TransformAr

Accelerating and upscaling transformational adaptation in Europe: demonstration of water-related innovation packages

Feasibility Study to produce a tailored Climate projection Database for Guadeloupe

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List of acronyms

ADEME	Agence de la Transition Écologique *(French Agency for Ecological Transition)*
CDF-t	Cumulative Distribution Function transform
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMIP5	Coupled Model Intercomparison Project Phase 6
CNRM-CM	Centre National de Recherches Météorologiques - Climate Model
CSV	Comma-Separated Values
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis v5
GCM	Global Climate Model
GEV	Generalized Extreme Value
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
NetCDF	Network Common Data Form (data format)
QM	Quantile Mapping
RCP	Representative Concentration Pathway *(e.g., RCP2.6, RCP7.0, RCP8.5)*
SSBC	Study-Specific Bias Correction
SSR	Singularity Stochastic Removal

1 Introduction

In the framework of the TransformAr project and in alignment with the objectives of Work Package 2 (WP2), which aims to provide harmonized, high-quality climate data across European demonstrator regions, a specific effort has been initiated to assess the feasibility of enhancing the spatial resolution of climate data for Guadeloupe. While WP2 leverages consolidated datasets and modelling approaches, such as those from CMIP6 and ISIMIP (simulation round 3b), current projections for Guadeloupe remain constrained by coarse spatial resolution (typically 0.5° x 0.5°, or approximately 50 km), offering only a limited number of grid points to represent the island's highly heterogeneous climate.

Guadeloupe's complex topography, coastal influence, and small-scale climatic gradients necessitate a more refined approach to accurately assess climate variability and future changes - especially in relation to precipitation, a key driver of natural hazards such as floods, droughts, and landslides, which are of critical concern in the Caribbean region.

This feasibility study addresses these limitations by focusing on precipitation data for Guadeloupe. It explores the availability, quality, and granularity of existing climate datasets and proposes methodologies to improve the spatial resolution of precipitation mapping through appropriate downscaling techniques. In this context, the study aligns with TransformAr's broader goals by aiming to enhance local-scale climate data usability, support evidence-based climate adaptation planning, and contribute to more accurate regional impact modelling.

At the request of ADEME Guadeloupe, the entity responsible for the local demonstrator, a tailored product was required to map climate hazards across the territory and support the demonstrator's applications, particularly in the sectors of tourism and agriculture. This demand for a fit-for-purpose dataset underscores the need for locally relevant, high-resolution outputs that can inform sector-specific resilience strategies.

The outcome of this work is intended to provide both strategic and technical guidance for the creation of high-resolution cartographic products reflecting precipitation trends and extremes under climate change scenarios (e.g., RCP2.6, RCP7.0, RCP8.5). These outputs will serve local stakeholders, including ADEME, by improving the representation of climate risks and supporting targeted adaptation strategies specific to Guadeloupe's environmental and socio-economic context.

The specific objectives of this study are to:

- **Propose a method for creating a multi-point cartographic product** for Guadeloupe's climate, specifically designed to capture the spatial variability of precipitation across the island's diverse microclimates.
- **Assess existing historical climate products**, including global reanalysis, observational datasets, and regional climate model outputs, and **evaluate their quality and suitability** for precipitation mapping, considering their spatial resolution, temporal coverage, and consistency.
- **Identify key data gaps** in the available precipitation records that limit the accuracy of climate impact assessments and that must be addressed to support future adaptation planning and policy development.
- **Downscale existing climate products** (e.g., from CMIP6) for Guadeloupe, using appropriate techniques to improve the spatial granularity and better represent the island's unique topographical and climatic features.

- **Provide recommendations for further developments**, including strategies to close identified data gaps, enhance future datasets, and strengthen climate data infrastructure for Guadeloupe.

2 Microclimatic Diversity and Climate Regimes in the Guadeloupe Archipelago

The Guadeloupe archipelago exhibits a complex and heterogeneous climate regime shaped by its insular character, varied topography, and the influence of the easterly trade winds. Although broadly categorized as a humid tropical climate, the region's atmospheric behavior is modulated by pronounced microclimatic gradients, especially in precipitation and temperature, over relatively short spatial scales.

2.1 Spatial Distribution of Precipitation

The spatial variability of annual precipitation across Guadeloupe is significant and closely linked to both **elevation** and **exposure to prevailing winds**. Orographic uplift along the Basse-Terre mountain range, oriented perpendicularly to the trade winds, results in highly asymmetric rainfall patterns:

- **Semi-arid conditions** are observed on low-lying islands such as **Les Saintes** and **La Désirade**, with mean annual rainfall ranging from **1,000 to 1,200 mm**.
- The **eastern and northern parts of Grande-Terre** receive **1,300 to 1,500 mm/year**, while the **Grands-Fonds region** and the **northern Basse-Terre foothills** receive **1,600 to 1,800 mm/year**.
- On the **windward slopes of Basse-Terre**, rainfall increases sharply with elevation:
    - Below 600 m: between **1,800 and 3,500 mm/year**;
    - Near the **summit of La Soufrière**, persistent orographic cloud cover leads to **precipitation exceeding 10,000 mm/year**.

In contrast, the **leeward coast (Côte-sous-le-vent)** is markedly drier, as descending air masses are depleted of moisture, resulting in annual totals between **1,300 and 1,500 mm** [3].

2.2 Temperature Regimes and Thermal Modulation by Altitude

Guadeloupe's thermal regime is characterized by **low inter-annual variability**, typical of oceanic tropical climates, with annual seasonal temperature differences generally limited to **2-4°C**. Diurnal ranges, however, are more pronounced, reaching up to **8°C** in inland lowland stations.

Two representative climate stations illustrate the altitudinal modulation of temperature:

- **Raizet (Les Abymes, lowland)**:
    - Mean annual maximum temperature: **30.6°C**;
    - Annual count of hot days (Tmax > 32°C): **~71 days/year**.
- **Duclos (Petit-Bourg, 110 m a.s.l.)**:
    - Mean annual maximum temperature: **29.2°C**;
    - Hot days (Tmax > 32°C): **~8 days/year**.

This highlights the **mitigating effect of elevation** on extreme temperatures and thermal comfort [3].

2.3 Hydro-Climatic Extremes

The region is highly exposed to both **hydrological deficits and surpluses**, with impacts amplified by the archipelago's topographic contrasts and small spatial scales:

- **Droughts** occur more frequently on **calcareous plateaus** (Grande-Terre), **southern islands**, and **leeward coasts**. The 1997-1998 drought remains the most severe on record (since 1951), with deficits exceeding **40%** in some locations (e.g., 860 mm at Raizet versus a 30-year average of 1,385 mm).
- **Heavy precipitation events**, often convective in nature, can occur in any season and are driven by both **mesoscale systems** (squall lines, convective clusters) and **synoptic-scale phenomena** (e.g., tropical waves, cyclones, or cold fronts). Notable events include:
    - 14 Sept 1995 (Hurricane Marilyn): **250-500 mm** in southwestern Basse-Terre;
    - 4-5 Jan 2011: frontal rainfall of **80-100 mm** across the Grands-Fonds and northern Basse-Terre [3].

These events are known to cause **flash flooding, landslides**, and **coastal or urban runoff crises**.

2.4 Cyclonic Risk and Seasonal Variability

The Atlantic hurricane season (June to November) constitutes the primary period of meteorological hazard. On average (1981-2010), **12.5 named tropical cyclones** form annually in the Atlantic basin, with **6.5 reaching hurricane strength**. Guadeloupe's exposure includes:

- **Tropical depressions** (winds < 63 km/h), generally associated with heavy rainfall;
- **Tropical storms** (63-117 km/h), often causing moderate wind and wave damage;
- **Hurricanes** (≥118 km/h), classified from Category 1 to 5 under the **Saffir-Simpson scale**, with Category 3-5 storms considered "major hurricanes" due to their destructive potential [3].

