



Data integration for climate services

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Executive summary

The SAFE4ALL project aims to harness the EU climate services landscape and leverage it with local knowledge from African case studies to co-create information and facilitate its uptake at the local to district and regional levels. With the increasing challenges posed by climate change, access to reliable and relevant climate data is crucial for co-creating tailored tools for various end-users to manage climate-related risks in Africa, particularly in Ghana, Kenya and Zimbabwe where the project focuses on.

This report focuses on the integration of diverse (climate) data sources to support the co-creation process for effective and user-centered climate services and tools tailored to specific use cases. This is a continuous process that involves maintaining a comprehensive overview of both available and required data sources, performing pre-processing steps to harmonize data, conducting quality checks, aligning data across temporal and spatial scales and the creation of specific climate indicators among others. Furthermore, establishing an infrastructure that facilitates seamless data integration is essential to ensure the long-term accessibility and reusability of these resources.

This report provides an overview of the data sources and their integration across climate tools and services within WP2 of SAFE4ALL. The ultimate goal is to establish a data basis for the co-creation of tailored, user-centered services for the end-use cases in Ghana, Kenya, and Zimbabwe.

1 Introduction

1.1 Need for data integration

Climate services involve tailored information, tools, products and services to support stakeholders in making informed decisions to manage climate-related risks. The co-creation of climate services has become increasingly important in Africa due to ongoing and accelerated climate change impacts and extreme events that jeopardize food and nutrition security of vulnerable communities in Africa with high exposure to climate risks and limited capacity to adapt. A fundamental requirement for the co-creation of effective climate services is access to relevant and reliable climate data and climate impact data, which is needed as input for developing climate services.

Complex landscape of available climate data sources

Many countries have established National Meteorological and Hydrological Services (NMHSs) and regional climate centers to provide critical weather and climate information. However, these institutions are often underfunded, which led to a significant decline in the number of operational ground-based weather stations in Africa, from approximately 3,300 in 1981 to fewer than 800 in 2023¹. Despite ongoing efforts to expand the network, Africa continues to have the lowest density of weather and climate monitoring stations globally. This shortage hampers accurate climate observations, forecasting, and the creation of effective climate services. Additionally, limited data accessibility further restricts the development and broader use of these services.

In addition to weather station data, there is a complex landscape of globally available data sources from various repositories such as from ECMWF, COPERNICUS, CORDEX, NASA, NOAA, ESA-EUMETSAT etc. However, the data has been challenging for non-specialists to identify, locate, use, process and interpret. Consequently, these repositories, including Europe's climate data assets, remain underutilized, limiting their potential to support the development of climate services and reduce vulnerabilities to climate change.

Existing tools and data ('climate services') have been challenging for non-specialists to identify, locate, use and interpret; as a result, Europe's climate data assets are not fully utilized while the scarcely available data sets for Africa are not readily made accessible.

¹ <https://www.climatelinks.org/blog/african-scientists-harness-power-3d-printing-monitor-and-forecast-extreme-weather>

