bias (deg C).

	Minimum temperature				Maximum temperature			
Station	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**
Arusha	1.16	**0.92**	1.03	1.10	1.06	**0.92**	0.98	1.11
KIA	1.15	0.99	0.93	**0.91**	1.00	0.93	**0.85**	0.95
Moshi	1.14	**0.70**	0.93	0.94	1.01	**0.73**	0.86	1.04
Handeni	1.03	**0.99**	1.00	**0.99**	1.00	**0.95**	**0.95**	1.01
Same	1.07	1.01	1.00	**0.95**	1.02	0.97	**0.95**	0.99
Igeri	1.45	1.30	**1.23**	1.29	1.22	**0.83**	1.09	1.20
Dodoma	1.03	1.04	0.97	**0.94**	1.00	1.01	**0.97**	1.02
Singida	1.03	0.99	0.98	0.89	1.00	0.97	**0.96**	0.99
Iringa	1.02	**0.96**	1.05	1.09	0.96	**0.88**	0.95	1.05

Table 23: As in Table 21 but for Temperature RMSE (deg C).

	Minimum temperature				Maximum temperature			
Station	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**	**CHIRTS**	**ERA5**	**ERA5 Land**	**MERRA2**
Arusha	2.70	1.59	**1.25**	1.94	1.60	2.32	**0.69**	2.96
KIA	2.75	**0.69**	1.38	1.71	**0.40**	2.29	5.64	1.91
Moshi	2.66	5.85	1.38	**1.31**	**0.96**	8.46	4.43	1.83
Handen	1.04	0.46	**0.42**	0.70	**0.67**	1.55	1.72	1.40
Same	1.37	0.44	**0.41**	0.93	**0.77**	0.93	1.56	1.35
Igeri	4.60	3.14	**2.40**	3.05	4.35	2.66	**1.93**	4.12
Dodom	0.82	0.70	**0.59**	1.04	**0.46**	0.56	1.20	1.56
Singida	0.67	0.32	0.41	1.73	0.60	0.96	1.32	0.84
Iringa	1.04	0.62	0.82	1.30	1.26	3.2	1.59	2.07

3.7 Case Study 7

Background

Case study 7 (CS7) aims at assessing future changes in the hydrological cycle of the Shire River catchment to evaluate the sustainability of the hydro-power resources. CS7 is built on a collaboration between EDF, UCT (University of Cape Town), WITS (University of the Witwatersrand, Johannesburg), DCCMS (the Malawi Department of Climate and Meteorological Services) and WEMC (World Energy and Meteorology Council) teams. EDF, UCT and WITS are in charge of developing and/or applying downscaling approaches to the CMIP6 projections in a format relevant to the hydrological model. The downscaled projections are then used by DCCMS to produce future hydrological projections for the whole Shire River catchment system: the upstream Lake Malawi catchment streamflow, the Lake Malawi water level and the Shire River catchment downstream Lake Malawi. These projections will be used to simulate future hydro-power resources for existing and future hydro-power installations. The whole set of data produced in this work will then be integrated into a Climate Service developed to inform local users across different water use sectors (see the diagram of the workflow).

Current status of the trial climate service co-production

<u>Climate model evaluation</u>

A first study was carried out by EDF to evaluate the CMIP6 historical simulations against different sets of observation databases and analyze the CMIP6 projections in terms of future trends in precipitation and temperature across the country. An ensemble of 41 CMIP6 climate models were evaluated across Malawi. The models were selected based on their availability in terms of climate variable (Pr, Tas, Tos) and scenarios (SSP2-4.5, SSP5-8.5 and historical). They were evaluated based on their representation of three variables:

- The Niño 3.4 index based on sea surface temperature anomalies (tos)
- Precipitation (pr)
- Near-surface temperature (tas)

Precipitations were evaluated against a range of datasets: CHIRPS, CRU, GPCC and gridded station data from the Malawi's met-service DCCMS. Near-surface temperature was evaluated using the CRU dataset. The Niño 3.4 index was computed as the spatial average of sea surface temperature anomaly across the 5N-5S, 170W-120W domain.

Overall, the CMIP6 models overestimate the number of el Niño extreme events, i.e., belonging to the strong and the very strong classes. The CMIP6 ensemble mean follows fairly the observed temperature and precipitations annual cycle. However, some models display very warm bias such as MIROC6, KACE and CESM2 while others show a cold bias such as INM-CM4 and INM-CM5, AWI-ESM, NESM3 and NorCMP1. In addition, in terms of precipitations the ensemble range is very large during the wet season. Moreover, the observed east-west spatial gradient for both variables is well simulated by most of the CMIP6 models, mainly those with higher spatial resolution such as HadGEM3, MPI-ESM1, CNRM-CM6-1-HR, EC-Earth3 and HadGEM3-GC31-MM.

Temperature projections show an increasing trend along the 21st century, with a higher increase for SSP5-8.5 of up to +8°C by the end of the century. Raw projections would induce mean annual temperature levels by 24°C against 22°C in the late 1990s for SSP2-4.5, and above 26°C for SSP5-8.5 (see **Figure 32**). Changes in annual precipitation show a north-south gradient for some models (wetter north and drier south). For SSP5-8.5 the monthly precipitation cycle shows a slight increase in winter (January to March) and a slight decrease in autumn (September to November) particularly by the end of the century (see **Figure 33**).

