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COMPREHENSIVE ACTION FOR CLIMATE CHANGE INITIATIVE

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CACCI FIELD NOTES

Guidelines for Measuring Changes in Greenhouse Gases, Land Uses and Climate Parameters using Satellite Remote Sensing Data

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About the CACCI Field Notes

AKADEMIYA2063 CACCI Field Notes are publications by AKADEMIYA2063 scientists and collaborators based on research conducted under the Comprehensive Action for Climate Change Initiative (CACCI) project. CACCI strives to help accelerate the implementation of Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) by meeting the needs for data and analytics and supporting institutional and coordination capacities. In Africa, CACCI works closely with the African Union Commission, AKADEMIYA2063, the African Network of Agricultural Policy Research Institutes (ANAPRI), and climate stakeholders in selected countries to inform climate planning and strengthen capacities for evidence-based policymaking to advance progress toward climate goals.

Published on the AKADEMIYA2063 website (open access), CACCI Field Notes provide broad and timely access to significant insights and evidence from our ongoing research activities in the areas of climate adaptation and mitigation. The data made available through this publication series will provide evidence-based insights to practitioners and policymakers driving climate action in countries where the CACCI project is being implemented.

AKADEMIYA2063's work under the CACCI project contributes to the provision of technical expertise to strengthen national, regional, and continental capacity for the implementation of NDCs and NAPs.

AKADEMIYA2063 is committed to supporting African countries in their efforts against climate change through provision of data and analytics using the latest available technologies. This Field Note describes all the essential parameters or metrics used under CACCI, with a focus on the measurement of greenhouse gas (GHG) emissions, covering low carbon economy, resilient environment and ecosystem, land use and land cover, land surface temperatures, normalized difference vegetation index (NDVI), rainfall, and evapotranspiration data.

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About AKADEMIYA2063

AKADEMIYA2063 is a pan-African non-profit research organization with headquarters in Kigali, Rwanda and a regional office in Dakar, Senegal. Inspired by the ambitions of the African Union's Agenda 2063 and grounded in the recognition of the central importance of strong knowledge and evidence-based systems, the vision of AKADEMIYA2063 is an Africa with the expertise we need for the Africa we want. This expertise must be responsive to the continent's needs for data and analysis to ensure high-quality policy design and execution. Inclusive, evidence-informed policymaking is key to meeting the continent's development aspirations, creating wealth, and improving livelihoods.

AKADEMIYA2063's overall mission is to create, across Africa and led from its headquarters in Rwanda, state-of-the-art technical capacities to support the efforts by the Member States of the African Union to achieve the key goals of Agenda 2063 of transforming national economies to boost economic growth and prosperity.

Following from its vision and mission, the main goal of AKADEMIYA2063 is to help meet Africa's needs at the continental, regional and national levels in terms of data, analytics, and mutual learning for the effective implementation of Agenda 2063 and the realization of its outcomes by a critical mass of countries. AKADEMIYA2063 strives to meet its goals through programs organized under five strategic areas—policy innovation, knowledge systems, capacity creation and deployment, operational support, and data management, digital products, and technology—as well as innovative partnerships and outreach activities. **For more information**, visit www.akademiya2063.org.

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1. Introduction

This technical document describes all the essential parameters or metrics used under the Comprehensive Action for Climate Change Initiative (CACCI). The basic parameters and metrics described are those under Thematic Cluster One (TC1) which deals with environmental parameters. The TC1 is divided into two result areas: low carbon economy, and resilient environment and ecosystem. The first result area deals with the measurement of greenhouse gas (GHG) emissions such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2o). The second result area considers land use and land cover, land surface temperatures, the normalized difference vegetation index (NDVI), rainfall, and evapotranspiration data. The sections that follow describe six databases, however, data on carbon dioxide and nitrous oxide are not covered as these will be the subject of another version of this document.

This document does not address the analytical or computational aspects of the study envisioned under CACCI; it describes the datasets that will be used to compute them. The document presents guidelines that set the technical basis for the datasets and equip the reader with a reference document to understand them better. Field notes and reports will be published throughout the implementation of CACCI that speak to the project's analytical or computational aspects.

The document has six sections representing each dataset. Each section follows the same structure:

1. An introduction to the parameter or indicator in terms of definition, use case, and data interpretation;

2. Technical characteristics of the parameter or indicator, such as temporal and geographical extent, and available year, among others;

3. Relevant metadata or critical information for their proper use.

It is worth noting that all the data mentioned in this document were obtained using satellite remote sensing methods due to their ability to cover areas with a large geographical extent, such as the CACCI implementation countries, namely, Senegal and Rwanda. Finally, all communication related to this document should be addressed to dpt@akademiya2063.org.

Disclaimer: This document uses publicly available satellite remote sensing data. Data contents clipped to Rwandan national borders may be added for illustration purposes. National borders are defined by shapefiles derived from the country's geodata portal at https://nsdi-rla.hub.arcgis.com. AKADEMIYA2063 uses the country shapefile mentioned above to limit the map data to the country's geographical extent. As such, the boundaries, names, and designations shown on maps do not imply official endorsement or acceptance by AKADEMIYA2063.

2. Measurement of Greenhouse Gas Emissions

A key parameter for the low carbon economy result area is the measurement of greenhouse gas (GHG) emissions. In this report, the only greenhouse gas we consider is methane. Greenhouse gas emissions are usually measured by obtaining estimates based on emission factors by sector and activity. Each activity is associated with the amount of greenhouse gases it produces. Estimates of greenhouse gas emissions can be obtained by multiplying the emission factor with the cardinal of the corresponding activity. In CACCI, greenhouse gas estimation is based on actual measurements using satellite remote sensing data.