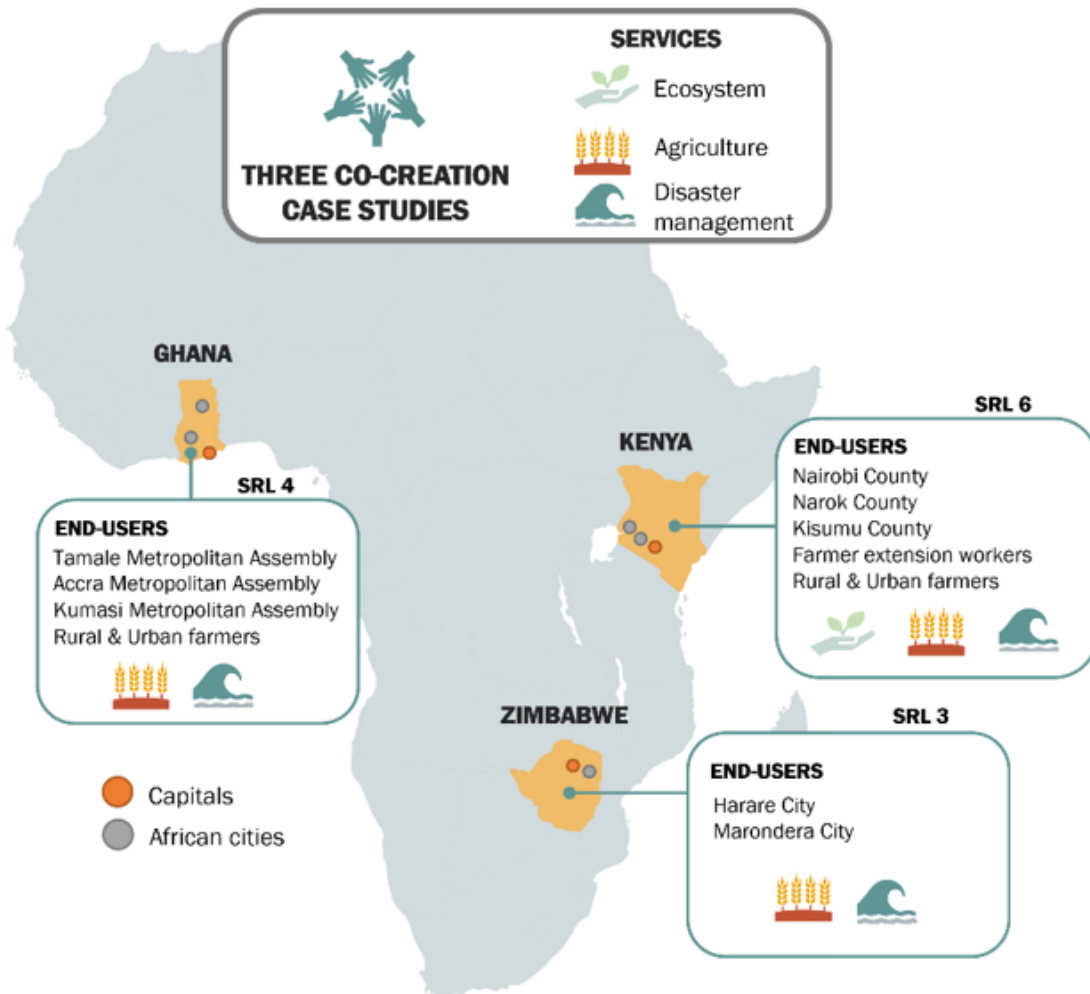


Figure 1: Three co-creation case studies within SAFE4ALL

Use case-driven climate services require tailored climate data provision and integration

In addition to navigating the complex landscape of available climate data sources, the data must be pre-processed to meet the specific needs of different end-users. Smallholder farmers, urban and rural authorities, industries, and communities etc. each require tailored information, in terms of which specific information is required from which data source, at what spatial and temporal scale and in which format. This also holds true for end-users included in SAFE4ALL (Fig. 1) and consequently the tools and services that are developed within WP2. They operate at different spatial scales from the local to the global scale and at different temporal scales ranging from nowcasting to using projections for the next decades (Fig. 2).

This requires a user-centered data provision and data integration within SAFE4ALL to ensure that the various data sources are harmonized and can support the co-creation process of climate services and tools within SAFE4ALL.

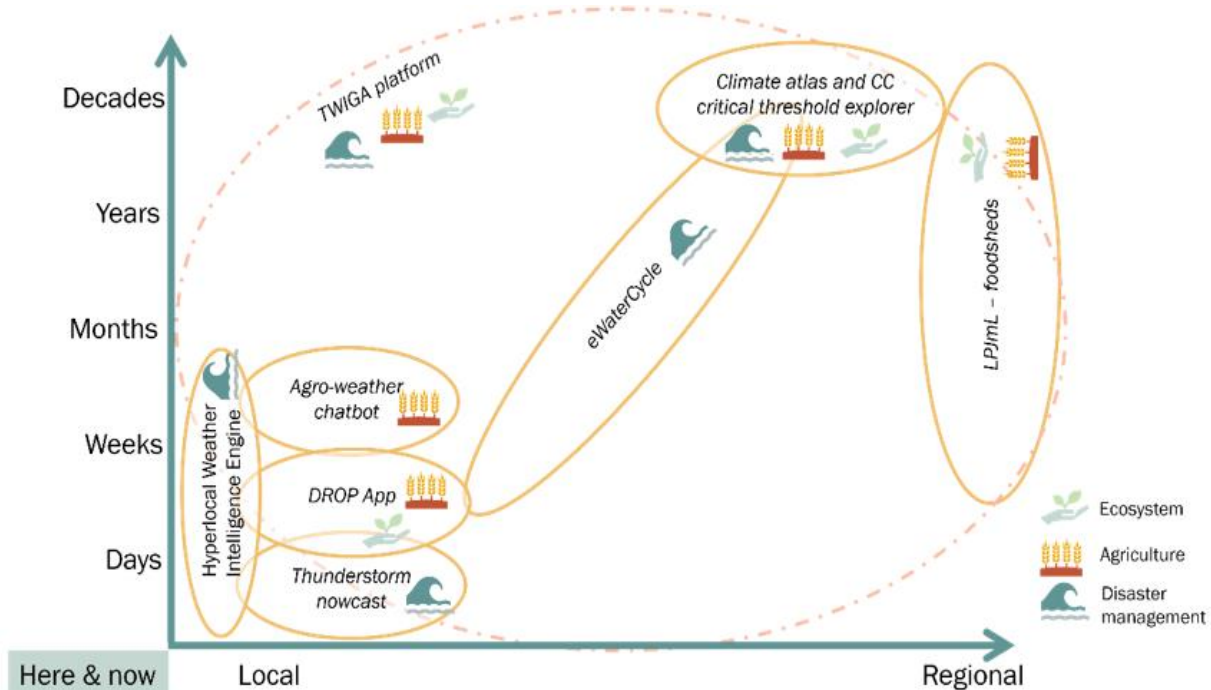


Figure 2: Relevant spatial and temporal scales of tools and services of WP2

1.2 Objective of the report

This report aims to provide an overview of data sources and their integration across climate tools and services within WP2 with the ultimate goal to provide a solid basis for the co-creation of tailored user-centered services for the end-use cases in Ghana, Kenya and Zimbabwe. The report has a focus on climate data due to its importance for the co-creation of climate tools and services and climate impact modelling. However, aspects of this report in relation to data integration apply to other data sources as well such as those related to water, land use, socio-economic parameters (e.g. population, GDP, literacy levels, standard of living, labour force, migration etc.).

