SICMA-Canarias summary of the methodology for climate variables

31/01/2025

This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement 101037424.

Table of contents

The work that has taken place during the development of the SICMA-Canarias project has used and needed different types of input data, as well as following certain methodological approaches depending on the variable or island. This document provides a guide and explanation of the main issues and doubts that the consultation of the platform may produce.

1. Weather observations & climate analysis

The work that has taken place to obtain future climate projections as output needs to be fed with a multiple set of data depending on the needs of the downscaling methodology that has been applied. This section will summarize this input information depending on the time scale that it covers and the purpose it has served. Mainly, two types of data are considered, that that covers or studies the historic climate, and the one that is used to peek at how climate change will affect past climate towards the future.

In order to analyze and understand where we are coming from, it is necessary to study and acknowledge what the climate has been like in the past and present days. The main purpose of this is to characterize the past climate and establish what was it like when most of the present infrastructures and services were designed and built up, what were they designed to be resilient to. This climate baseline is what is taken as a comparison point, established from where the climate models stop their historical experiment, being set in the years 1985-2014. Furthermore, in climate science, 30 years are considered to depict the mean climate state to smoothen short-term variability, as defined by the World Meteorological Organization (WMO[1]).

Past information, as gained through observations and reanalysis data, is used for verification purposes, checking when put in contrast to historical simulations how climate models behave, but also to feed statistical downscaling procedures. There are two main sources to obtain this information: weather observations and climate information.

1.1. Weather information gathered

1.1.1. Weather observations

As a basis for local point data, available surface observations were gathered for all of the Canary Islands. This involved creating a comprehensive database with long-standing weather observations (ideally 30 years, or for verification purposes, at least 2.000 registers), thanks to the collaboration and open-access policies of different island, regional and national entities. After tight collaboration of some of these entities for SICMA-Canarias purposes, observed data were retrieved in general from four distinct sources. These sources include:

- The Spanish Meteorological Agency (AEMet, *Agencia Estatal de Meteorología*):
- Cabildo Institutions, local island governments, through their respective Water Councils.
- Spanish and Canarian Government through the SiAR (*Sistema de Información Agroclimática para el Regadío,* Spanish for Agro-climatic Information System for Irrigation)
- National Parks (*Parques Nacionales*)

[1] https://community.wmo.int/en/wmo-climatological-normals

To ensure data quality, observed data underwent thorough evaluation and treatment, with tests for inhomogeneities, outliers, anomalies or trend changes, discarding entries that did not meet minimum quality requirements. The outcome is a high-quality observed database for study areas where observed information could be collected.

Hereafter there is a resume of the resulting stations that passed the checking for each island separately, with a detail of their number, location and respective source.

It needs to be explained that first, a quality and homogenization (Monjo et al., 2013) control takes place to assess the quality of the observation; right after it, **only stations that have a minimum of 2.000 values (~ 5 years) are taken as useful** to continue the modeling process. This change and steps are detailed in the explanatory tables.

Figure 1. Visual summary of the weather stations' distribution across the archipelago for the temperature registers.

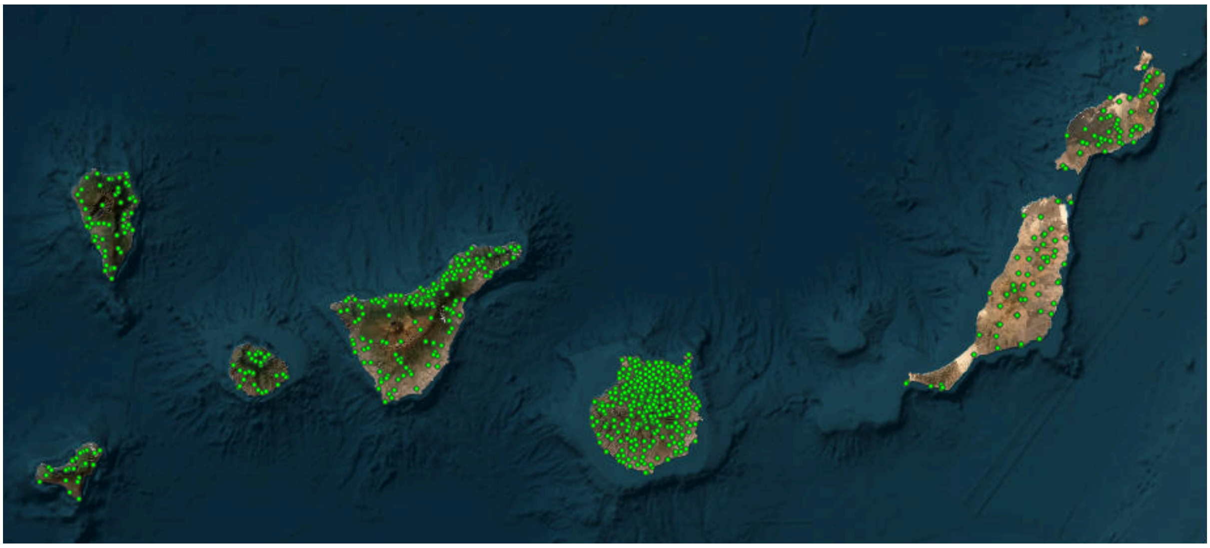

Figure 2. Visual summary of the weather stations' distribution across the archipelago for the precipitation registers.

La Palma

For La Palma island there are several sources of information available since in this area, like in all of the Canary Islands, there are different entities at the island, archipelago and national scale collaborating in monitoring the weather. All of the four identified data sources (AEMet, SiAR, Cabildo and National Parks) were available for consulting and retrieval of information, with a decent density at low and middle latitudes, but scarce data is located at the summits of the island.

A summary of the available and final stations and the data sources is shown in Table 1. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

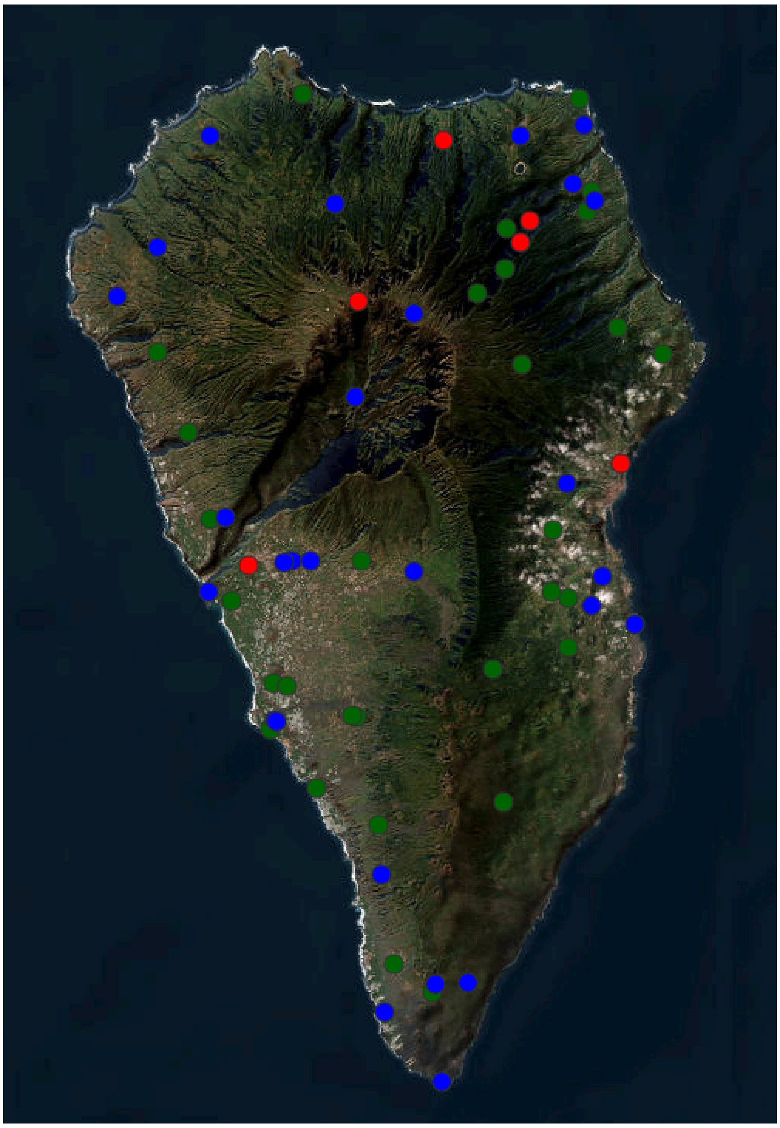

Figure 3. La Palma weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

Table 1. Stations retrieved for the meteorological variables to study for La Palma island. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	59	50	45	AEMet
Precipitation	14	14	1	Cabildo de La Palma
Precipitation	7	7	6	SiAR - Gobierno de Canarias
Precipitation	1	0	0	Parques Nacionales
TOTAL	**81**	**71**	**52**	
Temperature	33	27	27	AEMet
Temperature	14	14	1	Cabildo de La Palma
Temperature	7	6	5	SiAR - Gobierno de Canarias
Temperature	1	0	0	Parques Nacionales
TOTAL	**55**	**47**	**33**	

El Hierro

For El Hierro island there was also a good availability of data from AEMet, Cabildo and Government. Data from the Cabildo, despite its great quality, had not enough length to be included in the analysis (series started in 2020), and had to be therefore discarded.