2.1. Methane Concentration Measurements

For methane density measurements in CACCI, we used the TROPOspheric Monitoring Instrument (TROPOMI), which is the unique payload of the Sentinel 5 Precursor (S5P) mission of the European Space Agency (ESA). The instrument is a nadir-viewing shortwave spectrometer. It uses a passive remote sensing technique, that is, radiation reflected by and from the Earth, measured at the top of the atmosphere. The instrument collects information in the UV-Visible, Near Infrared (NIR), and Shortwave Infrared (SWIR) wavelengths using a two-detector sensor. The TROPOMI has a seven kilometer wide swath for the duration of a second and in the flight direction. Data collected for each swath is divided into two parts: the first embeds the position of the information in the swath, and the second, its spectral information. The TROPOMI enters its operational phase in April 2018 and its mission is scheduled to end in 2023.

2.1.1. Measurement Principles

The methane concentration provided by the TROPOMI is a column-averaged, dry air mixing ratio. Methane concentration is measured as a fraction of its quantity within an atmospheric column relative to a corresponding amount of dry air. The computation was done by calculating the concentration in each atmospheric sub-layer within the column and then summing this up. The formula is shown below:

$$X_{CH_4} = \sum_{i=1}^{n} \frac{x_i}{V_{air,dry}}$$

In the equation above, X_{CH_4} is the column-averaged dry air mixing ratio of methane, x_i is the methane concentration for each sub-layer of the atmosphere within the column and, $V_{air,dry}$ is the volume of dry air in the column. The European Centre for Medium-Range Weather Forecasts (ECMWF) provided the dry air volume and x_i was derived from the full physics (RemoTeC) algorithm. The formulation above also means that the methane concentration from TROPOMI should not be taken as an earth surface methane concentration but as its concentration within an atmospheric column. Two factors justify its use here: (i) its ability to cover large areas of interest, (ii) its temporal and spatial resolution, and (iii) its sensitivity to surface methane concentration which can be used as a proxy for methane concentration on the ground. In addition, the methane concentration was found to have a high sensitivity to its concentration in the layer closer to Earth.

2.1.2. Measurement Validation

The methane concentration XCH_4 has been validated by comparing its measurements with the reference data from all stations in the ground-based Total Carbon Column Observing Network (TCCON) and Infrared Working Group of the Network for the Detection of Atmospheric Composition Change (NDACC-IRWG) networks[1].

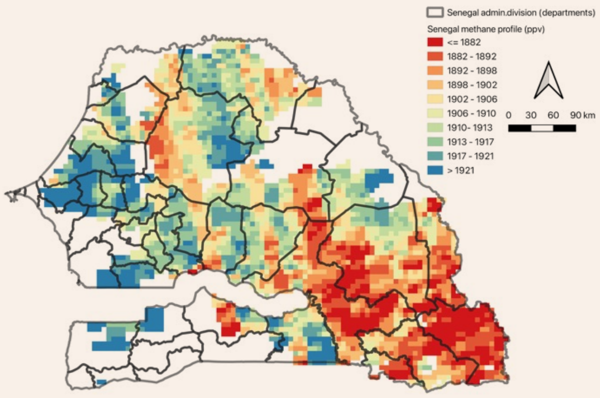
The TCCON consists of a network of ground-based Fourier transform spectrometers (FTSs) [1] which records direct solar absorption spectra in the NIR spectral range. The absorption in the NIR is then used to retrieve accurate column-averaged quantities of atmospheric gases such as methane. Data from all stations (23 in the Northern Hemisphere and 5 in the Southern Hemisphere) have been used for the S5P methane column-average concentration. The data has also been used to validate trace data produced by satellite observations such as OCO-2 and GOSAT. The stations also cover different atmospheric and surface conditions, making the validation process more robust.

The NDACC-IRWG also consists of a network of FTSs. However, its measurements differ from those of the TCCON as the NDACC-IRWG measures direct solar radiation absorption in the mid-infrared (MIR) spectral range. The absorption rate is then used to determine the quantity of trace gases such as methane. The NDACC-IRWG network consists of 20 stations distributed from pole to pole.

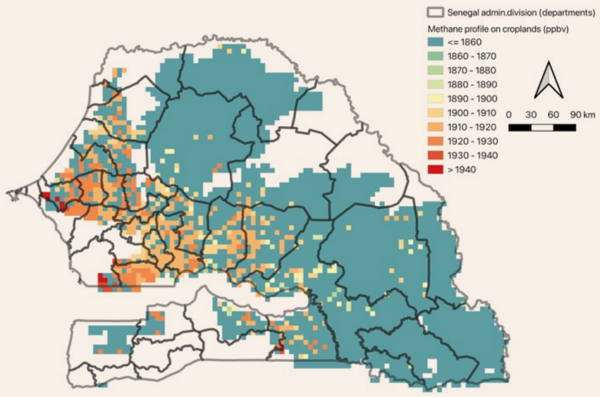
1 It is worth noting that there is no inland station in Africa for both TCCON and NDACC-IRWG.

Figure 1: *Examples of Senegal's methane profiles for the week, November 21-27, 2022.*

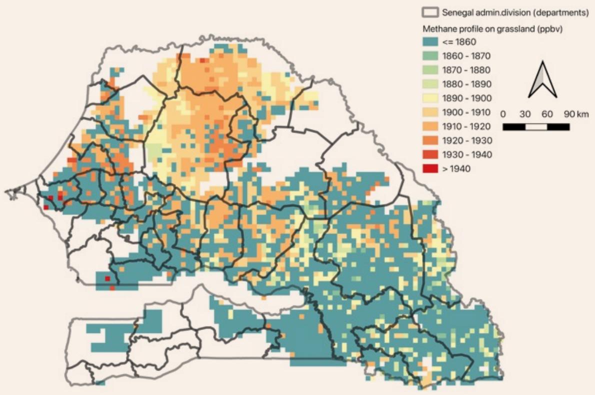
Panel (1-1) General methane concentration profile



Panel (1-2) Methane profile above croplands



Panel (1-3) Methane profile above grasslands.



