EUROPEAN SPACE AGENCY CONTRACT REPORT

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WASCIA – WATER STRESS AND CLIMATE INDICES FOR AFRICA

Algorithm Theoretical Basis Document and Product Specification – V2

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CHANGE LOG

Reason for change	Issue	Revision	Date	Page(s) and Paragraph(s) affected
Initial version	1	0	01/12/2023	All
MS2 Meeting Review	1	1	19/12/2023	• Section 2.1.2.2, addressing action *20231213.10* from *WaSCIA.MoM.0.39*. • Section 2.1.2.6 formula correction.
Second version	2	0	02/09/2024	• Section 2.2, updates throughout to climate indices
Comments from ESA	2	1	10/10/2024	• Section 1.3.2, Title of RD 2 corrected. • Corrections in Figure 2-2, Section 2.1.2.5, Section 2.1.2.6 and Section 2.1.2.7 to have consistency in the formulas.

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1 INTRODUCTION

1.1 *PURPOSE OF DOCUMENT*

This document is the deliverable 8 (D8) of the ESA Water Stress and Climate Indices for Africa (**WaSCIA**) project. Principally, it contains the Algorithm Theoretical Basis Document (ATBD) and the Products Specification. This is the second version of this document; updated based on the feedback collected during the implementation phase.

D8 is for public distribution.

1.2 *CONTENTS OF DOCUMENT*

Following this introductory section, the document layout is as follows:

Section 2 presents the Algorithm Theoretical Basis Document. This is partitioned as:

Section 2.1 Surface Wetness and Evaporative Loss

Section 2.2 Climate Indices

Section 2.3 Threshold Warnings

Section 3 presents the Product Specification. This is partitioned as:

Section 3.1 Surface Wetness and Evaporative Loss

Section 3.2 Climate Indices

Section 3.3 Threshold Warnings

Section 4 presents the Conclusions

1.3 REFERENCES

1.3.1 Applicable Documents

The following applicable documents are those referenced in the Contract or approved by the Agency. They are referenced in this document in the form [AD n.]:

AD	Title	Version / Date
AD 1.	Statement of Work - ESA Express Procurement [Plus] - [EXPRO+] - EO AFRICA - NATIONAL INCUBATORS EXPRO+	1.0 26/10/2021
AD 2.	KPT91865-AO11039-Proposal-EOAFRICA-R1r0.pdf	1.0 18/02/2022
AD 3.	WASCIA-KO-Minutes_1.0.pdf	1.0 07/10/2022

1.3.2 Reference Documents

The following reference documents are those referenced within this document. They are referenced in this document in the form [RD n.]. They are not applicable documents.

RD	Title / source	Version / Date
RD 1.	Price, J.C. The Potential of Remotely Sensed Thermal Infrared Data to Infer Surface Soil Moisture and Evaporation. Water Resources Research 1980, 16, 787–795.	1980
RD 2.	Toby N. Carlson & George P Petropoulos (2019): A new method for estimating of evapotranspiration and surface soil moisture from optical and thermal infrared measurements: the simplified triangle, International Journal of Remote Sensing, DOI: 10.1080/01431161.2019.1601288	2019
RD 3.	Gallion, G. (2023) Automatisation de la méthode d'extraction des indices d'humidité des sols et d'évapotranspiration Etude de cas : le Sénégal. M.Sc. thesis. University of Rennes II, Rennes, France.	2023
RD 4.	Aliyu Kasim, A.; Nahum Carlson, T.; Shehu Usman, H. Limitations in Validating Derived Soil Water Content from Thermal/Optical Measurements Using the Simplified Triangle Method. Remote Sens. 2020, 12, 1155. https://doi.org/10.3390/rs12071155	2020
RD 5.	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview	05/10/2023
RD 6.	https://data.bris.ac.uk/data/dataset/qb8ujazzda0s2aykkv0oq0ctp	11/10/2023

RD	Title / source	Version / Date
RD 7.	https://gadm.org/download_country.html	
RD 8.	Guidelines on Analysis of extremes in a changing climate in support of informed decisions for adaptation. Albert M.G. Klein Tank (Royal Netherlands Meteorological Institute); Francis W. Zwiers and Xuebin Zhang (Environment Canada). WCDMP_72_TD_1500_en_1.pdf (ecad.eu)	2009
RD 9.	EUMETNET/ECSN optional programme: 'European Climate Assessment & Dataset (ECA&D)' Algorithm Theoretical Basis Document (ATBD)	2013
RD 10.	Vicente-Serrano S.M., Santiago Beguería, Juan I. López-Moreno, (2010) A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index - SPEI. Journal of Climate 23: 1696-1718. https://spei.csic.es/home.html	2010
RD 11.	Gladstones, J., 1992. Viticulture and environment: Winetitles. *Adelaide, Australia*.	1992
RD 12.	Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H. and Martens, B., 2021. ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth system science data, 13(9), pp.4349-4383.	2021
RD 13.	Mohamed, H. A., Clark, J. A., & Ong, C. K. (1988). Genotypic Differences in the Temperature Responses of Tropical Crops. Journal of Experimental Botany, 39(8), 1121–1128. https://doi.org/10.1093/jxb/39.8.1121	1988

1.4 *ACRONYMS AND TERMS*

The following acronyms and abbreviations have been used in this document.

Acronym	**Definition**
AIC	Akaike's Information Criterion
ATBD	Algorithm Theoretical Basis Document
CDD	Maximum number of consecutive dry days (Drought spell)
CFD	Maximum number of consecutive frost days (Cold spell)
CSDI	Cold-spell duration index
CSU	Maximum number of consecutive summer days (Hot spell)

CWD	Maximum number of consecutive wet days (Wet spell)
DTR	Mean of diurnal temperature range
ECV	Essential Climate Variable
EF	Evaporative Fraction
EWL	Evaporative Water Loss
GDD	Growing Degree Days
GSL	Growing Season Length
LST	Land Surface Temperature
OLCI	Ocean and Land Colour Instrument
PET	Potential Evapotranspiration
R1mm	Wet Days
R10mm	Heavy precipitation days
R20mm	Very heavy precipitation days
RR	Precipitation sum
SDII	Simple Daily Intensity Index
SPEI	Standardised Precipitation Evapotranspiration Index
WaSCIA	Water Stress and Climate Indices for Africa
WSDI	Warm-spell duration index
WW	Warm and Wet days

2 ALGORITHM THEORETICAL BASIS

This section provides the physical and mathematical descriptions of algorithms used in generation of the project's products which includes the surface wetness and evaporation loss, the climate indices and the threshold warnings.

2.1 *SURFACE WETNESS AND EVAPORATIVE LOSS*

WaSCIA HydroSENS-Soil Water Stress (SWS) application (***wascia_hydrosens-sws***) generates Soil Moisture and Evaporative Water Loss outputs for Senegal. This section describes the input data, the processing algorithms and the validation results.

Soil moisture plays an important role in the water, carbon and energy cycles. The amount of moisture in the soil is an important variable for understanding surface-atmosphere coupling. As an Essential Climate Variable (ECV), soil moisture is a key component in improving weather forecasting and climate models as well as improving precipitation estimates, monitoring droughts, and forecasting natural hazards such as landslides and floods. Thanks to a series of satellite sensors with different characteristics, it is possible to study soil moisture content and related water stress at different spatial scales, from a few tens of kilometres to hundreds or even tens of metres. Many methods exist to derive water stress indicators from remote sensing, but performances can vary greatly. Therefore, a well-informed decision on what data types and what algorithm(s) to use should be based on data availability and user needs and requirements.

The goal of the WaSCIA service is to provide crucial information to help detect early onsets of water stress related to drought conditions, its severity and spatial extent all over Senegal. It will also improve the understanding of water-crop productivity in the long term and support efforts towards yield forecasting and food security.

2.1.1 Input Data

2.1.1.1 About Sentinel 3

Sentinel-3 is a European Earth Observation satellite mission developed to support Copernicus Ocean, land, atmospheric, emergency, security and cryospheric applications. Concerning land applications, the main objective of the Sentinel-3 mission is to measure land surface temperature, and land surface colour with high accuracy and reliability to support environmental monitoring and climate monitoring. The mission definition is driven by the need for continuity in provision of ERS, ENVISAT and SPOT vegetation data, with improvements in instrument performance and coverage. The Sentinel-3 mission is jointly operated by ESA and EUMETSAT to deliver operational observation services.

The two main instruments in Sentinel-3 satellite are:

- OLCI: Ocean and Land Colour Instrument. The OLCI instrument measures reflected solar radiation from the Earth's surface and clouds simultaneously in 21 spectral bands. OLCI products are available at two spatial resolutions:
  - Full Resolution (FR) at approximately 300 m
  - Reduced Resolution (RR) at approximately 1.2 km

  OLCI data is acquired in Full Resolution over Land and Ocean, but Level 1b processing can generate products in FR or RR resolutions, or both. Level 2 processing ingest either FR or RR Level 1b products and generate Level 2 products at the same resolution.

- SLSTR (Sea and Land Surface Temperature Instrument) with a spatial sampling of 500 m (VIS, SWIR), 1 km (MWIR, TIR).

2.1.1.2 About Sentinel-2

Sentinel-2 is a European wide-swath, high-resolution, multi-spectral imaging mission. The full mission specification of the twin satellites flying in the same orbit but phased at 180°, is designed to give a high revisit frequency of 5 days at the Equator. The mission carries an optical instrument payload that samples 13 spectral bands: four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution. The Sentinel-2 twin satellites carry on the legacy of SPOT and Landsat by continuing to provide similar types of image data and contributing to ongoing multispectral observations. These satellites are used to support a variety of services and applications offered by Copernicus, including land management, agriculture, forestry, disaster control, humanitarian relief operations, risk mapping, and security concerns.

2.1.2 Processing Algorithm

Studies have developed a method for extracting Evaporative Fraction (EF) or Evaporative Water Loss (EWL) and SM from Surface Temperature / Vegetation Index information, using Earth Observation data. The so-called "simplified triangle" method offers a simple and effective alternative, without the need for mathematical models or auxiliary data, for extracting both indices.

The triangle method introduced by Price in 1990 [RD 1], and cited by Toby Carlson (T. Carlson) [RD 2], is based on an interpretation of the distribution of pixels in the space of thermal infrared radiant temperatures (Tir) and near-infrared reflectances (Fr).

When a sufficiently large number of pixels are present, and clouds, surface water bodies and outliers are eliminated, the shape of the pixel envelope resembles a triangle (Figure 2-1). Using the triangle method, soil water content and surface turbulent energy fluxes can be obtained by fitting the model triangle to the observed shape, thus defining the values of each pixel within the triangle.

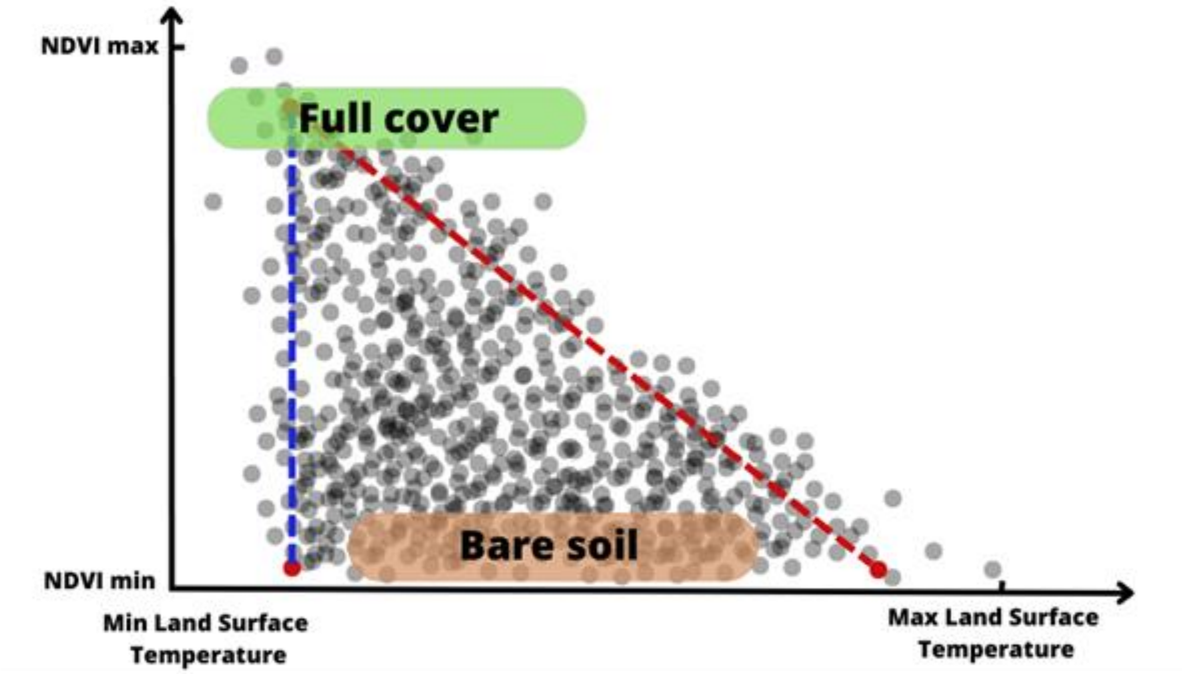

Figure 2-1. Graphical representation of the simple "triangle" method (by Gallion G., 2023 [RD 3];available at https://wascia.ssl.telespazio.com/).

The triangle method is a technique for estimating soil moisture and vegetation cover from satellite imagery. It is based on the relationship between surface radiant temperature (*Ts*) and vegetation fraction (*f*). *Ts* is a measure of the amount of thermal radiation emitted by the land surface, while *f* is the proportion of the land surface covered by vegetation.

The triangle method works by plotting *Ts* against *f* for a large number of pixels in an image. The pixels form a triangular shape, with the dry edge (high *Ts*, low *f*) at the top, the wet edge (low *Ts*, high *f*) at the bottom, and the low edge (low *Ts*, low *f*) representing bare soil.

The soil moisture and vegetation cover for a given pixel can be estimated by its position within the triangle. Pixels near the dry edge have low soil moisture and low vegetation cover, while pixels near the wet edge have high soil moisture and high vegetation cover. Pixels near the low edge have no vegetation cover.

The triangle method is a simple and effective way to estimate soil moisture and vegetation cover from satellite imagery. However, it can be sensitive to outliers and may not be accurate in all environments.

2.1.2.1 Simplified Triangle Method

The simplified triangle method is a variation of the triangle method that is easier to implement and does not require as much data. It is based on the observation that the shape of the triangle is relatively consistent across different images and environments.

The simplified triangle method works by defining two anchor points: one for dry soil and one for wet soil. The anchor points are then used to define a line that represents the relationship between *Ts* and *f*. The soil moisture and vegetation cover for a given pixel can be estimated by its distance from the line.

The simplified triangle method is less accurate than the original triangle method, but it is more robust to outliers and can be applied to a wider range of environments.

2.1.2.2 Downscaling with Random Forest

Random Forest is a machine learning algorithm that can be used to downscale the spatial resolution of the triangle method indices. Downscaling is the process of increasing the resolution of an image. In the context of the triangle method, downscaling means increasing the resolution of the soil moisture and vegetation cover maps. For downscaling, we employed simple, standard soil moisture indices based on Sentinel-2. Important to note here is that this required a reprojection from map projection in meters to degrees to be aligned with the Sentinel-3 data.