A summary of the available and final stations and the data sources is shown in Table 2. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

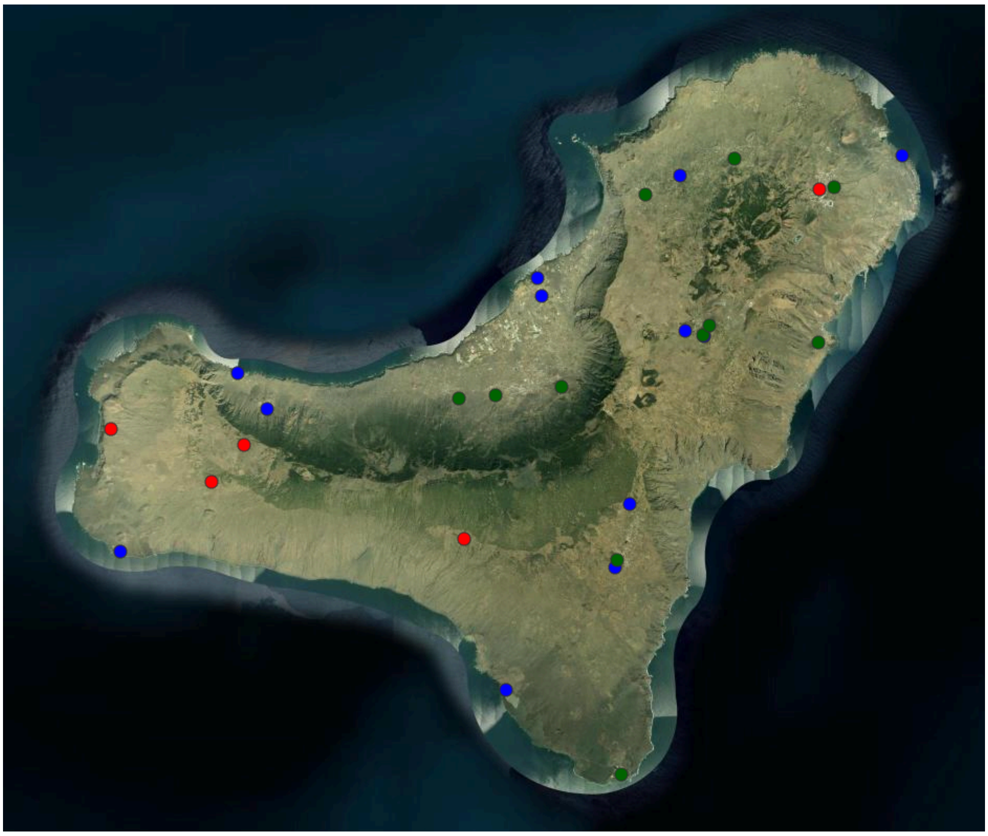

Figure 4. El Hierro weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

Table 2. Stations retrieved for the meteorological variables to study for El Hierro island. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	35	25	22	AEMet
Precipitation	17	17	0	Cabildo de El Hierro
Precipitation	1	1	1	SiAR - Gobierno de Canarias
TOTAL	**53**	**43**	**23**	
Temperature	18	16	16	AEMet
Temperature	17	17	0	Cabildo de El Hierro
Temperature	1	1	1	SiAR - Gobierno de Canarias
TOTAL	**36**	**34**	**17**	

La Gomera

For La Gomera island the availability of data was more restricted, since no reliable data from the Cabildo was available, nor the Parques Nacionales shared their data at Garajonay.

A summary of the available and final stations and the data sources is shown in Table 3. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

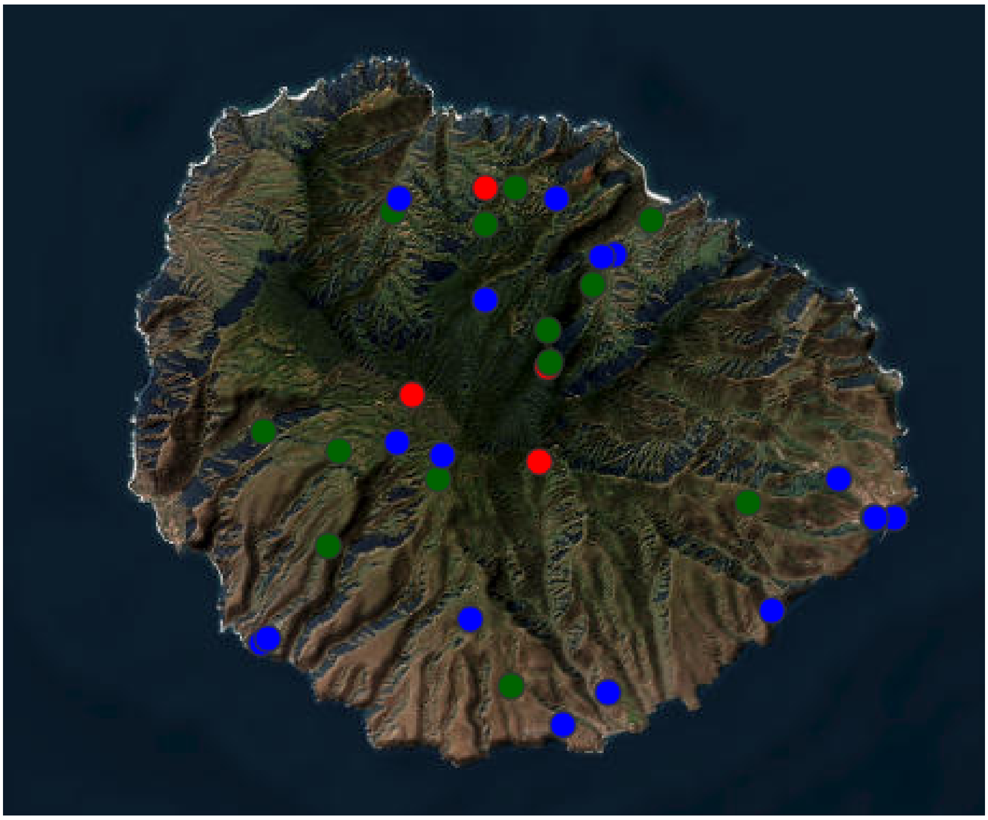

Figure 5. La Gomera weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

Table 3. Stations retrieved for the meteorological variables to study for La Gomera island. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	38	30	28	AEMet
Precipitation	2	2	2	SiAR - Gobierno de Canarias
TOTAL	**40**	**32**	**30**	
Temperature	23	18	18	AEMet
Temperature	2	2	2	SiAR - Gobierno de Canarias
TOTAL	**25**	**20**	**20**	

Tenerife

For Tenerife island, the availability of data was widespread and easy to access. Aside from AEMet and the National Government, with a good density around all the island, data from Agrocabildo covering all variables were obtained through API consulting, as well as stations from Teide National Park were also shared with the project.

A summary of the available and final stations and the data sources is shown in Table 4. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

Figure 6. Tenerife weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

Table 4. Stations retrieved for the meteorological variables to study for Tenerife island. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	153	133	115	AEMet
Precipitation	56	56	54	Cabildo de Tenerife
Precipitation	11	11	11	SiAR - Gobierno de Canarias
Precipitation	2	2	2	Parques Nacionales
TOTAL	**222**	**202**	**182**	
Temperature	90	73	73	AEMet
Temperature	56	56	54	Cabildo de Tenerife
Temperature	11	11	11	SiAR - Gobierno de Canarias
Temperature	2	2	2	Parques Nacionales
TOTAL	**159**	**142**	**140**	

Gran Canaria

Gran Canaria island comes to be the one with more data available for the use of the project. AEMet and Spanish Government data were available for the project, with good density for both variables; on the other hand, the Gran Canaria Water Council shared an immense dataset from their long-term precipitation registers covering the whole island with an astonishing density. No National Park can be found at Gran Canaria.

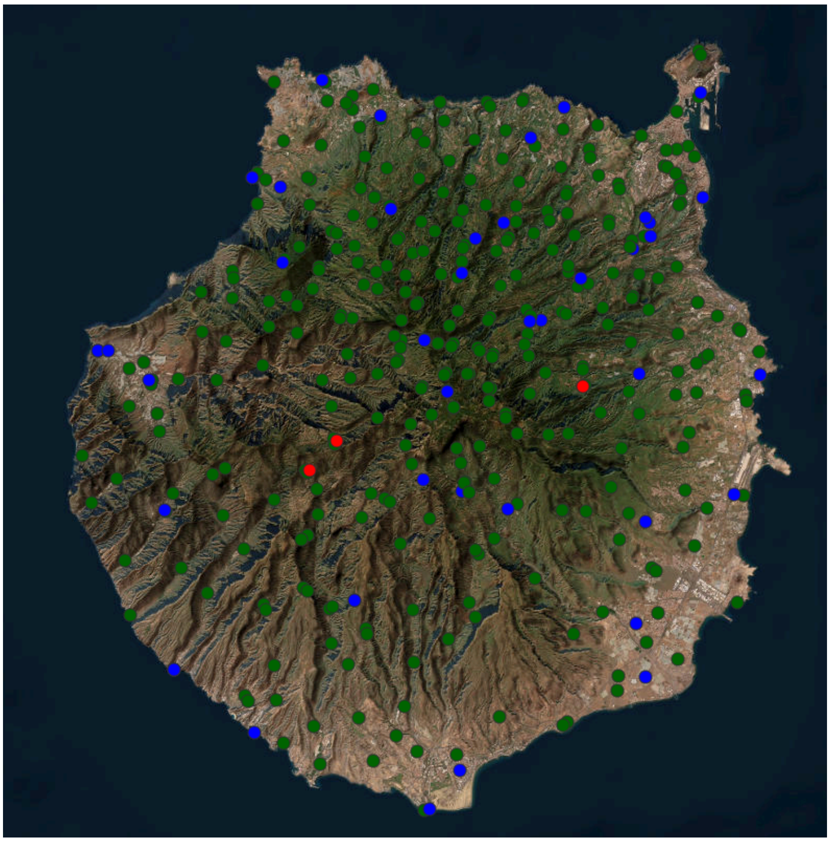

Figure 7. Gran Canaria weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

A summary of the available and final stations and the data sources is shown in Table 5. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

Table 5. Stations retrieved for the meteorological variables to study for Gran Canaria island. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	153	126	115	AEMet
Precipitation	270	270	252	Cabildo de Gran Canaria
Precipitation	6	6	5	SiAR - Gobierno de Canarias
TOTAL	**429**	**402**	**372**	
Temperature	46	39	39	AEMet
Temperature	6	6	5	SiAR - Gobierno de Canarias
TOTAL	**52**	**45**	**45**	

Fuerteventura and Lobos

For Fuerteventura island, the availability of data was good, although is the only place that could be said to lack a good density of observations considering its size (the second largest), especially for temperature registers, leaving most of the western shore of the island void of data. AEMet stations were retrieved, only consisting of 8 stations for temperature. The Fuerteventura Water Council shared with the project their historical rainfall data, helping to populate the database. Only 2 stations from the National Government were available. No National Park can be found on the island.