3. Measurement of Land Use Change Indicators

3.1. Land Use and Land Cover

Land use and land cover (LULC) refers to the human activities and physical features found on the Earth's surface. This parameter describes how people manage and utilize land on the Earth's surface, including infrastructure development, urbanization, and agriculture. Additionally, land cover represents the biological and physical features of the land, including vegetation, water bodies, and built-up areas. Analysis of LULC involves classifying, mapping, and monitoring different types of land use and land cover. It aims to identify and analyze LULC patterns, changes, and dynamics over time. This information is critical to investigating the complex relationships and dynamics between humans and the environment. LULC analysis is a valuable tool, essential for urban planning, agriculture, conservation, environmental management, natural resource management, environmental monitoring, biodiversity conservation, disaster risk assessment, and climate change studies.

Remote sensing techniques are extensively used for LULC analysis in conjunction with geographic information systems (GIS) and machine learning algorithms. Satellite photographs from missions such as PROBA-V, Sentinel, and other Earth observation platforms provide valuable data sources for mapping and tracking LULC patterns at various spatial and temporal scales.

3.1.1. Copernicus Global Land Cover

The release of the Copernicus Global Land Cover Collection 2 in May 2019 marked a significant advance in land cover mapping technology. This comprehensive dataset offers a wealth of information to researchers, scientists, and practitioners across various fields. At the core of Collection 2 is a discrete global map that provides detailed land coverage information at a spatial resolution of 100 meters. This high-resolution map accurately identifies and delineates different land cover types, facilitating in-depth analysis and decision-making processes.

The inclusion of cover fraction layers sets Collection 2 apart as this goes beyond the traditional discrete mapping approach. Cover fraction layers provide a highly nuanced perspective by depicting the percentage of coverage for the main land cover types within each pixel. This allows users to better understand areas with heterogeneous coverage, where multiple land cover types co-exist. By incorporating these cover fraction layers, the dataset offers a more comprehensive and precise representation of the Earth's surface, enabling the tailored preparation of land cover maps.

The dataset comprises 20 layers, providing a rich and diverse range of land cover information. This extensive collection caters to a wide array of user needs and applications. For example, researchers can utilize the dataset for forest monitoring to track changes in forest cover over time and assess deforestation rates. It also supports crop monitoring, which supports analysis of agricultural practices, yield estimation, and land management strategies. Additionally, the dataset is valuable in biodiversity and conservation studies, helping to identify habitat areas and monitor changes in ecological landscapes. Furthermore, climate modeling benefits from the dataset's accurate land cover information, assisting in understanding land-atmosphere interactions and predicting climate patterns.

The dataset has been significantly enhanced to ensure reliable and precise land cover classification. With an overall accuracy of approximately 80 percent or more, Collection 2 represents a significant improvement in map quality compared to its predecessor. The increased accuracy enhances the dataset's utility and reinforces its value for various applications. Moreover, the dataset's global coverage provides a comprehensive view of land cover dynamics across different regions and continents, facilitating analysis and comparison at the global scale.

3.1.2. Dataset Description

The dataset consists of annual land cover maps that provide detailed spatial information about different types or classes of physical cover on the Earth's surface. The maps have a spatial resolution of 100x100 meters, allowing for a high level of detail in land cover classification. The dataset includes the major land cover classes: forests, grasslands, farmlands, lakes, and wetlands.

In addition to the individual land cover classes, the dataset includes a continuous field layer or "fractional map" for each basic land cover class. This fractional map provides estimates of vegetation or land cover that are proportional to each type of land cover. It represents the degree or fraction of a specific land cover class within each pixel, allowing for a more accurate representation of areas with mixed or uneven land cover.

The dataset employs a dynamic mapping approach that considers land cover class transitions over time. This means that the maps capture changes in land cover types and highlight the most significant transformations over the specified period. The dynamic nature of these maps provides valuable information for monitoring land cover transitions, assessing environmental changes, and supporting various applications that rely on accurate land cover information.

3.1.3. Methodology

The dataset's land cover fractions and classification were generated using a dedicated satellite, PROBA-V and pre-processing was conducted on the Sentinel-2 tiling grid, which has a resolution of 110x110 kilometers. The pre-processing steps involved geometric and atmospheric corrections, data cleaning, and feature classification.

A classification algorithm was trained using quality training data comprising approximately 168,000 points to improve the accuracy of the land cover mapping. This training data was crucial in enhancing classification accuracy and generation of reliable land cover maps. Global production of land cover products began in 2015. The overall accuracy of the land cover maps has reached 80 percent at class level 1 on each continent.

Using the Sentinel-2 tiling grid facilitates a seamless transition from PROBA-V to Sentinel-2 data, which is planned for the next generation of annually produced maps as part of the continuous global land cover service under the Copernicus program. Ensuring temporal consistency across the annual land cover maps was a key focus during the classification process.

Areas exhibiting potential land cover changes are identified as different classes in annual maps, providing valuable information on land cover dynamics over time. Specific algorithms were applied to enhance the stability of the annual classifications to maintain temporal consistency. These algorithms minimize the discrepancies between annual maps that may arise from inconsistent classifications.

Production of annual land cover maps is essential to the Copernicus global land monitoring service. Support from the European Commission and member states of the European Union ensures the continuity of this service. The methodology for generating these maps has been published in [2], providing transparency and enabling further research and development in land cover mapping and monitoring.

3.1.4. Accuracy Assessment

The assessment of uncertainty and accuracy for the land cover maps derived from the dataset follows a rigorous approach. The assessment methodology adheres to the standards set by the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Land Product Validation (LPV).