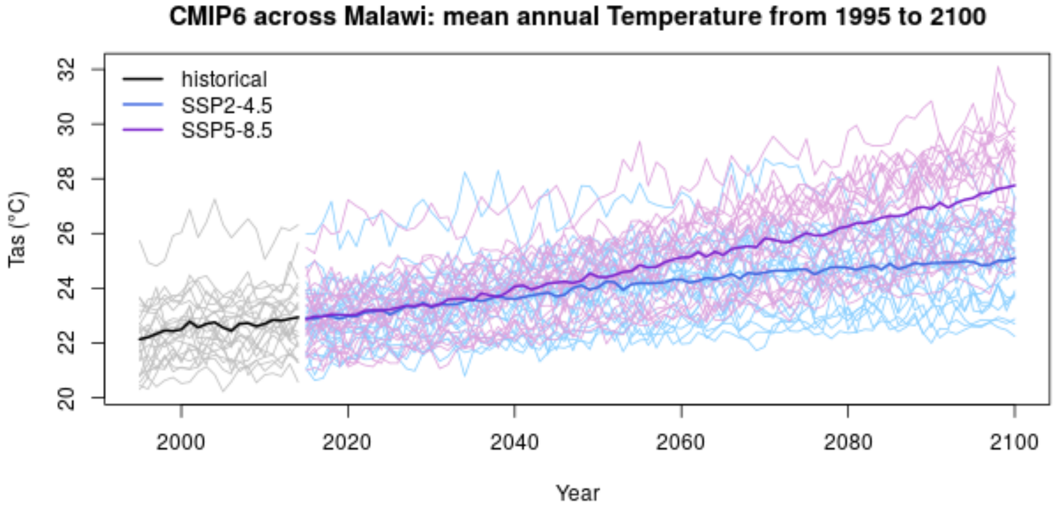

Figure 32: Interannual mean temperature across Malawi for the historical time period (black), SSP2-4.5 (blue), and SSP5-8.5 (purple). Thin lines: each GCM, bold lines: ensemble mean for each scenario

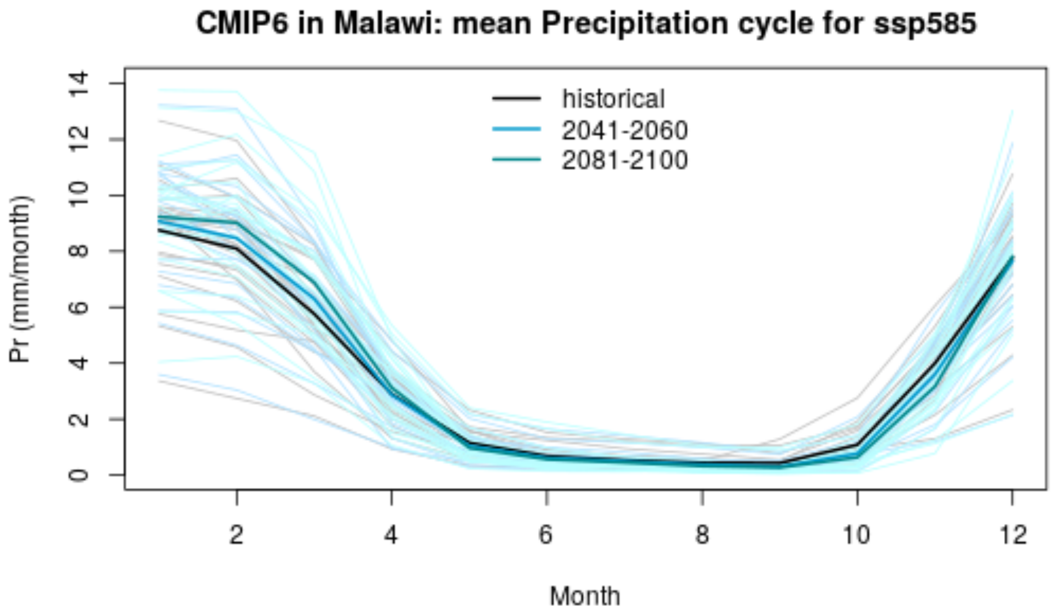

Figure 33: Mean monthly precipitation cycle across Malawi for the historical time period and the 2050 and 2090 horizons for SSP5-8.5. Thin lines: each GCM, bold lines: ensemble mean for each time period

<u>Model selection</u>

In addition, a second study on model selection was performed. The ensemble of CMIP6 climate simulations evaluated in the first study represents a very large volume of data. The exploitation of all the simulations would be extremely costly in computing time and storage. The main goal of this work was then to select a subset of simulations which represents the best the whole range of available simulations.

A first stage of selection which is quite trivial consists in selecting the simulations with the available:

- climate variables of interest (daily average, maximum and minimum temperature and daily precipitation)
- climate scenarios (historical, SSP126, SSP245, SSP370 and SSP585)

- models within the very likely range in terms of climate sensitivity.

This step resulted in a sub-ensemble of 16 different models. However, this sub-ensemble is still quite large for operational use when running the hydrological model.

A second stage of model selection was then necessary. Therefore, a second process of selection was performed by combining two main criteria:

1. The first one consists in choosing a subset of simulations that represents the range of future changes in temperature and precipitations trends represented by the whole ensemble of CMIP6 simulations.
2. The second one considers the historical performances of the CMIP6 simulations with respect to observation in order to discard the climate simulations with the poorest representation of the present climate.

The combination of the two stages of model selection resulted in a selection of a subset of 6 models that best encompasses the total ensemble.

Statistical downscaling

The selected models were bias corrected and downscaled over Malawi using a statistical downscaling technique used at EDF, CDF-t, and sent to DCCMS to perform the hydrological modeling. The CDF-t (Cumulative Distribution Function – transform) approach in a statistical quantile mapping downscaling method. It bias-corrects the modelled cumulative distribution function on both the historical and future time periods based on the observed cumulative distribution function. It was applied to temperature and precipitation projections for each selected climate model and emission scenario based on the gridded observed dataset provided by DCCMS. This dataset spatial resolution corresponds to the hydrological model spatial grid. The CDF-t method was applied on a monthly basis, with a direct approach for temperature and a threshold approach for precipitation. It resulted in daily time series for each hydrological model grid point showing bias close to nil (below 0.01°C for temperature and below 1% for precipitation).