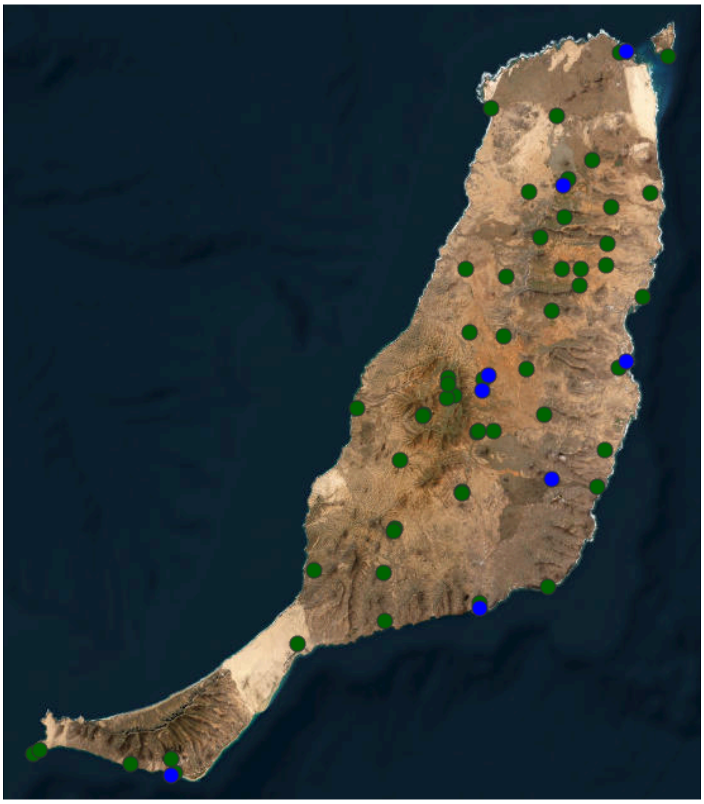

Figure 8. Fuerteventura and Lobos weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

A summary of the available and final stations and the data sources is shown in Table 6. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

Table 6. Stations retrieved for the meteorological variables to study for the Fuerteventura and Lobos islands. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	20	16	16	AEMet
Precipitation	48	48	44	Cabildo de Fuerteventura
Precipitation	2	2	2	SiAR - Gobierno de Canarias
TOTAL	**70**	**66**	**62**	
Temperature	8	6	6	AEMet
Temperature	2	2	2	SiAR - Gobierno de Canarias
TOTAL	**10**	**8**	**8**	

Lanzarote and Chinijo Archipelago

For Lanzarote island and the Chinijo Archipelago, the availability of data was notable, especially in density considering its relative mid-size. AEMet stations were retrieved, as well as those from the Cabildo and the SiAR system. Data from the Timanfaya National Park was not available in this case.

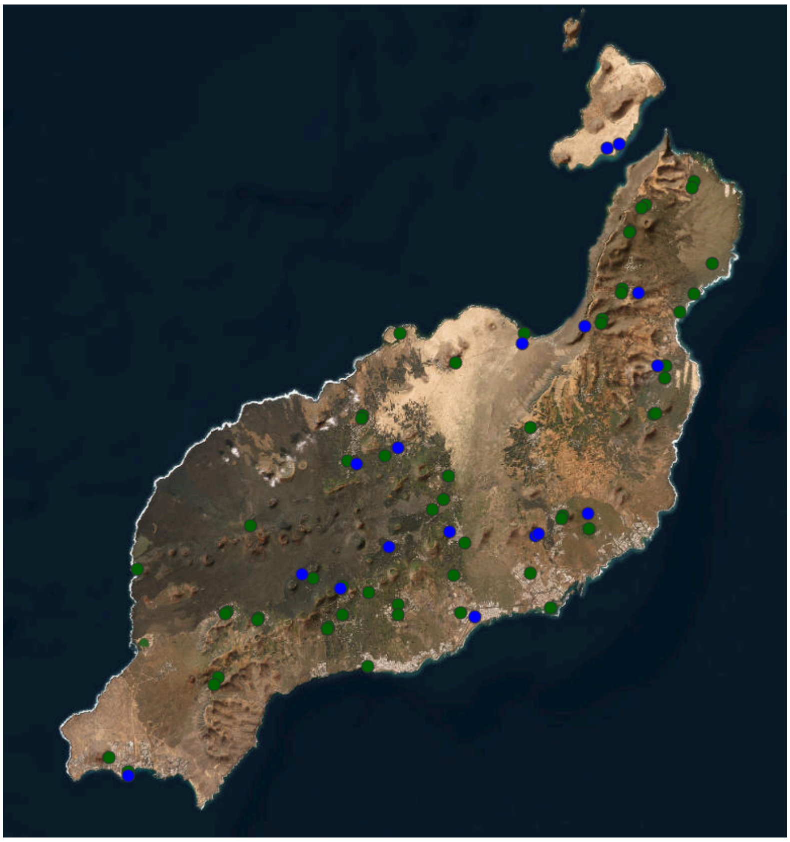

Figure 9. Lanzarote and Chinijo Archipelago weather stations' distribution for those that provide data about precipitation (green), temperature (red) or both variables (blue).

A summary of the available and final stations and the data sources is shown in Table 7. It must be noted that the final number of useful stations shown in that table is calculated after all quality tests have been passed.

Table 7. Stations retrieved for the meteorological variables to study for Lanzarote island and Chinijo Archipelago. The variable name, the original number of provided stations, the final number of useful stations and the data source are shown.

Variable	Number of provided stations	Number of quality stations	Number of useful stations	Source
Precipitation	35	34	34	AEMet
Precipitation	33	33	33	Cabildo de Lanzarote
Precipitation	7	7	5	SiAR - Gobierno de Canarias
TOTAL	**75**	**74**	**72**	
Temperature	12	12	12	AEMet
Temperature	7	7	5	SiAR - Gobierno de Canarias
TOTAL	**19**	**19**	**17**	

1.2. Climate and spatial information

As a complementary source of information for weather observations, climate information comes to cover mainly the gaps of what the weather and climate were like (and will be like) in the places where weather observations are not available. It could be said that this information provides data with a spatial coverage that allows for the process and management of data over the whole archipelago. In this sense, we could distinguish between GIS static information, reanalysis and climate models.

1.2.1. GIS climate information

SICMA-Canarias aims to produce local downscaled climate projections to cover all of the Canary Islands with a fine resolution of 100x100 m. To achieve this purpose, it is necessary to count on different layers of data that enable the proper management of the information in such an intricate and complex environment as the one of these islands.

Furthermore, it is also appropriate to feed research and this type of development with everything that has been done before in the same area, not just to save resources, but to foster the scientific community and help to continue the investigation in the field, aside from building better outcomes that pushed forward the state of the art in the field.

In this sense, thanks to the participatory approach taken by SICMA-Canarias and the support of different entities, a wide variety of rich and really useful information has been collected to help accomplish the objectives of this project:

- Historical climate data from the Canarian Atlas of SITCAN:
  A huge effort was made recently by the ULPGC (Universidad de las Palmas de Gran Canaria) and the Canary Government to create a climate atlas for the archipelago (*Luque Söllheim, A. L., et al., 2024*). Thanks to the collaboration of ULPGC researchers, these layers were shared to help construct better interpolation models and weather and climate databases for SICMA-Canarias. Layers such as monthly cloud cover (Figure 10), monthly RH, precipitation or temperature were collected.

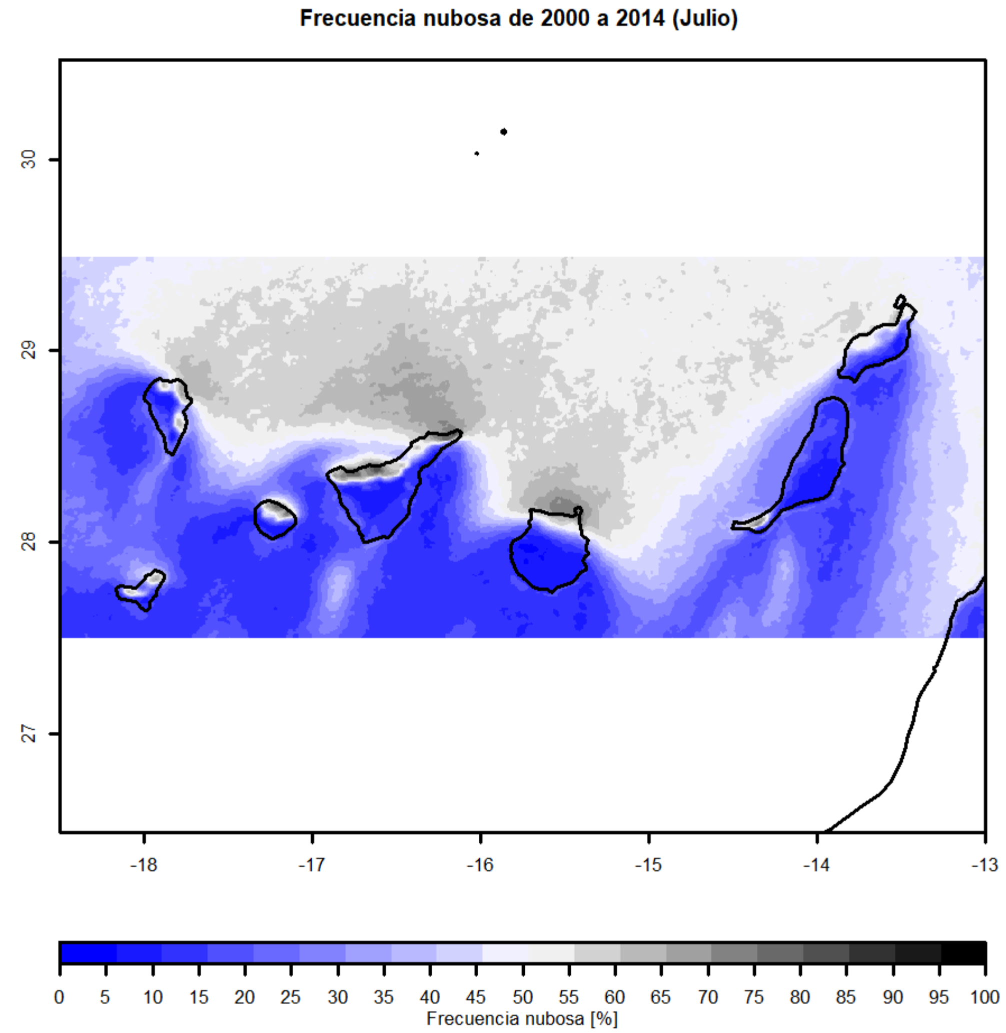

Figure 10. Example of the mean historical cloud cover throughout the Canary Islands for the month of July. Legend shows the frequency of cloud cover of the sky in %