2.5 Implications for Local-Scale Climate Assessment

This high variability in both **precipitation and temperature** over short distances underlines the importance of **fine-scale climate analysis** for Guadeloupe. The impact of microclimates is particularly significant in sectors like:

- **Agriculture**: crop suitability and irrigation requirements vary significantly between wetter highlands and drier plateaus.
- **Water resource management**: crucial for drought-prone zones.
- **Disaster risk reduction**: intense rainfall and tropical systems require localized monitoring and preparedness.
- **Tourism**: weather-dependent demand fluctuates across coastal and inland areas.

In the context of climate change, the **downscaling of coarse global climate data** is vital to capturing these localized dynamics and informing **evidence-based adaptation strategies**.

3 Development of high-resolution precipitation baseline and downscaling methodology for Guadeloupe

3.1 Production of reference climatology for historical precipitation

This section outlines the methodologies used to generate a high-resolution reference climatology of historical precipitation for Guadeloupe. This climatology serves as a base for the downscaling of global climate models (GCMs) and for developing a spatially detailed climate change product for the region. Three complementary approaches were tested, each leveraging different datasets to balance spatial and temporal resolution constraints.

3.1.1 Approach based on era5 and worldclim products

The first approach focused on combining two globally recognized climate datasets - **ERA5** and **WorldClim**- to build a preliminary reference climatology of precipitation for Guadeloupe.

ERA5, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), is a widely used climate reanalysis which offers high temporal resolution data (hourly to daily). However, its spatial resolution (approximately 30 km, or ~0.25°) is too coarse to fully capture the microclimatic variability of a small island like Guadeloupe, particularly given its complex topography and coastal influences.

To address the spatial limitations of ERA5, the dataset was complemented with **WorldClim**, which provides high-resolution (~1 km²) climatological data. WorldClim offers long-term monthly climate averages primarily derived from interpolated weather station data, with topography from satellite-derived digital elevation models used to improve accuracy. Despite its better spatial resolution, WorldClim lacks the daily or sub-monthly temporal detail that ERA5 provides. Therefore, WoldClim can serve as a valuable source to improve spatial granularity, while ERA5 ensures adequate temporal coverage.

The combination of these two sources aimed to create a hybrid product that leverages:

- The **fine temporal granularity** of ERA5, essential for capturing precipitation variability and extremes.
- The **high spatial detail** of WorldClim, which better represents the heterogeneity of rainfall patterns across the island.

The exploration of the ERA5 and ERA5-Land datasets was discontinued early in the process due to significant limitations identified during the preliminary analysis. The coarse spatial resolution of ERA5 (~30 km) was insufficient to represent Guadeloupe's highly localized precipitation patterns, driven by the island's complex topography and coastal influences.

Moreover, ERA5-Land, despite offering finer resolution (~9 km), exhibited missing or unreliable data near the coastline, which is a critical region for both climatic analysis and local impact assessments. This lack of coverage along the island's contours made it impossible to develop a spatially coherent climatology for Guadeloupe.

3.1.2 Approach based on chirps and worldclim products

The second approach aimed at improving the representation of historical precipitation in Guadeloupe by leveraging the strengths of the **CHIRPS** dataset in combination with **WorldClim**.

CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) provides high-resolution precipitation estimates by blending satellite imagery with in-situ station data. It offers **daily precipitation data at a spatial resolution of 0.05° (~5 km)**, making it particularly valuable for regions like Guadeloupe, where spatial variability in rainfall is pronounced.

This approach sought to address the limitations of the previous method by:

- Using CHIRPS to **capture daily rainfall patterns and trends**, crucial for understanding extreme precipitation events and seasonal variability.
- Combining CHIRPS with **WorldClim's high spatial resolution climatologies** to further enhance the fine-scale spatial detail, especially in areas where CHIRPS might still smooth out local variability due to terrain effects.

To effectively merge these two datasets and correct spatial and temporal biases, the following methodology was implemented:

Bias correction and spatial refinement methodology

To produce a spatially refined and bias-corrected precipitation dataset suitable for high-resolution analyses in Guadeloupe, a systematic correction procedure was applied, combining the temporal resolution of CHIRPS with the spatial resolution of WorldClim.

Step 1: Resampling of chirps

CHIRPS data was first **resampled from 0.05° (~5 km) to ~1 km** resolution using bilinear interpolation. This ensured that both CHIRPS and WorldClim were aligned spatially before bias correction.

Step 2: Calculation of monthly correction factors

For each month of the year (**January to December**), a **correction coefficient** was computed for each grid cell by calculating the ratio between the **WorldClim monthly climatology (30-year average)** and the **CHIRPS-derived monthly climatology** over the same reference period (typically 1981-2010):

$$Correction\ factor\ (Month,\ Pixel) = \frac{CHIRPS\ Mean\ (Month,\ Pixel)}{WorldClim\ (Month,\ Pixel)}$$

This produced **12 monthly correction grids** (one per month) at 1 km resolution.

Step 3: Application to daily time series

Each **daily CHIRPS value** was then **multiplied by the corresponding monthly correction factor** based on the month of the daily value:

$$Corrected\ CHIRPS\ Daily\ (Day,\ Pixel) = CHIRPS\ Daily\ (Day,\ Pixel) \times Correction\ Factor\ (Month,\ Pixel)$$

This approach preserved the **daily variability and temporal structure of CHIRPS**, while anchoring the **monthly means** of the corrected dataset to the **climatological norms provided by WorldClim**.

Final Product

The result of this process is a **daily, bias-corrected precipitation dataset** with a **spatial resolution of ~1 km** over the entire study domain. This refined product was then used as the **historical reference dataset** for the subsequent statistical downscaling procedures.

3.1.3 Approach based on Guadeloupe's meteorological network station

The third approach focused on utilizing local observational data from Guadeloupe's meteorological network, managed by **Météo-France**, to enhance the accuracy and local relevance of precipitation climatology for the island.

This approach recognizes that while global and regional datasets like ERA5, WorldClim, and CHIRPS provide valuable large-scale and satellite-based information, they often lack the fine spatial resolution and localized detail necessary to fully capture the diverse and complex precipitation patterns influenced by Guadeloupe's mountainous terrain and coastal environment.

Key elements of this approach included:

- **Collecting and analyzing historical precipitation records** from meteorological stations across Guadeloupe, ensuring representation of different climatic zones and elevation gradients.
- Using station data as **ground-truth references** to validate, calibrate, and adjust the downscaled climate model outputs and satellite-derived datasets.
- Employing station observations to improve bias correction techniques, thereby enhancing the fidelity of precipitation estimates in the statistical downscaling process.
- Identifying spatial and temporal data gaps within the station network to guide the integration with remote sensing and model-based products.

By anchoring the climatological analysis in high-quality, in-situ measurements, this approach aims to achieve a more precise characterization of historical precipitation variability and extremes, which is critical for developing robust climate adaptation strategies for Guadeloupe.

3.2 Statistical downscaling and analysis of historical and future models

To improve the representation of precipitation data for Guadeloupe at a finer spatial scale, two statistical downscaling techniques were tested: the **Study-Specific Bias Correction Method (SSBC)** and the **Singularity Stochastic Removal (SSR)** method. **Both approaches are built upon the Cumulative Distribution Function transform (CDF-t)**, which serves as the core framework for adjusting the statistical properties of modeled precipitation data to match local observations.

These methods were applied to both historical and future climate projections with the objective of correcting biases and improving the representation of precipitation characteristics relative to the reference station datasets in Guadeloupe.