The field trip to Malawi

In October 2022 a field visit to the country was conducted to meet with local stakeholders: DCCMS, EGENCO, ESCOM, EDF (local branch), Department of Lands (member of the Mpatamanga Project Implementation Unit).

The CS7 country mission to Malawi took place from 3-12 October 2022. The mission included partners active in case study 7 and case study 2 for Food Security in Malawi. The mission started in Blantyre, Malawi with a team meeting at the DCCMS premises. The CS7 team spent the following two days visiting hydroelectric sites and infrastructures while meeting key stakeholders. For the last two days of the mission, the CS7 team moved to Lilongwe to meet with representatives of the Ministry of Natural Resources and Climate Change, the Ministry of Energy and the Lilongwe Water Board. The mission allowed us to collect data and feedbacks throughout the discussions and the interviews conducted with representatives from different stakeholder institutions (eg. energy, water, land) which provided a deeper understanding of the local socio-economic context, the country's energy sector and the interlinkages among energy, water and food in Malawi. The main finding of this field trip was the strong nexus between water, energy and food security in the country. For instance:

- Water: water management between drinking, irrigation and energy production needs;
- Energy: energy poverty leading to dramatic deforestation for charcoal which impacts hydroelectric production by increasing the sedimentation issue;
- Food security: irrigation, fishing and water hyacinth problem worsening through the use of fertilizers in agricultural areas on the river's banks.

All these aspects need to be represented in the climate service for it to be useful across all water use sectors, and not only in the energy sector.

Climate service

The Climate service was initially thought to meet the needs of EDF as the only end user. However, and thanks to the field trip, it appears that the energy sector in Malawi is closely linked to the water and food security sectors. The climate service must take into account these interlinkages and provide a bigger picture of how future climate changes will impact the different sectors with a focus on energy of course.

As a first step we identified EDF requirements for the climate service which are:

- future water availability in the Shire River in terms of daily streamflow and extremes: low-flow (droughts), high-flows (floods) and cyclones;
- future changes in the annual cycle of precipitation (rainy season/dry season) in terms of duration and intensity;
- impact of heavy precipitation events on the sedimentation (erosion) issue;
- impact of temperature increase on the development of water hyacinth.

This information can be delivered:

- As raw data: time series of climate and hydrological projections
- Reports: analysis of future climate impacts on the water cycle with graphics, tables, etc.
- A web-based tool

These requirements can also meet the needs of the local energy companies such as EGENCO and ESCOM as well as the water boards (see **Table 24**). However, further discussions are needed with CS2 for instance to include specific needs for the food security sector (in Malawi).

Next Steps

A work in progress on the dynamical downscaling for CMIP6 projections performed by WITS will provide high-resolution climate projections over Malawi. These projections will be used as input of the hydrological model run by DCCMS. The aim of this work is to evaluate the added value of using high resolution climate simulations to model the hydrological cycle of Lake Malawi and the Shire River.

Table 24: Climate service user requirements for Case Study 7

User	User requirements	Sector indicators	Input
EDF, EGENCO and ESCOM	1. Surface air temperature 2. Total precipitation 3. Lake level 4.Water flow over the Shire river	1.Future change in the duration of the rainy season; 2. Future change in the frequency of extreme events (e.g. dry spells and heavy rainfall events); 3. Future change in the lake level.	Climate projection data and reanalysis
Water boards	1. Surface air temperature 2. Total precipitation 3. Water temperature	1.Future change in the duration of the rainy season; 2. Future change in the frequency of extreme events (e.g. dry spells and heavy rainfall events); 3. Future change in the frequency of water temperature threshold overrun.	Climate projection data and reanalysis