Random Forest works by training a forest of decision trees on a set of training data. The training data consists of pairs of pixels, where each pixel has a known soil moisture and vegetation cover value. The decision trees are trained to predict the soil moisture and vegetation cover value for a new pixel based on its position in the image.

Once the Random Forest model is trained, it can be used to downscale any image. To downscale an image, the Random Forest model is applied to each pixel in the image, and the predicted soil moisture and vegetation cover values are used to create a new, higher-resolution map.

Random Forest has been shown to be an effective method for downscaling the triangle method indices. It is a robust and accurate method that can be applied to a wide range of images.

2.1.2.3 Summary

In the WaSCIA project, the triangle method was used to estimate soil moisture and vegetation cover from Sentinel-2 imagery. The spatial resolution of the indices was then downscaled from 1000 meters to 20 meters using Random Forest (Figure 2-2).

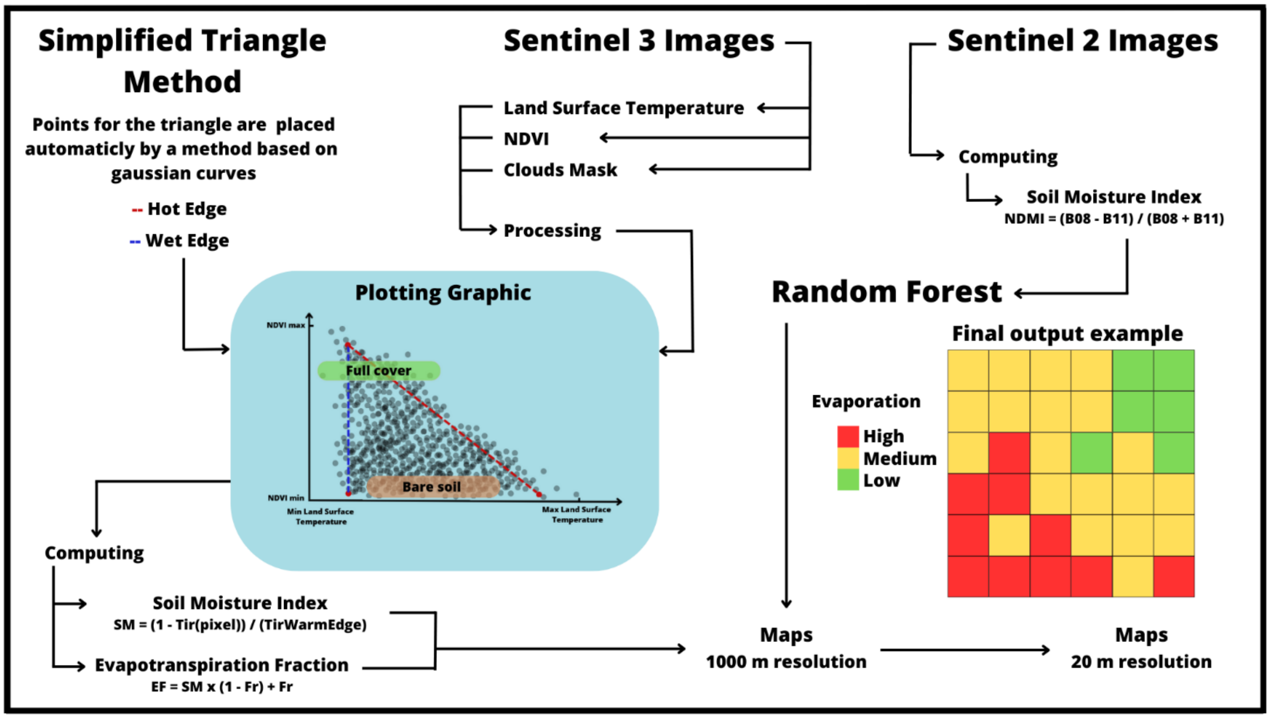

Figure 2-2. Workflow of the WaSCIA Soil Moisture and Evaporative Water Loss tool.

The downscaled indices were used to create a map of soil moisture and vegetation cover for Senegal. The map was then used to assess the water resources in the country.

The triangle method and Random Forest are powerful tools for estimating soil moisture and vegetation cover from satellite imagery. They have been used in a wide range of applications, including agriculture, hydrology and climate change research.

2.1.2.4 Method Implementation

The data employed for testing the method and algorithm implementation was acquired from the Copernicus Open Access Hub, comprising 15 Sentinel-3 SLSTR products spanning the entirety of 2019. These products adhere to the NetCDF file format, a standardized architecture for storing and disseminating multidimensional scientific data.

The initial algorithm is employed to automate the extraction of desired data, including temperature, vegetation index, image coordinates, and the cloud mask provided within the file. Following this initial extraction phase, the images are saved in GeoTIFF format. However, despite the assignment of the data's spatial dimensions and the WGS 84 / UTM zone 28N reference coordinate system, reprojection is still required. The extracted variables, longitude_in and latitude_in, facilitate the correct projection of the generated GeoTIFFs.

Once the images have been successfully projected, data preparation commences. This involves applying a cloud mask, which corresponds to the Sentinel-3 cloud mask, to eliminate clouds, their shadows, and water pixels from the images. This step ensures that only pixels representing solid ground-level bodies are retained, while eliminating disruptive pixels. Due to the spatial extent of Sentinel-3 images exceeding that of Senegal, it is crucial to remove pixels outside the study area, particularly in neighbouring countries with differing latitudes and longitudes, and consequently, distinct climates (tropical vs arid).

Upon completion of the data processing phase, the land surface temperature (LST) values should be rescaled to a range spanning from 0 to 1. Similarly, the vegetation index, designated as Fraction, should undergo a rescaling process to adhere to the same range. This rescaling step ensures that the LST and Fraction values fall within a standardized interval, facilitating subsequent analyses and interpretations. The rescaled values can then be employed for various purposes, such as identifying patterns and anomalies in LST and Fraction distributions, evaluating temporal trends, and conducting comparative analyses across different regions or time periods.

Upon completion of the sampling process, point graphs incorporating triangular shapes can be generated. To simplify implementation, a right-angled triangle was selected as the preferred shape for these point graphs. The right-angled triangle offers several advantages, including its straightforward construction, visual clarity, and well-defined properties. These attributes make it an ideal choice for representing the relationships between the sampled data points. Moreover, the right-angled triangle's structure aligns with the tripartite nature of the sampled data, encompassing land surface temperature (LST), vegetation index (Fraction), and the sampling location. The base of the triangle can represent LST, the height can represent Fraction, and the hypotenuse can represent the sampling location. This arrangement provides a visually intuitive and easily interpretable representation of the sampled data (Figure 2-3).

This next part provides the basis for calculating the soil moisture index and evapotranspiration index. To position the three anchor points of the triangle, it is necessary to study the two variables Tir and Fraction.

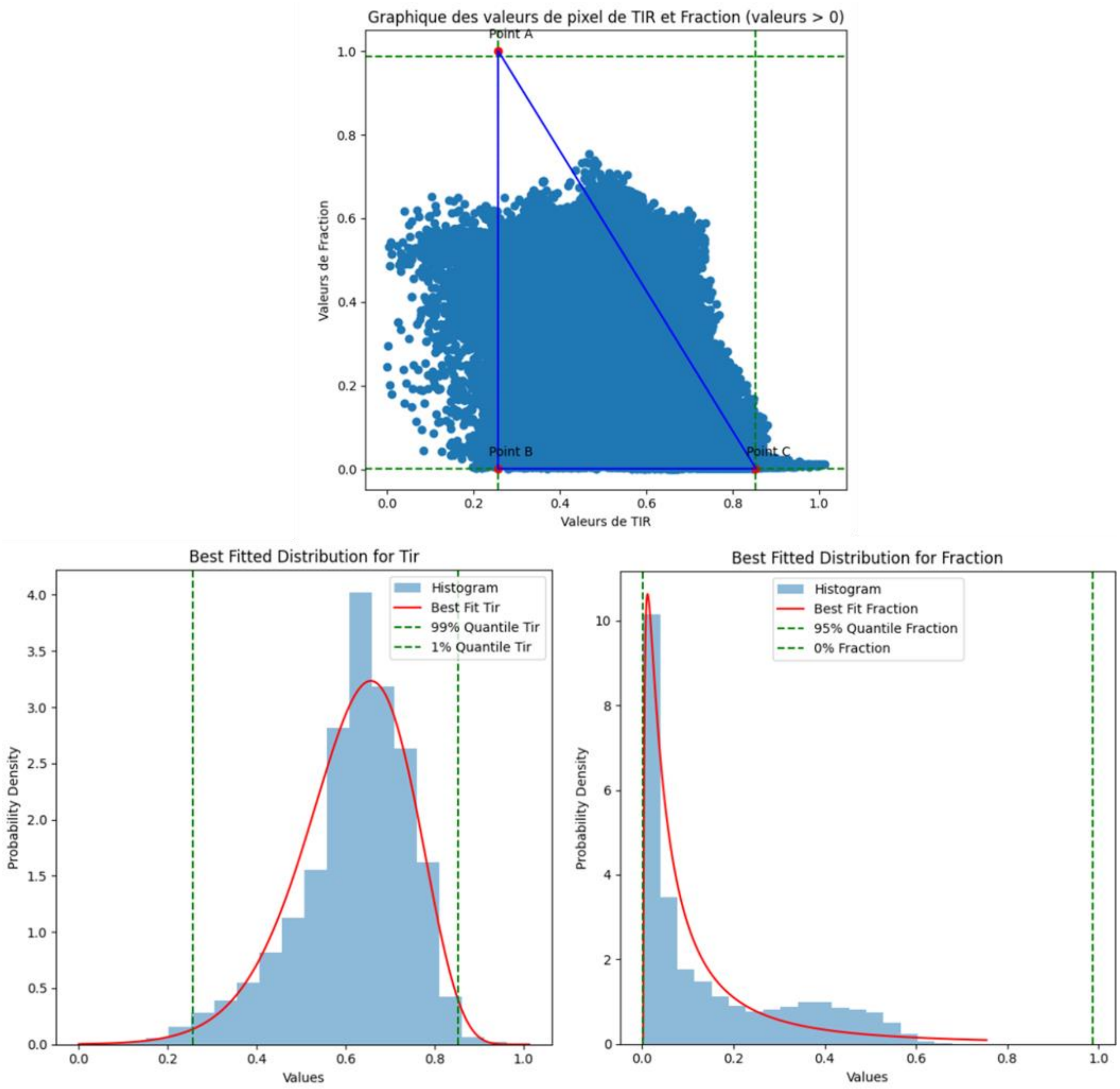

Figure 2-3. Simple Triangle approach used in this project.

The coordinates of each point are expressed as A(xa;ya), B(xb;yb) and C(xc;yc). To determine the coordinates x and y of A, B and C, it is necessary to create a histogram of the distribution of Tir and Fraction. This allows to obtain different types of distributions such as the normal, exponential, log normal, beta, gamma, uniform and Laplace distributions, and thus to define the most relevant one for the histogram. This is done using AIC, which provides a relative measure of the quality of a statistical model and allows to compare each statistical model against each other. It is calculated as follows:

$$\mathbf{AIC = 2K - 2ln(L)}$$

where *k* is the number of parameters to be estimated by the model,

and *L* is the maximum of the likelihood function of the model.

The statistical model with the lowest AIC value is generally considered to be the best among the compared models and will therefore be chosen for the rest of the algorithm.

Once the coordinates of the points B and C have been found using quantiles (Figure 2-3), the values of these points are projected onto the point graph. Point A will have a value of y = 1. Indeed, this boundary value must be constant at 1, which allows all values ranging from 0 to 1 to be taken into account in this interval [RD 4].

2.1.2.5 Soil moisture index calculation

The soil moisture index is calculated using the following formula:

$$\mathbf{SM = (1 - Tir_{(pixel)}) / Tir_{WarmEdge}}$$

where $Tir_{WarmEdge}$ is the value x of the perpendicular projection to AB of a point in the cloud onto the tangent AC.

[RD 4] describes that the value $Tir_{WarmEdge}$ can be easily found using the equation of the tangent: y = ax+b since the triangle is a right-angled triangle. The equation can then be written as x = (y-b)/a, with y: value of Fraction of the pixel.

2.1.2.6 Evapotranspiration index calculation

The evapotranspiration index is calculated using the following formula:

$$\mathbf{EF = SM \times (1 - Fr) + Fr}$$

2.1.2.7 Additional explanations

- AIC stands for Akaike's Information Criterion. It is a statistical measure of the relative goodness of fit of a statistical model to a data set.
- Quantiles are values that divide a probability distribution into equal parts. In this case, the quantiles are used to determine the coordinates of the points B and C on the triangle.
- Tangent is a line that touches a curve at a single point. In this case, the tangent is used to calculate the value of $Tir_{WarmEdge}$.
- Volumetric unit is a unit of measurement that expresses the volume of a substance. In this case, the volumetric unit is cubic centimeters.
- Climate is the long-term pattern of weather in a particular place.
- Vegetation is the plant life in a particular area.

2.1.3 Validation

2.1.3.1 Validation of Evaporative Water Loss

In the absence of any field data, MSG evapotranspiration MET data, derived from MSG/SEVIRI, was used for validation. MSG is the geostationary meteorological satellite mission developed by ESA and EUMETSAT. These satellites orbit at about 36,000 kilometers above Earth, providing real-time meteorological data. The SEVIRI product on board the MSG satellites is primarily designed to provide meteorological and climate data using infrared and visible channels to measure sea surface temperature, cloud temperature, and other important atmospheric parameters. The MET products are therefore available for Europe and Africa every 30 minutes at a resolution of 3 kilometers.

Table 2-1. Name of the various MET products used. Data download from LSA SAF Data Service platform

Name	Date	Hour
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201905112300	11/05/2019	23h00
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201908101100	10/08/2019	11h00
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201909121100	12/09/2019	11h00
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201910181100	18/10/2019	11h00
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201911221100	22/11/2019	11h00
NETCDF4_LSASAF_MSG_ET_MSG-Disk_201912191100	19/12/2019	11h00

To allow comparison with the results obtained by the simplified triangle method, it is important to resample these data to 1 km. This resampling was performed using the "nearest-neighbour" method. Then the MET data were cropped to the boundaries of Senegal.

2.1.3.2 Validation of Soil Moisture

As noted in document WaSCIA_TN.011_D6-VM_R2r0, none of the data from the field sites we initially planned to use could be obtained free of charge.

Ultimately, the project team decided to go with (free of charge) data collected at two new field stations operated since September 2023 by project partner Cheikh Anta Diop University, Dakar, Senegal. One station is located at the University campus in Dakar and the other near the City of Pout.

The team received 2.5 months of soil moisture data at 5 cm depth and at a 5-minute interval recording. Evaluation of the derived soil moisture data from Sentinel-3 and downscaled to 20 m pixel resolution is underway.

The full detail of the soil moisture validation is provided in deliverable document WaSCIA_TN.011_D6-VM_R2r0.

2.2 CLIMATE INDICES

This section describes the data, the processing algorithms and the validation information in relation with the climate indices developed in WaSCIA project. Table 2-2 summaries the 20 indices that are generated by the WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***).