The report is structured as follows: **Chapter 2** examines general data sources relevant to co-creating climate tools and services within SAFE4ALL, detailing types of data, repositories, and formats, before expanding to specific data sets identified during the General Assembly 2024, including available and required datasets of SAFE4ALL project partners. **Chapter 3** focuses on the pre-processing steps necessary for data integration, such as temporal and spatial alignment, quality checks, and the generation of climate indicators. **Chapter 4**, building on the Data Management Plan (D7.4), outlines the infrastructure required for data integration, addressing access, storage, data-sharing practices and data

standards. The report concludes with recommendations and an outlook **in Chapter 5** section, offering guidance for future work. An **Appendix** includes notes from the General Assembly 2024.

This report on data integration for climate services is due M12 and will feed into the next update of the data management plan which is scheduled to be released by month 42 (TUD responsible) as well as the periodic project reports.

2 Data sources for climate tools and services within WP2

2.1 Data sources

Climate data used within WP2 for the co-creation of tools and services can be broadly categorized into ground-based point observations, ground-based gridded observations, and modeled data. Table 1 provides a brief description of the data sources along with example datasets.

Table 1: Relevant data sources for WP2

Climate data source	Short description	Examples
Ground-based point observations		
<i>Weather station data</i>	Direct measurements of e.g. weather variables such as temperature, precipitation, solar radiation etc. collected from ground-based weather stations; often very accurate for local conditions, but with limited spatial coverage, especially in remote regions	Station data collected from Met Offices (GMet, ZMD, KMD), TAHMO
Ground-based gridded observations		
<i>Primary observations</i>	Data that integrates ground-based measurements, satellite observations and advanced modelling techniques to provide spatially continuous datasets	CHIRPS, CRU-TS, Berkeley-Earth, GPCC, TRMM, MSWEP
<i>Reanalysis</i>	Blend of observational data and model simulations, providing consistent, gridded datasets of past climate conditions, global coverage for continuous spatial and temporal scales, often biased and inaccurate in regions with sparse observational data	ERA40, ERA-Interim, ERA5, ERA5-Land, NCEP-NCAR R1, NCEP-DOE R2, NOAA-CIRES-DOE 20thcentury reanalysis
<i>Bias adjusted reanalysis</i>	Reanalysis data that has been corrected to reduce systematic biases, using observational data; improved accuracy over re-analysis data, however quality of adjustments depends on the availability and quality of reference data	WATCH-FD, WATCH-EI, W5E5, Princeton Global Forcing (PGF), GSWP3
Modelled data		
<i>Global models</i>	Climate models that simulate the Earth's climate system on a global scale, including the atmosphere, oceans, and	CMIP3, CMIP5, CMIP6, ISIMIP-FastTrack, ISIMIP2b,

	land, allow large-scale climate impact modelling and long-term projections, coarse spatial resolution and potential inaccuracies in regional representation	ISIMIP3b
<i>Regional models</i>	High-resolution climate models that simulate climate dynamics for specific regions, often nested within global models; often better representation of local climates, depend on boundary conditions from global models, which may propagate errors	CORDEX, CORDEX-ESD, NEX-GDDP-CMIP6

Each of the data source has its own advantages and disadvantages and must be carefully selected to meet the specific requirements of the model and the objectives of the co-creation of climate tools and services. The choice of a particular data source depends on factors such as data availability, required accuracy, spatial and temporal resolution, and format.

A comparison of different data sources can provide valuable insights into the spatial and temporal (dis)agreements among datasets for the specific case study area, guiding the selection of the most suitable data source. The level of (dis)agreement often varies depending on the climate variable. For instance, while temperature-related variables generally show a high level of agreement between different data sources (Fig. 3), precipitation-related variables tend to exhibit more variability. This even holds true for primary observations as shown by the spatial differences in the precipitation trend from 1981 to 2014 for Ghana between the two observational data sets CHIRPS and CRU (Fig. 4).