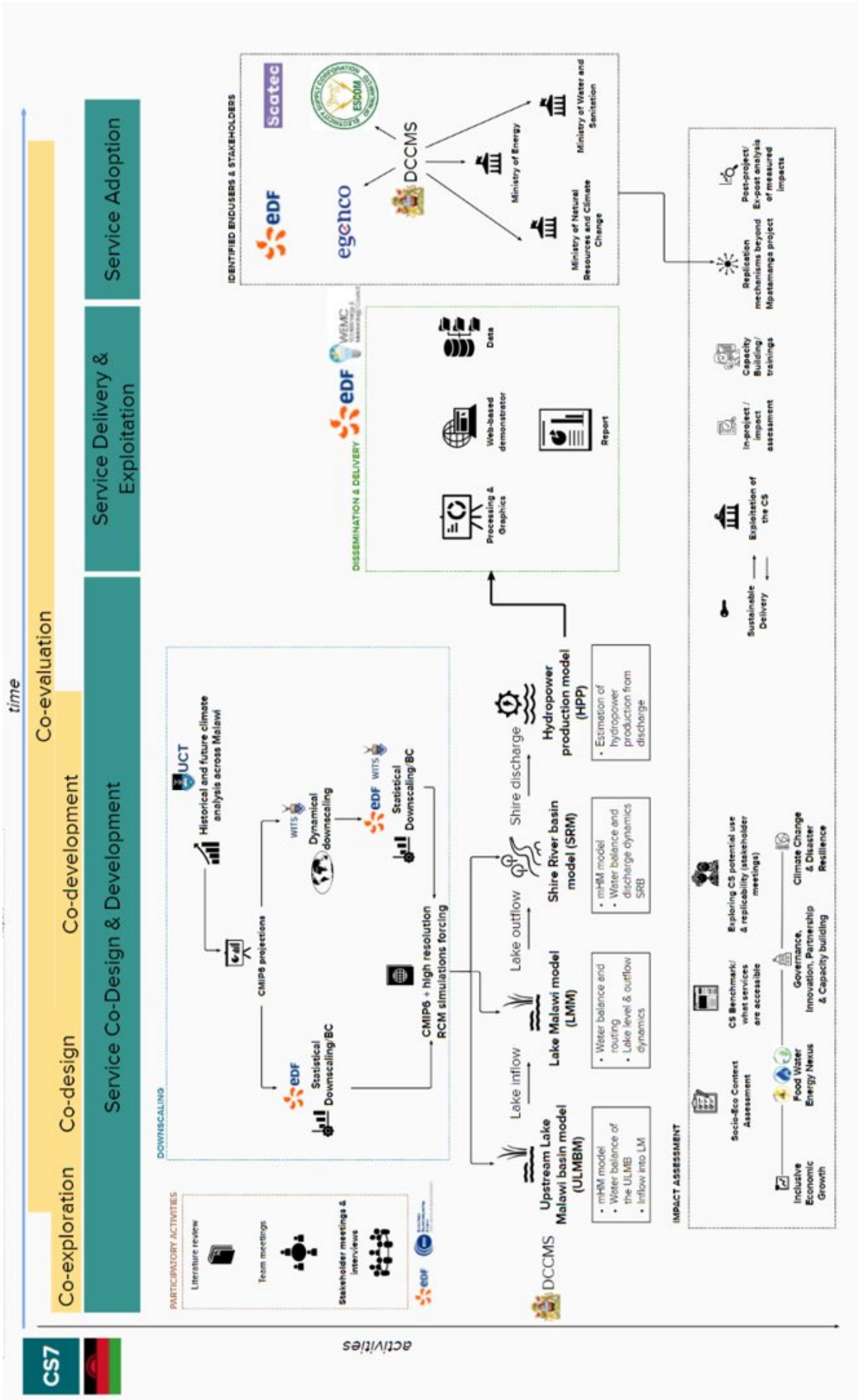

Figure 34: Workflow of the climate service development for Case Study 7

3.8 Case Study 8

Background, data requirements and workflow

Changes in rainfall distribution both temporal and spatial leading to longer dry spells and stronger high intensity rainfall event are presenting challenges for the food security and water sector in Mauritius. One of the key adaptation strategies is the development of seasonal forecast products based on available model output (typically from C3S) and their tailoring to the specific user needs and relevant decision-making spatial scales.

The case study identified a need for development of a capability for hybrid statistical and dynamical downscaling for the Mauritius to strengthen the provision of seasonal forecast information by the Meteorological Service (MMS). The deployment of operational seasonal forecasting models, with the MMS, using both statistical and dynamical downscaling techniques, is found to be feasible. This is on account of the in-house high-performance computing facility and adequate observation data. The data collected and archived by MMS hold precipitation records that date as far back as the 19th century (in the case of rainfall). The station network over the Islands includes 35 automatic weather stations (AWS). The long track record of climate observations, covering most of the Island, could potentially support high resolution statistical downscaling or even bias adjustment of dynamical downscaling of seasonal forecasts. The exiting course spatial resolution of the forecasts for the Mauritius Island are reflected in **Figure 35**.

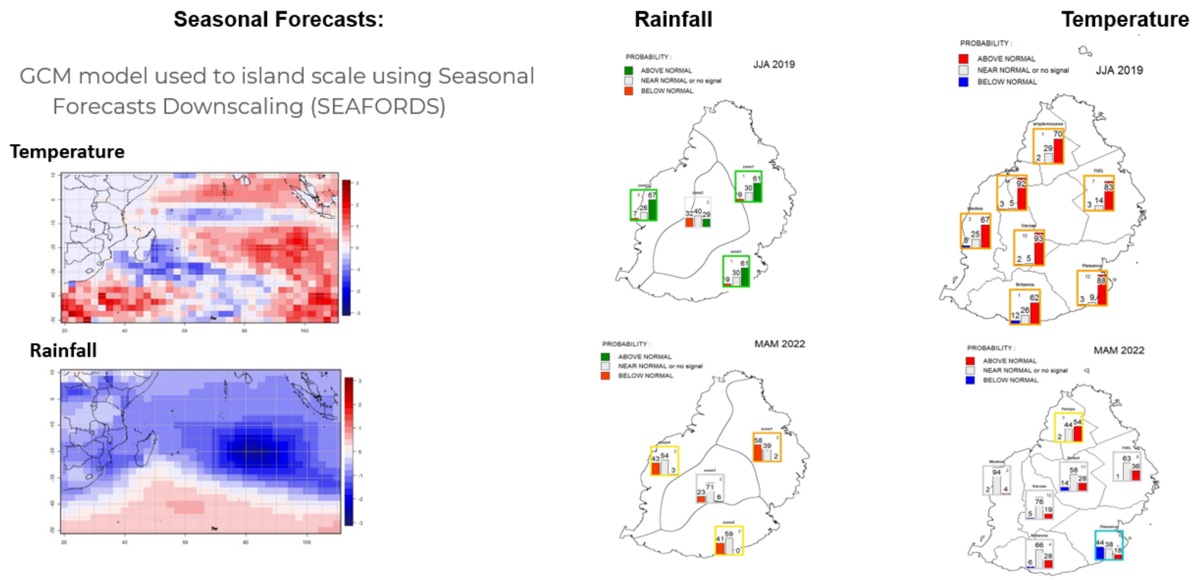

Figure 35: Example statistical Model Forecasts of rainfall and temperature for JJA 2019 and MAM 2022 issued at MMS

The envisaged high resolution seasonal forecast outputs developed will be tailored for specific users from the food security and water sectors. The co-design and co-development phase are informed by the first stakeholder consultation mission in Mauritius in March 2022 and third stakeholder workshop in South Africa in May 2022. During the first stakeholder consultation, the CSIR and MMS successfully engaged in consultative meetings during which the information on the status of climate services, socio economic context and an initial list of user requirements, as summarized in **Table 25**, were compiled. The third stakeholder workshop, in South Africa allowed for a detailed understanding of the use cases of climate data or information and services within the respective user decision-making processes, specifically representative delegates form the Water Resource Unit (WRU) and the Food and Agriculture Research and Extension Institute (FAREI) their respective climate information needs and requirements.