Table 2-2. Summary of the Climate Indices

Indicator	Acr.	Units	Temporal Resolution	Input Variable
Total Precipitation	TP	mm	Daily	Precipitation
Mean 2 metre Temperature	T2M	°C	Daily	Temperature
Maximum Temperature	TASMAX	°C	Daily	Temperature
Minimum Temperature	TASMIN	°C	Daily	Temperature
Maximum number of consecutive dry days (Drought spell)	CDD	days	Monthly	Precipitation
Maximum number of consecutive wet days (Wet spell)	CWD	days	Monthly	Precipitation
Warm Day-times	TX90p	days	Monthly	Temperature
Cold Nights	TN10p	days	Monthly	Temperature
Standardised Precipitation Evapotranspiration Index	SPEI	-	Monthly	Precipitation & Evapotranspiration
Precipitation sum	RR	mm	Weekly	Precipitation
Wet Days	R1mm	days	Weekly	Precipitation
Heavy precipitation days	R10mm	days	Weekly	Precipitation
Very heavy precipitation days	R20mm	days	Weekly	Precipitation
Warm and Wet days	WW	days	Weekly	Precipitation & Temperature
Warm-spell Duration Index	WSDI	days	Monthly	Temperature
Cold-spell Duration Index	CSDI	days	Monthly	Temperature
Growing Season Length	GSL	days	Yearly	Temperature

Growing Degree Days	GDD	°C	Weekly	Temperature
Mean of Diurnal Temperature Range	DTR	°C	Weekly	Temperature
Simple Daily Intensity Index	SDII	mm	Weekly	Precipitation

Note: *The climate indices for of Maximum number of Consecutive Summer Days (CSU) and Maximum number of Consecutive Frost Days (CFD) were removed after it was confirmed to be not applicable to Africa. Alternative indices for Warm Day-times (TX90p) and Cold Nights (TN10p) were implemented instead.*

2.2.1 Input Data

2.2.1.1 ERA5-Land Reanalysis Data

The WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***) generates Climate Indices from ERA5-Land reanalysis data for Senegal.

ERA5-Land is a dataset produced from the land component of the ERA5 climate reanalysed with a finer spatial resolution, 0.1 degrees or ~9 km grid spacing. The model used in the production of ERA5-Land is the tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). ERA5-Land dataset provides hourly high-resolution information of surface variables. The ERA5-Land dataset is available for public use for the period from 1950 to 5 days behind the current date. See [RD 5] for further details.

In this project, the ERA5-Land data, have been used to calculate the climate indices. Only data from 1981 onwards has been used. The data prior to 1981 is not as accurate as the newer data, largely due to the sparsity of observational data, and the low availability and accuracy of satellite products. The limited availability of observational data will significantly increase the likelihood of bias and errors, due to poorly constrained initialisation of the reanalysis models. In addition, the calculation of some climate indices involves comparison with the climatology. The climatology period chosen is 1991-2020, therefore any data prior to this is not so relevant.

The ERA5-Land dataset is accessed in WASDI directly from the Copernicus Climate Data Store (CDS). The data is provided as hourly data in daily netcdf data files. In particular the variables used are:

Table 2-3. ERA5-Land Variables used in this project

Variable name	Units	Description
Total Precipitation	m	Accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface.
2 metre Temperature	°C	Temperature of air at 2m above the surface

2.2.1.2 Potential Evapotranspiration (PET) Data

For the calculation of the indicator SPEI, the WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***) needs potential evapotranspiration (PET) data.

The PET data used in this project is provided by the University of Bristol, see [RD 6]. The hourly (PET) dataset is available for the period 1981 to December 2023. The dataset is extended every January to add the previous year.

The hourly PET data product is derived from using FAO's Penman-Monteith formulation with hourly climate variables from ERA5-Land. This dataset has 0.1 degrees spatial resolution over the global land area. A daily PET data product is also provided.

To make this dataset available in WASDI, the PET data is manually downloaded, as daily files, from the University of Bristol website once per year and uploaded into WASDI.

2.2.2 Data Preparation

Before the ERA5-Land and PET datasets are used by the WaSCIA Climate Indicators application some pre-processing is needed to prepare the data.

The **ERA5-Land** dataset is provided as hourly data. The ERA5-Land input data for the selected variables (Total Precipitation and 2 metre Temperature) are resampled from hourly to daily values and used to compute the following 4 variables. The data is also cropped to the borders of Senegal. The shapefile of Senegal that has been used is: gadm41_SEN_0.geojson [RD 7], which is a widely accepted shapefile provider.

- **Daily total precipitation** (tp), taking the accumulated precipitation for each day
- **Daily mean temperature** (t2m), averaging the hourly temperature values for each day.
- **Daily maximum temperature** (tasmax), taking the maximum hourly temperature for each day.
- **Daily minimum temperature** (tasmin), taking the minimum hourly temperature for each day.

The daily data is then aggregated to produce a single pre-processed data file for each variable, for the full period (1981 to 5 days behind the current date) cropped to the borders of Senegal. These files updated automatically in WASDI every week, so that the latest available ERA5-Land data is always used and are input to all subsequent processing.

The **PET** input data is already provided as daily values, therefore does not require resampling. However, the data is again cropped to the borders of Senegal and aggregated into a single pre-processed data file for the full period available.

2.2.3 Processing Algorithms

The 5 pre-processed datasets are the inputs needed by the WaSCIA Climate Indicators Application (***wascia_processor_climate_indicators***) to calculate all the climate indices.

Climate indices are **standardised metrics** for assessing **climate variability** based on various meteorological variables. This section describes each climate index that can be generated by the WaSCIA application. The climate indices are calculated according to Guidelines from the World Meteorological Organisation: WCDMP_72_TD_1500_en_1.pdf (ecad.eu). For each index, the data is resampled to the most appropriate temporal resolution – e.g. yearly, monthly, weekly.

The following information will be provided per index:

Description:	Definition of the index
Units:	SI units of the variable
Temporal resolution:	Time frequency of the provided index
Function:	Algorithm for computing the index using daily climate data
Reference:	Document used for the index definition

2.2.3.1 Total Precipitation (TP)

Description:	Total precipitation
Units:	mm
Temporal resolution:	Daily
Function:	Total amount of precipitation recorded for each day
Reference:	n/a

2.2.3.2 Mean 2 metre Temperature (T2M)

Description:	Mean temperature of the air at 2 metres above the surface

Units:	°C
Temporal resolution:	Daily
Function:	Mean temperature recorded for each day
Reference:	n/a

2.2.3.3 Maximum Temperature (TASMAX)

Description:	Maximum temperature
Units:	°C
Temporal resolution:	Daily
Function:	Maximum temperature recorded for each day
Reference:	n/a

2.2.3.4 Minimum Temperature (TASMIN)

Description:	Minimum temperature
Units:	°C
Temporal resolution:	Daily
Function:	Minimum temperature recorded for each day
Reference:	n/a

2.2.3.5 Maximum number of Consecutive Dry Days (CDD)

Description:	Maximum number of consecutive dry days (Drought spell)
Units:	Days
Temporal resolution:	Monthly
Function:	Let RRij be the daily precipitation amount for day i of period j. Count the largest number of consecutive days where: $$RR_{ij} < 1\ mm$$
Reference:	[RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.6 Maximum number of Consecutive Wet Days (CWD)

Description:	Maximum number of consecutive wet days (Wet spell)
Units:	Days

Temporal resolution: Monthly

Function: Let RRij be the daily precipitation amount for day i of period j. Count the largest number of consecutive days where:

$$RR_{ij} > 1\ mm$$

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.7 Warm Day-times (TX90p)

Description: Warm day-times: Count of days where daily maximum temperature (TX) > 90th percentile.

Units: Days

Temporal resolution: Monthly

Function: Let TXij be the daily maximum temperature on day i in period j and let TXin90 be the calendar day 90th percentile of daily maximum temperature calculated for a five-day window centred on each calendar day in the base period n (1991-2020). Count the number of days where TXij > TXin90.

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.8 Cold Nights (TN10p)

Description: Cold nights: Count of days where daily minimum temperature (TN) < 10th percentile.

Units: Days

Temporal resolution: Monthly

Function: Let TXij be the daily maximum temperature on day i in period j and let TXin10 be the calendar day 10th percentile of daily maximum temperature calculated for a five-day window centred on each calendar day in the base period n (1991-2020). Count the number of days where TXij < TXin10.

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.9 Standardised Precipitation Evapotranspiration Index (SPEI)

Description: A multi-scalar drought index based on climatic data.

The Standardized Precipitation Evapotranspiration Index (SPEI) is an extension of the widely used Standardized Precipitation Index (SPI). The SPEI is designed to take into

	account both precipitation and potential evapotranspiration (PET) in determining drought.
Units:	[none]
Temporal resolution:	Monthly
Function:	With a value for *PET*, the difference between the precipitation (*P*) and *PET* for the month *i* is calculated as: $$D_i = P_i - PET_i$$ the calculated D_i values are aggregated at different time scales, following the procedure described at the reference below.
Reference:	[RD 10] Vicente-Serrano S.M., Santiago Beguería, Juan I. López-Moreno, (2010) A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index - SPEI. Journal of Climate 23: 1696-1718. https://spei.csic.es/home.html

2.2.3.10 Precipitation Sum (RR)

Description:	Sum of precipitation over a selected period
Units:	mm
Temporal resolution:	Weekly
Function:	Let RRij be the daily precipitation amount for day i of period j. Then sum values are given by: $$RR_j = \sum_{i=1}^{I} RR_{ij}$$
Reference:	[RD 9] European Climate Assessment & Dataset (ECA&D) Algorithm theoretical basis document (ATBD)

2.2.3.11 Wet Days (R1mm)

Description:	Number of wet days (precipitation ≥ 1 mm)
Units:	Days
Temporal resolution:	Weekly

Function: Let RR_{ij} be the daily precipitation amount for day *i* of period *j*. Then counted is the number of days where:

$$RR_{ij} \geq 1\ mm$$

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.12 Heavy precipitation days (R10mm)

Description: Heavy precipitation days (precipitation ≥ 10 mm) (days)

Units: Days

Temporal resolution: Weekly

Function Let RRij be the daily precipitation amount for day i of period j. Then counted is the number of days where:

$$RR_{ij} > 10\ mm$$

Reference [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.13 Very heavy precipitation days (R20mm)

Description: Very heavy precipitation days (precipitation ≥ 20 mm) (days)

Units: Days

Temporal resolution: Weekly

Function Let RRij be the daily precipitation amount for day i of period j. Then counted is the number of days where:

$$RR_{ij} > 20\ mm$$

Reference [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.14 Warm and Wet days (WW)

Description: Number of days where mean temperature and precipitation are both above 75^{th} percentile

Units: Days

Temporal resolution: Weekly

Function:	Let TG_{ij} be the daily mean temperature at day *i* of period *j* and let TG_{in75} be the calendar day 75th percentile calculated for a 5-day window centered on each calendar day in the 1981–2010 period. Let RR_{wj} be the daily precipitation amount at wet day *w* ($RR \geq 1.0\ mm$) of period *j* and let RR_{wn75} be the 75th percentile of precipitation at wet days in the 1981–2010 period. Then counted is the number of days where: $$TG_{ij} > TG_{in75} \text{ AND } RR_{wj} > RR_{wn75}$$
Reference	[RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.15 Warm Spell Duration Index (WSDI)

Description:	Count of days in a span of at least six days where TX > 90th Percentile.
Units:	Days
Temporal resolution:	Monthly
Function:	Let TX_{ij} be the daily maximum temperature on day *i* in period j and let TX_{in90} be the calendar day 90th percentile of daily maximum temperature calculated for a five-day window centered on each calendar day in the base period (1981-2010). Then counted is the number of days where, in intervals of at least six consecutive days: $$TX_{ij} > TX_{in90}$$
Reference:	[RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.16 Cold Spell Duration Index (CSDI)

Description:	Count of days in a span of at least six days where TN > 10th percentile
Units:	Days
Temporal resolution:	Monthly
Function:	Let TN_{ij} be the daily minimum temperature on day *i* in period *j* and let TN_{in10} be the calendar day 10th percentile of daily minimum temperature calculated for a five-day window centred on each calendar day in the base period (1981-2010). Then counted is the number of days where, in intervals of at least six consecutive days: $$TN_{ij} < TN_{in10}$$

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.17 Growing Season Length (GSL) - Optimum

Description: Annual count of days between first span of at least six days where TG (daily mean temperature) > 33°C and first span in second half of the year of at least six days where TG < 33°C. This is a modified version of the GSL indices to reflect optimal growing temperature of millet and groundnut.

Units: Days

Temporal resolution: Yearly

Function: Let TG_{ij} be the daily mean temperature on day *i* in period *j*. Count the annual (1 Jan to 31 Dec in Northern Hemisphere, 1 July to 30 June in Southern Hemisphere) number of days between the first occurrence of at least six consecutive days where:

$$TG_{ij} > 33°C$$

and the first occurrence after 1 July (1 Jan in Southern Hemisphere) of at least six consecutive days where:

$$TG_{ij} < 33°C.$$

Reference: [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

Note: This index has been tailored slightly to better represent the crop types grown in Senegal, groundnut, and millet [RD 13].

2.2.3.18 Growing Degree Days (GDD)

Description: Sum of daily mean temperatures above 10°C and less than 30°C for a given period

Units: °C

Temporal resolution: Weekly

Function: Let TG_{ii} be the daily mean temperature at day *i* of period *j*. BEDD is calculated by:

$$BEDD = \sum_{i=1}^{I} min\left[max\left[TG_{ij} - T_{low}\, ,0\right], T_{high} - T_{low}\right]$$

where T_{high} and T_{low} are effective temperature upper and lower thresholds respectively.

$$T_{low} = 10\ °C$$

$$T_{high} = 40\ °C$$

Reference: [RD 11] Gladstones, J., 1992. Viticulture and environment: Winetitles. *Adelaide, Australia*.

Note: This index has been tailored slightly to better represent the crop types grown in Senegal, groundnut, and millet [RD 13].

2.2.3.19 Mean Diurnal Temperature Range (DTR)

Description: Mean difference between daily maximum temperature (TX) and daily minimum temperature (TN) on a given day (°C)

Units: °C

Temporal resolution: Weekly

Function Let TX_{ij} be the daily maximum temperature on day *i* in period *j*.

Let TN_{ij} be the daily minimum temperature on day *i* in period *j*.

If *I* represents the total number of days in j then the mean diurnal temperature range in period j is:

$$DTR_j = \frac{\sum_{i=1}^{I}(TX_{ij} - TN_{ij})}{I}$$

Reference [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.3.20 Simple Daily Intensity Index (SDII)

Description: Mean precipitation amount on a wet day

Units: mm

Temporal resolution: Weekly

Function Let RR_{wj} be the daily precipitation amount on wet day w ($RR \geq$ 1 mm) in period *j*. Then mean precipitation amount of wet days is given by:

$$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$$

Where *W* is the number of wet.

Reference [RD 8] WCDMP_72_TD_1500_en_1.pdf (ecad.eu)

2.2.4 Validation

Like any scientific measurements or observations, climate indices are subject to uncertainties. The main sources of uncertainty of the WaSCIA climate indices relate to the uncertainties associated with the climate data. There is extensive literature available on the main sources of uncertainty in ERA5-Land reanalysis data. The uncertainties are generally due to an incomplete understanding of Earth's systems and their interactions; natural variability in the climate system; the limitations of the reanalysis models; bias; and measurement errors from imprecise observational instruments. The paper [RD 12] provides high level information about the input data uncertainties.