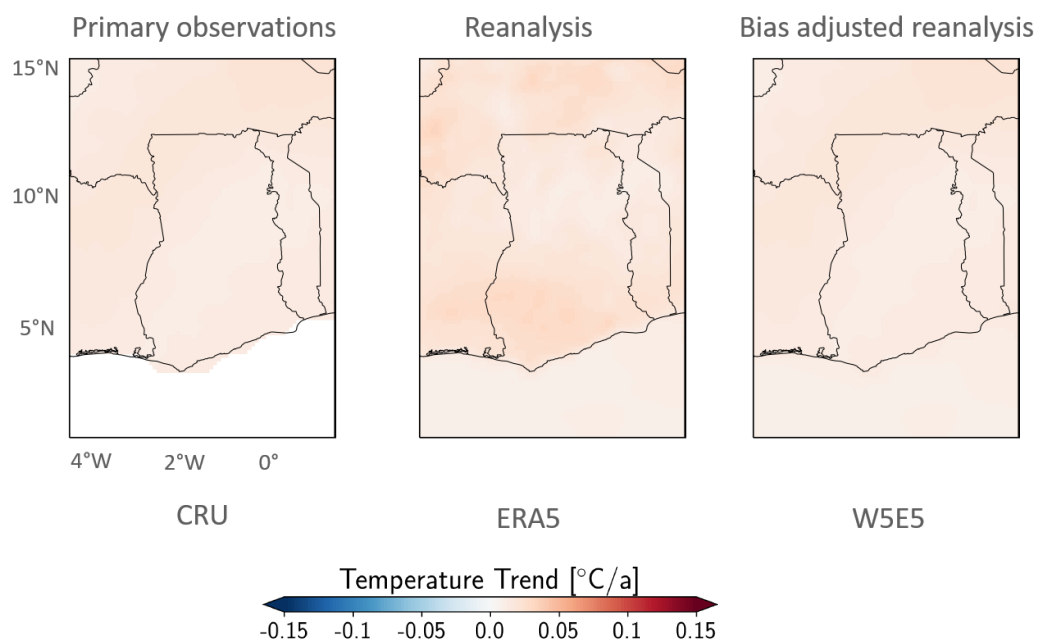


Figure 3: Temperature trend in °C/a from 1981 to 2014 for Ghana

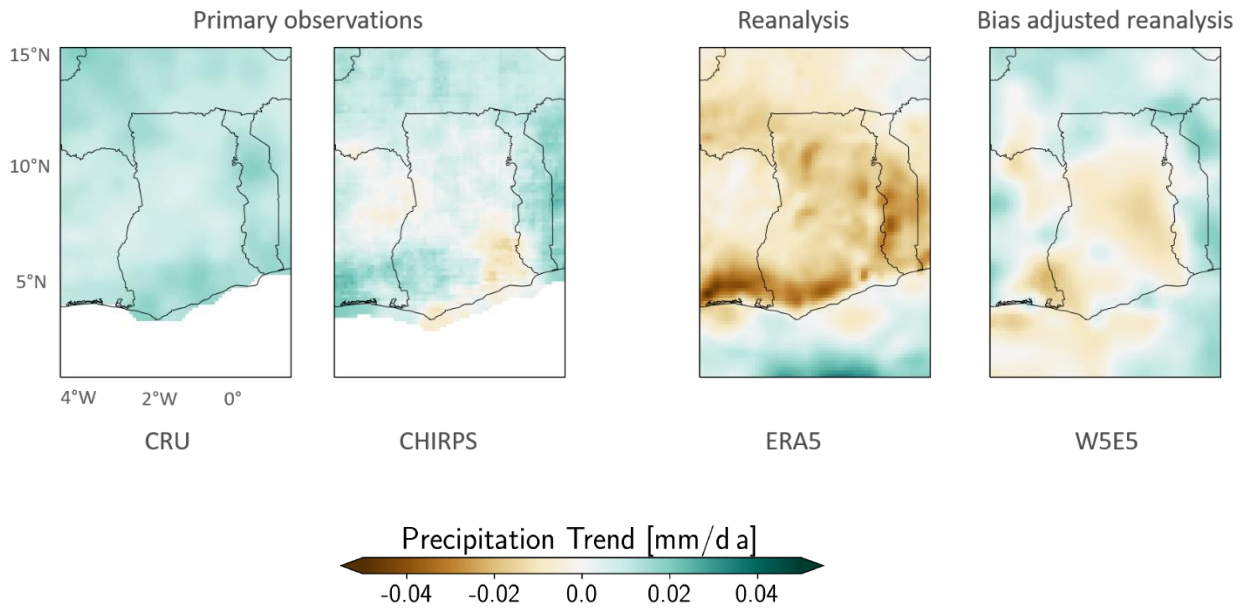


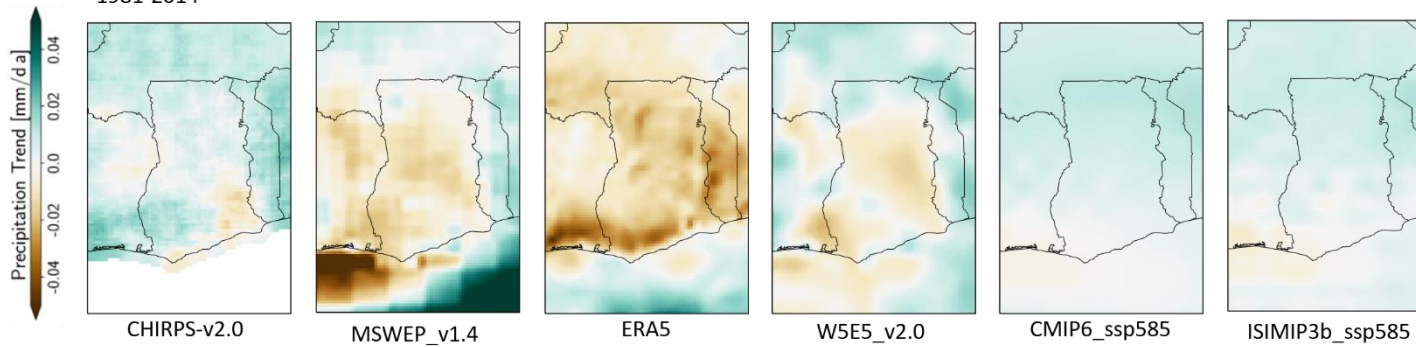
Figure 4: Precipitation trend in mm/d a from 1981 to 2014 for Ghana

Additionally, Figures 5, 6 and 7 provide an overview of the trend in annual precipitation and temperature trends for different gridded climate data sets for the past and the future for Ghana, Kenya and Zimbabwe.