- Historical and geographical information layers of physical properties of the archipelago from CanaryClim:
  Thanks to the collaboration of Teide National Park and its researchers, a past project that took place in the Canary Islands and delivered really useful results around climate change and Canarian microclimates was identified. This project, named CanaryClim (*Patiño & Collart et al., 2023*), categorized local climate behaviors of each island, identifying a useful set of parameters to produce a fine set of topographical layers (100 x 100 m) in such orographically complex locations, such as northness (Figure 11) or eastness.

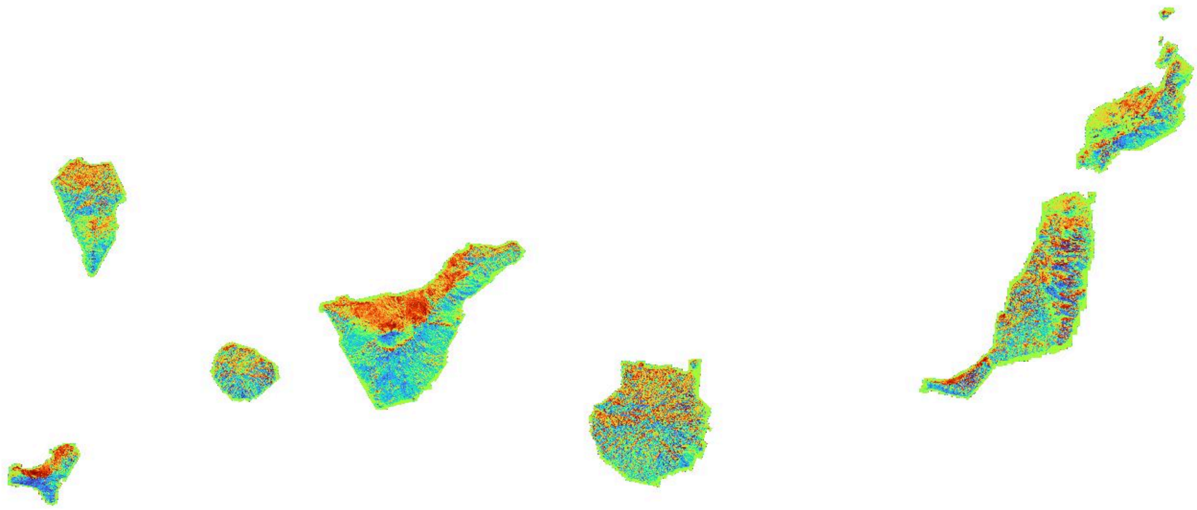

Figure 11. Example of the "northness" TIF layer covering the whole Canary Archipelago at a 100 x 100 m resolution.

- Different GIS layers of use:
  Other GIS layers needed for interpolations or spatial analysis were collected from public sources. These layers comprise information like DEM, Aspect, Orientation, or other more technical like NDVI (Normalized Difference Vegetation Index) or LST layers (Land Surface Temperature).

1.2.2. Climate reanalysis

There are instances where the spatial distribution or temporal coverage of weather stations is inadequate, leading to inconsistencies and inhomogeneities, and do not have to represent their surroundings. SICMA-Canarias chose to also use reanalysis data for verification and training purposes, as they offer improved spatial-temporal coherence and physical consistency, and also for the development of climate scenarios, as they are a key part of the statistical procedures.

Climate reanalysis combines numerical weather models with assimilated observations, furnishing numerical and physical representations of recent climate conditions. These encompass estimates of atmospheric variables like air temperature, pressure, and wind at various levels, as well as surface variables such as rainfall, soil moisture content, ocean-wave height, and sea-surface temperature.

Since the Canary Islands sometimes don't have a size wide enough to consider ERA5-Land, the main chosen atmospheric reanalysis for the project is the European reanalysis ERA5 to also cover marine and coastal areas, although some fields of ERA5-Land are indeed chosen for inland locations. This selection is based on several considerations: 1) it is developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), whose primary operational area aligns with the geographical scope of the Canary Archipelago, and is renowned for delivering top-notch weather forecasts, 2) it represents the latest version of the European reanalysis, boasting enhanced spatial and temporal resolution compared to its predecessors, and 3) it is freely accessible for download through the Copernicus program's Climate Change Service (C3S, 2019)

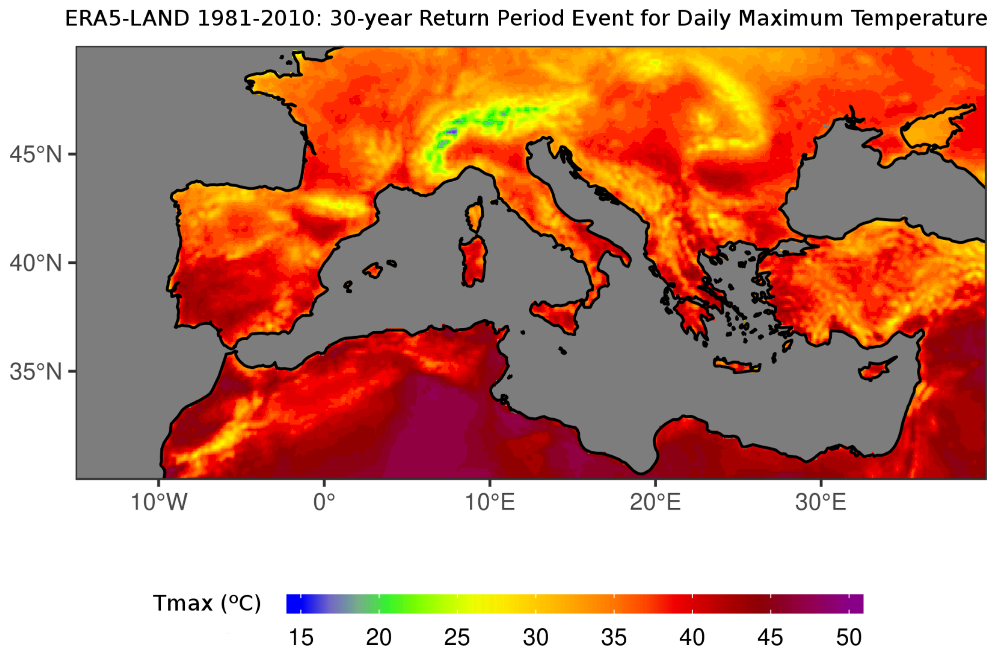

Figure 12. Example of the spatial representation of ERA5-Land reanalysis, representing a 30-year return period event for daily maximum temperature. (Source: C3S)

ERA5 is the most recent reanalysis developed by the ECMWF. Released in July 2019, it provides hourly data with a temporal coverage that goes from 1950 to the present day. It covers all the globe at a 0.25°x0.25° resolutions; plus ERA5-Land, which only covers land terrain, has a grid of 0.1°x 0.1° spatial resolution (9 km approx. at mid-latitude).

From all the variables available to download, for ERA5-Land only precipitation and temperature were retrieved, whereas for ERA5, since it is used in the FICLIMA method for statistical downscaling, more layers were sought, such as: RH, Q, precipitation, geopotential thickness, u-v wind components, temperature... all of them at different heights.

1.2.3. The IPCC AR6 and CMIP6 Earth System Models

One of the most important advances that SICMA-Canarias poses for the development of this project is the alignment of the science used with the state of the art of climate science. The latest advancements in climate science revolve around the use of CMIP6 models, as mentioned in the IPCC AR6. The use of these models implies a leap in the information available for the Canary Islands and an enrichment in all future adaptation and mitigation strategies that could take place in the scope of the archipelago.

The Intergovernmental Panel on Climate Change (IPCC) coordinates global climate change efforts by producing comprehensive reports on human-induced climate risks, impacts, and adaptation/mitigation strategies. Its Sixth Assessment Report (AR6), endorsed by leading scientists and governments, sets the state-of-the-art in climate science. AR6 utilizes the latest Global Climate Models (GCMs) from the Coupled Model Intercomparison Project (CMIP, *Eyring et al., 2016*), which standardizes climate experiment protocols and outputs. The sixth phase of CMIP features advancements in Earth System Models (ESMs) and introduces new emission scenarios, addressing evolving needs for climate adaptation and mitigation strategies.

ESMs are advanced climate models that couple atmosphere, land, ocean, and cryosphere components, allowing interactive calculation of atmospheric CO2 and emissions. These models project future climate outcomes using concentration scenarios derived from emissions scenarios, which consider factors like socioeconomic development and technological evolution. CMIP6 introduces Shared Socioeconomic Pathways (SSPs), an advancement from CMIP5's Representative Concentration Pathways (RCPs), offering narratives on societal evolution leading to emissions scenarios. The new generation of CMIP6 models features higher sensitivity, greater spatial resolution, and predicts more severe climate impacts than CMIP5 (*Masson-Delmotte et al., 202*1). Consequently, CMIP6 data is recommended for future studies and risk assessments.