Table 25: Climate service user requirements for Case Study 8

Sector	Service Input Climate data	Users	User requirements	Sectors indicators
Food security/ Agriculture	Historic Climate data (Monthly Temperature and Precipitation) Cropping areas shapefiles	Small holder farmers welfare fund	• Evapotranspiration • SPEI, SPI	Web based services for forecast delivery with a backend implementing scripts for: • Warning thresholds for drought • SPEI and SPI analysis • High resolution seasonal forecasts for crops areas
		Sugar Cane farmers association	• Temperature and solar radiation • Seasonal precipitation and temperature forecasts • Update of agro-climatic map	Improved identification of rainfall zones and planting sugar cane growing areas seasonal rain and temperature forecasts.
		Food and Agriculture and Extension Institute	• Evapotranspiration • Precipitation • Maximum and Minimum Temperature • Humidity	
Water	Historic Climate data (Monthly temperature and precipitation) Catchment shapefiles	Water Resource Unit	• Catchment specific precipitating forecasts	River Basin probabilistic rainfall and temperature forecasts
		Irrigation authority	• Climate extremes indices relevant for irrigation and drainage system design and monitoring	Irrigation design thresholds precipitation.

The co-design and co-development phase of the seasonal forecasting capability development is carried out with a goal of ensuring the seasonal forecast service sustainability in mind. To this end, the CSIR and WEMC continuously advance the case studies' research aspects while allocating time to train MMS staff to co-develop the services through regular sessions. The focus of the sessions is to assist the MMS technical team to deploy and support the developed seasonal forecasting capability. The workflow for all the seasonal forecasting service capability development phases is summarized in **Figure 36.**

Current status of the trial climate service co-production

For the Island of Mauritius, we found 10 years of monthly precipitation data covering the period 2001-2010 from 12 different stations distributed over the island. To optimize the development of the downscaling and bias adjustment method (based on the Cumulative Distribution Function transform, CDFt, approach) and also to extend the number of years and the spatial coverage of observational data, different reanalysis datasets were considered too. These reanalyses were first assessed against the ground observations. Having longer timeseries for climate data, and with a better spatial coverage, allows for a better assessment of the output of both the statistical and dynamical downscaling developed as part of CS8. The statistical downscaling uses the Random Forest (RF) algorithm by combining dynamical forecast and observation. The dynamical forecast uses a regional dynamical model taking the global seasonal forecast models as boundary conditions.