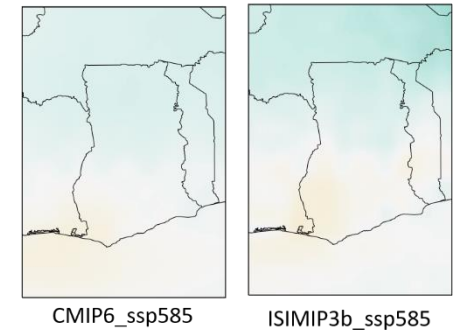
Ghana

Annual precipitation trend

1981-2014

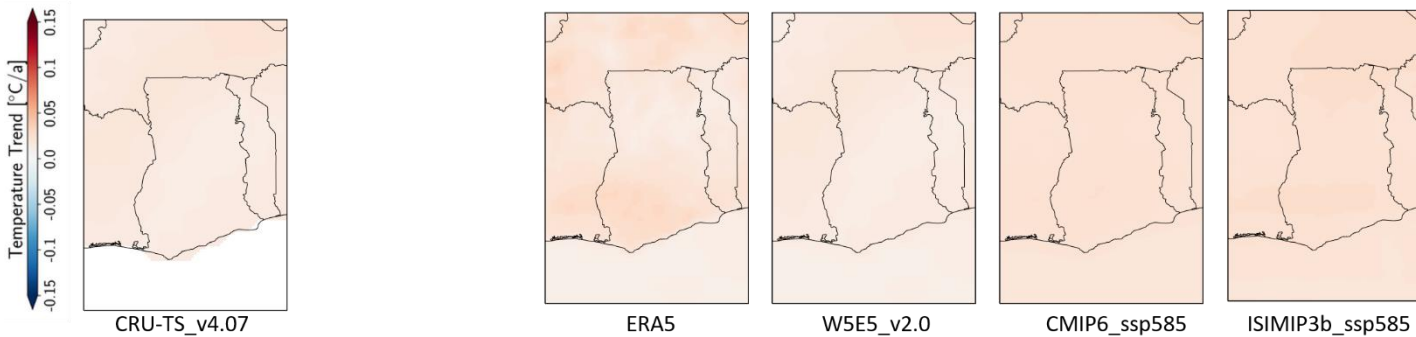


2001-2050



Annual temperature trend

1981-2014



2001-2050

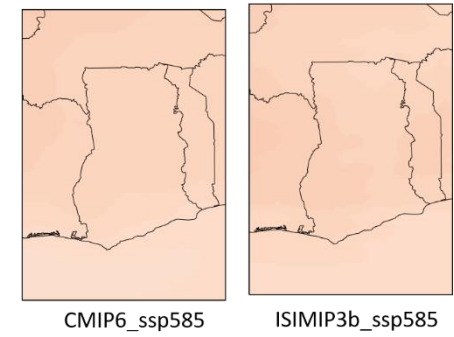
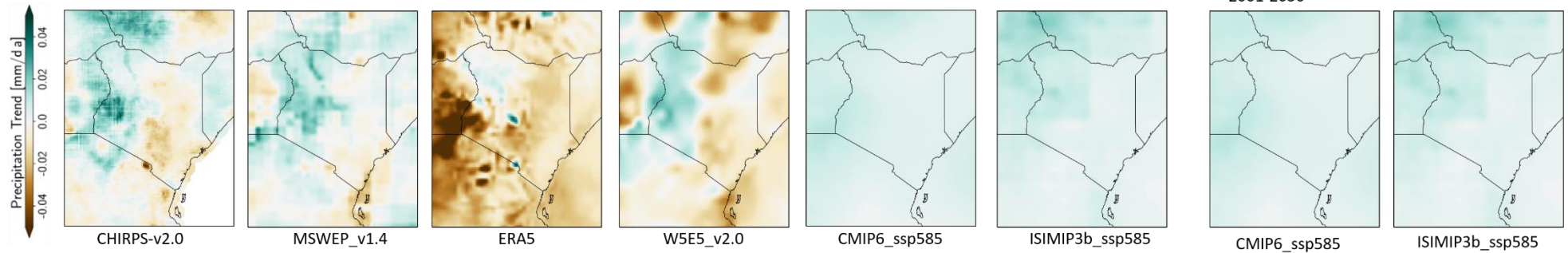


Figure 5: Annual precipitation trend in mm/d a and annual temperature trend in °C/a from 1981 to 2014 and from 2001 to 2050 for various gridded climate data sets for Ghana