The calculations performed to get the climate indicators are not adding uncertainty as they are just different statistics calculated from the ERA5-Land data.

The accuracy of temperature and precipitation data in ERA5-Land, like other variables in the dataset, is generally considered to be high. ERA5-Land is known for its advanced assimilation techniques and comprehensive use of observational data.

Validation studies and comparisons of ERA5-Land temperature data with ground-based observations typically show good agreement. However, the accuracy of temperature data can still vary depending on factors such as location, altitude, and time period. Additionally, the accuracy of ERA5-Land data may improve over time as the dataset is updated and refined.

The following plots show examples of the outputs provided by the climate indices processor. All indices have been cross-checked against the input daily temperature and precipitation datasets to ensure that the algorithms implemented are generating expected results:

- Figure 2-4 plots the Total Precipitation (TP) index, which has daily temporal resolution. The values in the plot are the daily mean over the whole of Senegal.

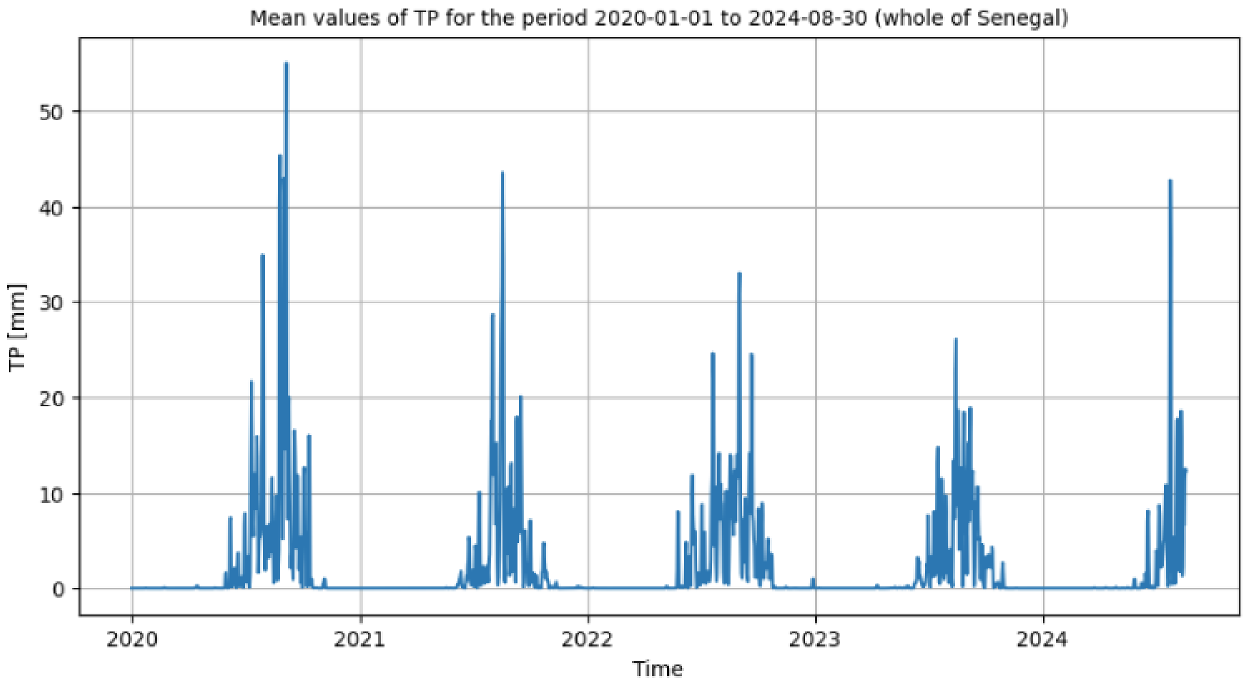

Figure 2-4. Total Precipitation (TP) plot showing the mean value for the whole of Senegal from 2020 to 2024.

- Figure 2-5 plots the Mean 2m Temperature (T2M) index, which has daily temporal resolution. The values in the plot are the daily average over the whole of Senegal.

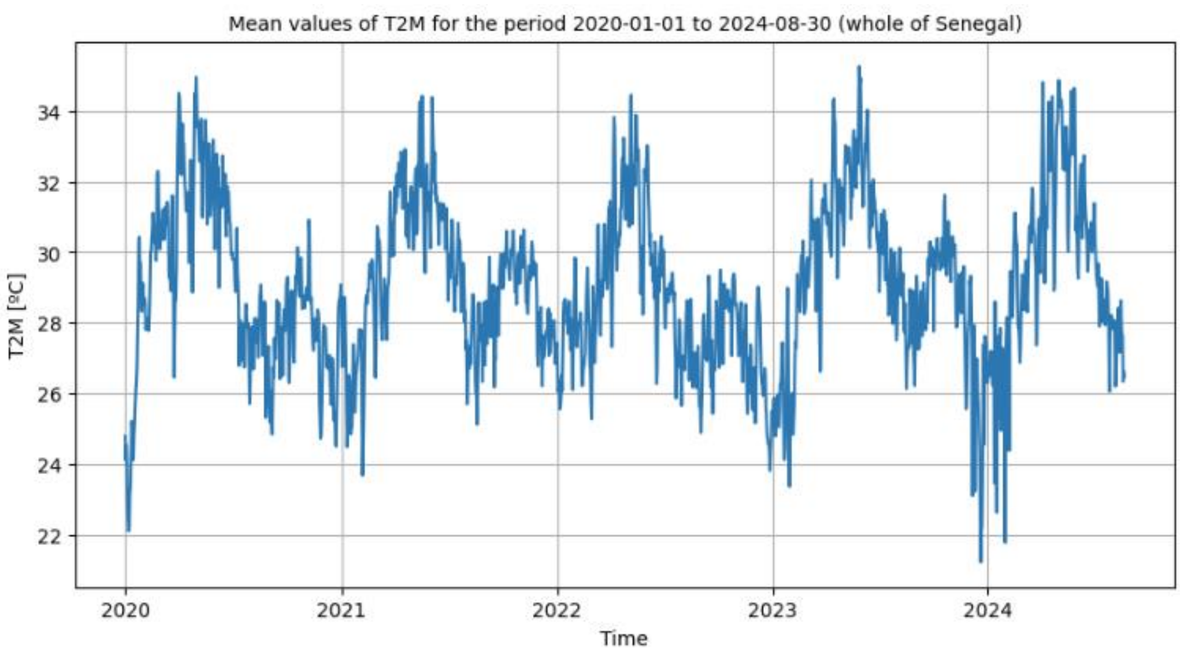

Figure 2-5. Mean 2m Temperature (T2M) plot showing the mean value for the whole of Senegal from 2020 to 2024.

- Figure 2-6 plots the Maximum Temperature (TASMAX) index, which has daily temporal resolution. The values in the plot are the daily maximum over the whole of Senegal.

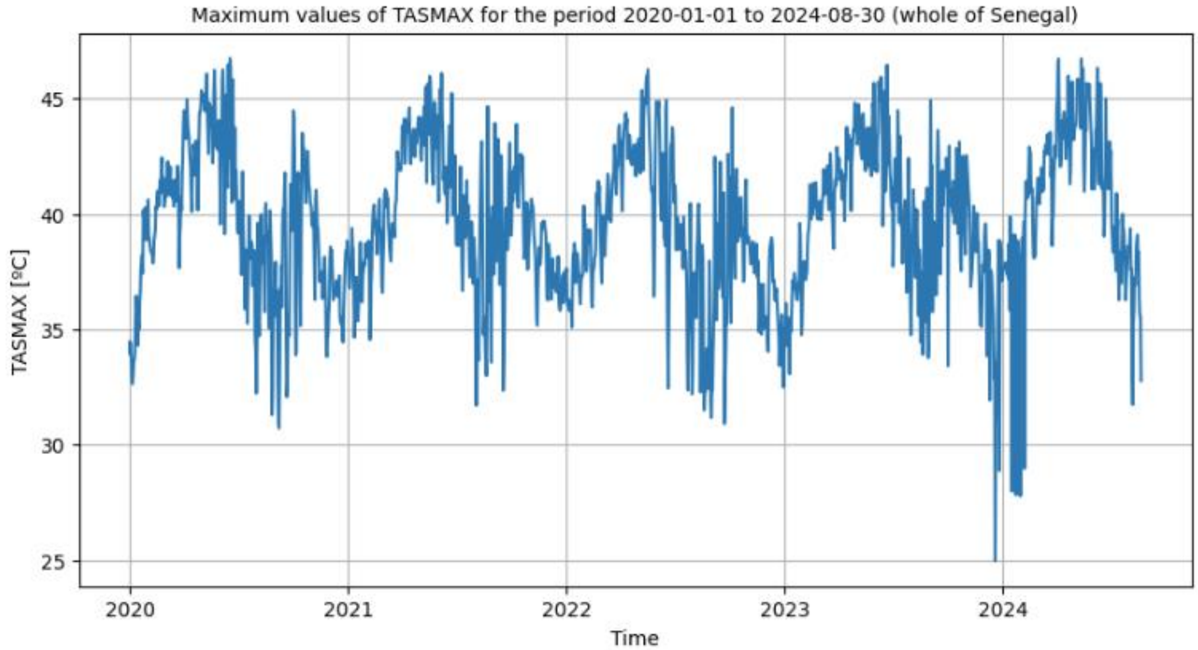

Figure 2-6. Maximum Temperature (TASMAX) plot showing the maximum value for the whole of Senegal from 2020 to 2024.

- Figure 2-7 plots the Minimum Temperature (TASMIN) index, which has daily temporal resolution. The values in the plot are the daily minimum over the whole of Senegal.

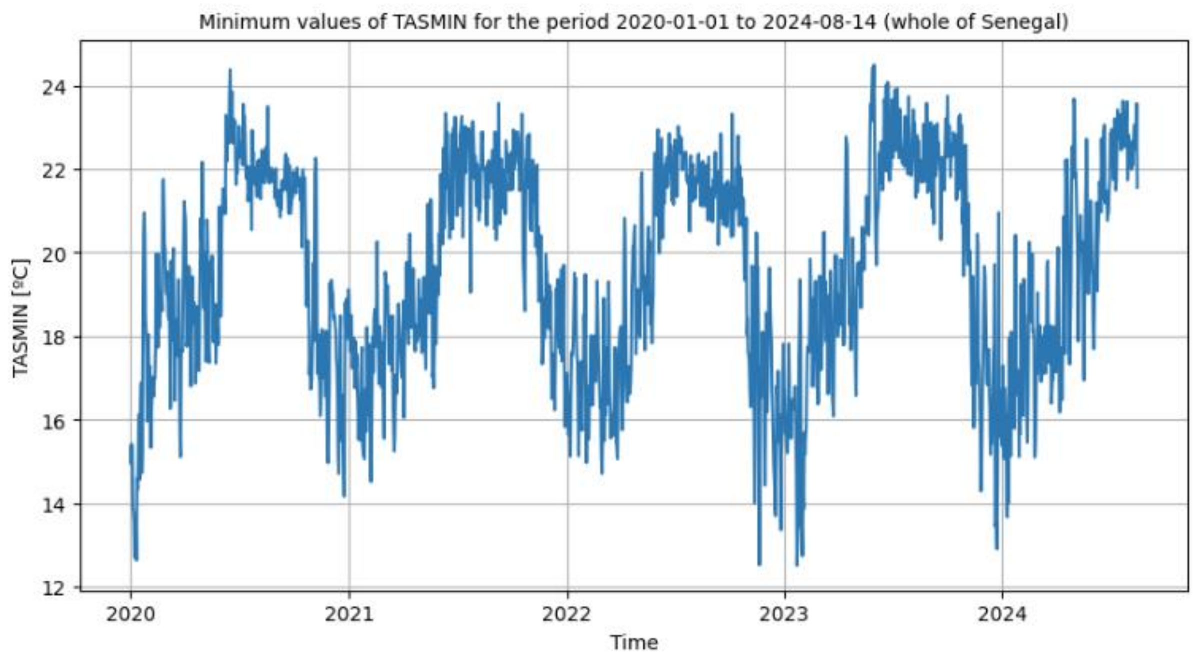

Figure 2-7. Minimum Temperature (TASMIN) plot showing the minimum value for the whole of Senegal from 2020 to 2024.

- Figure 2-8 plots the Consecutive Dry Days (CDD) index, which has monthly temporal resolution. The values in the plot are the monthly maximum over the whole of Senegal.

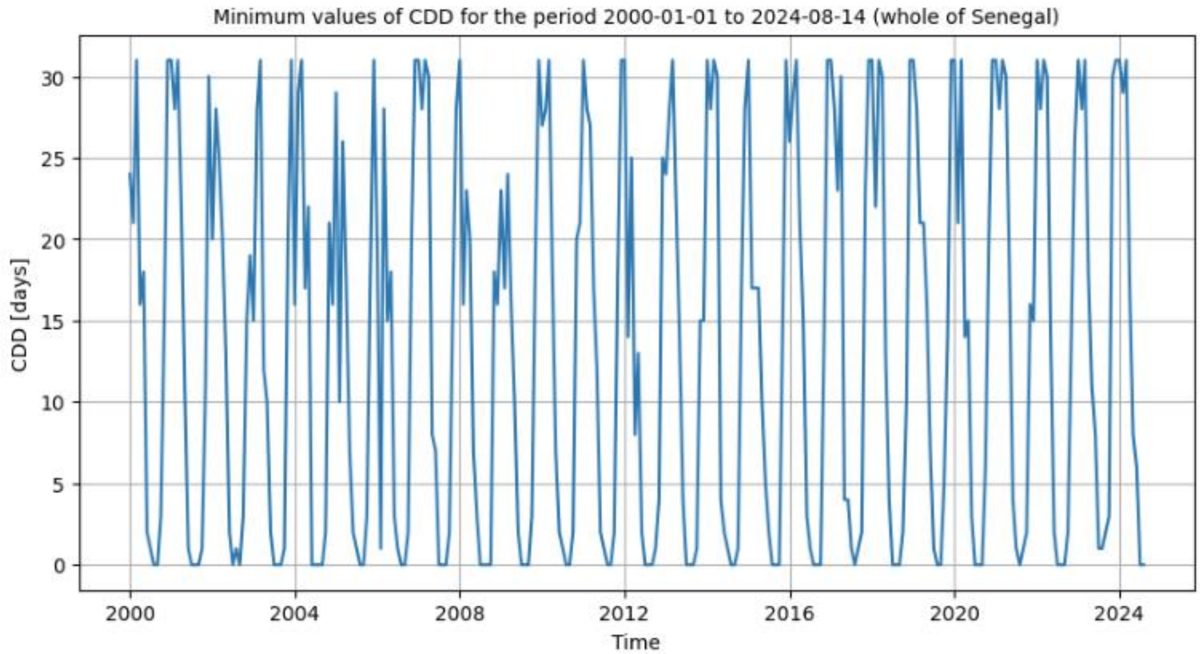

Figure 2-8. Maximum number of Consecutive Dry Days (CDD) plot showing the maximum value for Senegal from 2000 to 2024.

- Figure 2-9 plots the Consecutive Wet Days (CWD) index, which has monthly temporal resolution. The values in the plot are the monthly minimum over the whole of Senegal.