A global stratification approach is utilized, independent of any land cover map, using the Sentinel-2 Universal Transverse Mercator (UTM) grid as a geographic base to evaluate the accuracy. This stratification results in more than 21,000 primary sampling units (PSUs) reference pixels for 2015-2019.

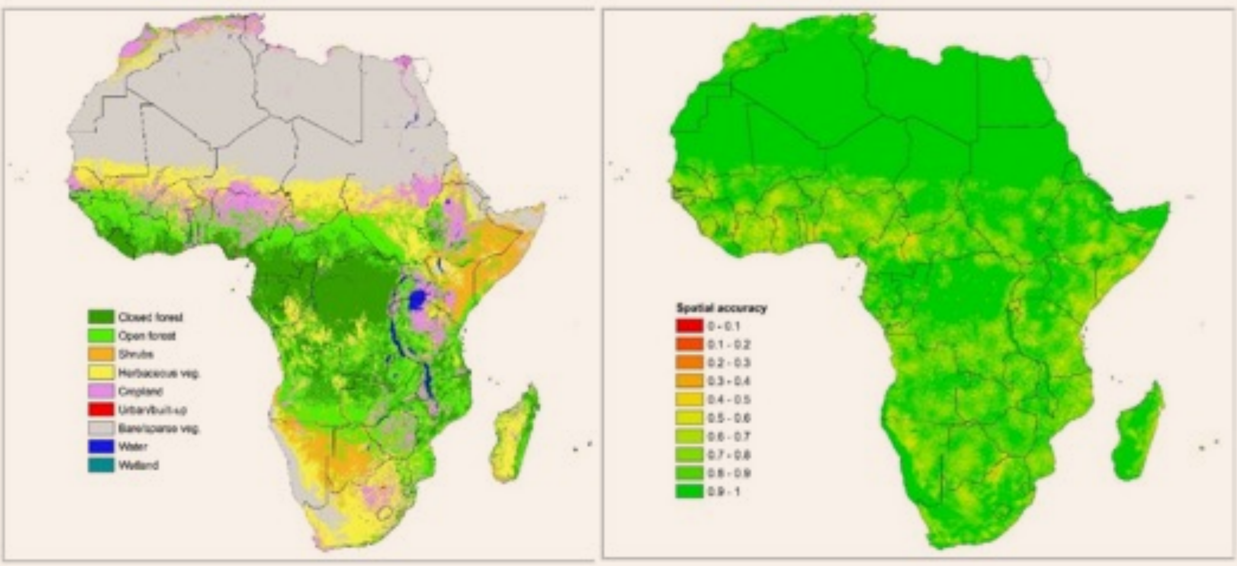
For the discrete Copernicus Global Land Service land cover map (CGLS-LC 100m V3.0 Level 1), the overall accuracy for 2015 is 80.6 percent (±0.7 percent). The subsequent years (2016-2019) exhibit overall accuracies ranging from approximately 80.3 to 80.5 percent. At the continental level, the overall accuracy is approximately 80 percent, with Asia having the highest accuracy at 83.7 percent and North America having the lowest accuracy at 77.6 percent (for 2015).

At Level 2, where closed and open forest classes are separated, the overall global accuracy is 75.4 percent (±0.7 percent). The overall accuracies at the global and continental levels demonstrate consistency in the quality of the yearly land cover maps.

The "no-change" class, which covers most of the land area, is mapped with very high accuracy. Among the cover fraction layers, the maps for snow/ice, built-up areas, water, and lichen/moss fractions exhibit the lowest errors. The overall accuracy of the change/no-change map for 2015-2018 is reported to be 99.6 percent. However, the "change" class is more prone to errors of commission (45.6 percent) than omission (36 percent).

The stability and consistency in the accuracy of the yearly land cover maps supports the reliable results obtained for change detection. It is important to note that any estimation of area change in the context of GHG inventories should consider utilizing reference data for stratified area estimation, due to the potential uncertainties and errors associated with land cover classifications.

Figure 2: *The CGLS-LC 100m discrete (left) and the corresponding spatial accuracy (right). Data source: Buchhorn, M.; B. Smets; L. Bertels; M. Lesiv; N.-E. Tsendbazar; D. Masiliunas; L. Linlin; M. Herold; S. Fritz. 2020. Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch <2015-2019>: Globe (Version V3.0.1). Zenodo. DOI: < 10.5281/zenodo.3939050 >*[2]



2 The digital object identifier (DOI) is for the year 2019. From 2015 to 2018, the DOIs are different and are available at the following page: https://lcviewer.vito.be/about#citation

3.2. Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a remote sensing method used to measure vegetation health and density within a given area. In this project, we used NDVI data provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. MODIS is a crucial instrument in NASA's Earth Observing System (EOS) program. It has operated aboard two EOS satellites, Terra and Aqua, since 1999 and 2002, respectively. MODIS has 36 spectral bands, covering a wavelength range of 0.4 to 14.4 micrometers. The instrument's spatial resolution varies depending on the band and platform, ranging from 250 meters to one kilometer at the nadir. MODIS also has a swath width of 2,330 kilometers, meaning it can image the entire Earth's surface every one to two days. The data are provided in several formats, including Level-1B calibrated radiance, Level-2 atmospheric and land products, and Level-3 gridded products.

The (MOD13A2) Version 6.1 product, used in this project, provides Vegetation Index (VI) values per pixel basis at 1 kilometer (km) spatial resolution and 16 days temporal resolution. This product has two primary vegetation layers: the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). The algorithm for this product chooses the best available pixel value from all the acquisitions collected over the 16 day period. The criteria are low clouds, low view angle, and the highest NDVI/EVI value. For data processing purposes, MODIS vegetation indices are generated in square tile units that are approximately 1200x1200 km (at the equator) and mapped in the Sinusoidal (SIN) grid projection (equal area projection). Only tiles containing land features are processed. When mosaicked, all tiles cover the Earth's landmass. The global MODIS-VI can thus be generated every 16 days and each calendar month.