Kenya

Annual precipitation trend

1981-2014



Annual temperature trend

1981-2014

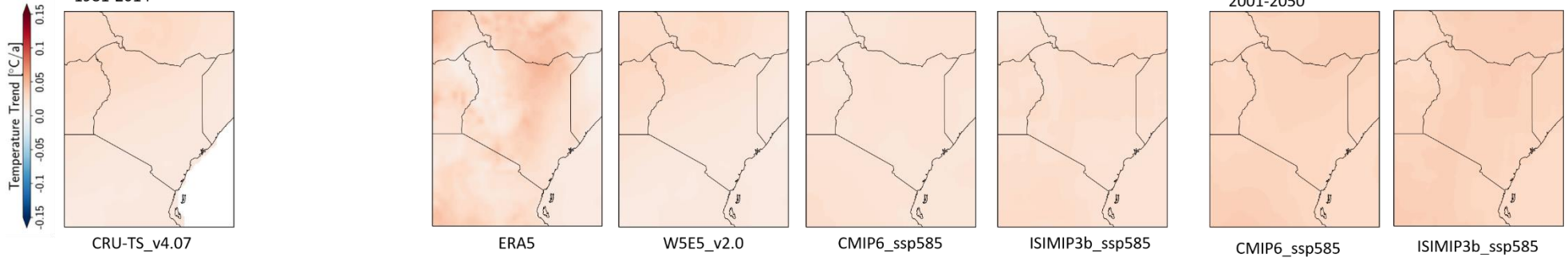


Figure 6: Annual precipitation trend in mm/d a and annual temperature trend in °C/a from 1981 to 2014 and from 2001 to 2050 for various gridded climate data sets for Kenya

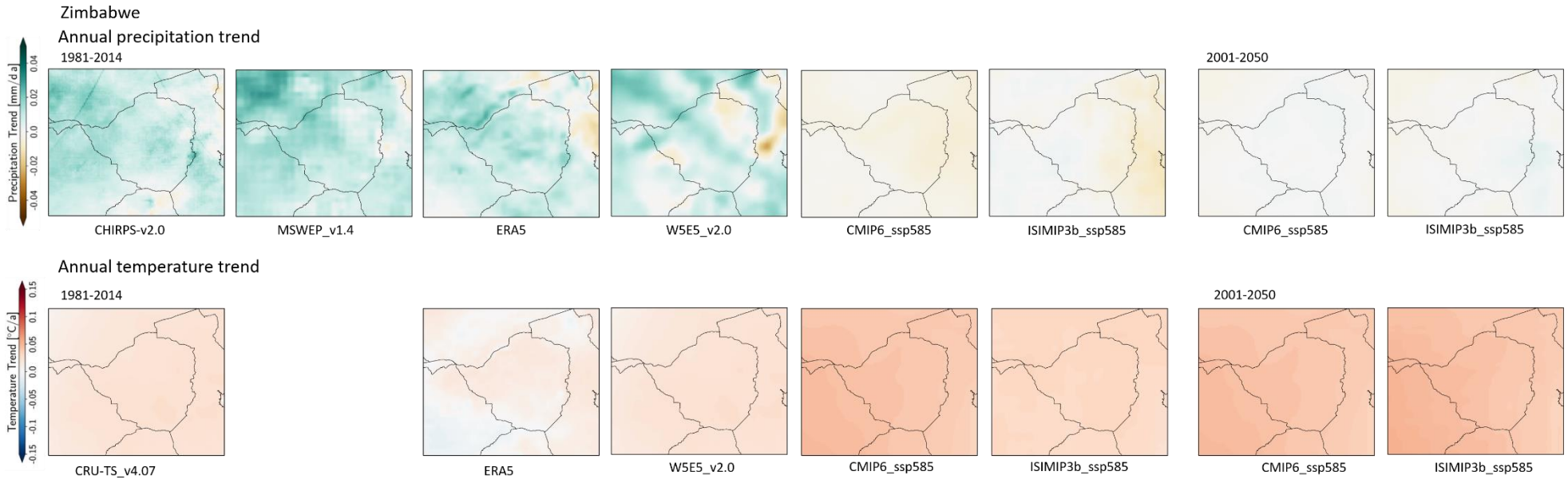


Figure 7: Annual precipitation trend in mm/d a and annual temperature trend in °C/a from 1981 to 2014 and from 2001 to 2050 for various gridded climate data sets for Zimbabwe

Non-climate related data sources

Additional to the climate data sources described, the co-creation of climate services and tools often require other domain specific data sources. In the case of the SAFE4ALL use cases, this involves data on land use and socio-economic variables (e.g. population, GDP, literacy levels, standard of living, labour force, conflicts, migration etc.).

2.2 Data repositories and formats

The project builds on existing data repositories and platforms such as ECMWF, Copernicus Climate Change Service (C3S), NASA Earth Data, NOAA, ESA-EUMETSAT, ISIMIP and those of the Met Offices KMD, ZMD and GMet and TAHMO. The data provided on these platforms are commonly in the format of shapefiles (in ESRI formats), raster data sets in NetCDF, TIFF and GeoTIFF formats or timeseries and metadata in CSV and JSON formats. Other data could also be derived from PDF or MS Excel formats.

2.3 Available and required data sources and sets of project partners of SAFE4ALL

To foster and facilitate discussions on data integration for specific data sources and sets among SAFE4ALL project partners, a dedicated session was organized during the General Assembly Year 1 in 2024. The session aimed to address the following key topics:

- Available datasets
- Required datasets
- Collaboration opportunities and knowledge exchange related to specific datasets
- Data sharing policies

Discussions during the session covered both individual case study countries (Table 2, 3 and 4) and cross-country perspectives (Table 5), emphasizing the extensive knowledge and expertise of project partners related to data sources and sets needed for co-creating climate tools and services within SAFE4ALL. Available data includes observed and gridded climate data, agricultural and socioeconomic information, household data, and population data, while required data spans high-resolution climate and weather station data, hydrological and satellite observations, agricultural risk data, but also social media and marketing trends.