SSPs are scenarios projecting global socioeconomic changes up to 2100, describing alternative pathways for human development, including mitigation policies, adaptation strategies, and social factors like sustainability or economic inequality. These pathways influence future climate behavior. CMIP6 introduces four main SSP scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (Tier 1), expanding the range from CMIP5's two main scenarios (RCP 4.5 and RCP 8.5). CMIP6's improved understanding of the global climate system allows for a broader range of projected global mean temperatures compared to CMIP5. These SSPs predict temperature outcomes beyond the range covered by previous RCP scenarios (*Meinshausen et al., 2019*).

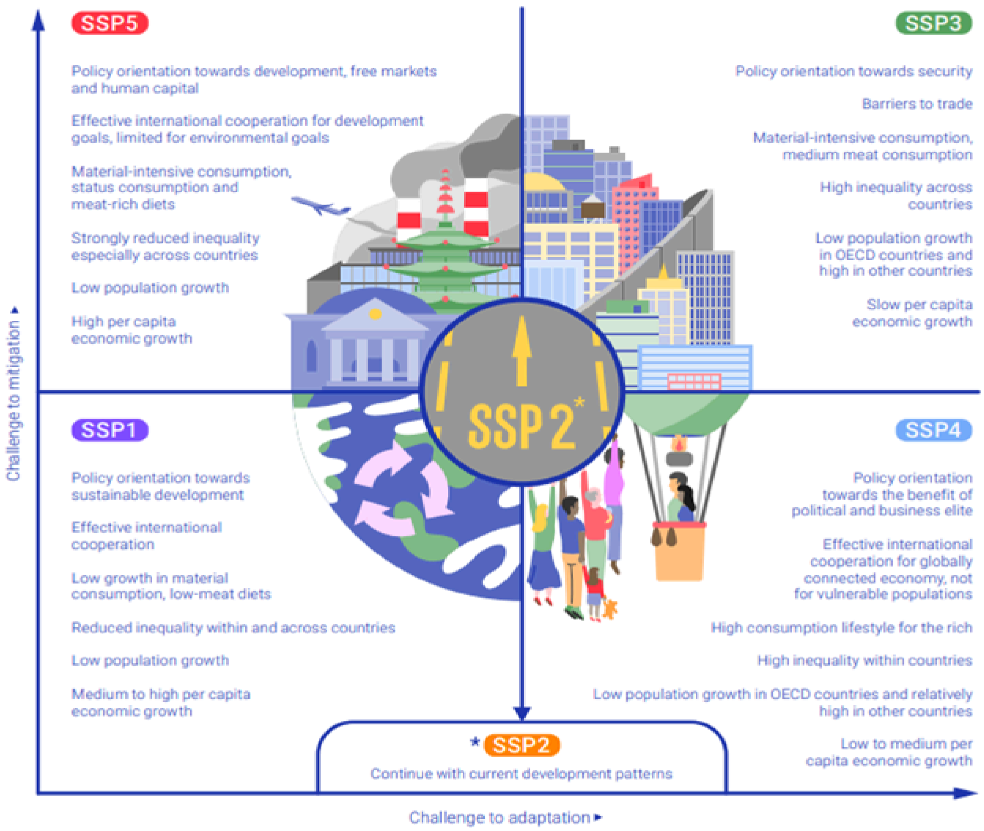

Figure 13. Shared Socioeconomic Pathways (in the figure, OECD stands for Organizations of Economic Co-operation and Development). *Source: figure adapted from O'Neill et al., 2017.*

Following prior scientific recommendations, SICMA-Canarias climate information is already based on CMIP6 models and incorporating in its workflow the current SSPs. Therefore, the presented high-resolution future climate projections display a unique dataset.

As a way to create the best possible evaluation of uncertainty, an ensemble approach is followed, and a total of 10 different CMIP6 models have been retrieved (10 models at a daily scale give us enough information for quantifying their intrinsic uncertainty in projecting changes). Each model has its particularities, so a thorough analysis of each model and the documentation available was performed to select the 10 best ones for the Canary Islands. The same analysis period was considered, from 01/01/1950 to 31/12/2014 and the 4 Tier 1 SSPs (ssp126, ssp245, ssp370 and ssp585) ranging from 01/01/2015 to 31/12/2100. The relation of the selected models is detailed in Table 8:

Table 8. Information about the 10 climate models belonging to the 6 Coupled Model Intercomparison Project (CMIP6) corresponding to the IPCC AR6. Models were retrieved from the Earth System Grid Federation (ESGF) portal in support of the Program for Climate Model Diagnosis and Intercomparison (PCMDI).

CMIP6 MODELS	Resolution	Responsible Centre	References
ACCESS-CM2	1,875º x 1,250º	Australian Community Climate and Earth System Simulator (ACCESS), Australia	Bi, D. et al (2020)
BCC-CSM2-MR	1,125º x 1,121º	Beijing Climate Center (BCC), China Meteorological Administration, China.	Wu T. et al. (2019)
CanESM5	2,812º x 2,790º	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá.	Swart, N.C. et al. (2019)
CMCC-ESM2	1,000º x 1,000º	Centro Mediterraneo sui Cambiamenti Climatici (CMCC).	Cherchi et al, 2018
CNRM-ESM2-1	1,406º x 1,401º	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia.	Seferian, R. (2019)
EC-EARTH3	0,703º x 0,702º	EC-EARTH Consortium	EC-Earth Consortium. (2019)
MPI-ESM1-2-HR	0,938º x 0,935º	Max-Planck Institute for Meteorology (MPI-M), Germany.	Müller et al., (2018)
MRI-ESM2-0	1,125º x 1,121º	Meteorological Research Institute (MRI), Japan.	Yukimoto, S. et al. (2019)
NorESM2-MM	1,250º x 0,942º	Norwegian Climate Centre (NCC), Norway.	Bentsen, M. et al. (2019)
UKESM1-0-LL	1,875º x 1,250º	UK Met Office, Hadley Centre, United Kingdom	Good, P. et al. (2019)

2. Climate projections

2.1. Historical climate of the Canary Islands

The main and key outcome of SICMA-Canarias is the generation and delivery of a set of climate projections covering the whole Canary Islands. However, prior to the start of this task, there is a need to set the basis of what it is that we will be working with: to analyze and identify in detail what the climate was like in the past, and how it is in the present times to establish the baseline to compare future climate changes. It is also important to recall that the Canarian Archipelago might be in a quite homogeneous climate zone, but when their location is crossed with an outstanding topography and the particular climate in the area, a wide set of microclimates and local behaviours arise. This gives account of the huge importance of first identifying these key features prior to running any climate projection, as this is something that needs to be taken into account and represented in the forcings that the statistical downscaling needs to handle.

The Canary Islands are well-known for their huge abundance of local microclimates, with extreme changes in temperature, cloudiness, rainfall and humidity conditions in a matter of kilometres. And this happens in multiple planes, with remarkable changes in pedoclimatic conditions with height, orientation, location within the island, local orographic features… being practically each island a climate cosmos in miniature, with some of them such as Gran Canaria having the nickname of "miniature continent" due to the multiple variations that climate suffers. The way that the trade winds interact with orography throughout the year, plus the effect of mountains against low-pressure systems or Saharian dust intrusions marks each island's climate. It is therefore mandatory to analyze in depth each island separately to discover the distribution of climate variability.

To do so, it is necessary to represent the spatial distribution of temperature and rainfall in each island. For this task, the total amount of weather observations has been used to check each region's climate, plus crossing results with reanalysis data and also, very importantly, with local knowledge of the Canary climate. Researchers in SICMA-Canarias have wide experience, after years of observation and monitoring, in the climate in the islands, which is essential to distinguish really local climate features that just by the analysis of weather observations could be misleading or wrong, such as "*bajaradas*" events (slope Föehn winds) or typical convergence of winds in rainfall situations.

To accomplish this analysis, a multiple set of different topographic and climate layers have been crossed and considered, together with weather observations, to analyze and identify the best way to extrapolate local climate conditions and cover and represent them in each island's geography. For this purpose, a complex and advanced Geographically Weighted Regression (GWR) algorithm has been used to generate the needed results, with each set of layers corresponding to each test feeding the algorithm. The identified tests can be consulted in Table 9.

As mentioned before, each of the 25 tests was run on each island separately, and for each of the climate variables identified of interest (maximum temperature, minimum temperature, precipitation), with a thorough quality analysis both by the use of statistics for errors and correlation, and also with spatial and visual analysis of each output, produced at annual, monthly and seasonal scale. The checking and validating of results ended in the selection of the following tests for each island and climate variable (Table 10).