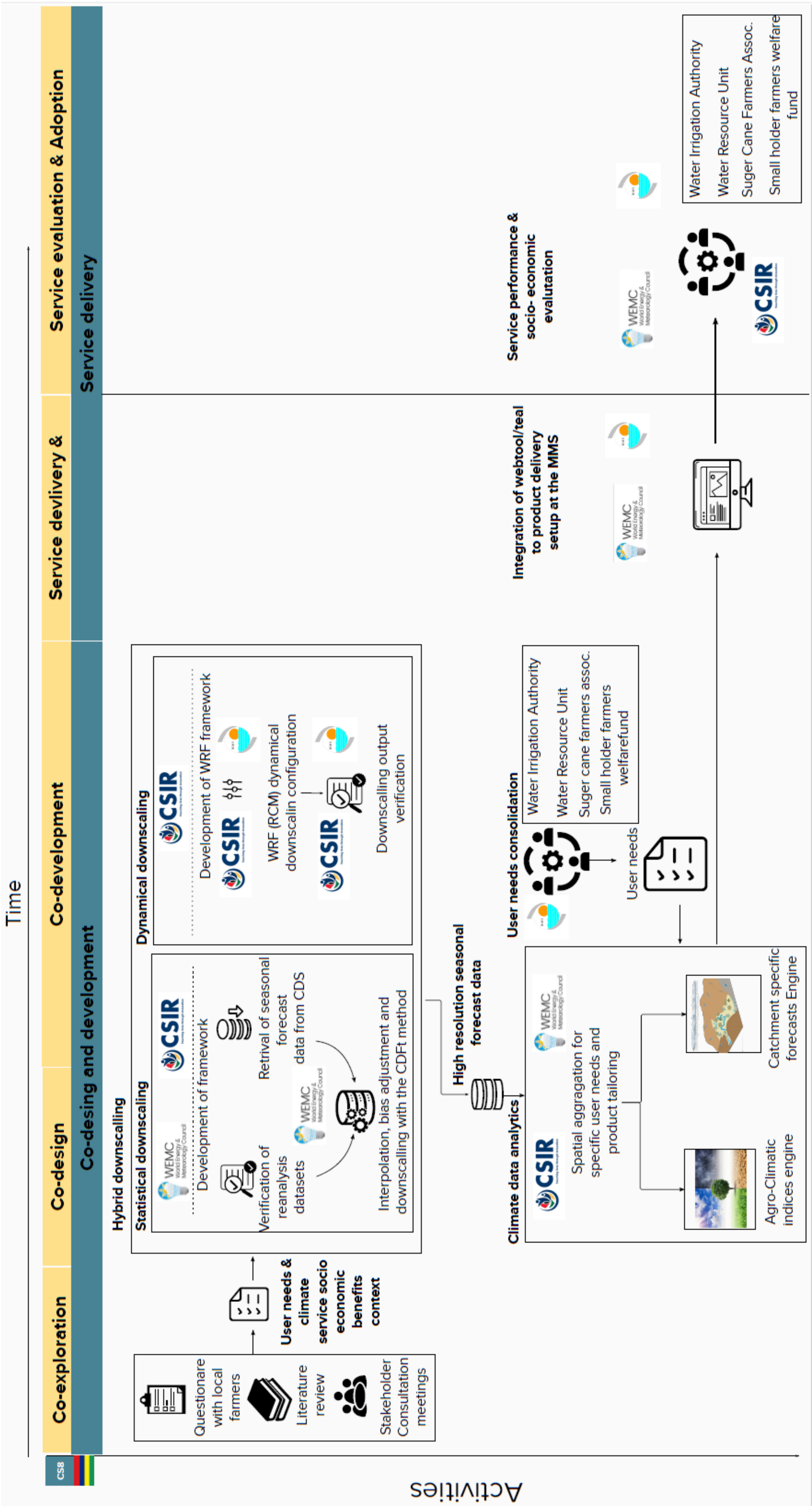

Figure 36: Workflow of the climate service development for Case Study 8

The station data consists of 10 years of monthly precipitation record for the period 2001-2010 from 12 different stations distributed over the Island of Mauritius (**Figure 37**). All data has been retrieved from The Ministery of Energy and Public utilities[6]. All stations have a complete record for all the months with no values that seemed unphysical. From the documentation on the website, it was also stated that a quality control has been performed on this data, however details was not given.

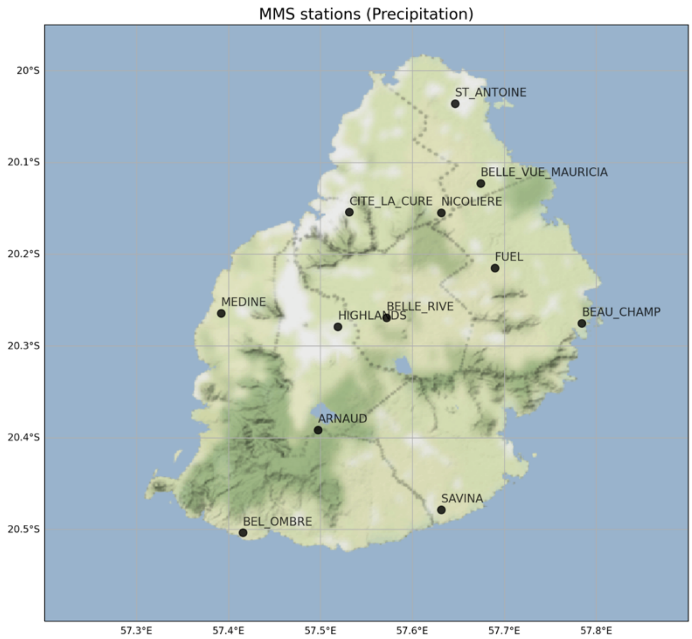

Figure 37: Locations of the observational stations (black dots) over the Island of Mauritius

A total of six different rainfall datasets were considered. These were selected based on the criteria that they all covered the period of the station observations (2001-2010) and preferably the period covering the dynamical seasonal forecasts including both the hindcasts and forecasts, namely from 1993 to present. Finally, they had to be commonly used and freely available. The systems chosen with their main characteristics are shown in **Table 26**. All datasets are retrieved at a monthly temporal resolution.

Table 26: Climate service user requirements for Case Study 8

Dataset	Institution	Spatial resolution (deg)	Temporal coverage (years)	Reference
CHIRPS	UC Santa Barbara Climate Hazards Group	0.05x0.05	1981-current	Funk et al. 2014
GPCC	DWD	0.25x0.25	1981-2020*	Schneider et al. 2022
IMERG	NASA	0.2x0.2	2000-present **	Huffman et al. 2020
ERA5	ECMWF	0.25x0.25	1950-present***	Hersbach et al. 2020
ERA5-LAND	ECMWF	0.1x0.1	1950-present***	Muñoz Sabater et al. 2019
MERRA2	NASA GMAO	0.5x0.615	1980-current	GMAO and Pawson 2015

* Note that the temporal coverage depends on the version of the dataset, here it is the high resolution used, where the 1x1 deg is being produced up until currently.

** In 2015 the satellite used was changed

***The quality of the early years of ERA5 is low.

[6] https://publicutilities.govmu.org/Documents/2020/Legislation/Water/Hydrology%20Data%20Book/Book%202000-2005/Chapter%202/Precipitation%20data.pdf

Three different metrics has been chosen for the evaluation of the rainfall datasets against the station observations: Root Mean Square Error (RMSE), which is a measure of the average squared distance between the datasets, the Pearson correlation (r), which is a measure of the strength and direction of linear association between the datasets, and the Mean Bias Error (MBE). Each station is individually verified against the closest grid point in the different rainfall datasets. This also means that for some of the datasets with coarser spatial resolution the same grid point can be used for more than one observation stations. As an example, the anomaly correlation with respect to the closest station for ERA5 is shown **Figure 38.**

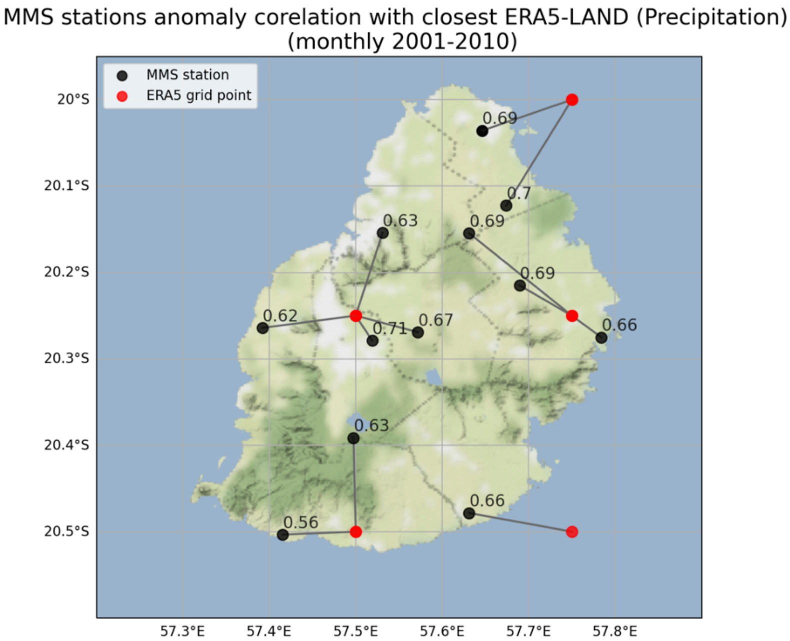

Figure 38: Anomaly correlation coefficients for precipitation from 2001-2010 between the observation stations (black dots) and the closest ERA5 grid point (red dots).