3.2.1 Cumulative distribution function transform (CDF-t)

CDF-t is a statistical downscaling and bias correction method that adjusts climate model outputs by aligning their cumulative distribution functions with those of a reference dataset (typically observational or reanalysis data). The method corrects systematic biases in the modeled data, such as shifts in mean, variance, and skewness, while preserving the modeled climate change signal.

The Cumulative Distribution Function-transform (CDF-t) approach was originally developed for bias correction and downscaling of wind speed data [2]. Since then, it has been widely applied to other climate variables, including temperature and precipitation [1,6], as well as to various other environmental parameters, such as solar radiation, three-dimensional relative humidity and wind components, and even hydroclimatic descriptors relevant to aquatic ecosystems, like river flows and temperature percentiles.

CDF-t can be viewed as a refined version of empirical quantile mapping (QM). It begins by estimating the cumulative distribution functions (CDFs) of both the reference dataset (F_{Yp}) and the model dataset (F_{Xp}) over the projection period (future or evaluation period). The model CDF (F_{Xp}) is directly computed from the simulation to be corrected, while the reference CDF (F_{Yp}) is derived using a transformation function T, based on the assumption that a mathematical relationship links the model CDF (F_X) to the reference CDF (F_Y) over the calibration period:

$$\boldsymbol{T[F_X(z)] = F_Y(z)}$$

It is further assumed that this transformation remains valid for the projection period:

$$\boldsymbol{T[F_{Xp}(z)] = F_{Yp}(z)}$$

By substituting z with the inverse of the model's CDF $F_X^{-1}(u)$, where u is a probability in [0, 1], the transformation can be simplified to:

$$\boldsymbol{T(u) = F_Y(F_X^{-1}(u))}$$

This leads to the following estimation of F_{Yp} over the projection period:

$$\boldsymbol{F_{Yp}(z) = F_Y\{F_X^{-1}[F_{Xp}(z)]\}}$$

With both F_{Yp} and F_{Xp} estimated, the bias correction is then performed through quantile mapping based on these distributions. Unlike standard quantile mapping, CDF-t explicitly accounts for potential changes in the CDF between the calibration and projection periods, making it suitable for climate change impact assessments [5,6].

In cases where the model and reference datasets have very different distributions, the range of F_{Yp} may need to be constrained [2]. For precipitation, a normalization step is introduced to mitigate this issue. During calibration, model precipitation values x_i are rescaled to $\tilde{x}_i$ so that they fall within [0, M_{ref}], where M_{ref} is the maximum observed precipitation in the reference dataset:

$$\boldsymbol{\tilde{x}_i = x_i \times \frac{M_{ref}}{M_{Cmod}}}$$

Here, M_{Cmod} is the maximum model precipitation during the calibration period. The same normalization formula is applied to model data $x_{p,i}$ in the projection period:

$$\boldsymbol{\tilde{x}_{p,i} = x_{p,i} \times \frac{M_{ref}}{M_{Cmod}}}$$

In this study, CDF-t was used to correct precipitation time series from CMIP models using observed station data. While the method is effective at adjusting the intensity distribution of precipitation, it is less suited

to addressing the occurrence structure - in particular, the frequency and distribution of dry days, which are common and climatically significant in island regions like Guadeloupe.

3.2.2 Study-Specific Bias Correction Method (SSBC)

For precipitation, a preliminary step involves correcting the number of rainy days simulated by climate models. Models often produce an excessive number of low-intensity precipitation days compared to observations. Without this correction, the CDFt method would substantially overestimate the annual precipitation amount, degrading the quality of the resulting climate projections. To correct the number of rainy days, we first calculate the overestimation ratio between the model and observed rainy days for the reference period. We then randomly remove the corresponding number of rainy days from the model data, assuming that the overestimation rate remains constant between the present and future periods. This correction is a sensitive step that requires extensive testing to properly calibrate the algorithm and avoid overfitting.

In some regions, models may instead underestimate the number of rainy days. This error has a smaller impact, as the CDFt method can handle such situations effectively.

3.2.3 Singularity Stochastic Removal (SSR): A unified correction for occurrence and intensity

The **Singularity Stochastic Removal (SSR)** method was also tested as a complementary bias correction approach, specifically developed to simultaneously adjust both the **occurrence** (frequency of dry and wet days) and **intensity** of precipitation within a unified framework [7].

Core Principle:

SSR addresses the **discontinuity** ("singularity") present in precipitation data due to the large number of zero values (dry days). This discontinuity poses challenges for traditional bias correction methods, such as **CDF-t**, which assume smooth, continuous distributions.

Procedure:

- **Threshold definition:** A very small positive threshold (**th**) is defined, smaller than any strictly positive precipitation value in the datasets.
- **Random replacement of zeros:** All zero precipitation values in both model simulations and observations are replaced with random values drawn from a uniform distribution **U(0, th)**, effectively transforming dry days into extremely light rainfall events.
- **Bias correction:** With the singularity removed, traditional bias correction methods (e.g., **CDF-t**) can be applied consistently across the entire series.
- **Restoration of dry days:** After correction, any precipitation values below the threshold **th** are reset to zero, restoring a realistic frequency of dry days.

By combining singularity removal with standard bias correction, SSR improves both the statistical distribution and occurrence frequency of precipitation data, especially for applications sensitive to dry-day representation.

3.2.4 Statistical adjustment of extremes using GEV

In order to assess and validate the extreme precipitation events in both historical and future climate projections, the **Generalized Extreme Value (GEV)** distribution was employed. The GEV framework

consists in the statistical modeling of **annual maximum precipitation events**, allowing the assessment of rare events (e.g. with a probability of once in ten years) which are particularly relevant for hydrological risk assessment and adaptation planning in Guadeloupe.

Why use GEV?

- **Standard in hydrology and climate studies**: The GEV distribution is widely used in climatology and hydrology to model extreme events, particularly for precipitation and flood risk analysis.
- **Probabilistic framework**: GEV provides probabilistic estimates of extreme event magnitudes associated with different return periods, such as 10-year, 20-year, or 100-year rainfall events.
- **Quantitative validation tool**: By fitting the GEV distribution to both observed and modeled datasets, we can **validate whether the corrected model outputs adequately reproduce historical extremes**. This step is crucial to ensure that bias correction methods (like CDF-t or SSR) are not only improving averages but also capturing the **tails of the distribution**, i.e., the extreme values that drive risks.

Methodological procedure:

- **Extraction of annual maxima**: For each dataset, observed, raw model output, and bias-corrected projections, the **annual maxima of daily precipitation** was extracted. This forms the basis of extreme value analysis.
- **Fitting the GEV distribution**: A GEV distribution was fitted to these annual maxima for each period (historical and projected future horizons). This statistical fit provides a continuous probabilistic description of extreme precipitation behavior.
- **Estimation of return levels**: From the fitted GEV, return levels were estimated for key recurrence intervals (e.g., **10, 20, 50, and 100 years**). These values represent the expected precipitation associated with rare but impactful events.
- **Validation through comparison**:
    - **Historical period**: Return levels derived from the corrected model outputs were compared against those from **station observations**, providing a direct validation of the statistical downscaling and correction process.
    - **Future periods**: Projected return levels for the near, mid, and end-of-century horizons were then compared with historical values to **quantify changes in extreme event magnitudes** under climate change scenarios.

By integrating GEV analysis into the methodology, the study not only enhances the reliability of the bias correction techniques but also **links statistical adjustments directly to practical, risk-relevant outcomes** such as flood hazard assessment, infrastructure design, and resilience planning.

4 Results and expected outcomes

4.1 Mapping and evaluation of available climate databases

This section presents a comparative evaluation of the main climate datasets considered in the study, focusing on their applicability for analyzing and downscaling precipitation in Guadeloupe. Each product is assessed in terms of its spatial and temporal resolution, data frequency, period covered, and its strengths and limitations, particularly in the context of small-island climate characterization.