Ghana

Table 2: Available and required data sets for the co-creation of tools and services in Ghana

Available data	Needed data
<ul style="list-style-type: none"> - Labour data (independent) - Market data (local and regional) - Climate data (meteorological services) - Education data (Ministry of Education) - Internet & comms <ul style="list-style-type: none"> o Broadband data (coverage, users, and penetration rates) o Coverage by Region (households, businesses, and government) 	<ul style="list-style-type: none"> - Yield data for main crops and admin level - GMES - Data for soil/ weather - Satellite Data - Landuse/ landcover data - Vegetation/ greenness data - Market data - LST - Dry/ wet spells

Kenya

Table 3: Available and required data sets for the co-creation of tools and services in Kenya

Available data	Needed data
<ul style="list-style-type: none"> - Households survey data - Population & housing census (2019) - Censuses from various counties - Health data from Ministry of Health - Education data from Ministry of Education - Emp. Data from NIPS - NBS, LFS (2016-2019) 	<ul style="list-style-type: none"> - Rainfall & Weather Data - Satellite (EO) Data - Radar Data - Radio, Mobile Data (CF) - Infrastructure Data (Roads) - Social/Economic Analysis: Agreement Data

Zimbabwe

Table 4: Available and required data sets for the co-creation of tools and services in Zimbabwe

Available data	Needed data
<ul style="list-style-type: none"> - Border data (less than 24 hrs) - Census data and descriptions of enumerated events for 10 years from 2002 - ZMO IDP data 	<ul style="list-style-type: none"> - Gridded data for climate projections to provide more refined analysis with national stations - Satellite data

Across all countries

Table 5: Available and required data sets for the co-creation of tools and services across all countries

Available data	Needed data
<p>Observed climate data</p> <ul style="list-style-type: none"> - Temperature & rainfall - Station-level data - Data from regional climate centers <p>(Global) gridded climate data</p> <ul style="list-style-type: none"> - Historical & future scenarios - WorldClim - Go-BC <p>DROPapp weather</p> <ul style="list-style-type: none"> - Local weather forecast indicators (indigenous knowledge) - Spires - Dominance unit <p>Agricultural production data</p> <ul style="list-style-type: none"> - Crops, harvest areas, production on national/subnational level <p>Crop & livestock data</p> <ul style="list-style-type: none"> - Livestock - Land Use - Agricultural practices & benefits of adoption <p>Socioeconomic data</p> <ul style="list-style-type: none"> - Poverty - Population density - GDP - Subnational levels - Harmonized household data - Economy-wide social accounting matrix <p>Population projection data</p> <ul style="list-style-type: none"> - Health data - Maternal & child health <p>Other:</p> <ul style="list-style-type: none"> - Current & future maize analysis - Cross-cutting data (with geo-coordinates) 	<p>Climate and weather data</p> <ul style="list-style-type: none"> - High-resolution gridded climate data - Weather station data - CPC data - CHIRPS - Temp. & precip. records - Preliminary observed temp - Precipitation data: TAHMO -historic, and recent, TRMM / CHIRPS / GPCC - API / URL with nearest start-to-now/last ten years forecast (Rainfall / Temp) for DROP support - Spires - Cropped weather forecast (calling from Met offices) <p>Satellite data</p> <ul style="list-style-type: none"> - Raw EUMETSAT satellite data <p>Hydrological data</p> <ul style="list-style-type: none"> - Hydrological proxy discharge - River discharge / level data - Lake data: in-situ observations in the lakes <p>Agricultural data</p> <ul style="list-style-type: none"> - Agricultural DRM / DRR <p>Other:</p> <ul style="list-style-type: none"> - Social media data / public opinion - Marketing

The session revealed significant alignment between available and required datasets among partners, particularly for weather station data, gridded climate projections, agricultural data, and remote sensing. This underlines the importance of fostering collaboration and exchange. However, data-sharing policies remain to be addressed, requiring ongoing dialogue to ensure access and effective integration.

3 Pre-processing steps for data integration

The use of climate data in the co-creation of climate tools and services within WP2 involves several pre-processing steps to ensure the data meets the specific requirements of the use cases in Ghana, Kenya, and Zimbabwe. These steps are essential to ensure that the data is aligned with the spatial and temporal scales needed, and is in a format suitable for further analysis. Proper pre-processing ensures that the climate data can be effectively integrated into the tools and services being developed, ultimately leading to more user-relevant outputs. The following sections provide a more detailed discussion of the key pre-processing steps: temporal and spatial alignment, quality checks, and the creation of specific climate indicators.

3.1 Temporal and spatial alignment

Temporal and spatial alignment are crucial steps in ensuring that the available climate data matches the specific needs of the use cases. This is particularly important as the tools and services within WP2 operate on different scales – both temporally and spatially. Temporal alignment involves ensuring that the climate data corresponds to the time periods required by the user, whether it is historical data or future projections. This might include aggregating daily data into monthly or seasonal summaries or aligning data from different sources to the same time intervals. Spatial alignment focuses on ensuring that the data is matched to the geographic scales needed for the use cases, such as national, regional, or local levels. This may involve re-gridding or interpolating data to ensure consistency in the spatial resolution, allowing for meaningful comparison and analysis across regions. Proper alignment allows for the integration of datasets that come from different sources. This is particularly important when it comes to integrating weather station data, which is point-based on gridded climate data.