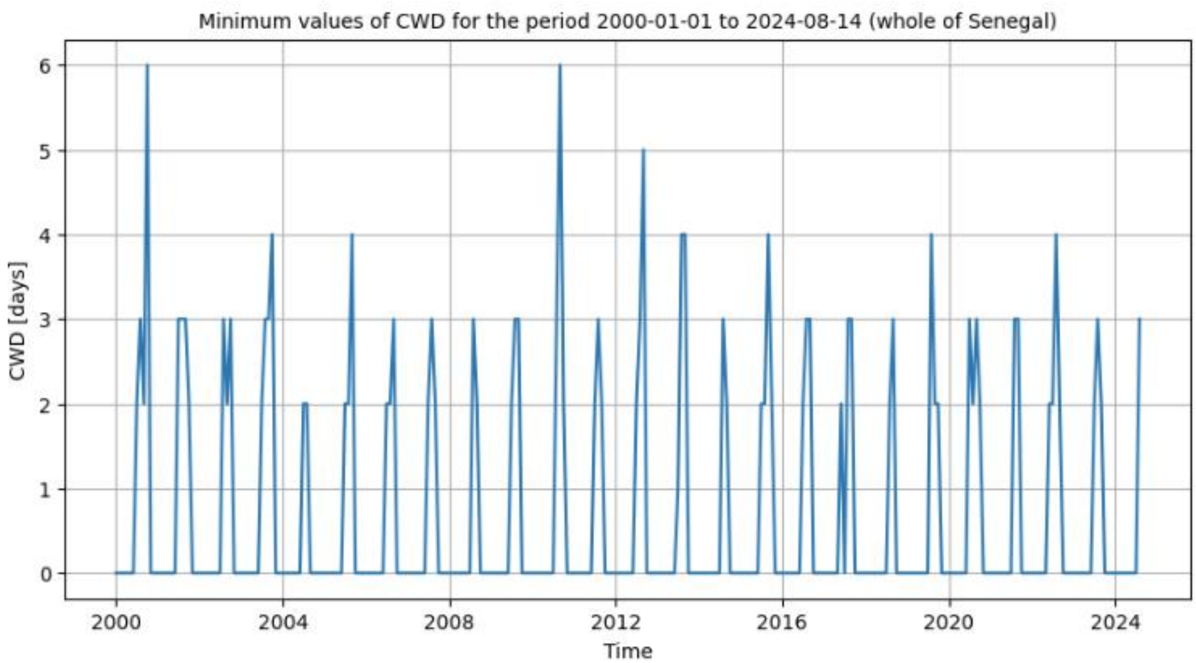

Figure 2-9. Maximum number of Consecutive Wet Days (CWD) plot showing the maximum value for Senegal from 2000 to 2024.

- Figure 2-10 plots the Warm Day-times (TX90p) index, which has monthly temporal resolution. The values in the plot are the monthly average over the whole of Senegal.

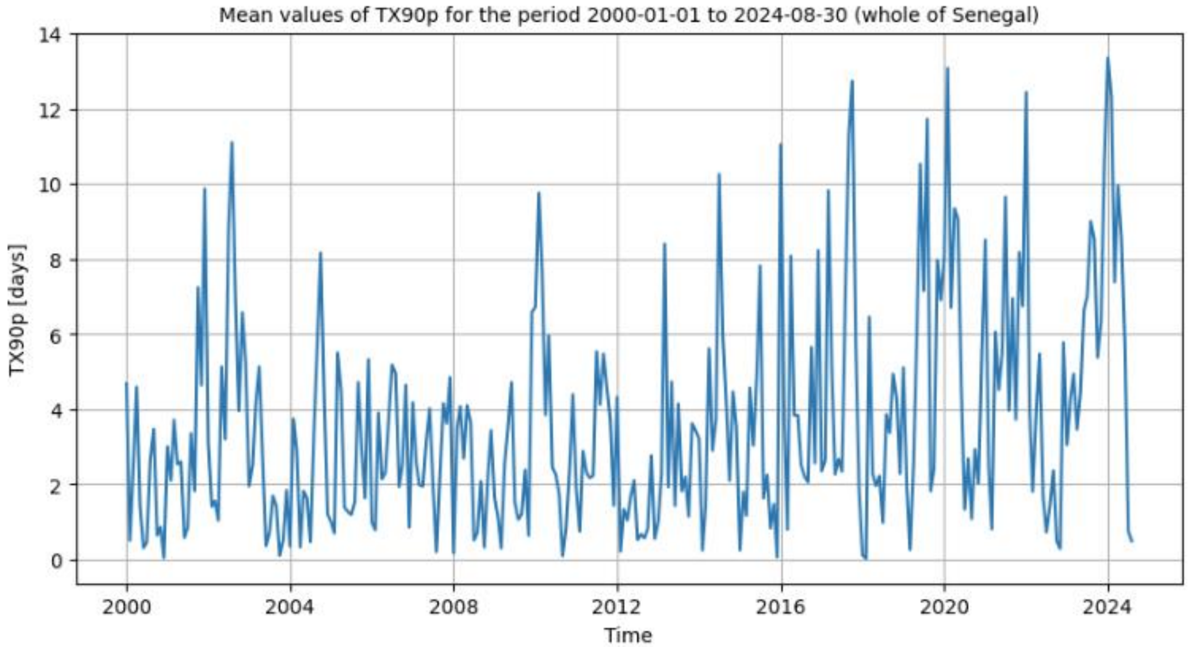

Figure 2-10. Warm Day-times (TX90p) plot showing the mean value for Senegal from 2000 to 2024.

- Figure 2-11 plots the Cold Nights (TN10p) index, which has monthly temporal resolution. The values in the plot are the monthly average over the whole of Senegal.

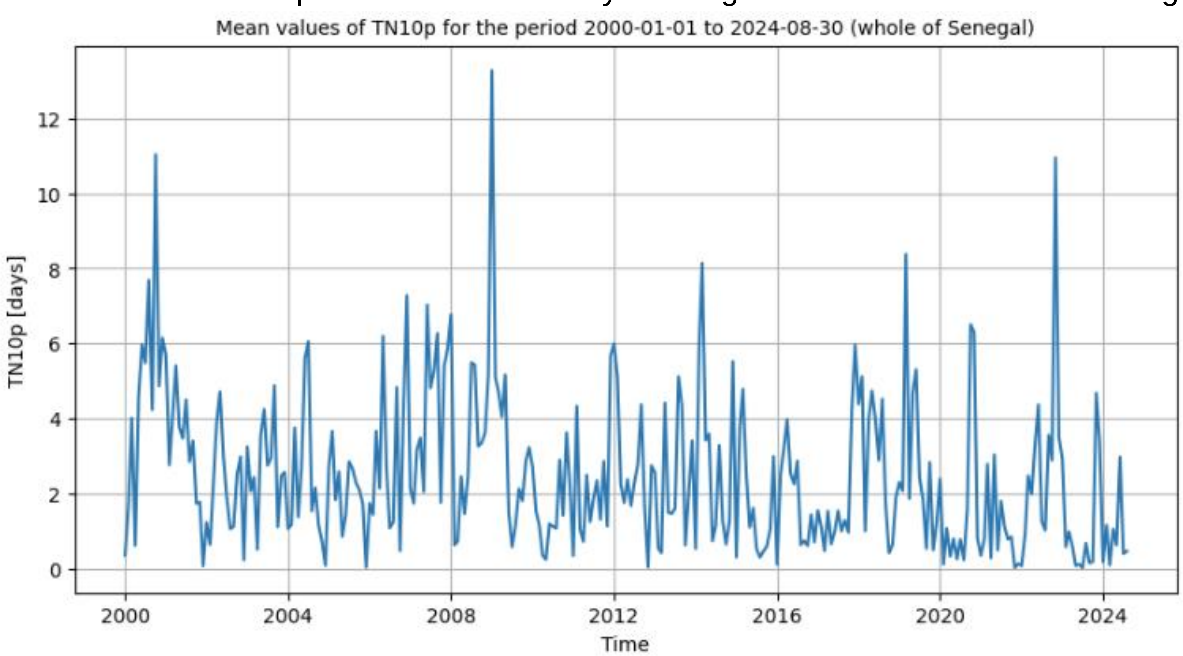

Figure 2-11. Cold Nights (TN10p) plot showing the mean value for Senegal from 2000 to 2024.

- Figure 2-12 plots the Standardised Precipitation Evapotranspiration Index (SPEI), which has monthly temporal resolution. The values in the plot are the monthly average over the whole of Senegal.

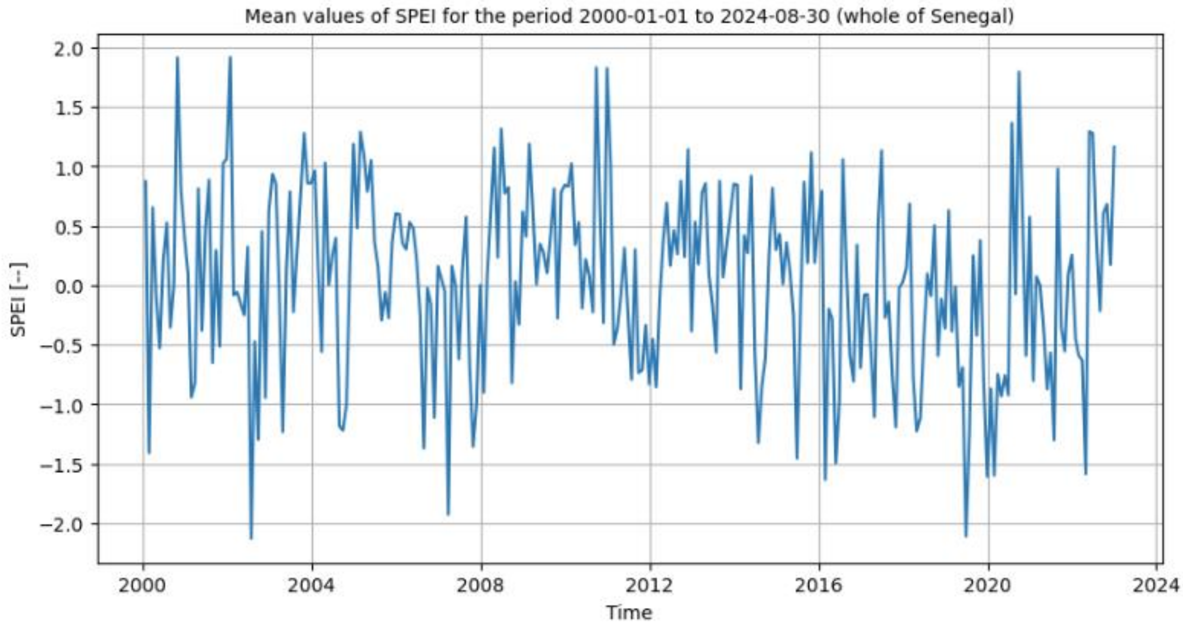

Figure 2-12. Standardised Precipitation Evapotranspiration Index (SPEI) plot showing the mean value for Senegal from 2000 to 2024.

- Figure 2-13 plots the Precipitation Sum (RR), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

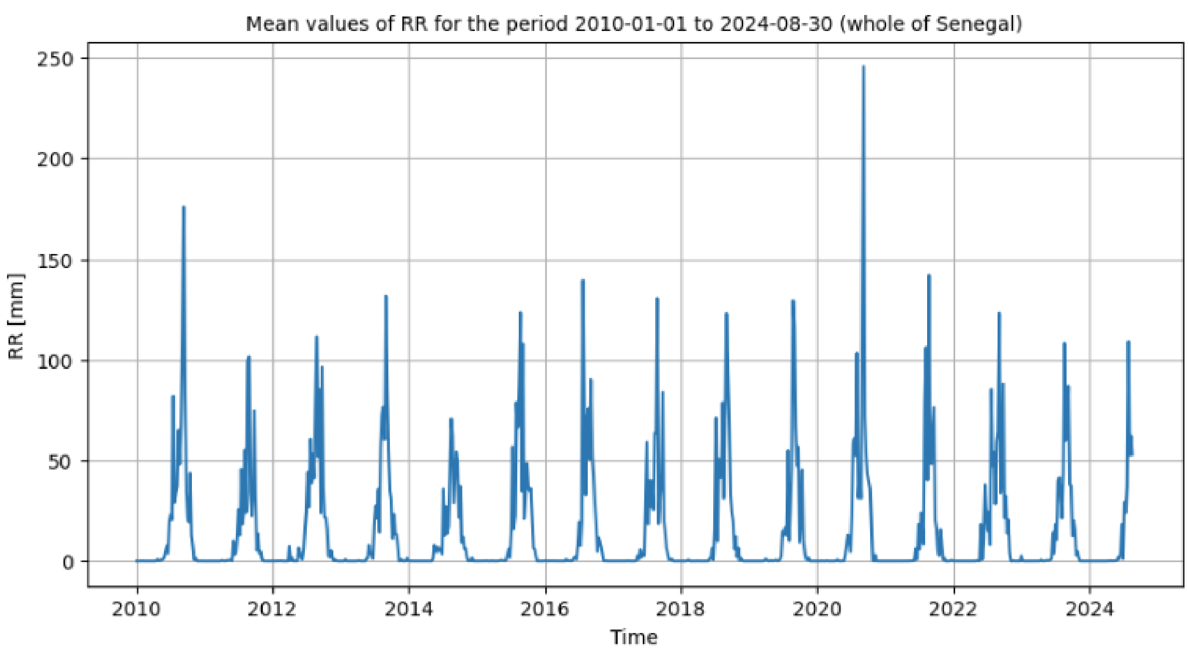

Figure 2-13. Precipitation Sum (RR) plot showing the mean value for Senegal from 2010 to 2024.

- Figure 2-14 plots the Wet Days (R1mm), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

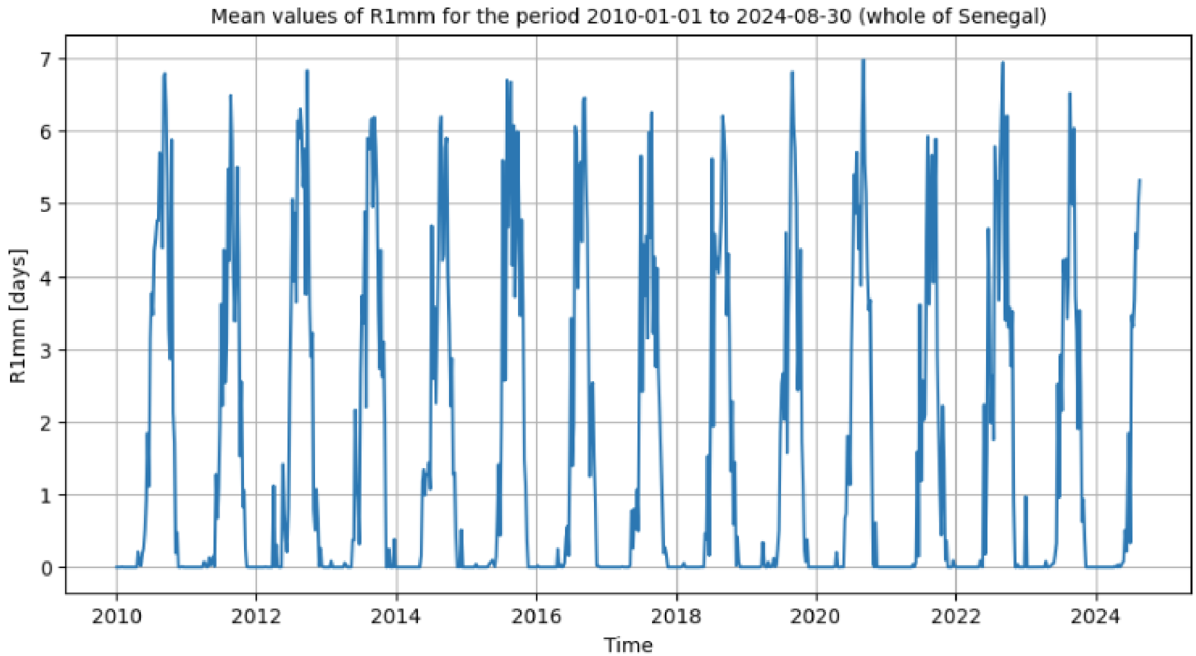

Figure 2-14. Wet Days (R1mm) plot showing the mean value for Senegal from 2010 to 2024.