Dataset	Spatial Resolution	Temporal Resolution	Period	Format	Strengths	Limitations
ERA5	~31 km (0.25°)	Hourly / Daily	1950-present	Gridded NetCDF	Consistent long-term data, high temporal resolution	Coarse spatial resolution for a small island; may miss local effects
ERA5-Land	~9 km	Hourly / Daily	1950-present	Gridded NetCDF	Better land representation than ERA5; improved spatial detail	Still may not capture microclimates; land-only product excludes coastal/ocean-adjacent grid cell
WorldClim	~1 km	Monthly (climatology)	1970-2000	Raster (GeoTIFF)	High spatial resolution, especially useful for climatological baselines	No interannual variability; not suitable for trend analysis
CHIRPS	~5 km	Daily / Monthly	1981-present	Gridded NetCDF	Combines satellite and station data; good for rainfall in tropical regions	Limited station density in Caribbean may affect accuracy
Météo-France Stations	Point-based (local)	Daily	Varies by station	CSV or custom	Ground-truth data; high accuracy and reliability	Sparse spatial coverage; some missing data; difficult to interpolate

Table 1: Comparative summary of climate datasets for precipitation analysis in Guadeloupe

4.2 Results of historical precipitation climatology approaches

4.2.1 CHIRPS and WorldClim approach

Given ERA5's coarse spatial resolution and limited coastal coverage, the alternative approach combining CHIRPS and WorldClim was used. As a result of the integration process, we obtained NetCDF files

providing precipitation data at fine spatial (~1 km) and daily temporal resolution over Guadeloupe. To validate the quality and ensure the robustness of this newly generated product, we compared the outputs directly with in-situ observations from Guadeloupe's meteorological stations. This validation step was essential to assess the ability of the combined dataset to accurately reproduce observed precipitation characteristics across the island.

To evaluate the performance of this product, three key visualizations were produced:

- A spatial map of the monthly average precipitation from the combined CHIRPS × WorldClim dataset.
- A comparison map of the combined product against in-situ observations from Guadeloupe's meteorological stations.
- A bias map illustrating the relative percentage difference between the combined product and station measurements.

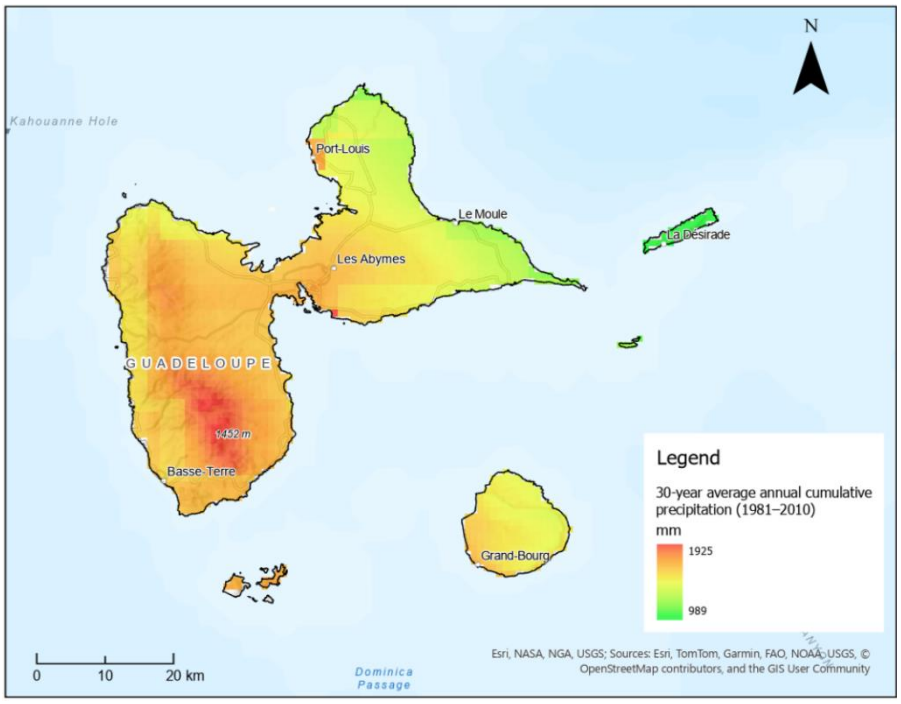

Figure 1: Monthly average precipitation map (1981-2010) from CHIRPS × WorldClim product

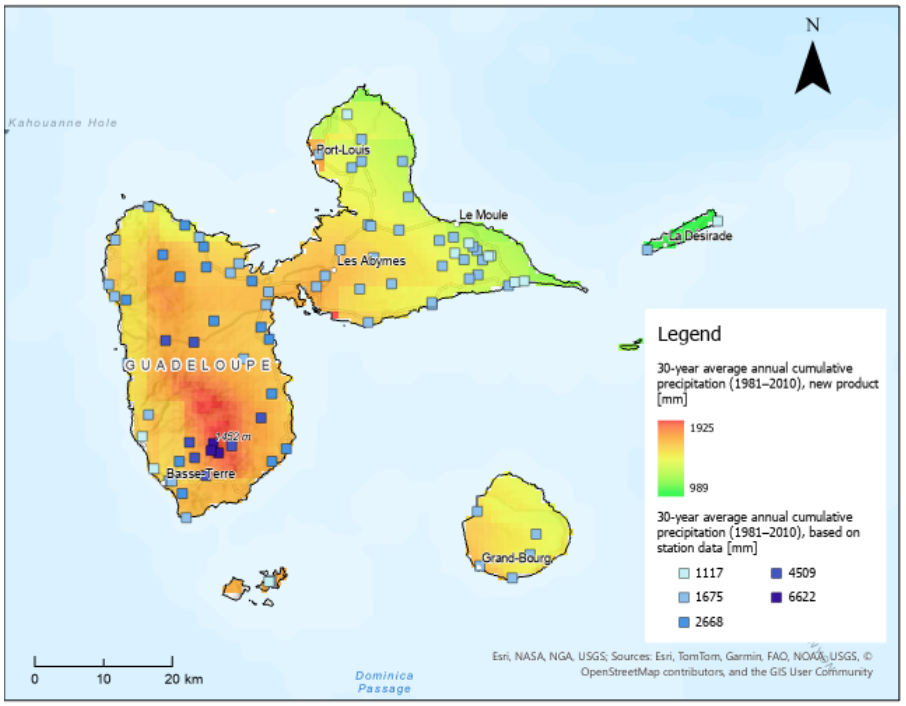

Figure 2: Comparison of CHIRPS × WorldClim product with Guadeloupe meteorological station observations