3.2 Quality checks

Quality checks are a fundamental part of the pre-processing process, ensuring that the data is accurate, consistent, and suitable for use in the climate tools and services being co-created. This step involves identifying and correcting errors or inconsistencies within the dataset, such as missing values, outliers, or discrepancies between different data sources. Various techniques, such as data imputation, interpolation, or statistical methods, can be used to address these issues. Consistently high-quality data is crucial for the success of the co-created tools and services.

3.3 Creation of specific climate indicators

The creation of specific climate indicators is a key step in transforming raw climate data into actionable information that can be used in decision-making processes. Climate indicators are derived from the raw data and are designed to highlight specific aspects of the climate that are relevant to the use cases. For example, temperature thresholds, precipitation anomalies, or drought indices might be created to provide insights into climate risks and trends. The creation of these indicators involves the application of statistical methods to aggregate, normalize, or transform the raw data into more interpretable formats, such as indices or time series. These indicators can be tailored to meet the needs of specific stakeholders, allowing them to assess climate conditions and make informed decisions regarding agricultural practices, disaster management, or climate adaptation strategies.

4 Infrastructure for data integration

In order to facilitate data integration, an appropriate data infrastructure needs to be set up. This has been described in more detail in the data management plan of SAFE4ALL (Deliverable D7.4 Version 1). The following sub-chapters highlight key aspects for data integration related to access, storage, sharing and dissemination and standardization building on the data management plan.

4.1 Data access

To enhance the uptake and utilization of data and outputs from the SAFE4ALL project, a well-organized and easily accessible data infrastructure, including a metadata-rich database, is being established. This builds on data infrastructure and tools developed in previous projects and aligns with open science practices. To facilitate seamless data integration into models within SAFE4ALL and for external use, most data will be accessed or made available through Application Programming Interfaces (APIs).

4.2 Data storage

All general project data collected within the project will be curated using the 4TU servers since it is continuously backed up with a total data recovery period of 2 days maximum for any data lost. Using these servers and related services will enhance the accessibility of data to internal and external users.

Project data is maintained and securely preserved on 4TU servers at TUD and WU during and after the project, ensuring long-term FAIR data archiving for over 10 years. Additionally, the Copernicus DIAS servers are used to support data processing, analysis, and temporary storage. Existing datasets on cloud servers maintained by partners remain in place to sustain data flows beyond the project.

4.3 Data sharing and dissemination

To facilitate seamless data integration across use cases and partners, the project follows the FAIR principles, making SAFE4ALL data Findable, Accessible, Interoperable, and Reusable. Data and metadata are standardized using consistent naming conventions with version numbers. Metadata includes details such as data collection methods, equipment used, ownership and proprietorship, location (latitude, longitude, elevation), quality control flags, variable definitions, units of measurement, file formats, and software used for data collection and processing. Integration with GEOSS is facilitated through the existing

TWIGA platform.

In the SAFE4ALL project, geodata is shared via GeoServer and time-series databases, while other datasets and reports are shared through secure cloud platforms like OneDrive, SharePoint, Google Workspace, and Teams with restricted access. Data sharing follows SAFE4ALL ethics principles, ensuring any personal data remains confidential and governed by FAIR principles if shared.

To make information accessible, all peer-reviewed publications related to SAFE4ALL methods and outputs are published as Gold Open Access. Preprint platforms like Advanced Science, Open Research Europe, ArXiv, and institutional archives are used to share early results. Methods and tools developed adhere to open-source principles, promoting transparency, collaboration, and participation during and beyond the project. Outputs such as algorithms and workflows are shared on platforms like GitHub or Bitbucket and archived on Zenodo. Open data sources, such as Copernicus, are prioritized, with results distributed in open data formats following FAIR principles.

4.4 Data standardisation

To enhance data interoperability, the ISO 19115/19139 and OGC (JSON, GeoJSON, XSD) schemas will be used by SAFE4ALL. The geospatial data sets will be connected using GeoServer with data formats in ESRI Shapefiles, NetCDF, TIFF and GeoTIFF. Other data sets could be in CSV, Microsoft Word, Pdf or Excel formats as stated in section 2.2 of this report.

5 Recommendations and outlook

This report provides an overview of data sources for their integration across climate tools and services within WP2, aiming to provide a basis for co-creating tailored, user-centered services for end-use cases in Ghana, Kenya, and Zimbabwe. Data integration within SAFE4ALL is an on-going and iterative process that evolves through deeper collaboration among project partners, a growing understanding of user needs, the appreciation of changes in those needs during the co-creation process and the development and tailoring of the specific tools and services. While data harmonization is essential for ensuring comparability and transferability across use cases, tailoring is equally important to develop climate tools and services that address specific user requirements in diverse contexts. This underscores the need for flexibility and adaptability in integration efforts.

Looking forward, fostering trust and collaboration among project partners, alongside sustainable project management, will be essential to ensuring effective data integration, sharing and accessibility. This requires establishing processes and resources to support continuous data integration, including regular updates to datasets, tools, and methods to adapt to evolving project needs, as well as promoting transparent communication to build trust and engagement among all stakeholders.



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