Table 9. Information about the up to 25 different tests that were developed in each island to identify the best combination of layers to represent the island's climate diversity. Distcost = distance to seashore

Test	Topographic and climate layers used
P1	altitude, distcost, slope, aspect, northness, eastness
P2	altitude, distcost, aspect, northness, eastness
P3	altitude, aspect, northness, eastness

P4	altitude, distcost, northness, eastness
P5	altitude, distcost, northness
P6	altitude, distcost, aspect, northness, eastness, cloudiness
P7	altitude, aspect, northness, eastness, cloudiness
P8	altitude, aspect, cloudiness
P9	altitude, distcost, aspect, cloudiness
P10	altitude, distcost, cloudiness
P11	altitude, aspect, northness, cloudiness
P12	altitude, distcost, northness, eastness, cloudiness
P13	altitude, distcost, aspect, northness, cloudiness
P14	altitude
P15	altitude, cloudiness
P16	altitude, distcost, aspect, northness, eastness, cloudiness, LST, NDVI
P17	altitude, distcost, aspect, northness, eastness, cloudiness, NDVI
P18	altitude, distcost, aspect, northness, eastness, NDVI
P19	distcost, aspect, northness, eastness, NDVI
P20	aspect, northness, eastness, NDVI
P21	aspect, northness, eastness, LST, NDVI
P22	aspect, northness, eastness, cloudiness, NDVI
P23	northness, eastness, cloudiness, NDVI
P24	northness, eastness, cloudiness, LST, NDVI
P25	altitude, distcost, northness, eastness, cloudiness, LST, NDVI

Table 10. Information about the results of the selection of layers for the spatial characterization of each of the Canary Island climate distributions for the climate variables selected. Distcost = distance to seashore

Island	Climate variable	Selected test	Topographic and climate layers used
La Palma	Precipitation	P25	altitude, distcost, northness, eastness, cloudiness, LST, NDVI
	Maximum temperature	P6	altitude, distcost, aspect, northness, eastness, cloudiness
	Minimum temperature	P6	altitude, distcost, aspect, northness, eastness, cloudiness
El Hierro	Precipitation	P7	altitude, aspect, northness, eastness, cloudiness
	Maximum temperature	P9	altitude, distcost, aspect, cloudiness
	Minimum temperature	P9	altitude, distcost, aspect, cloudiness
La Gomera	Precipitation	P11	altitude, aspect, northness, cloudiness
	Maximum temperature	P11	altitude, aspect, northness, cloudiness
	Minimum temperature	P11	altitude, aspect, northness, cloudiness
Tenerife	Precipitation	P11	altitude, aspect, northness, cloudiness
	Maximum temperature	P11	altitude, aspect, northness, cloudiness
	Minimum temperature	P11	altitude, aspect, northness, cloudiness
Gran Canaria	Precipitation	P13	altitude, distcost, aspect, northness, cloudiness
	Maximum temperature	P13	altitude, distcost, aspect, northness, cloudiness
	Minimum temperature	P13	altitude, distcost, aspect, northness, cloudiness
Fuerte ventura	Precipitation	P12	altitude, distcost, northness, eastness, cloudiness
	Maximum temperature	P15	altitude, cloudiness
	Minimum temperature	P15	altitude, cloudiness
Lanza rote	Precipitation	P8	altitude, aspect, cloudiness
	Maximum temperature	P12	altitude, distcost, northness, eastness, cloudiness
	Minimum temperature	P12	altitude, distcost, northness, eastness, cloudiness

2.2. Climate projections. Ensemble strategy

When talking about the generation of climate information, one of the main concerns that both climate scientists (as information providers) and sectoral partners or decision-makers (as information receivers) have to deal with is the inherent uncertainty of climate data. Climate Models (CMs), as stated above, are numerical models that represent the climate system with varying degrees of complexity and are based on the physical, chemical and biological properties of its components, their interactions and feedback processes. Therefore, each CM, depending on its inner architecture, simulates past and possible future climate states in a unique way, which translates into a degree of uncertainty depending on the CM selected. Additionally, the climate system has inherent inner variability due to the different time scales of the components involved (e.g. atmosphere days, ocean years) and related impacts on weather patterns, as well as other patterns such as ENSO or AMO. This is the reason why a 30-year period is selected for climate analysis. Furthermore, CMs simulate broad atmospheric circulation well but lack the resolution (around 100 km) for smaller-scale local phenomena. To address this limitation, downscaling techniques are employed, and this treatment of CMs further incorporates more uncertainty into the equation. Apart from model and climate-related variability and uncertainties, the emission scenarios used for driving future climate projections (SSPs) represent possible evolutions that cause possible climate states, adding another level of complexity and uncertainty in the interpretation and communication of climate model results and related (local) impacts.

Efforts within the scientific community focus on addressing and quantifying uncertainties in climate simulations. The main way to address this is the ensemble strategy[2], where either the same model is initialized with slightly different conditions or different models are used for computing the same SSP scenario, both approaches being done for CMIP6, thus combinations of models/SSPs/horizons for consistent projections are available. This approach displays the different outcomes and impacts for future climate states, clearly displaying the spread within the model simulations. Often the medians and quantiles (10-90%) are applied to gain better knowledge and reduce uncertainty, enhancing the understanding of future climates for specific locations. This is applied in SICMA-Canarias, with the display of Median and Percentiles 10-90 of the models considered, plus the consultation of model spread by clicking over the map. Having a low spread from median to quantiles casts reliability onto main climate outcomes, allowing the use of trustworthy information; if they largely differ, this has to be taken into account since it means that the future state is highly uncertain.

For the presentation of the results concerning future climate projections in SICMA-Canarias, a three-time-periods strategy has been taken to represent them depending on the remoteness in time: **short-term (2021-2050), mid-term (2041-2070) and long-term (2071-2100)**. The baseline (or historic period) is aligned with the IPCC AR6 also considering CMIP6 historical experiments, being set to the **1985-2014** 30-year period. Also, the temporal scale of results obtained go from monthly means up to seasonal and annual values for each of the climate periods mentioned.

2.3. Statistical downscaling. FICLIMA methodology

The statistical downscaling methodology applied in SICMA-Canarias, named FICLIMA (Ribalaygua et al. 2013), consists of a two-step analogue/regression statistical method which has been used in national and international projects with good verification results (i.e.: Monjo et al. 2016). The first step (see Figure 14) is common for all simulated climate variables and it is based on an analogue

[2] https://climateinformation.org/knowledge-base/why-use-a-model-ensemble2/

stratification (Zorita et al. 1993). An analogue method was applied based on the hypothesis that 'analogue' atmospheric patterns (predictors) should cause analogue local effects (predictands), which means that the number of days that were most similar to the day to be downscaled was selected. The similarity between any two days was measured according to three nested synoptic windows (with different weights) and four large-scale fields using a pseudo-Euclidean distance between the large-scale fields used as predictors. For each predictor, the weighted Euclidean distance was calculated and standardised by substituting it with the closest percentile of a reference population of weighted Euclidean distances for that predictor. This method is a good method for reproducing nonlinear relationships between predictors and the predictands, but it could not be used to simulate values outside of the range of observed values. In order to overcome this problem and obtain a better simulation, a second step was required.

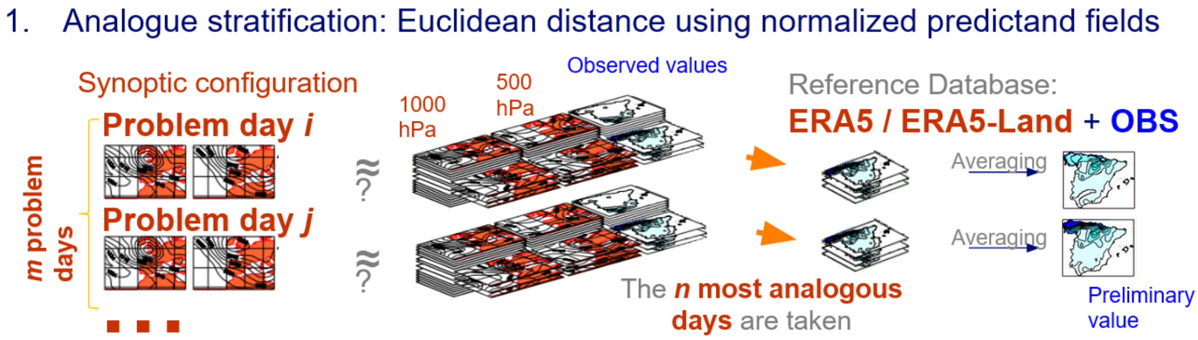

Figure 14. Key features of the first step of the FICLIMA statistical downscaling.

For this second step (see Figure 15), the procedures applied depend on the variable of interest. To determine the temperature, multiple linear regression analysis for the selected number of most analogous days was performed for each station and for each problem day. From a group of potential predictors, the linear regression selected those with the highest correlation, using a forward and backward stepwise approach.

For precipitation, a group of m problem days (we use the whole days of a month) is downscaled. For each problem day we obtain a "preliminary precipitation amount" averaging the rain amount of its n most analogous days, so we can sort the m problem days from the highest to the lowest "preliminary precipitation amount". For assigning the final precipitation amount, all amounts of the m×n analogous days are sorted and clustered in m groups. Every quantity is finally assigned, orderly, to the m days previously sorted by the "preliminary precipitation amount".

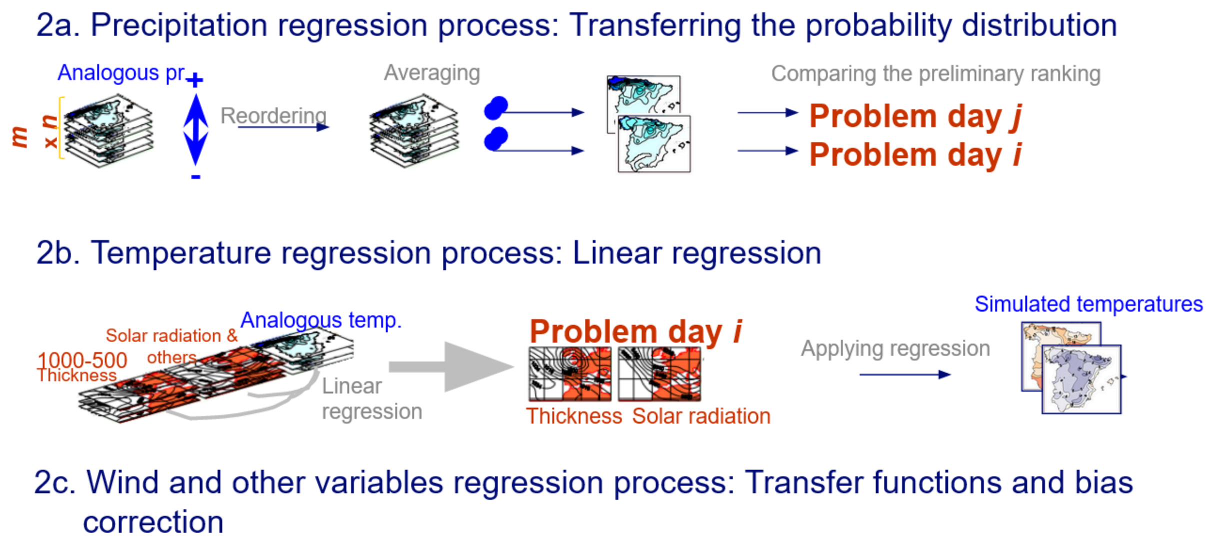

Figure 15. Key features of the second step of the FICLIMA statistical downscaling, with graphic details of the work done for each type of variable.