An overview the climatic mean for the period 2001-2010 for each station is shown in **Figure 39**. For the rainfall datasets the closest grid point to the location of each station is used. All datasets display a good representation of the observed seasonal changes, showing the wettest months to be Jan, Feb and Mar. However, in terms of bias, there are large discrepancies with values of more than 50-150 mm/month, for most the months of the year (cf. e.g. Arnaud and Belle Rive stations).

As a second step, the monthly anomaly was calculated for each month with respect to each rainfall dataset climate. The same was done for the station observations with respect to their climate. This allowed to find the Pearson anomaly correlation between the datasets and the observations without the effect of the annual cycle (**Figure 39** top). The RMSE and the MBE were calculated in a similar way to the anomaly correlation (**Figure 39** middle and bottom, respectively). As a final step, the mean of the scores for all stations are shown in **Table 27**, where the mean for each season (DJF, MAM, JJA and SON) is also calculated.

Considering the three metrics, CHIRPS and GPCC were, on average, the best performing datasets in terms of representing the station precipitation observations. The CHIRPS dataset was the selected dataset for ensuing analysis. It was chosen even if GPCC is slightly superior for some metrics (by 0.04 in correlation and 0.4 mm/day in RMSE, though with a better MBE, by 0.3 mm/day). Other considerations include the (high) spatial resolution (0.05x0.05 deg.) which allows for more refined products based on both the statistical and dynamical downscaling.

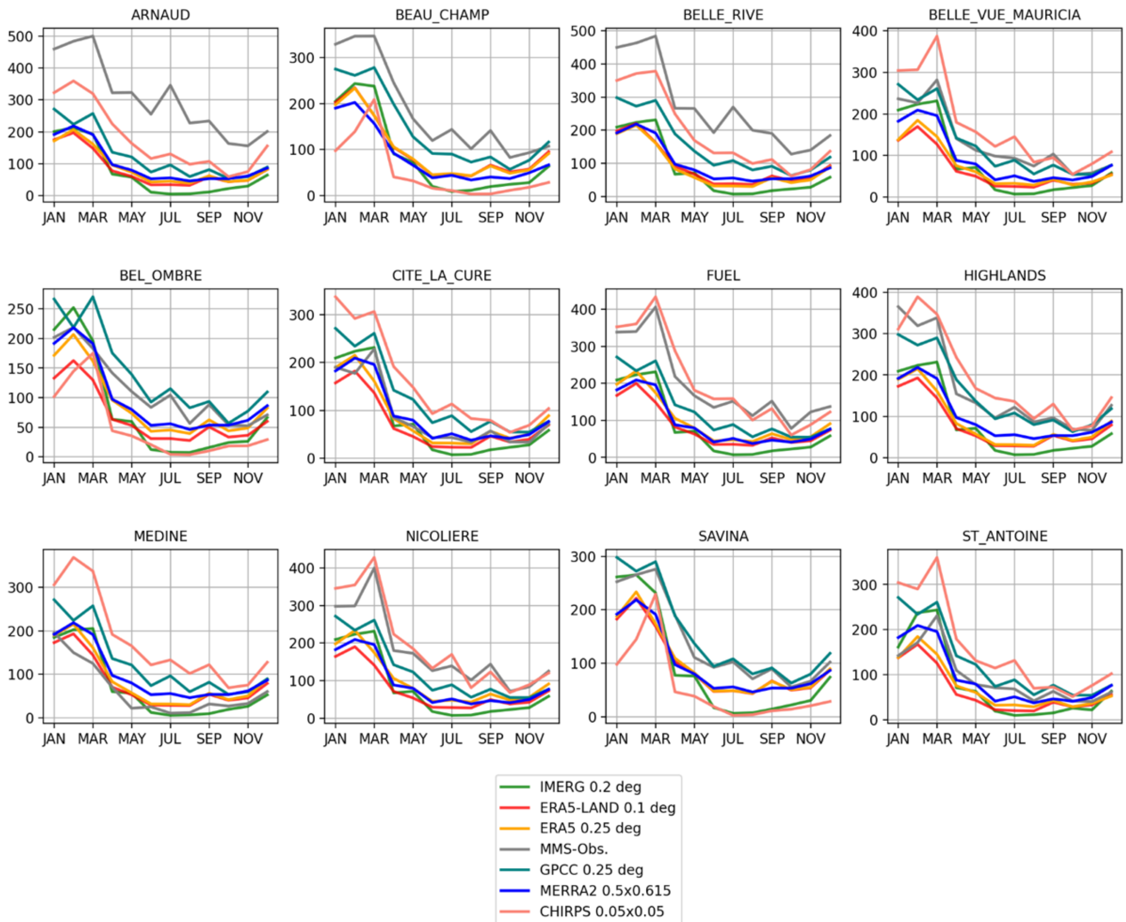

Figure 39: The climatic mean monthly precipitation (mm/month) for the period 2001-2010 from station observations (grey line) and each of the reanalysis datasets (colored lines) from each of the 12 stations.