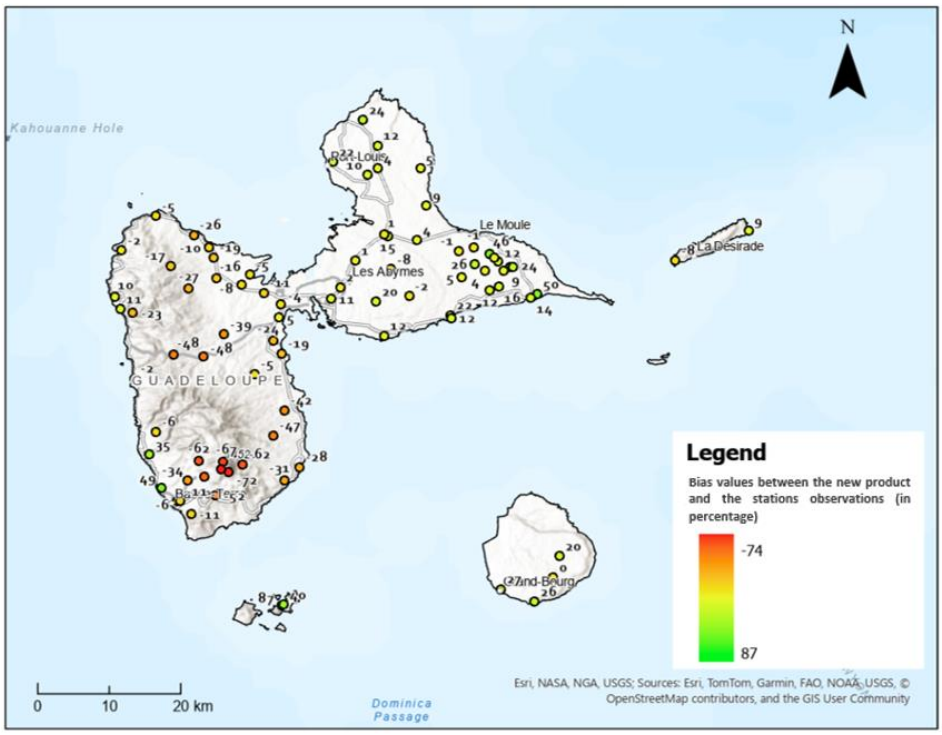

Figure 3: Percentage bias Map Between CHIRPS × WorldClim product and station data

The analysis reveals that while the combined product significantly improves spatial representation across much of the island, particularly in coastal and lowland areas, it exhibits substantial biases in the mountainous regions of Basse-Terre. Here, the gridded dataset underestimates precipitation by a considerable margin, with relative biases exceeding -70%, reflecting the difficulty of capturing complex orographic precipitation patterns solely through gridded interpolations.

These findings underscore the necessity of applying station-based calibration or bias correction techniques to the combined product, especially in areas with complex topography, to ensure robust and accurate precipitation representation for climate impact and adaptation studies in Guadeloupe.

4.2.2 Station-based approach

Given the limitations identified in the previous approaches, particularly the significant biases and spatial inaccuracies observed in complex terrain areas like Basse-Terre, we decided to rely directly on station data for the production of the historical reference climatology. Using the observational station network as the sole basis ensures that the reference dataset accurately captures Guadeloupe's localized precipitation patterns.

To represent the diversity of climatic conditions across the island, two reference stations were selected:

Station ID	Station Name	Latitude	Longitude	Altitude (m)
97101015	LE RAIZET AERO	16.264000	-61.516333	11
97124008	ST-CLAUDE SOUFRIERE	16.045000	-61.662667	1417

Table 1: Description of the two meteorological stations used for the study in Guadeloupe. LE RAIZET AERO is located in Grande-Terre at low altitude near the coast, while ST-CLAUDE SOUFRIERE is situated in Basse-Terre at high altitude in the mountainous region.

These two stations were chosen not only for their strategic locations representing the main climatic contrasts of Guadeloupe. LE RAIZET AERO capturing the low-altitude, drier leeward conditions of Grande-Terre, and ST-CLAUDE SOUFRIERE capturing the high-altitude, wetter windward conditions of Basse-Terre, but also because they provide the most complete observational records among all stations in Guadeloupe. This makes them sufficient to reliably characterize the island's precipitation variability for the historical reference climatology.

The following chapter presents the statistical downscaling of future climate projections, using these station datasets as reference points for bias correction through the two methods described in Chapter 2.2

4.3 Statistical downscaling of future climate projections

4.3.1 Overview and objectives

Following the evaluation of available datasets and bias correction techniques, this chapter presents the application of statistical downscaling to future precipitation projections for Guadeloupe, using the two selected meteorological stations as reference points.

The primary objective here was to test the feasibility and performance of bias correction techniques on climate model data to obtain more reliable local projections of precipitation, particularly with regard to extreme rainfall events.

4.3.2 Climate model selection

For this initial experiment, we used one global climate model from the CMIP6 ensemble:

- **Model:** *CNRM-CM6-1-HR*
- **Spatial resolution:** Ocean ~0.25° (~28 km at the equator), Atmosphere ~0.5° (~55 km at the equator)
- **Produced by:** Centre National de Recherches Météorologiques (CNRM, France)
- **Scenario analyzed: SSP5-8.5** (high-emission scenario, representing a pessimistic pathway for testing adaptation strategies)
- **Temporal coverage:**
    - **Historical period:** 1985-2014
    - **Future projections:** 2021-2100

This model was chosen for its relevance in European research frameworks and its availability within existing CMIP6 datasets.

4.3.3 Bias correction methods applied

Two different bias correction techniques were tested:

1. **Study-Specific Bias Correction method** (SSBC):
    - A method developed for this study. Details are provided in **Chapter 3.2**.
2. **Singularity Stochastic Removal (SSR):**
    - Addresses both occurrence and intensity biases by replacing dry days with random low values, enabling continuous correction via CDF-t adjustment. Method fully described in **Chapter 3.2**.

Both techniques were applied consistently to the **historical** and **future** periods for each station.

4.3.4 Historical period validation (1985-2014)

The performance of the two statistical correction methods was assessed through a detailed comparison of the bias-corrected historical simulations (1985-2014) against observed station data.

Note that these observations were also used in the training of the statistical downscaling models, so this assessment does not constitute a fully independent validation. Nevertheless, it provides a useful evaluation of how well the methods reproduce historical precipitation characteristics for the purposes of this study.

The evaluation focused on two key dimensions of precipitation behavior:

1. Monthly climatologies, to assess the reproduction of seasonal rainfall patterns.
2. Extreme precipitation events, evaluated both by frequency thresholds and statistical fitting.

The following quantitative indicators were used:

- Number of wet days: Days with precipitation exceeding 1 mm/day.
- Number of heavy precipitation days: Days exceeding 20 mm/day.
- Number of very heavy precipitation days: Days exceeding 50 mm/day.
- Extreme value analysis: Annual maxima of daily precipitation were fitted to a Generalized Extreme Value (GEV) distribution to estimate return levels corresponding to 10, 20, 50, and 100-year return periods.

Results for Le Raizet Aéroport (Grande-Terre)

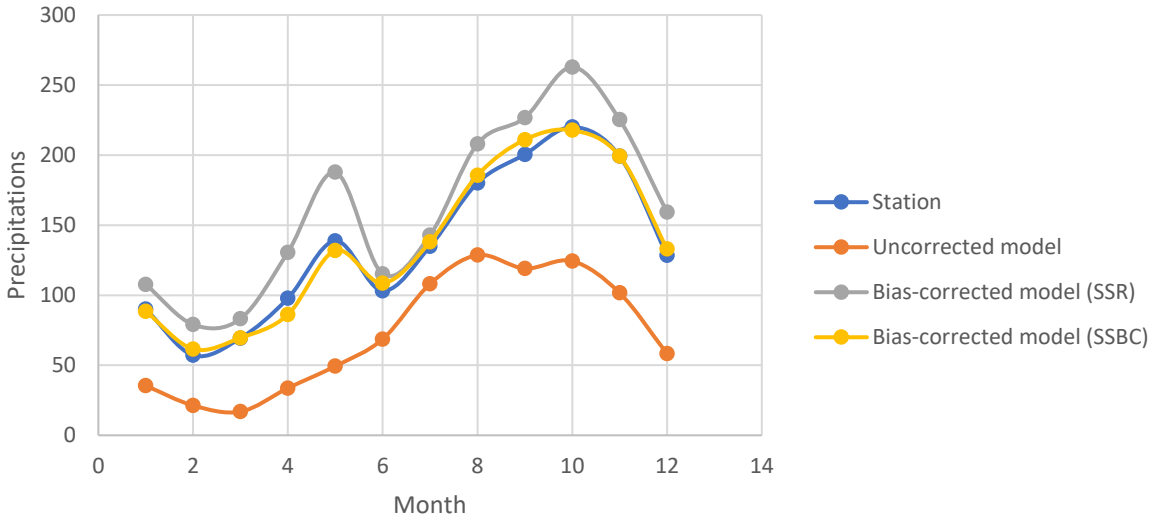

Figure 4: Seasonal cycle of precipitation (1985-2014): Comparison of raw model, bias-corrected simulations (SSR and the SSBC Methods), and station observations - Le Raizet Aéroport