3.2.1 Measurement Principles

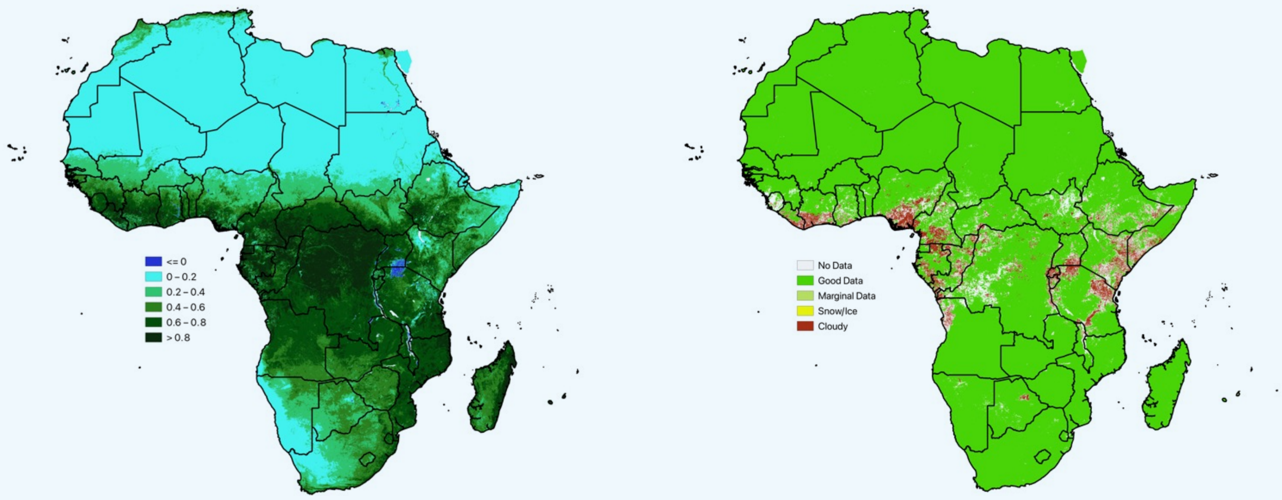
Vegetation Indices (VI) are robust, empirical measures of vegetation activity on the land surface. They are designed to enhance the vegetation reflected signal from measured spectral responses by combining two (or more) wavebands, often in the red (0.6-0.7 µm) and NIR wavelengths (0.7-1.1 µm) regions. The principle behind NDVI calculation is that healthy vegetation reflects more NIR radiation than red radiation. Conversely, non-vegetated surfaces like bare soil and water reflect more red than NIR radiation. The NDVI is therefore calculated by taking the difference between the reflectance values of the NIR and red bands, and dividing this by their sum:

$$\frac{NIR - Red}{NIR + Red}$$

NDVI values range from -1 to +1, with negative values indicating the presence of water or other non-vegetated surfaces, while positive values indicate the presence of vegetation. Higher positive values correspond to denser and healthier vegetation.

The NDVI data obtained from MODIS is a 16-bit signed integer ranging from -2,000 to 10,000. The scaling factor of the data is 0.0001. This scaling factor of 0.0001 is applied to the data to get the correct NDVI value (between -1 and +1).

Figure 3. *Sample NDVI map of Africa in 2023 (left); NDVI clustering by values (right).*



3.2.2 Measurement Validation

The accuracy of the MODIS VI product was assessed through comparisons with AERONET-corrected data, other space and airborne sensors, and radiometric field measurements over a range of biomes and seasonality. At stage 3, the accuracy of MOD13A2 NDVI was found to be within ± 0.025, which represents the ability of the 16-day VI products to retrieve a top of the canopy (TOC) and nadir VI value when observations are of high quality (clear, no sub-pixel cloud, low aerosol, and sensor view angle that is less than 30 degrees).

Validation analyses from various airborne and field campaigns demonstrate that MODIS near-nadir satellite VI has good concordance with top-of-canopy nadir VI and land surface biophysical properties over most biomes. Comparisons of seasonal MODIS VI with seasonal flux tower (FLUXNET) measurements of gross primary production show strong concordance across a global set of biome types. MODIS VI values have also been found to be well aligned with VI computed from the MODIS Nadir BRDF-Adjusted Reflectance (NBAR) product (MCD43A4), eight-day surface reflectance (MOD09), as well as with VIs generated from the ASTER and Landsat ETM+, OLI, and S-NPP VIIRS sensors.

The primary source of NDVI errors is the occurrence of errors in the red band associated with residual atmospheric effects. When the per-pixel quality information is uncertain or erroneous (errors of omission or commission), the overall NDVI error increases to about 0.04 - 0.1 (NDVI units). This larger error envelope captures the sum of all error sources (sensor, atmosphere correction, and uncertainty in quality) and, as such, is the more general global error envelope for the MODIS NDVI time series.

Overall, the MODIS VI product is generated from daily, atmosphere-corrected, bi-directional surface reflectance. The VI values are computed in the same way in time and space, regardless of land cover and soil type, and represent true surface measurements (not modeled and no assumptions) that can be readily validated. However, caution should be exercised in using the VI values over highly bright or dark surfaces, such as snow, desert playas, and inland water bodies. It is also advisable to examine the per-pixel product quality information in order to screen poor quality data before use in applications, science, or research.