This second step done at a daily scale with an inner thorough verification procedure is essential and the main differentiating process of the FICLIMA method. It extends beyond mean values to include extremes and covers all time scales, including daily intervals. With the verification it can be proven if the method correctly simulates changes from one day to the next, indicating an effective capture of the underlying physical connections between predictors and predictands. These physical links remain relatively consistent, even in the face of climate change (as opposed to purely empirical relationships that might shift). In essence, this approach theoretically addresses the primary challenge in statistical downscaling known as the non-stationarity problem. This problem questions the stability of predictor/predictand relationships established in the past, probing whether these relationships will persist in the future.

The FICLIMA method assesses its own uncertainty with inner processes of verification through the use of different procedures and statistics, ensuring that the methodology introduces the least amount of uncertainty into the outcomes, thus reducing this factor of the climate uncertainty equation.

As can be seen in Table 11, after a thorough analysis of the validation results for the seven canary islands, it was found that **CMCC-ESM2 model does not perform well for temperature** variable, producing odd values that must be dismissed. For the case of **precipitation, the model that underperforms is CanESM5, which must be dismissed**, with CMCC-ESM2 not performing as well as the rest but still being considered. Therefore, these two models won't be visible in the display of SICMA-Canarias nor considered for the calculation of statistics. Derived variables that feed from them, such as SPEI considering precipitation and temperature, won't present results in those cases.

Table 11 Validation results for all the Canary Islands considering temperature and precipitation results, and the performance from each of the 10 models used. After evaluation of the models performance from MAE and monthly bias, the final assessment of those used is presented. Green means "ok", yellow "good but use with care" and red "dismissed".

Models	Validation results for CMIP6 models in Canary Islands		
	Max temperature	Min temperature	Precipitation
ACCESS-CM2			
BCC-CSM2-MR			
CanESM5			
CMCC-ESM2			
CNRM-ESM2-1			
EC-EARTH3			
MPI-ESM1-2-HR			
MRI-ESM2-0			
NorESM2-MM			
UKESM1-0-LL			

3. Climate indicators and derived variables

After the completion of the works performed in WP1 and most of those within WP2 during the first seven months, WP2 progressed in adapting the climate downscaling over the Canary Islands to calculate several related climate indicators. For this purpose, WP2 has collected all the information provided by WP1 and previous WP2 tasks regarding weather and climate information, including the 10 CMIP6 downscaled model projections with FICLIMA method for temperature and precipitation, to generate the derived climate variables and related indicators and their posterior spatial distribution of results.

These indicators and variables are gathered around their link with precipitation, temperature, or both of them. In a brief list, these are the complete group of elements obtained:

- Temperature-linked indicators:
  - Heat wave frequency
  - Heat wave intensity (mean and max)
  - Heat wave length
- Precipitation-linked indicators:
  - SPEI (3, 12 and 24 months)
  - Hydric balance
- Temperature and precipitation-derived indicators:
  - Aridity index
  - Potential evapotranspiration
  - Real evapotranspiration

In the next section, the definition and methodology of obtaining of each of them is detailed. Since some of them must be used for the calculation of others (like potential evapotranspiration is needed to compute the hydric balance), the order of the definitions goes from the most direct one (just needing temperature or precipitation) to the most complex ones in dependencies.

3.1. Definition and methodology

3.1.1. Heat Waves

A heat wave is meant to be an extremely high-temperature event that poses a risk to human health, infrastructure and other critical assets. For a temperature event like this, in order to consider it extreme enough to be classified as a hazard and affect the normal development of local activities, it should cover a set of requirements such as:

- <u>High intensity</u>. Temperature values need to be extremely high related to what is common in the local climate. This is to suppose a risk for the way infrastructure was previously designed and to what human bodies are normally used to deal with. With this, values need to be above the average maximum values registered in the warmest period of the year, i.e. summer.
- <u>Low frequency</u>. Linked to the previous point, a heat wave should be rare to suppose an event extreme as a definition linked to a probability distribution of the local climate. Percentiles are therefore a good approach in this sense.

- Certain duration in time. For a temperature-related event, it is proved that the impact and risk grow bigger the more time it lasts rather than a great intensity event of some hours of duration. This is so since a long-time event will have the time to impact infrastructure (materials, thermal isolation…) and activities (leisure, outside labour) as well as the health of the population (worse rest, thermal shock…).

Following these points, and including the particularities of the climate distributions of the case studies, heat wave episodes (i.e. a period of consecutive days with extreme maximum temperatures) have been calculated considering the definitions proposed by the State Meteorological Agency (AEMET, in its document Olas_Calor_Actualizacion2024.pdf), by the World Meteorological Organization (WMO, in WMO, 2010) and by the IPCC, on the basis of which the criteria for calculating and evaluating a heat wave have been established (Gaitán et al. 2019). After various analyses, and in order to align with the most recurrent method and with the greatest added value for the end users of SICMA-Canarias, we opted for the AEMet's own definition, which is also applied in the study and compilation of heat waves in the archipelago in the same document:

Heat wave: *a temperature-related episode of at least three consecutive days where the weather observations considered register maximum temperatures above the 95% percentile of their daily maximum temperature records for the months of July and August of the 1985-2014 period.*

Heat waves are events of extreme impact in the Canary Islands, a region that is located really close to the Sahara desert but that generally enjoys mild comfortable temperatures due to the trade winds effect all along the year. When the wind pattern shifts and the hot Saharan wind layer irrupts, the interaction of the wind, the complex orography and the inversion layer of the Azorian High causes very local extreme conditions with temperatures as high as 48ºC and nights not falling below 30ºC.

A heat wave episode is analysed based on several characteristics for each of which a different indicator has been defined:

- *Average length of Heat waves*

The average length of a heat wave episode is defined as the number of consecutive days in which the maximum temperature is above the set threshold (3 days). It is calculated for each of the 30 years of each period in question. In the case of more than one heat wave in the same year, the value is obtained as the average of all cases.

- *Average Intensity of Heat Waves*

The average intensity of a heat wave episode is the average of the maximum temperature values recorded on the days constituting the heat wave episode. It is calculated for each of the 30 years of each period in question. If more than one heat wave in the same year, the value is the average of all.

- *Maximum intensity of Heat Waves*

The maximum intensity of a heat wave episode is the most extreme value of the maximum temperature values recorded on the days constituting the heat wave episode. It is calculated for each of the 30 years of each period in question. If more than one heat wave in the same year, the value is the average of all.

- *Number of Heat Waves (frequency)*

The average number of heat waves per year makes it possible to analyse possible trends in the increase or decrease in the occurrence of this type of phenomena. It is calculated for each of the 30 years of each period in question.

3.1.2. Potential Evapotranspiration (ETo)

With the aim of characterizing the climatic particularities of each location, the estimation of the water regime of a habitat is fundamental to recognise its capacity to support a species, crop or plant community. To do this, it is necessary to know not only the precipitation of the site, but also the potential water losses that the soil may suffer through evapotranspiration under ideal conditions, which in turn depend to a large extent on solar radiation, among many other factors.

In order to estimate this loss, the 'reference or potential evapotranspiration (ETo)' is used, which can be approximated in various ways, some of which are more accurate (and data demanding) than others. In our case, the 'Penman-Monteith FAO98' model is the most accurate method to calculate ETo. It is a complex function dependent on a multitude of variables, based on classical physics principles and derived from the physical model of energy conservation. It involves all energy exchange fluxes at the soil-atmosphere interface, including the change of state of water from liquid to vapour, either directly by evaporation in the soil or transpiration in plants. In order to set standard measurement conditions for its application, the soil is approximated to that of a crop of 0.12 m height, 70 s/m resistance and 0.23 albedo. The units of measurement are 'mm'.

According to the Penman-Monteith definition of ETo, we would have the following:

$$ETo = \frac{0{,}408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot (\frac{900}{T + 273}) \cdot v_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0{,}34 \cdot v_2)} \; [Eq.\ 1]$$

where:

ETo = reference evapotranspiration, *Δ* = slope of the saturated vapour stress curve (kPa/ºC), R_n = net solar radiation on the surface (MJ/m2-day), *G* = heat flux to the ground (MJ/m2-day), *γ* = psychrometric constant (kPa/ºC), *T* = mean air temperature (ºC), v_2 = mean wind speed (m/s), e_a = actual vapour pressure (kPa), e_s = saturated vapour pressure (kPa).

It should be noted that the calculation of ETo developed here goes one step further than that defined as standard, since the term Rn, corresponding to the net radiation incident on the study surface, is not approximated as incident on a flat surface, but a correction coefficient has been introduced to adjust it to the real topography, taking into account the slope of the ground and its orientation, critical factors in the real ETo of an area. Thus:

$$Rn = (1 - \alpha) \cdot (\frac{2 + \alpha \cdot (1 - cos\, p)}{2}) \cdot R_s \cdot \frac{s_n}{sh_n \cdot cos\, p} - R_{ol} \; [Eq.\ 2]$$

where:

s_n = solar incidence, y sh_n = normalized solar incidence.

Thus, applying the previous equations at each grid point stipulated over the Canary Islands, to obtain the value of ETo we have made use of input values of all those variables required for its direct or indirect use (in some coefficients), being: the temperatures **TMax** and **Tmin**, the dew temperature (**TDew**), the atmospheric pressure reduced to sea level (**PSL**), the estimated wind at 2m (**V2**), the altitude of each point (**Z**) and its latitude, the solar incidence (**Sn**) and the slope of the ground (**p**). These variables have been obtained from different sources:

- Tmax and Tmin are taken directly from each of the climate models, after correction and downscaling of their values from the native grid to the Canarian grid. This is the work produced and justified in the previous D1.