- Figure 2-15 plots Heavy Precipitation days (R10mm), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

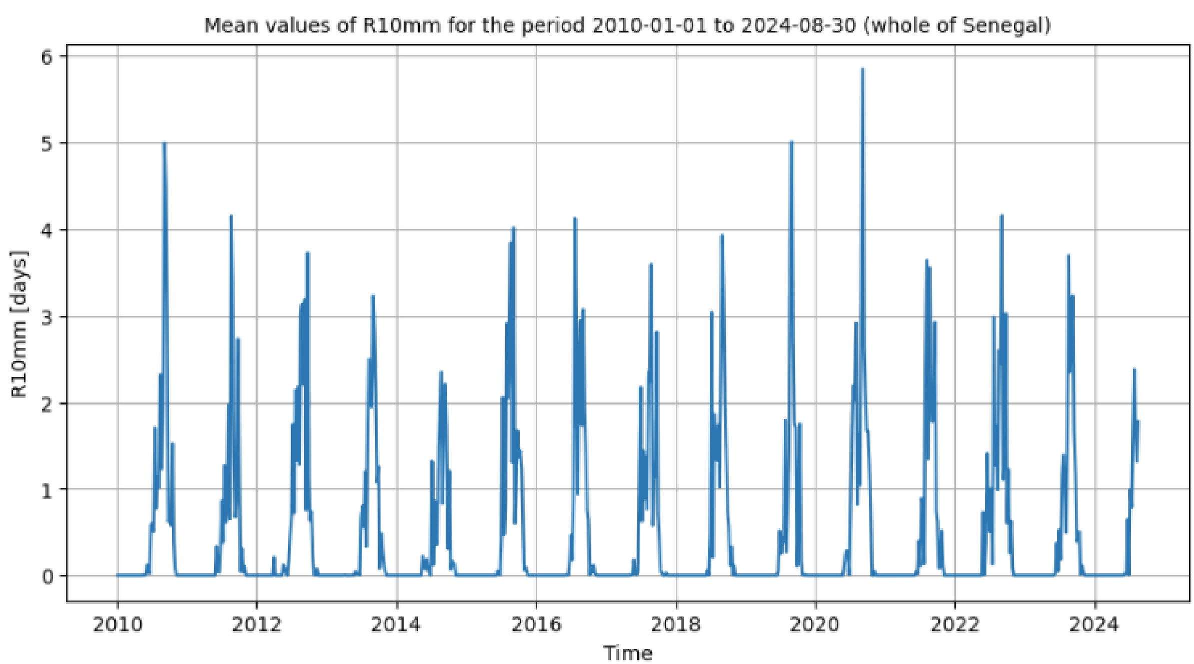

Figure 2-15. Heavy precipitation days (R10mm) plot showing the mean values for Senegal from 2010 to 2024.

- Figure 2-16 plots Very Heavy Precipitation days (R20mm), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

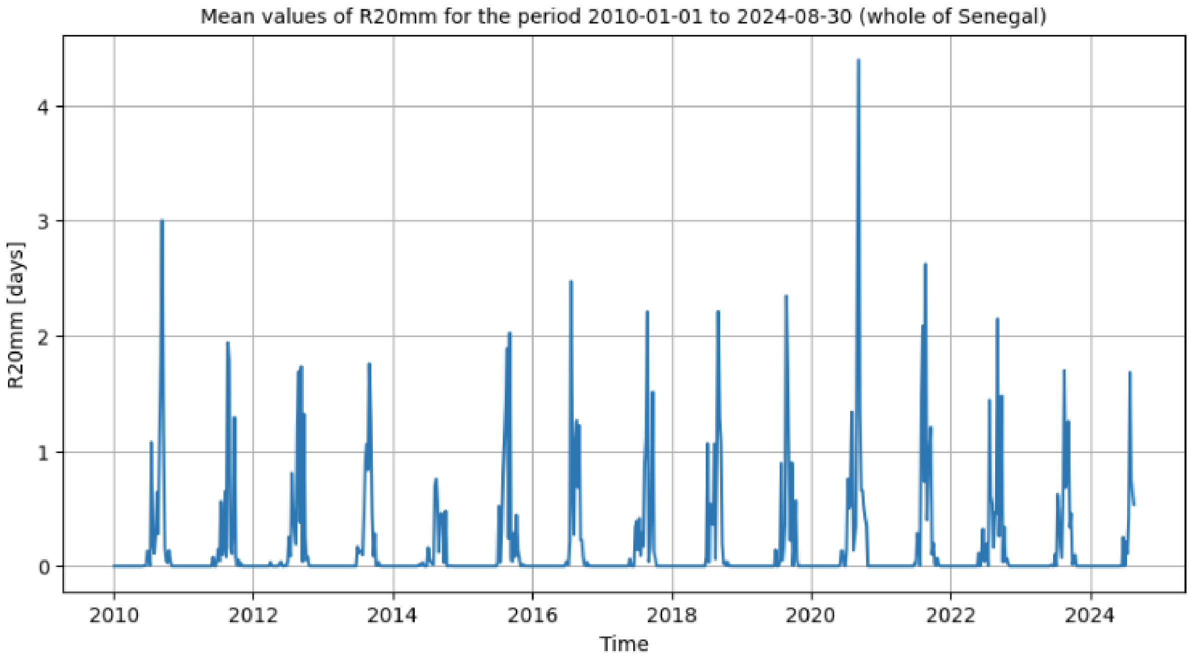

Figure 2-16. Very heavy precipitation days (R20mm) plot showing the mean value for Senegal from 2010 to 2024.

- Figure 2-17 plots the Warm and Wet Days (WW), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

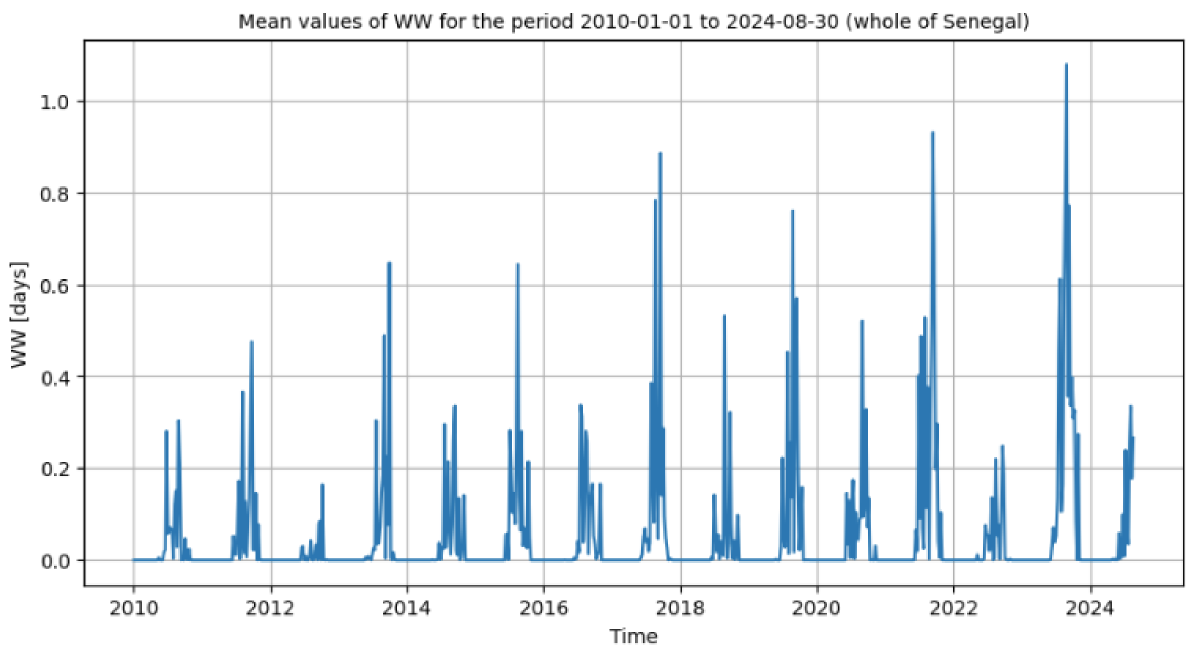

Figure 2-17. Warm and Wet Days (WW) plot showing the mean value for Senegal from 2010 to 2024.

- Figure 2-18 plots the Warm Spell Duration Index (WSDI), which has monthly temporal resolution. The values in the plot are the monthly average over the whole of Senegal.

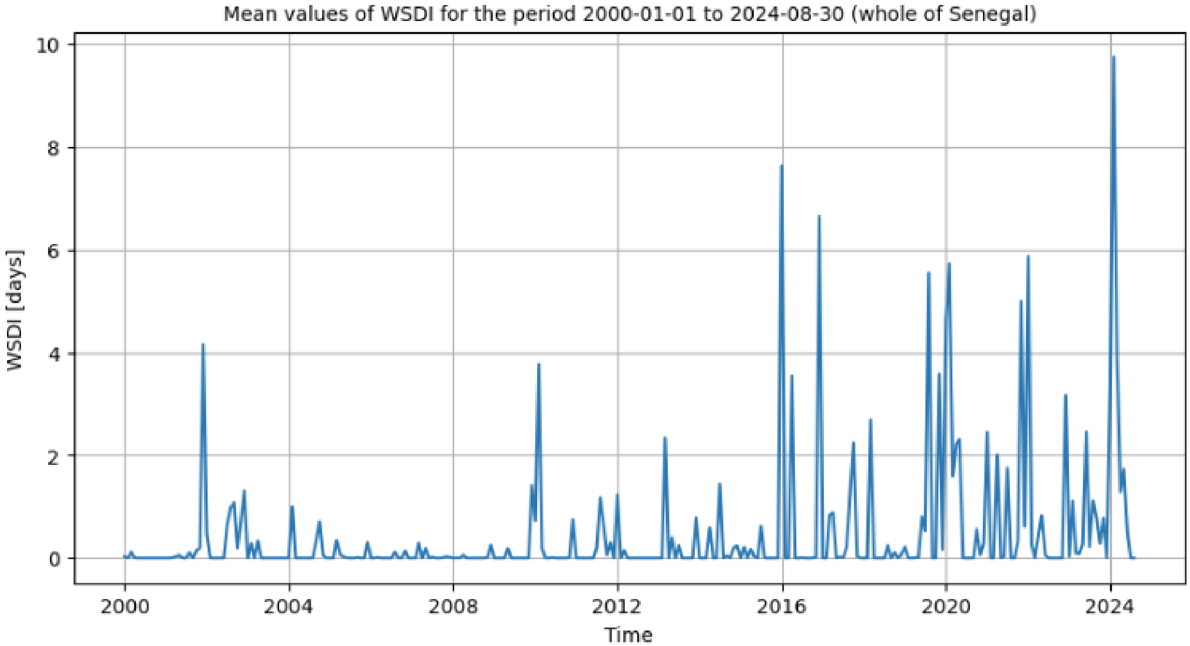

Figure 2-18. Warm Spell Duration Index (WSDI) plot showing the mean value for Senegal from 2000 to 2024.

- Figure 2-19 plots the Cold Spell Duration Index (CSDI), which has monthly temporal resolution. The values in the plot are the monthly average over the whole of Senegal.

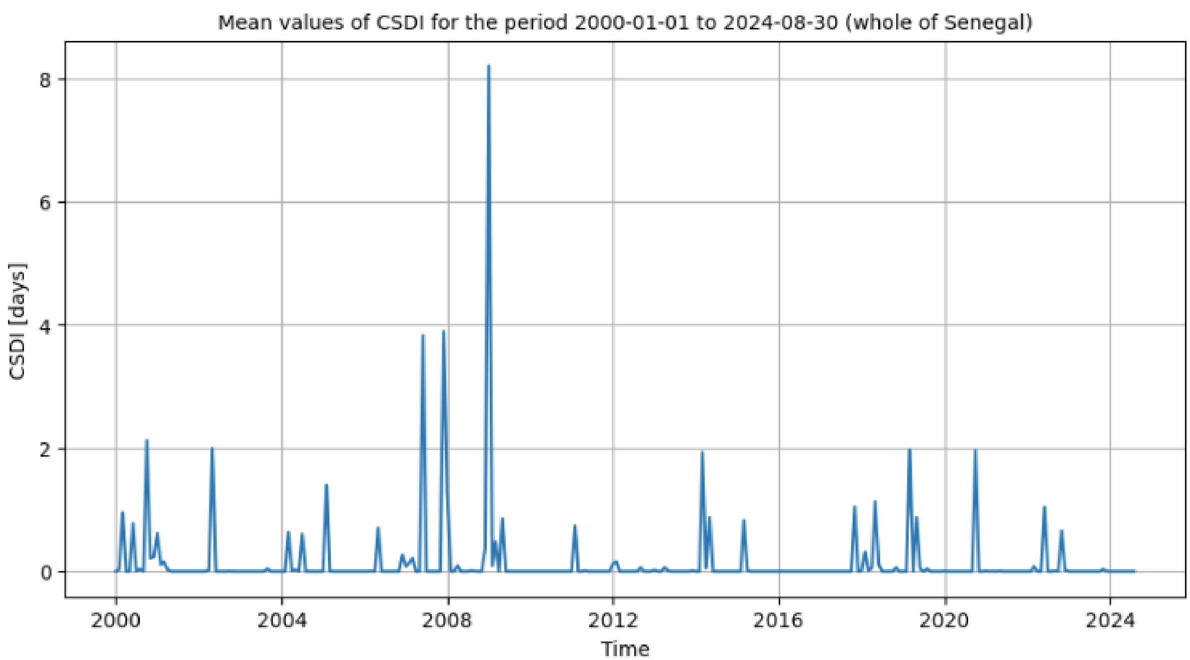

Figure 2-19. Cold Spell Duration Index (CSDI) plot showing the mean value for Senegal from 2000 to 2024.

- Figure 2-20 plots the Growing Season Length (GSL), which has yearly temporal resolution. The values in the plot are the yearly average over the whole of Senegal.