4. Measuring Weather Change Indicators

4.1. Rainfall

This project uses the Climate Hazards Group InfraRed Precipitation (CHIRPS) to estimate rainfall. CHIRPS is a high-resolution precipitation dataset developed by the University of California, Santa Barbara, Climate Hazards Group. CHIRPS uses satellite data and ground station observations to produce a gridded dataset of precipitation estimates at a resolution of 0.05 degrees (approximately 5.5 km). The dataset covers the period from 1981 to the present day. CHIRPS combines several data sources to produce its precipitation estimates. These include satellite-based estimates from the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission, as well as infrared brightness temperature data and land surface data. Ground station data from the Global Historical Climate Network (GHCN) and the Food and Agriculture Organization (FAO) are also used to calibrate and validate the satellite data.

4.1.1 Measurement Principles

CHIRPS version 2 consists of three main steps. The first is the construction of a monthly precipitation climatology dataset known as CHPclim. The latter is a high-resolution precipitation dataset that provides a monthly precipitation climatology map at a spatial resolution of 0.05 degrees (approximately 5 km) from 1980-2009. Over 27,000 monthly stations from the FAO and approximately 21,000 stations from the Global Historical Climate Network (GHCN) were used to construct CHPclim. The data from these stations were combined with satellite-based precipitation estimates from Tropical Rainfall Measuring Mission (TRMM) 2B31 microwave precipitation estimates, Climate Prediction Center MORPHing (CMOPRH) technique, microwave-plus-infrared based precipitation estimates, monthly mean geostationary infrared brightness temperatures, and land surface estimates. These different data sources were resampled to a typical 0.05 degree grid. In order to create the 1980-2009 climate normal, a moving window regression was used for each grid cell. The regression models were fit to FAO climate normals, and GHCN station data were used to estimate ratio biases at each station. This process helps to correct any potential biases in the precipitation data and improve the accuracy of the final product.

Once the CHPclim mean has been calculated, the next step is to develop pentadal CHIRP fields. These variations in the CHPclim means are calculated using a local calibration of satellite precipitation estimates with thermal infrared (TIR) cold cloud duration (CCD) statistics. To develop the pentadal CHIRP fields, 0.25-degree TMPA 3B42 (TMPA stands for TRMM Multi-satellite Precipitation Analysis), pentadal precipitation estimates and TIR CCD data are used to develop regression slopes and intercepts. These values are then resampled to a 0.05-degree grid to develop the pentadal precipitation estimates from 1981 to the present day. Then, the pentadal CHIRP values are disaggregated to daily precipitation estimates. This involves using a disaggregation model to distribute the pentadal precipitation estimates into daily estimates.

Finally, the CHIRPS dataset uses a unique station blending procedure to estimate precipitation values at each pixel of its 0.05 degree grid. The first step is to use the CHIRP data to define a local de-correlation distance, at which the estimated point-to-point correlation is zero. This de-correlation slope is calculated using time series of CHIRP data and tends to be stronger in heavy, well-organized convection areas. For any given pixel, the CHIRPS blending procedure involves taking a weighted average of the ratios between the five closest stations and the CHIRP. Ratios greater than three are capped at three, and bias values for any station beyond the de-correlation distance are assumed to be one. A weighted average of these five bias values is then calculated based on their distances and the de-correlation slope. This value is adjusted based on the expected correlation with the nearest station and the expected correlation between 'true' precipitation values and the CHIRP data. The final CHIRPS estimate is a combination of unadjusted and bias-adjusted CHIRP data. This blending procedure ensures that even in co-located stations, the CHIRPS dataset will have some influence from the CHIRP data. The weighting of the CHIRP data in the final estimate is determined by the de-correlation distance, the correlation between the CHIRP and actual precipitation values, and the correlation with the nearest station.

4.1.2 Measurement Validation

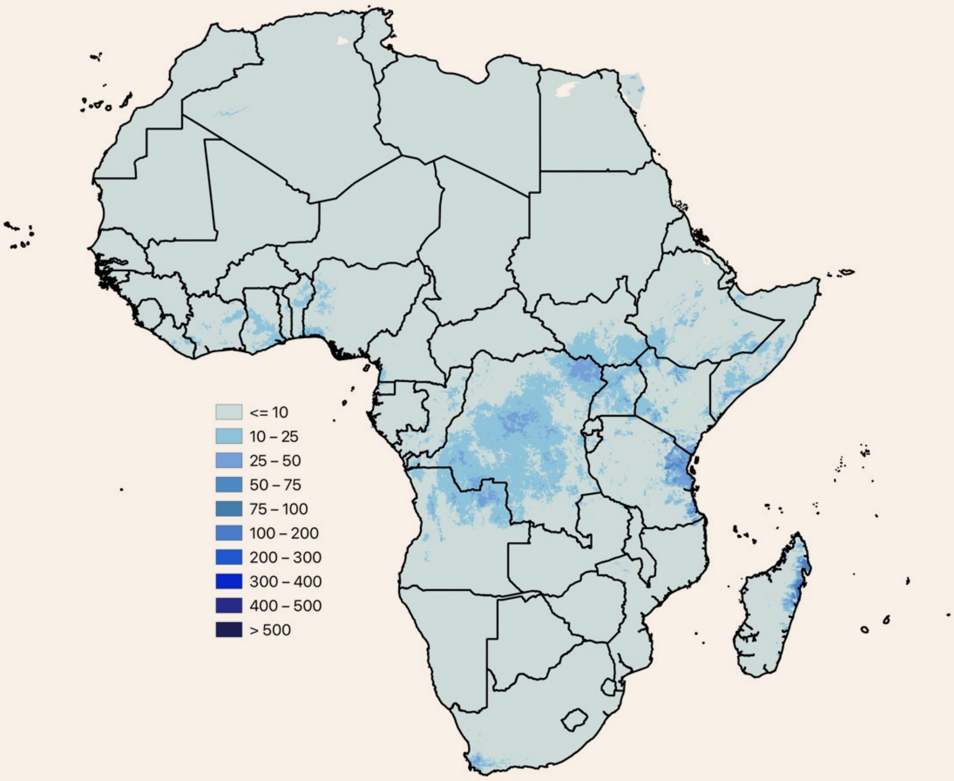
Validation focuses on performance of precipitation estimates during the year's wettest three months. Data from CHIRP and CHIRPS were evaluated and compared with different precipitation products (TMPA 3B42 v7 real-time (RT) estimates, the Climate Forecast System (CFS), the European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis products, and the CPC Unified interpolated gauge products) for a standard 2000-2010 period using the GPCC precipitation dataset as a baseline. These products were chosen because they have coverage and latencies comparable to CHIRP and CHIRPS. The experiments are carried out using the typical 2000-2010 period for analysis and masked areas with mean wet season precipitation totals of less than 50 mm.