	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
Annual number of wet days (>1 mm/day)	169	146	349	169
Annual number of heavy precipitation days (>20 mm/day)	19	7	19	20
Annual number of very heavy precipitation days (>50 mm/day)	4	1	4	4

Table 2: Annual frequency of precipitation threshold exceedances at Le Raizet Aéroport (1985-2014)

Return Levels (mm):

	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
5-year return period	123	86	89	131
10-year return period	152	106	102	154
20-year return period	182	128	115	175
50-year return period	227	161	134	204
100-year return period	269	190	150	224

Table 3: Extreme precipitation return levels (mm) for Le Raizet Aéroport (1985-2014)

Interpretation:
For Le Raizet Aéroport, both correction methods demonstrated clear improvements over the uncorrected model, particularly in reproducing the frequency of heavy and very heavy precipitation events when compared to observations. The SSBC Method notably provided a close match to the observed number of wet and extreme rainfall days, offering better overall consistency. In contrast, the SSR method tended to overpredict the frequency of wet days, especially for events exceeding 1 mm/day. Regarding extreme event magnitudes derived from the GEV analysis, the SSBC Method consistently produced return level estimates closer to observed values. The SSR method, however, systematically underestimated return levels.

Results for Saint-Claude Soufrière (Basse-Terre)

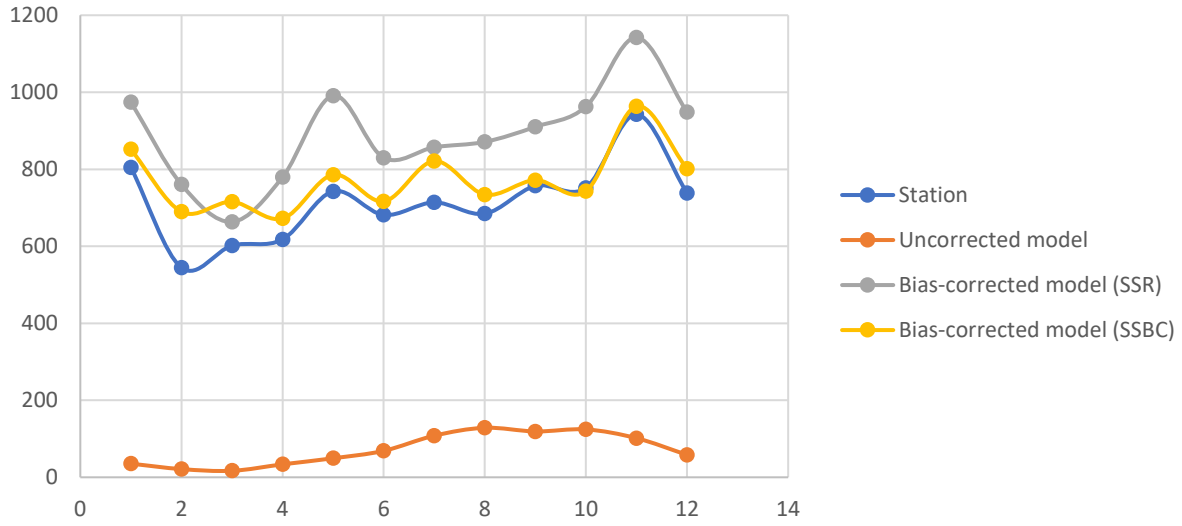

Figure 5:Seasonal cycle of precipitation (1985-2014): Comparison of raw model, bias-corrected simulations (SSR and the SSBC Methods), and station observations - Saint-Claude Soufrière

	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
Annual number of wet days (>1 mm/day)	329	146	365	351
Annual number of heavy precipitation days (>20 mm/day)	139	7	265	143
Annual number of very heavy precipitation days (>50 mm/day)	45	1	41	48

Table 4: Annual frequency of precipitation threshold exceedances at Saint-Claude Soufrière (1985-2014)

Return Levels (mm) :

	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
5-year return period	282	86	131	308
10-year return period	340	106	165	369
20-year return period	401	128	224	439
50-year return period	488	161	366	549
100-year return period	560	190	562	649

Table 5: Extreme precipitation return levels (mm) for Saint-Claude Soufrière (1985-2014)

Interpretation:

At the Saint-Claude Soufrière station, the uncorrected model severely underestimated both the frequency and magnitude of extreme rainfall events, particularly for very heavy precipitation. The SSR method also failed to capture the observed frequency of heavy precipitation events (>20 mm/day), significantly underestimating both the number of events and the GEV-derived return levels for the 5-, 10-, and 20-year return periods. Although the SSBC closely matched the observed frequencies and extreme values, its performance must be interpreted with caution: the raw model is so far from reality that any statistical bias correction relies on compensating for fundamental physical errors rather than correcting the model's dynamics. Nevertheless, for this high-altitude, complex-terrain station, SSBC still represents a substantially better choice than uncorrected or SSR-corrected outputs.

The application of the GEV distribution was fundamental in validating the correction methods, particularly concerning extreme precipitation events. By comparing return levels estimated from corrected simulations with those derived from observations, it was possible to rigorously quantify the remaining discrepancies. This validation confirmed that while both correction methods improved the representation of extremes compared to the raw model, the SSBC Method consistently provided better agreement, especially in orographically influenced regions like Basse-Terre.

4.4 Future Projections (2021-2100)

4.4.1 Analysis by time horizons

The analysis of future precipitation projections was organized across three conventional time horizons, allowing for a progressive assessment of projected trends throughout the 21st century:

Horizon	Period
Near Future	2021-2050
Mid-Century	2041-2070
End of Century	2071-2100

This breakdown provides a structured view of how precipitation patterns may evolve, from the short-term planning horizon to long-term climate impacts relevant to adaptation strategies. As with the historical analysis, bias correction of the raw outputs from the **CNRM-CM6-1** global climate model was performed using the SSBC and the SSR methods, ensuring consistency in methodological approach.

4.4.2 Visualization and analysis outputs

The future analysis employed the same set of **precipitation indicators** used in the historical validation to ensure consistency in the methodological approach.

The following visual outputs were produced:

- **Seasonal cycle plots**: For each station, monthly averages of precipitation were plotted across the three future time horizons. These plots allowed for a direct comparison of the raw model outputs with the two bias-corrected versions (SSR + SSBC). The seasonal cycles illustrated how rainfall patterns are projected to evolve throughout the year and across future periods.
- **Precipitation frequency indicators**: The analysis specifically focused on three precipitation thresholds:
    - Wet days (>1 mm/day)
    - Heavy precipitation days (>20 mm/day)
    - Very heavy precipitation days (>50 mm/day)
- **Return level tables for extreme events**: For extreme precipitation, return levels corresponding to 5-, 10-, 20-, 50-, and 100-year return periods were estimated using GEV distributions. These tables provided a clear view of how the magnitude of rare extreme events is projected to change over time.