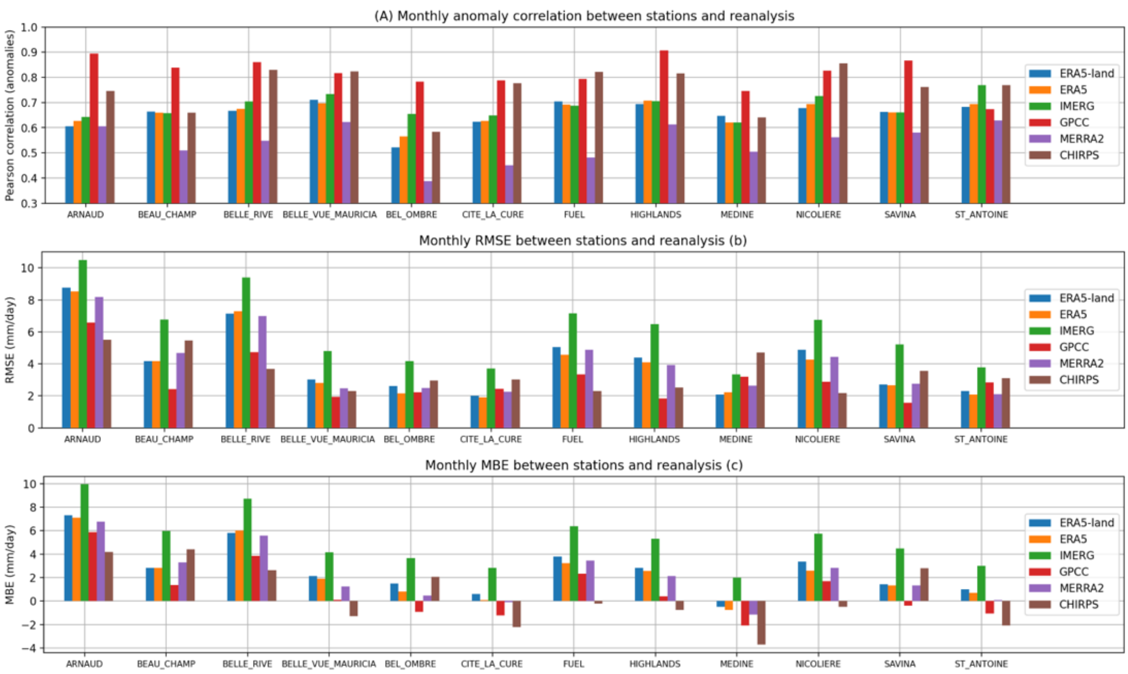

Figure 40: Anomaly correlation (top), RMSE (middle) and MBE (bottom) between station observations and each of the rainfall datasets (colored bars) for the period 2001-2010.

Table 27: Mean values for anomaly correlation, RMSE (mm/day) and MBE (mm/day) for precipitation from all 12 stations and for all months of the year, DJF, MAM, JJA and SON.

System	CHIRPS	GPCC	IMERG	ERA5-LAND	ERA5	MERRA2
Anom. Cor. **(All months)**	0.78	0.81	0.68	0.66	0.66	0.54
RMSE (mm/day) **(All months)**	3.4	3.0	6.7	4.0	3.9	4.0
MBE (mm/day) **(All months)**	0.5	0.8	5.2	2.7	2.4	2.1
Anom. Cor. **(DJF)**	0.60	0.59	0.47	0.51	0.49	0.43
RMSE (mm/day) **(DJF)**	3.2	3.0	6.5	4.1	4.0	4.2
MBE (mm/day) **(DJF)**	0.4	0.5	5.1	2.6	2.2	2.4
Anom. Cor. **(MAM)**	0.63	0.64	0.4	0.59	0.58	0.45
RMSE (mm/day) **(MAM)**	3.2	3.0	6.6	0.40	0.40	3.9
MBE (mm/day) **(MAM)**	0.5	0.8	5.1	2.8	2.5	2.1
Anom. Cor. **(JJA)**	0.61	0.65	0.4	0.55	0.55	0.47
RMSE (mm/day) **(JJA)**	3.3	3.0	6.9	4.1	4.0	3.8
MBE (mm/day) **(JJA)**	0.4	0.6	5.2	2.5	2.3	1.9
Anom. Cor. **(SON)**	0.55	0.56	0.38	0.45	0.46	0.42
RMSE (mm/day) **(SON)**	3.5	3.0	6.6	4.1	3.9	4.0
MBE (mm/day) **(SON)**	0.5	0.8	5.1	2.7	2.5	2.0

The dynamical downscaling of seasonal forecasts using the WRF model has been set up and tested. A procedure for downloading the initial boundary conditions has been deployed at MMS high performance computing system. The dynamical downscaling is now running on the MMS's local machine and it is starting to produce gridded output. Python programming language protocols have been developed for visualizing the outputs.

It is also noteworthy that a targeted training mission by one of the MMS technical staff to CSIR in South Africa was very useful to speed up the uptake and adoption of dynamic downscaling workflow developed by the CSIR. In addition, two technical sessions held by WEMC have been undertaken towards the transfer of the statistical downscaling and forecast bias correction capacity to MMS.

Next steps

A high spatial density of observational records covering the near present and a climatological period are being prepared by MMS to allow for additional model output evaluation. This will pave the way for the hindcast runs which are needed for the development of probabilistic forecasts from the high-resolution dynamical forecast downscaling. Moreover, additional technical training sessions have been planned throughout Task 5.2 to continue and complete the capacity transfer process from CSIR and WEMC to MMS.

Several meetings have been held during Task 5.1 where the focus has been both on sharing and discussing new developments (e.g. the two downscaling methods) and on overcoming technical issues. Alongside, the discussion has also started to include consideration about the design and development of the delivery method for the trial climate service. This included a discussion of how and when to include the end user in these discussions to ensure optimal interactions and engagement from their side. It was agreed that to get constructive feedback, it should only be undertaken when a trial climate service is developed, so as to have something concrete to show to them. As a potential starting point for a visual interface for delivering the forecasts, the Teal Tool has been suggested. Discussions are currently ongoing on the benefits and limitations of using this already-developed tool, especially regarding it not being open source.

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