The CHIRPS and CHIRP datasets exhibit less bias than the other products, likely due to the use of the CHPclim and the inclusion of station data in the CHIRPS. The CHIRP bias is substantially better than the TMPA 3B42 RT, CFS, and ECMWF. The CPC Unified substantially underestimates precipitation in East Africa, the Middle East, and Southwest Asia, probably due to low station densities.

The wet season correlations between the GPCC and other precipitation estimates were also examined, and CHIRPS exhibited higher correlations than the non-station-based estimates such as CHIRP, CFS, ECMWF, and TMPA 3B42 RT. The CHIRP and TMPA 3B42 RT7 had similar performance, while their overall performance appeared worse than the ECMWF and CFS correlation performance over certain areas, likely due to their improved representation of precipitation processes and storm systems in those areas.

The mean absolute error (MAE) analysis provided a simultaneous evaluation of systematic error (bias) and random errors, and the low bias of CHIRPS resulted in the lowest MAE scores. Even without station inputs, the MAE performance of CHIRP was similar to the CPC Unified over certain areas and substantially lower than the CFS, ECMWF, and TMPA 3B42 RT7.

Figure 4: *Sample rainfall map of Africa in March 2023. The units are in millimeters.*



4.2. Land Surface Temperatures

The land surface temperature (LST) measures the emission of thermal radiance from the Earth's terrestrial surface where the incoming solar energy interacts with and heats the ground or the canopy surface in areas with vegetation. Identified as one of the most important Earth System Data Records by NASA and other international organizations, LST is a fundamental aspect of climate and biology, affecting organisms and ecosystems from the local to the global scale. The LST data products are created from sensors in low earth orbit (LEO), such as the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), which is a key instrument in NASA's Terra and Aqua satellites, providing global coverage of land, ocean, and atmospheric parameters. We used the LST version 6 product data extracted from the MODIS with a spatial resolution of one kilometer, providing users with detailed information about the surface temperature of the Earth's land surface.

- Advantages

The LST has been used to examine the consequences of land cover changes on climate and to investigate the association between maximum thermal anomalies, heat waves, melting ice sheets, and droughts in tropical forests. It combines the results of surface-atmosphere interactions and energy fluxes between the atmosphere and the ground. It is, therefore, a crucial parameter in the analysis of land-surface processes, both regionally and globally, and serves as a reliable indicator of the energy balance on the Earth's surface, including greenhouse gas effects. It is critical to various climatic, hydrologic, ecological, and biogeochemical studies.

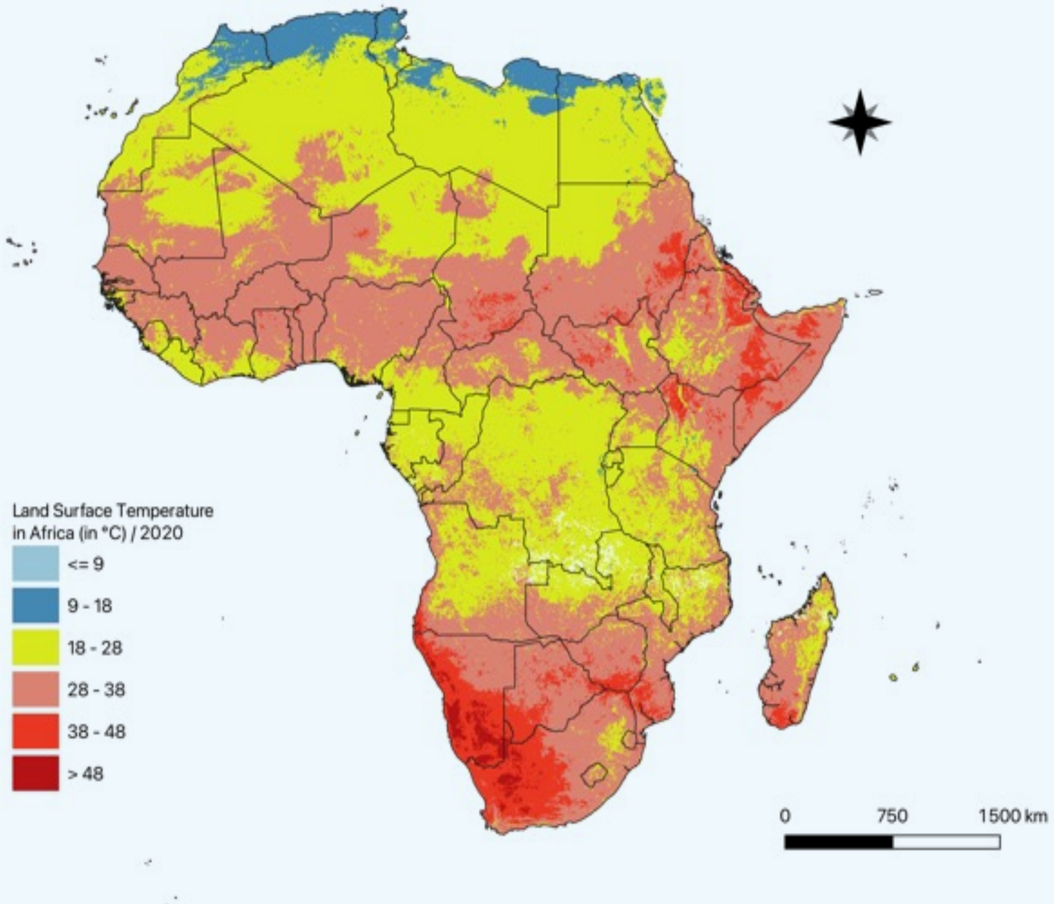
The MODIS LST dataset has several advantages, including its high spatial and temporal resolution. The LST product from MODIS is derived from the thermal bands of the instrument, which are sensitive to emitted radiation from the Earth's surface. The LST product is also available for daytime and nighttime observations, which helps study diurnal patterns in land surface temperatures.