- **Results for Le Raizet Aéroport (Grande-Terre)**

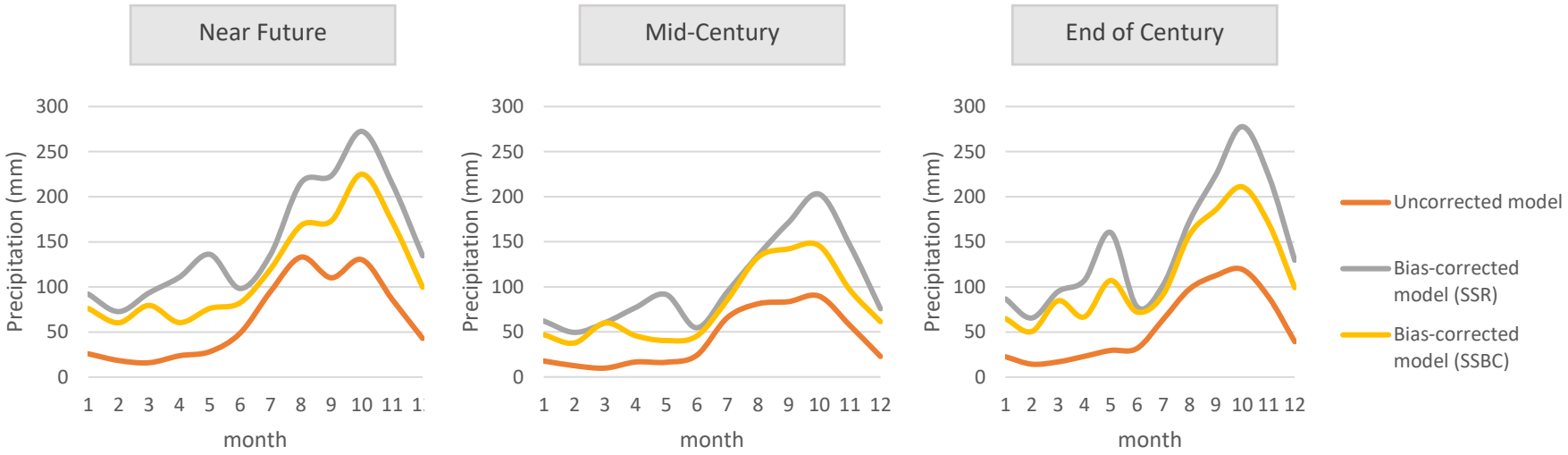

Figure 6: Projected seasonal cycle of precipitation at Le Raizet Aéroport (2021-2100)

Monthly precipitation averages by time horizon (from left to right: Near Future, Mid-Century, End of Century). Each panel compares the uncorrected model with bias-corrected outputs using the SSBC and SSR methods.

	Reference Period				Near Future			Mid-Century			End of Century		
	Station	**Uncorrected model**	**Bias-corrected model (SSR)**	**Bias-corrected model (SSR)**	**Uncorrected model**	**Bias-corrected model (SSR)**	**Bias-corrected model (SSR)**	**Uncorrected model**	**Bias-corrected model (SSR)**	**Bias-corrected model (SSBC)**	**Uncorrected model**	**Bias-corrected model (SSR)**	**Bias-corrected model (SSBC)**
Annual number of wet days (>1 mm/day)	169	146	349	169	133	348	159	121	349	162	117	348	157
Annual number of heavy precipitation days (>20 mm/day)	19	7	19	20	5	16	15	5	15	16	4	14	14
Annual number of very heavy precipitation days (>50 mm/day)	4	1	4	4	2	3	4	2	4	4	1	4	4

Table 6: Precipitation frequencies at Le Raizet Aéroport (historical & future 2021–2100): comparison of raw and bias-corrected (SSR, SSBC) model outputs.

Return Levels (mm) :

	Reference Periode				Near Future			Mid-Century			End of Century		
	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
5-year return period	123	86	89	131	77	93	131	100	129	116	70	99	132
10-year return period	152	106	102	154	106	125	156	123	189	135	88	122	163
20-year return period	182	128	115	175	142	170	179	147	286	153	106	148	200
50-year return period	227	161	134	204	209	265	208	180	517	177	133	187	256
100-year return period	269	190	150	224	277	376	228	206	827	195	156	222	307

Table 7: Extreme precipitation return levels at Le Raizet Aéroport (5-, 10-, 20-, 50-, and 100-year return periods; historical & 2021–2100): comparison of raw and bias-corrected (SSR, SSBC) model outputs

Results for Saint-Claude Soufrière (Basse-Terre)

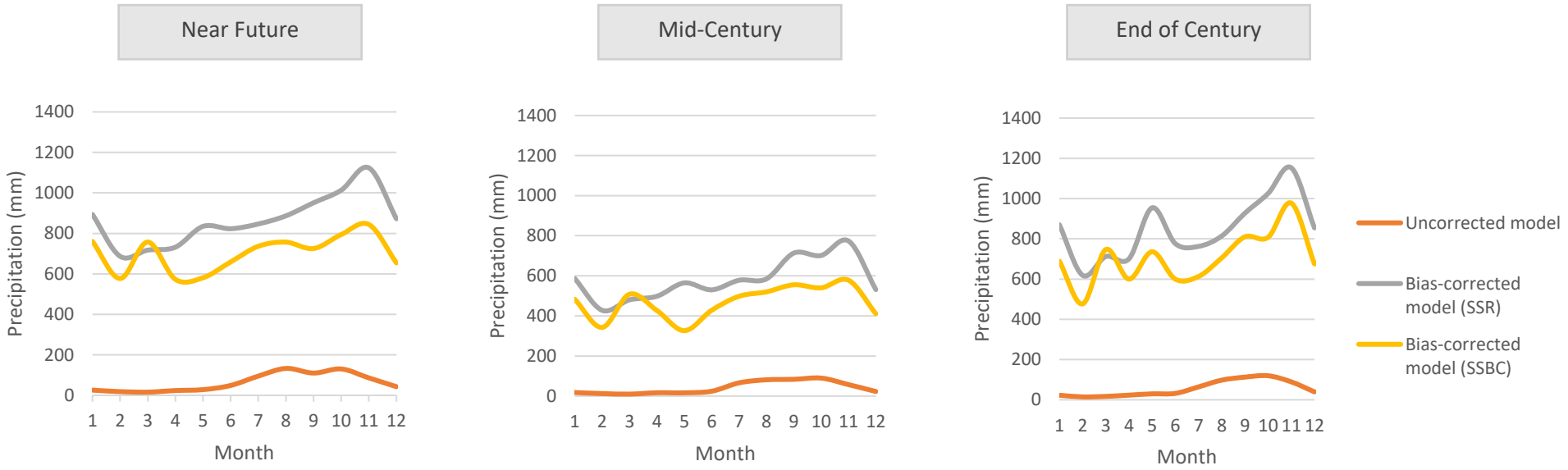

Figure 7: Projected seasonal cycle of precipitation at Saint-Claude Soufrière (2021-2100)

Monthly precipitation averages by time horizon (from left to right: Near Future, Mid-Century, End of Century). Each panel compares the uncorrected model with bias-corrected outputs using the SSBC and SSR methods.