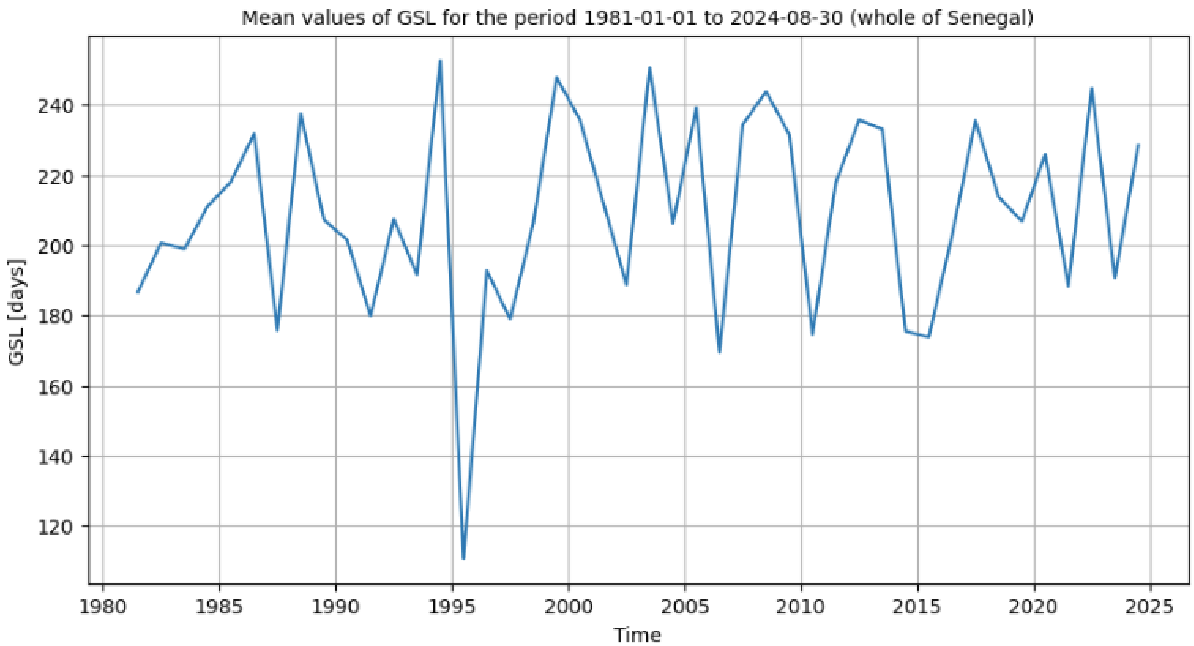

Figure 2-20. Growing Season Length (GSL) plot showing the mean value for the whole of Senegal from 1981 to 2024.

- Figure 2-21 plots the Growing Degree Days (GDD), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

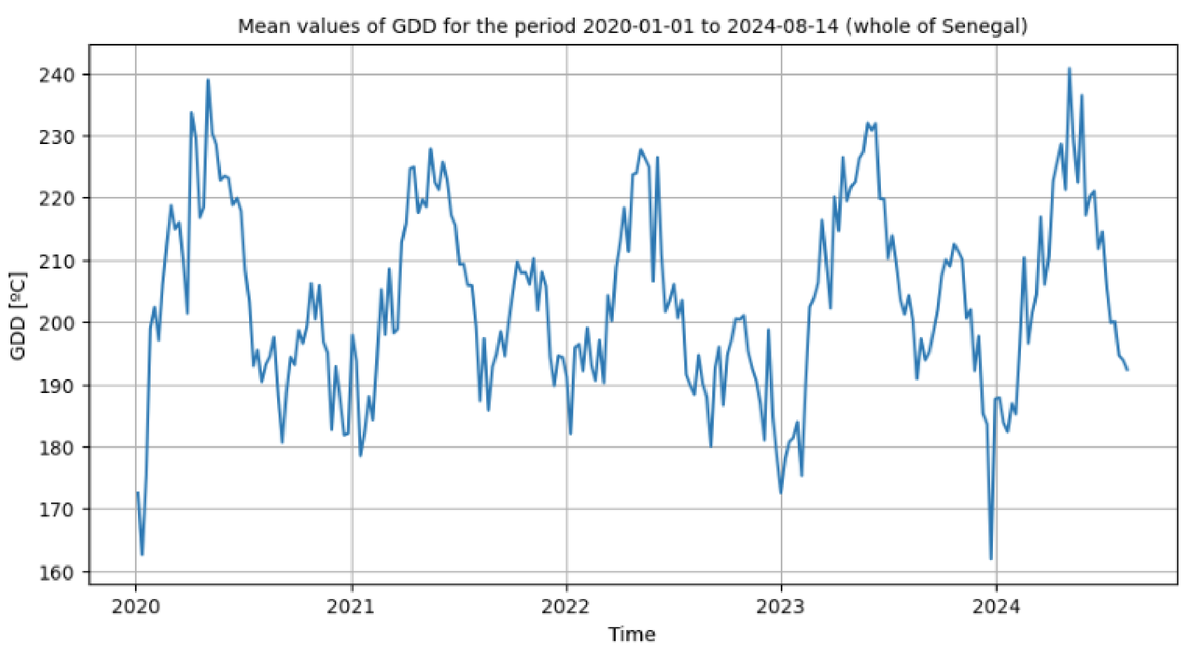

Figure 2-21. Growing Degree Days (GDD) plot showing the mean value for Senegal from 2020 to 2024.

- Figure 2-22 plots the Mean Diurnal Temperature Range (DTR), which has weekly temporal resolution. The values in the plot are the weekly average over the whole of Senegal.

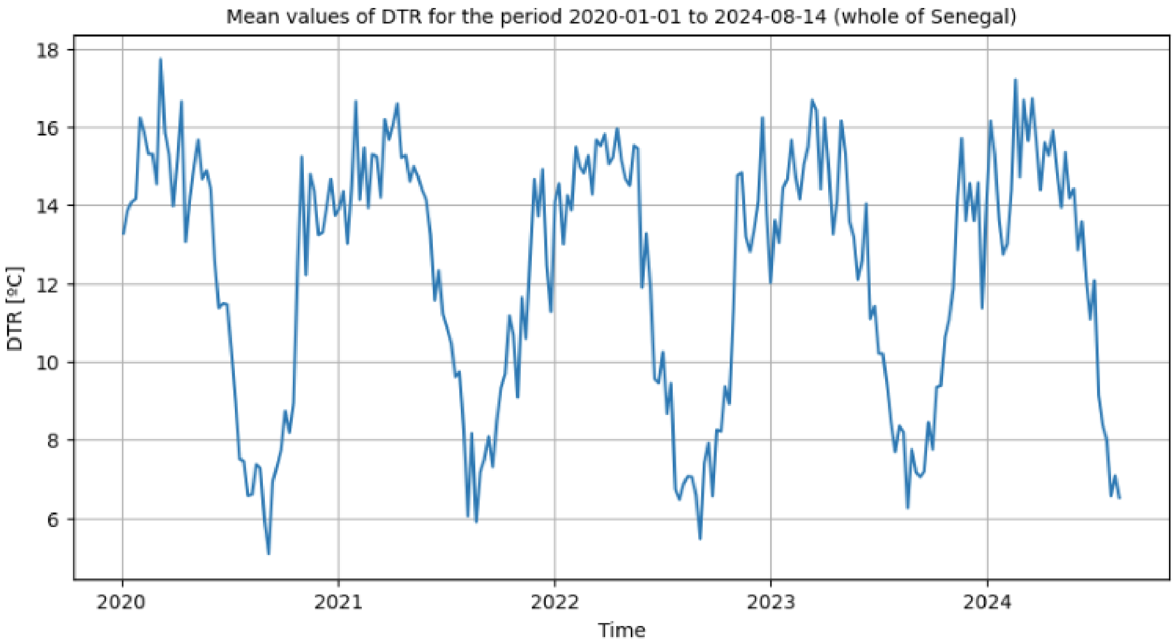

Figure 2-22. Mean Diurnal Temperature Range (DTR) plot showing the mean value for Senegal 2020 to 2024.

- Figure 2-23 plots the Simple Daily Intensity Index (SDII), which has weekly temporal resolution. The values are the weekly average over the whole of Senegal.

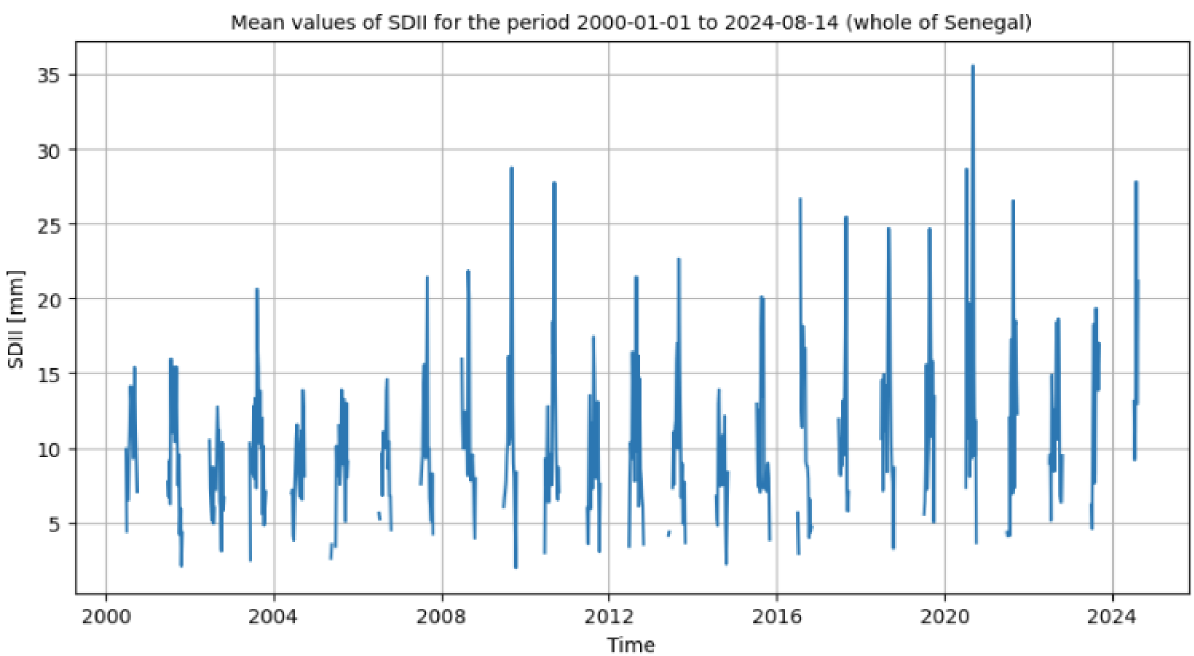

Figure 2-23. Simple Daily Intensity Index (SDII) plot showing the mean value for Senegal from 2000 to 2024.

2.3 THRESHOLD WARNINGS

The **Warning Threshold Jupyter Notebook** utilises historical time series data of climate indices, along with near real-time (NRT) observations. This offers a valuable tool for enhancing decision-making, designed to assist farmers, agronomists, and agricultural stakeholders in making informed decisions related to crop management and protection.

2.3.1 Input Data

This tool leverages the long-term historical time series data of climate indices, generated by the WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***), as described in Section 2.2. The climate indices, derived from temperature, precipitation and PET data, are generated for the period of 1981 to shortly behind real time (6-12 days).

2.3.2 Processing Algorithm

The key feature of this decision support tool is the provision of a user-friendly plot that displays both the climatology and the in-season time series of a selected climate index.

Calculating the climatology of a climate index involves determining the average indicator values for each time-step within the year (e.g. week 1, week 2, etc. for a weekly index) using the historical data from the baseline period 1991 to 2020. This climatology can be used as a reference to understand how the climate index typically varies throughout the year. Using the climatology of climate indices can be a valuable tool for identifying warning thresholds for extreme events. These thresholds can help in various fields, including agriculture, public health, drought management, etc.

For the comparison of a specific year with the climatology data, the warning thresholds can be set in the following ways:

- **Percentiles**: To calculate percentiles of the baseline climatology data (1991-2020) for the specific climate index. The user can select the 90^{th} percentile or 10^{th} percentile, which are useful to highlight the climate extremes, accounting for the variability in local climate.

- **Standard deviation**: To compute the standard deviation of the baseline climatology data (1991-2020) for the specific climate index.

- **Absolute Values:** The user can select absolute threshold values, such as 4 or more heavy precipitation days (precipitation above 20 mm) per week, which may be considered a warning threshold for flooding at a specific location.

The **Warning Threshold Jupyter Notebook** generates two outputs.

- **Threshold Warnings Plot:** The plot is generated for the selected climate index, area of interest, period of interest and thresholds. It shows a comparison between the climate index values and the climatology, by plotting:
    i. The mean climatology for the climate index selected (black dotted line)
    ii. The thresholds specified calculated from the mean climatology for the climate index selected (grey shaded area)
    iii. The values of the climate index for the time period selected (coloured line)

- **Plot Description**: The plot description provides a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location. This allows the user to easily detect times when the selected climate index fell outside of the thresholds selected.

Figure 2-24 shows an example of the daily mean 2 metre temperature (T2M) in 2022, compared with the climatology data (1991-2020). The dark grey area represents the mean plus and minus the standard deviation of the climatology data. Figure 2-25 shows the accompanying plot description.

Figure 2-26 shows an example of monthly SPEI in 2022, compared with the climatology data (1991-2020). The dark grey area represents the 10th and 90th percentiles of the climatology data. Below the plot, the results are described. Figure 2-27 shows the accompanying plot description.

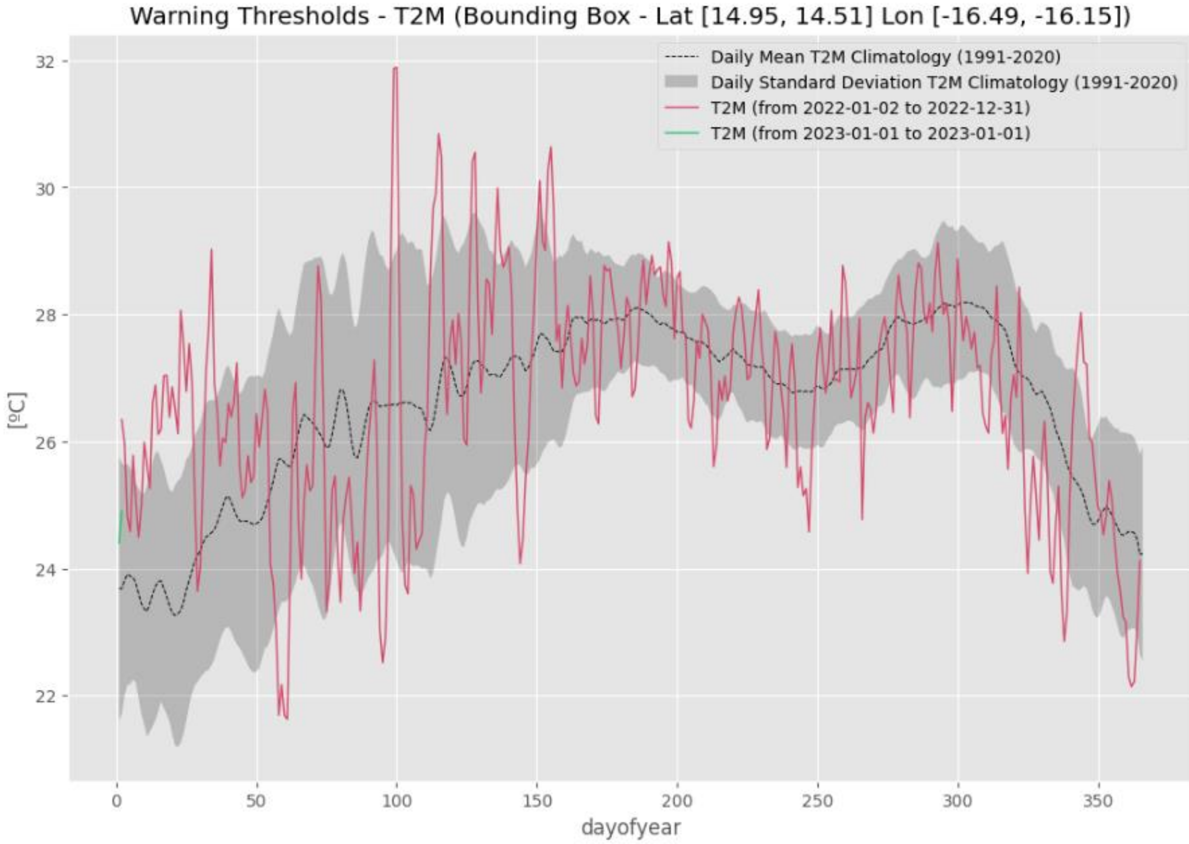

Figure 2-24. Example of daily Mean 2 metre Temperature (T2M) in 2022, compared with the climatology data (1991-2010). The dark grey area represents the mean plus and minus the standard deviation of the climatology data.