Using LST data to examine environmental conditions helps in understanding heating patterns and the development of predictive models to learn how fast the planet is warming. This, in turn, enables the prioritization of targeted mitigation measures in areas where they are most urgently needed.

- Technical Considerations

The LST retrieval algorithm is based on a split-window technique that uses two thermal channels at 11 and 12 micrometers, respectively. This technique accounts for atmospheric effects, such as water vapor and aerosols, which can affect the accuracy of LST measurements. The product is generated by re-gridding the monthly Climate Modeling Grid (CMG) products from MODIS-Aqua starting in 2002, and Visible Infrared Imaging Radiometer Suite (VIIRS) starting in 2011. The output is then made available on 0.25, 0.5, and 1 degree optimized climate grids with well-characterized per-pixel uncertainties. The MODIS Version 6 product provides an average eight-day, per-pixel, land surface temperature with a one kilometer (km) spatial resolution, in a 1,200 by 1,200 km grid. The eight-day compositing period was chosen because two is the exact ground track repeat period of the Terra and Aqua platforms. It provides the daytime and nighttime surface temperature bands associated with quality control assessments, observation times, clear-sky coverages, and bands 31 and 32 emissivity from land cover types.

Figure 5. *Sample map of land surface temperature anomalies in Africa for 2020.*



4.3. Evapotranspiration

The MODIS sensor also provides estimates of evapotranspiration (ET) rates from land surfaces. Evapotranspiration refers to the combined processes of evaporation and transpiration of water from the Earth's land surface to the atmosphere. It is a crucial component of the water cycle and the planet's energy fluxes.

Evaporation refers to the conversion of liquid water into water vapor (vaporization) through application of heat and the subsequent removal of the vapor from the heated surface (also known as vapor removal). This process occurs on various surfaces, including lakes, rivers, pavements, soils, and wet vegetation. Transpiration consists of the vaporization of the liquid water contained in plant tissues and the evacuation of this vapor into the atmosphere.

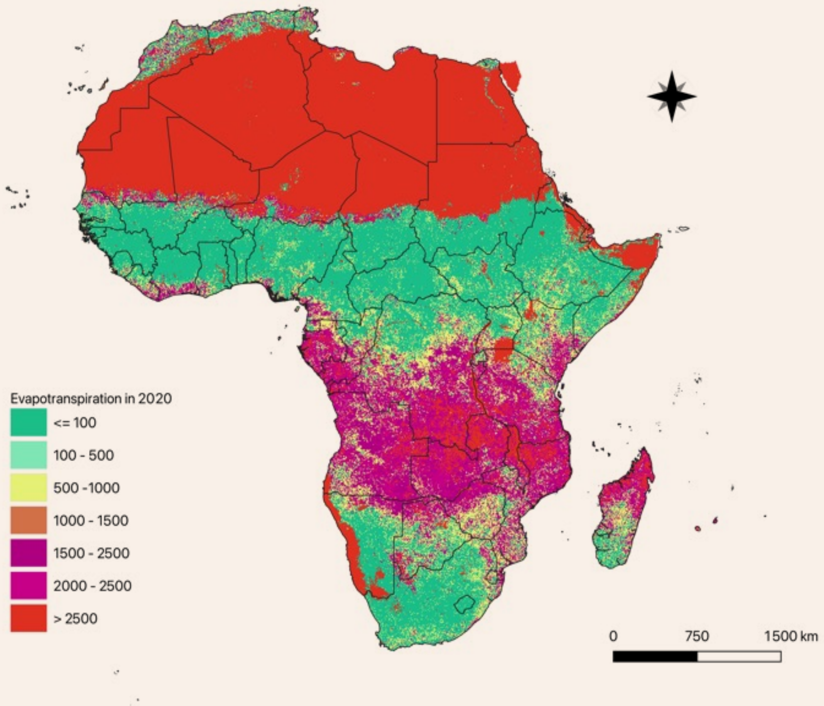
- Advantages

The evapotranspiration parameter is a valuable metric for studying the water cycle and its interactions with various environmental factors. It can be used to determine the water requirements of crops, which can help farmers and policymakers manage water resources more efficiently. Because evapotranspiration is affected by changes in temperature and precipitation, it is a valuable tool for studying climate change impacts on the water cycle and for estimating water availability in watersheds, which is essential for managing water resources.

- Technical Considerations

We used the MODIS Version 6 Evapotranspiration product, an eight-day composite dataset produced at 500 meter pixel resolution. The MODIS product is based on a simplified version of the Penman-Monteith equation, widely used in hydrological modeling to estimate evapotranspiration rates. The equation uses meteorological data inputs (such as air temperature, wind speed, and humidity) and remotely sensed data (such as land surface temperature and vegetation indices) to estimate evapotranspiration rates. However, pixel values for the evapotranspiration layers are the sum of eight days in the composite period, and the pixel values for the latent layers are the average of eight days within the composite period. Each year, the final acquisition period consists of a composite period of five or six days, depending on the year in question.

Figure 6: *Sample evapotranspiration clustering map of Africa for 2020.*



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