	Reference Period				Near Future			Mid-Century			End of Century		
	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
Annual number of wet days (>1 mm/day)	329	146	365	351	133	365	344	121	365	342	117	365	338
Annual number of heavy precipitation days (>20 mm/day)	139	7	265	143	5	264	136	5	264	139	4	263	138
Annual number of very heavy precipitation days (>50 mm/day)	45	1	41	48	2	30	9	2	27	35	1	24	36

Table 8: Precipitation frequencies at Saint-Claude Soufrière (historical & future 2021–2100): comparison of raw and bias-corrected (SSR, SSBC) model outputs

Return Levels (mm) :

	Reference Period				Near Future			Mid-Century			End of Century		
	Station	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)	Uncorrected model	Bias-corrected model (SSR)	Bias-corrected model (SSBC)
5-year return period	282	86	131	308	77	171	304	100	215	293	70	180	337
10-year return period	340	106	165	369	106	199	363	123	218	357	88	198	394
20-year return period	401	128	224	439	142	228	423	147	219	434	106	212	451
50-year return period	488	161	366	549	209	269	508	180	220	562	133	227	528
100-year return period	560	190	562	649	277	302	577	206	225	685	156	235	588

Table 9: Extreme precipitation return levels at Saint-Claude Soufrière (5-, 10-, 20-, 50-, and 100-year return periods; historical & 2021–2100): comparison of raw and bias-corrected (SSR, SSBC) model outputs

4.4.3 Analysis of Future Projections

Context and Limitations

Given Guadeloupe's relatively small geographic extent, **the CNRM-CM6-1 model provides only a single grid point** over the island. This limited spatial resolution introduces several key challenges:

- The model cannot fully resolve the complex topography, particularly the sharp contrasts between coastal lowlands (e.g., Le Raizet) and mountainous regions (e.g., Saint-Claude Soufrière).
- The same grid cell drives projections for both contrasting locations, leading to structural biases in the raw model outputs that must be addressed through bias correction.

These limitations make robust bias correction essential for credible local projections, especially for hydrological and infrastructure-related planning.

Le Raizet Aéroport (Coastal Lowland Site)

Projected Precipitation Frequencies

Despite the model's coarse representation, the SSBC correction method successfully adjusts the single-grid output to produce station-specific, plausible rainfall frequencies:

- Annual wet days stabilize around 157-162/year across all horizons, aligned with known climatology for the coastal site.
- Heavy and very heavy precipitation days (14-16 and ~4 per year, respectively) remain relatively stable, suggesting no marked intensification in frequency, even though extremes may grow in magnitude.

In contrast, the SSR correction overpredicts wet days (≈348/year), exposing a misalignment with local climatic behavior.

Projected extreme events

Despite spatial resolution constraints, GEV-derived return levels with the SSBC correction reflect credible trends, with moderate but consistent increases in extreme event magnitudes by the end of the century:

- For example, the 100-year return level rises from 228 mm (near future) to 307 mm (end of century), indicating a likely intensification of extreme rainfall risk under climate change.
- The SSR-corrected extremes remain inconsistent and frequently underestimate risk, suggesting SSR's correction scheme is unsuitable in this low-resolution context

.

Saint-Claude Soufrière (Mountainous Interior Site)

Projected precipitation frequencies

The bias correction task is more difficult here, given the sharp mismatch between the grid-scale raw model (coastal, lowland dominated) and the station's high-altitude, orographically influenced climate.

Nonetheless, the SSBC correction substantially improves representativity:

- Annual wet days (~338-344/year) align reasonably with the known wet conditions at this mountain station.
- Heavy precipitation days stabilize around 135-139/year, with very heavy events reaching 35-36/year by the end of the century.
- The SSR method projects implausibly high values (e.g., >250 heavy rain events/year), making it unreliable for projections in this orographic zone.

Projected extreme events

Extreme event projections show significant increases in return levels under the SSBC correction, despite the limitations imposed by the single grid:

- 100-year return period increases from 577 mm (near future) to 685 mm (mid-century), with values remaining elevated through the century's end.
- These trends support an increased risk of extreme rainfall events in mountainous regions, consistent with theoretical expectations for a warming tropical climate.

Conclusion

- The SSBC Correction → Suitable for Application: Despite the limitations of having only one model grid point for the entire island, the SSBC method offers consistent and credible projections for both stations. It effectively bridges the gap between coarse-scale model output and local climatological reality.
- Projection Uncertainty: Users of these projections should remain aware of the inherent uncertainty introduced by coarse resolution, particularly when applying results to site-specific engineering, hydrological planning, or risk management. Where feasible, future work should incorporate higher-resolution regional climate models (RCMs) to further refine local-scale projections.

5 Conclusion

This feasibility study assessed the potential for bias correction and future precipitation projection over Guadeloupe using climate model outputs. Despite the small spatial scale of the island and the limitation of a single model grid point, valuable insights were obtained by comparing raw and corrected climate projections with station data from Le Raizet Aéroport and Saint-Claude Soufrière. The analysis was constrained by incomplete station records, the absence of a high-resolution gridded observational product, and reliance on a single GCM grid point, limiting spatial representativity and the use of downscaling methods. Nevertheless, statistical bias correction, particularly the Project-Developed Method, demonstrated improved alignment with observed precipitation patterns and extremes compared to raw model outputs and the SSR method. To build on these findings, future work should focus on consolidating and homogenizing station records across the island, developing high-resolution gridded precipitation datasets, extending bias correction and downscaling to additional stations, and incorporating regional climate models to better capture spatial variability. Moreover, integrating corrected projections into sectoral impact studies and co-developing adaptation scenarios with local stakeholders will ensure that results support actionable planning for hydrology, agriculture, urban development, and disaster risk management.

Reference

[1] Lavaysse, C., Déqué, M., Somot, S., et al. (2012). Statistical downscaling of the French Mediterranean climate: Assessment for present and projection in an anthropogenic scenario. *Natural Hazards and Earth System Sciences, 12*, 651-670. https://doi.org/10.5194/nhess-12-651-2012

[2] Michelangeli, P.-A., Vrac, M., & Loukos, H. (2009). Probabilistic downscaling approaches: Application to wind cumulative distribution functions. *Geophysical Research Letters, 36*, L11708. https://doi.org/10.1029/2009GL038401

[3] OREC (Observatoire Régional de l'Énergie et du Climat de Guadeloupe). (2014). Évolution du climat et ses impacts en Guadeloupe. Guadeloupe Énergie. https://www.guadeloupe-energie.gp/wp-content/uploads/2014/05/Edition-2014-Evolution-du-Climat-et-ses-Impacts-en-Guadeloupe.pdf

[4] SciPy Community. (2025). *Statistical functions (scipy.stats)*. SciPy v1.16.1 Manual. https://docs.scipy.org/doc/scipy/reference/stats.html

[5] Vrac, M., & Friederichs, P. (2015). Multivariate-Intervariable, Spatial, and Temporal-Bias Correction. Journal of Climate, 28, 218-237. https://doi.org/10.1175/JCLI-D-14-00059.1

[6] Vrac, M., Michelangeli, P.-A., & Dubuisson, B. (2012). Dynamical and statistical downscaling of the French Mediterranean climate: Uncertainty assessment. *Natural Hazards and Earth System Sciences, 12*, 2769-2784. https://doi.org/10.5194/nhess-12-2769-2012

[7] Vrac, M., Noël, T., & Vautard, R. (2016). Bias correction of precipitation through Singularity Stochastic Removal: Because occurrences matter. *Journal of Geophysical Research: Atmospheres*, 121, 5237-5258. https://doi.org/10.1002/2015JD024511

Climate change impacts are here and now. The impacts on people, prosperity and planet are already pervasive but unevenly distributed, as stated in the new EU Blueprint strategy (European Commission-EC, 2019). To reduce climate-related risks, the EC and the IPCC agree that transformational adaptation is essential. The TranformAr project aims to develop and demonstrate products and services to launch and accelerate large-scale and disruptive adaptive process for transformational adaptation in vulnerable regions and communities across Europe.

impacts of climate change. Based on existing successful initiatives, the project will develop, test and demonstrate solutions and pathways, integrated in Innovation Packages, in 6 territories.

Transformational pathways, including an integrated risk assessment approach are co-developed by means of 9 Transformational Adaptive Blocks. A set of 22 tested actionable adaptive solutions are tested and demonstrated, ranging from nature-based solutions, innovative technologies, financing, insurance and governance models, awareness and behavioral change solutions.

TransformAr

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101036683.