Plot Description

The plot shows a comparison between the T2M climatology data (1991-2020) and the T2M data from 2022-01-01 to 2023-01-01 (Bounding Box - Lat [14.95, 14.51] Lon [-16.49, -16.15]):

- **Below is a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location.**
  - Lower threshold (Standard Deviation)
    - The lower threshold was exceeded 3 times in 2022-02.
    - The lower threshold was exceeded 5 times in 2022-03.
    - The lower threshold was exceeded 5 times in 2022-04.
    - The lower threshold was exceeded 4 times in 2022-05.
    - The lower threshold was exceeded 2 times in 2022-06.
    - The lower threshold was exceeded 6 times in 2022-07.
    - The lower threshold was exceeded 6 times in 2022-08.
    - The lower threshold was exceeded 6 times in 2022-09.
    - The lower threshold was exceeded 3 times in 2022-10.
    - The lower threshold was exceeded 17 times in 2022-11.
    - The lower threshold was exceeded 7 times in 2022-12.
- **There were 64 day(s) below the threshold. The longest period below the threshold was 7 consecutive day(s). This started on 2022-11-19 and lasted until 2022-11-25.**
  - Upper threshold (Standard Deviation)
    - The upper threshold was exceeded 21 times in 2022-01.
    - The upper threshold was exceeded 4 times in 2022-02.
    - The upper threshold was exceeded 8 times in 2022-04.
    - The upper threshold was exceeded 7 times in 2022-05.
    - The upper threshold was exceeded 3 times in 2022-06.
    - The upper threshold was exceeded 7 times in 2022-07.
    - The upper threshold was exceeded 2 times in 2022-08.
    - The upper threshold was exceeded 3 times in 2022-09.
    - The upper threshold was exceeded 1 times in 2022-11.
    - The upper threshold was exceeded 4 times in 2022-12.
- **There were 60 day(s) above the threshold. The longest period above the threshold was 15 consecutive day(s). This started on 2022-01-12 and lasted until 2022-01-26.**
  - *Please note: The longer that the threshold is exceeded, the greater the potential impact.*

Figure 2-25. Plot description accompanying the plot above which provides a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location.

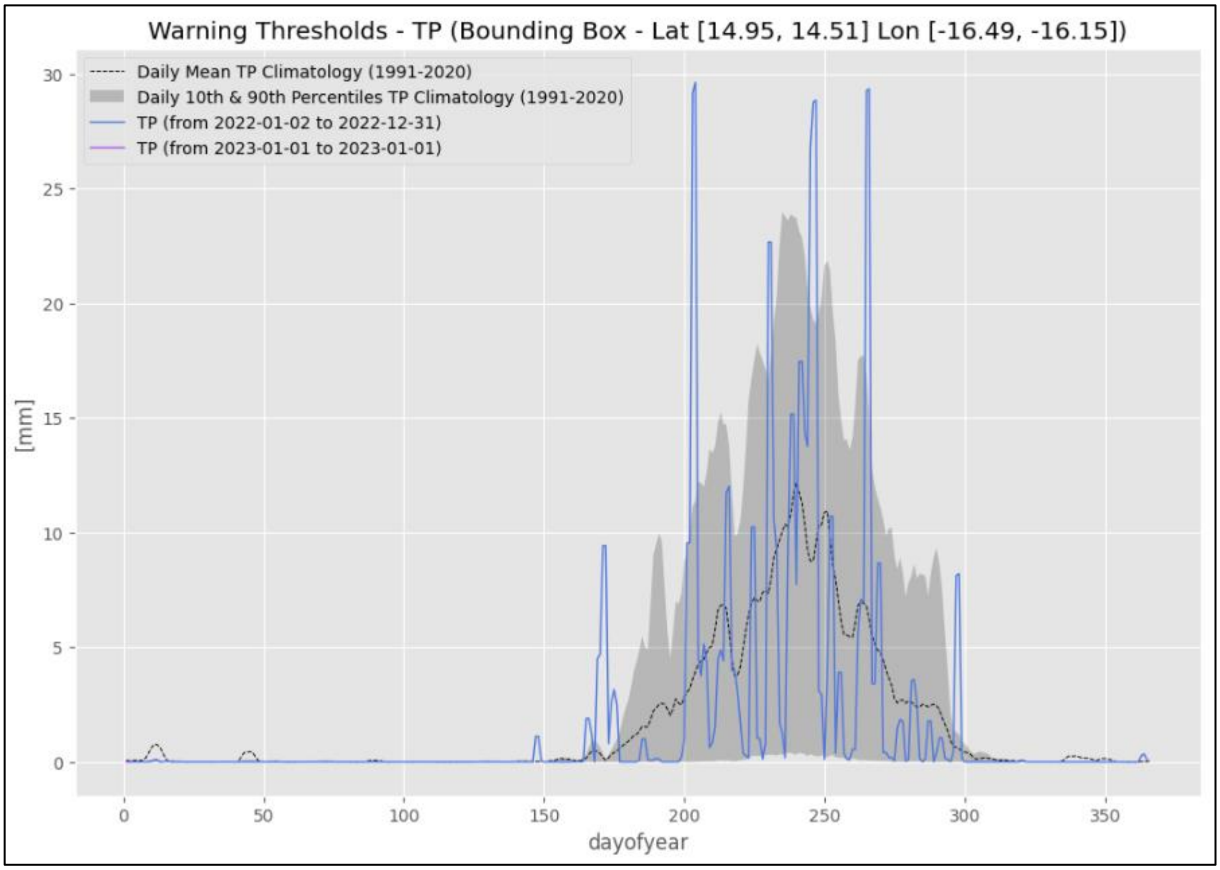

Figure 2-26. Example of daily Total Precipitation in 2022, compared with the climatology data (1991-2010). The dark grey area represents the 10th and 90th percentiles of the climatology data.

Plot Description

The plot shows a comparison between the TP climatology data (1991-2020) and the TP data from 2022-01-01 to 2023-01-01 (Bounding Box - Lat [14.95, 14.51] Lon [-16.49, -16.15]):

- **Below is a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location.**
  - Lower threshold (10th Percentile)
    - The lower threshold was exceeded 5 times in 2022-01.
    - The lower threshold was exceeded 7 times in 2022-02.
    - The lower threshold was exceeded 2 times in 2022-03.
    - The lower threshold was exceeded 4 times in 2022-04.
    - The lower threshold was exceeded 6 times in 2022-05.
    - The lower threshold was exceeded 2 times in 2022-06.
    - The lower threshold was exceeded 1 times in 2022-07.
    - The lower threshold was exceeded 2 times in 2022-08.
    - The lower threshold was exceeded 3 times in 2022-09.
    - The lower threshold was exceeded 2 times in 2022-10.
    - The lower threshold was exceeded 2 times in 2022-11.
    - The lower threshold was exceeded 1 times in 2022-12.
- **There were 37 day(s) below the threshold. The longest period below the threshold was 4 consecutive day(s). This started on 2022-01-04 and lasted until 2022-01-07.**
  - Upper threshold (90th Percentile)
    - The upper threshold was exceeded 2 times in 2022-01.
    - The upper threshold was exceeded 2 times in 2022-03.
    - The upper threshold was exceeded 3 times in 2022-05.
    - The upper threshold was exceeded 11 times in 2022-06.
    - The upper threshold was exceeded 4 times in 2022-07.
    - The upper threshold was exceeded 2 times in 2022-08.
    - The upper threshold was exceeded 5 times in 2022-09.
    - The upper threshold was exceeded 2 times in 2022-10.
    - The upper threshold was exceeded 2 times in 2022-11.
    - The upper threshold was exceeded 3 times in 2022-12.
- **There were 36 day(s) above the threshold. The longest period above the threshold was 8 consecutive day(s). This started on 2022-06-17 and lasted until 2022-06-24.**
- *Please note: The longer that the threshold is exceeded, the greater the potential impact.*

Figure 2-27. Plot description accompanying the plot above which provides a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location.

3 PRODUCT SPECIFICATION

3.1 *SURFACE WETNESS AND EVAPORATIVE LOSS*

The HydroSENS-SWS application (***wascia_hydrosens-sws***) primarily uses Sentinel-3 data for water stress monitoring, given the suitability of its sensors and the correct temporal resolution. For calculating evaporative losses and soil wetness dynamics, the "Simplified Triangle" technique is used. In order to achieve a better spatial resolution, the application fuses Sentinel-3 with Sentinel-2 based soil moisture indices.

3.1.1 Product Specification Table

The outputs from the HydroSENS-SWS application (***wascia_hydrosens-sws***) are the soil moisture (SM: Soil Moisture) and evaporative loss (EWL: Evaporative Water Loss) products. The format of these data files follow the specifications below.

Table 3-1. Soil Moisture data specifications

Specifications	
Format	GeoTiff/JPEG
Spatial resolution	1 km or downscaled to 20 m
Temporal resolution	1/week
Latency	24 hr
Naming convention	**{data type}**_**{spatial resolution}**_**{coverage}**_**{metric}**_**{date}** e.g. **SW**_**1000**_**w**_**max**_**20231010** **Where:** - **{data type}: SM** = soil moisture; - **{spatial resolution}:** resolution in meters. **1000** = 1000 m resolution, **20** = 20 m resolution - **{coverage}: w** = week, **d** = day - **{metric}: max** = maximum of weekly series values, **min** = minimum of weekly series values, **mean** = average of weekly series values. **{date}:** date in format **YYYYMMDD.** This variable only appears in files with **w** for weekly products.

Table 3-2. Evaporative Water Loss data specifications

Specifications	
Format	GeoTiff/JPEG
Spatial resolution	1 km or downscaled to 20 m
Temporal resolution	1/week
Latency	24 hr
Naming convention	**{data type}_{spatial resolution}_{coverage}_{metric}_{date}** e.g. **EWL_1000_w_max_20231010** **Where:** - **{data type}: EWL** = evapotranspiration; - **{spatial resolution}:** resolution in meters. **1000** = 1000 m resolution, **20** = 20 m resolution - **{coverage}: w** = week, **d** = day - **{metric}: max** = maximum of weekly series values, **min** = minimum of weekly series values, **mean** = average of weekly series values. - **{date}:** date in format **YYYYMMDD.** This variable only appears in files with **w** for weekly products.

3.2 CLIMATE INDICES

The WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***) provides a set of Climate Indices derived from ERA5-Land reanalysis data. The climate indices are a reliable and decision-relevant climate information at a local and national level and on all weather and climate time scales useful for monitoring drought and water stress. The list of climate indices and their definition are provided in Section 2.2.

3.2.1 Product Specification Table

For each climate index calculated an output data file is generated. The format of these data files follow the specifications below.

Table 3-3. Climate indices data specifications

Specifications	
Format	netcdf (.nc)
Spatial resolution	0.1 deg (lat/lon)
Temporal resolution	Dependent on climate index, see Section 2.2.3

Latency	6 – 12 days
Naming convention	**SEN_{climate index}_tempRes-{temporal resolution}_{start date}_{end date}.nc** **Where:** **SEN:** Spatial coverage of the output climate index (SEN= Senegal) **{climate index}:** Abbreviation of your chosen climate index, as defined in Section 2.2 **{temporal resolution}:** Temporal resolution of the output climate index (Y = yearly, M = monthly, W = weekly) **{start date}:** Start date of the timeseries, automatically taken from the input dataset **{end date}:** End date of the timeseries, automatically taken from the input dataset

3.3 *WARNING THRESHOLDS*

The **Warning Threshold Jupyter Notebook** developed in this project utilises historical time series data of climate indices, along with near real-time observations.

3.3.1 Product Specification Table

The **Warning Threshold Jupyter Notebook** generates two outputs (see Section 2.3.2 for examples).

- **Threshold Warnings Plot:** The plot is generated for the selected climate index, area of interest, period of interest and thresholds. It shows a comparison between the climate index values and the climatology, by plotting:
  i. The mean climatology for the climate index selected (black dotted line)
  ii. The thresholds specified calculated from the mean climatology for the climate index selected (grey shaded area)
  iii. The values of the climate index for the time period selected (coloured line)

- **Plot Description**: The plot description provides a breakdown of the number of times the upper and lower thresholds were exceeded each month for the chosen time period and location. This allows you to assess how the climate index for period of interest compares to the thresholds selected.

4 CONCLUSIONS

This document describes the Algorithm Theoretical Basis and the Products Specification related with the ESA Water Stress and Climate Indices for Africa (WaSCIA) project. This document is for public distribution.

The WaSCIA HydroSENS-Soil Water Stress (SWS) application (***wascia_hydrosens-sws***) generates surface wetness and evaporation loss outputs by applying an effective algorithm to Sentinel-3 imagery for Senegal. An automated method is used for extracting Evaporative Fraction (EF) and Soil Moisture (SM) from Surface Temperature/Vegetation Index (TS/VI) data using Earth Observation (EO) data. The simplified triangle method is proposed as an alternative to existing methods, offering simplicity and effectiveness without requiring mathematical models or auxiliary data. The results show that the simplified triangle method accurately extracts EF and SM, and the downscaled indices provide valuable insights into the spatial distribution of these parameters. Random Forest, a machine learning algorithm, is employed to downscale the spatial resolution of the triangle method indices. Downscaling increases the resolution of an image, and in this context, it enhances the resolution of the EF and SM maps. Random Forest is trained on a set of training data, pairing pixels with known EF and SM values. The trained model can then predict the EF and SM values for new pixels based on their position in the image.

The WaSCIA Climate Indicators application (***wascia_processor_climate_indicators***) provides a set of Climate Indices derived from ERA5-Land reanalysis data. 20 climate indices have been computed using definitions from the Guidelines from the World Meteorological Organisation and other literature, see [RD 8], [RD 9], [RD 10] and [RD 11]. Following the index descriptions provided in these references, the most appropriate temporal resolution has been selected for each index. Section 2.2. describes the parameters used for each index and its acronym, which is also needed to run the implemented tool.

The **Warning Threshold Jupyter Notebook** utilises historical time series data of the climate indices and near real time observations (the outputs from the Climate Indicators application) to allow analysis of the climate indices in the context of historical trends. This analysis is based on the comparison between the climatology values and the near real-time data. The warning threshold tool is intended to be a decision support tool, so the output is a plot figure and the description of the plot to enable the user to easily and quickly understand the results. This offers a valuable tool for enhancing decision-making, designed to assist farmers, agronomists, and agricultural stakeholders in making informed decisions related to crop management and protection.

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