- TDew, PSL and V2 have been considered, due to their nature and after several other climate projections performed by FIClima in different areas where values and uncertainty of these variables led to the conclusion that changes are normally not significant enough, as climatic constant values. In this case, the constant values were taken for the agreed baseline (1985-2014), and approximated for each desired time scale with the mean value (monthly mean, annual mean, etc.). In more detail, the values have been retrieved from:
    - TDew (more exactly RH) and V2 were obtained from the SITCAN Historical Canary Climate Atlas (Luque Söllheim, A. L., et al., 2024), at a perfect 100x100m grid covering the time scales needed, which grants a wonderful resolution and behaviour for such crucial variables.
    - PSL was obtained by using the ERA5-Land reanalysis taking as reference period the interval 1985-2014

- Aspect, Slope and Z have been obtained directly from the 100x100m DTM with the grid equivalent to the one used.

- Solar Incidence has been calculated, at 100x100m, by crossing the complex Canarian orography, for each day of the year, with the natural path of the Sun in the sky (azimuth, elevation, declination...), taking into account the projection of shadows of the orography to account on shades cast afar that block sunrays in places where, without obstacles in the horizon, the light would directly incide. The daily value comes from the calculation and aggregation of hourly values, from sunrise to sunset, not just taking the Sun position at midday, so that each of the shadows of the day is considered. Some examples of results are shown in Figure 16.

ETo plays an important role in the distribution of vegetation in the Canary Islands, a place with huge contrasts between the north and south parts of each island and also even within a single canyon. The abundance of cloud cover and wet conditions in northern parts plus the lesser impact of solar radiation, especially in Winter due to the great orography (high altitudes and steep slopes), allow the formation of exuberant masses of forests with modest amounts of rainfall, while southern parts of the island suffer from constant high radiation and drier air conditions, being in this parts where orientations and slope can facilitate slightly moister conditions for vegetation.

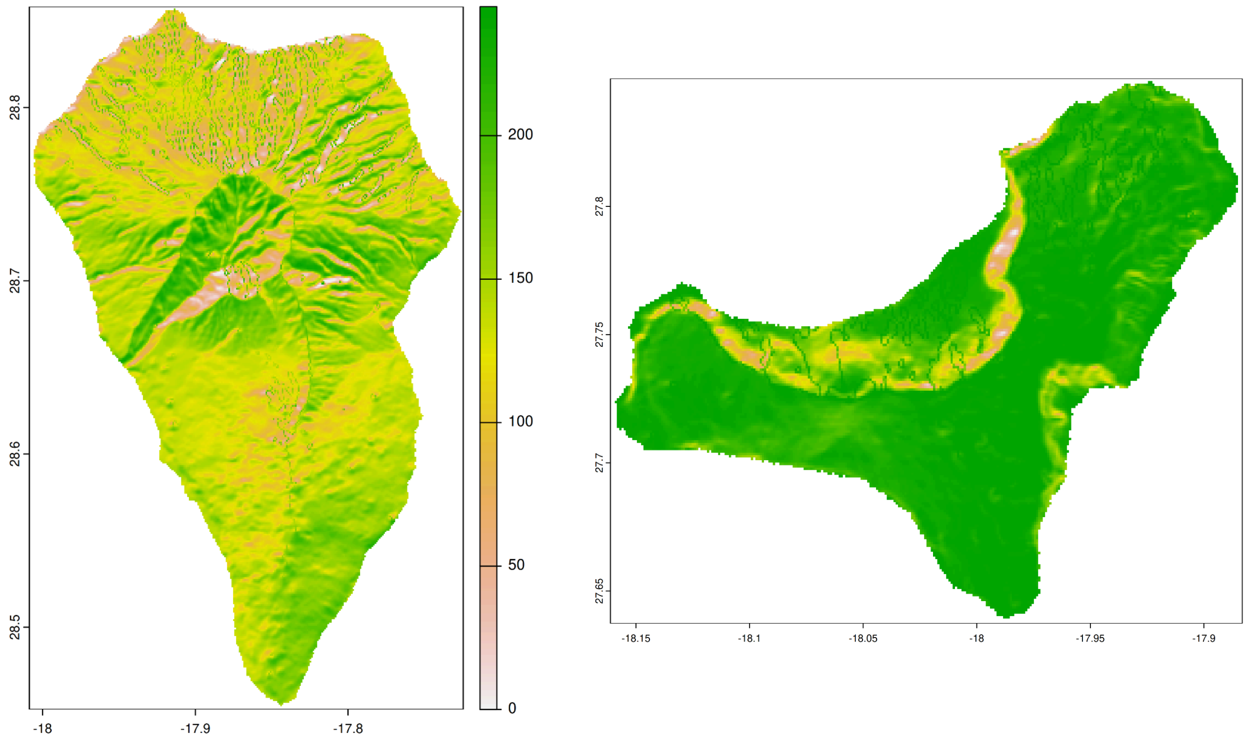

Figure 16. Example of real estimated solar incidence in the month of January in La Palma island (left), and in the month of August in El Hierro island (right). Legend values do not match between images.

3.1.3. Hydric Balance (BH)

The monthly water balance makes it possible to approximate the availability of water in the soil by, in our case and in a very simplified form, calculating the incoming precipitation and evapotranspiration. The water balance used here is therefore potential and only climate-dependent. It is also assumed that the soil has an 'infinite' water reserve capacity, with no storage limit (although normally a 100mm threshold is applied, here for the sake of simplicity and considering the scarce pluviosity of the archipelago and the permeable volcanic soil, the threshold was deleted). If the soil loses its entire reserve, the BH = 0, without taking negative values.

The calculation is made using the following expression:

$$BH_m = BH_{m-1} + Pr_m - ETo_m \quad \Leftrightarrow \quad BH_m > 0 \ [Eq.\ 3]$$

Where BH_m is the water balance of month m, Pr_m and ETo_m are the total precipitation and reference evapotranspiration of month m, and BH_{m-1} is the water balance of the previous month. Its units are 'mm'.

The calculation of the BH normally starts at the beginning of the Hydrical Year (which varies according to the area), being in the Canary Islands set to the month of October. Here the soil is considered to be devoid of any humidity, so that BH_{m-1} = 0 in the whole territory. From this point onwards, the corresponding value has been calculated month by month, taking care that in cases where BH takes negative values, it is equal to zero, taking the total precipitation values estimated each month by the climate models and the corresponding ETo previously calculated. The annual water balance is usually considered as the average annual water availability and is calculated as the average of the water balance over the whole year. From this climate variable, it is possible to infer a multitude of new indices, such as Real Evapotranspiration, described below.

3.1.4. Real Evapotranspiration (ETr)

As another indicator derived from the BH, ETr provides an estimate of the actual soil moisture loss by evapotranspiration. Unlike ETo which indicates the potential loss in the permanent presence of water, ETr indicates the evapotranspiration that the moisture present in the soil actually allows.

Its value is achieved by the conditions:

$$If\ ETo_{m} > (BH_{m-1} + Pr_{m}) \Rightarrow ETr_{m} = BH_{m-1} + Pr_{m}$$

$$If\ ETo_{m} < (BH_{m-1} + Pr_{m}) \Rightarrow ETr_{m} = ETo_{m}\ [Eq.\ 4]$$

In other words, if the total ETo exceeds the sum of the moisture already available and that provided by precipitation that month, the maximum that can be evapotranspirated will be the sum of both water values. If ETo is less than this sum, in the presence of sufficient moisture, this value will be the one evapotranspirated, leaving a remainder of water in the soil.

3.1.5. Aridity Index (IA)

The aridity index (AI) is one of many indices used to characterise the aridity of a location by directly relating precipitation and reference evapotranspiration at a point using the expression:

$$IA = \frac{Pr}{ETo}\ [Eq.\ 5]$$

This formula has been applied directly to each grid point treated in the Canary Islands by introducing the accumulated precipitation in the time interval in question and the corresponding ETo. It is a dimensionless index, with values 0<IA<1 depending on how arid a point is, and IA>1 if, on the contrary, the point is ‘humid’.

3.1.6. Standardized Precipitation and Evapotranspiration Index (SPEI)

The Standardized Precipitation Index (*SPI*, Standard Precipitation Index) (McKee et al.,1993) is defined as a numerical value representing the number of standard deviations of the precipitation falling over the accumulation period in question, with respect to the mean, once the original distribution of precipitation has been transformed to a normal distribution.

In this way, a scale of values is defined which is grouped into sections related to the character of the precipitation (Table 1). It has the advantage of being able to work on temporal scales by identifying different types of droughts and their responses to different natural systems.

Going further, the Standardized Precipitation Evapotranspiration Index (**SPEI**, proposed by Vicente-Serrano et al., -2010-) is a variant of the *SPI*. It has a higher potential as it is sensitive to the impact of climate change by considering the water balance as the difference between monthly precipitation and potential evapotranspiration (calculated according to Hargreaves). As with the *SPI*, a scale of values is defined and grouped into tranches (Table 12).

Table 12. Climate classification depending on Standardized Precipitation Evapotranspiration and Precipitation Index (SPEI).

Climate type SPEI	Thresholds
Extremely wet	SPEI ⩾ 2.0
Severely wet	1.50 ⩽ SPEI < 2.00
Moderately wet	0.50 ⩽ SPEI < 1.50
Normal	-0.50 ⩽ SPEI < 0.50
Moderately dry	-1.50 ⩽ SPEI < -0.50
Severely dry	-2.00 ⩽ SPEI < -1.50
Extremely dry	SPEI < -2.00

SPEI values allow for a highly detailed following of the actual status of drought conditions due to lack of rainfall, incorporating precipitation, and also because of the presence of anomalously high-temperature conditions, such as heat waves, which impact the evapotranspiration in the vegetation and the soils in the area. SPEI values gain high importance in a region like the Canary Islands, normally hit by extreme heat waves and with moderate rainfall amounts, highly spatially and temporally uneven and with marked patterns in time throughout the year and on each island. In a region where aridity always is a threat and water availability a key concern, SPEI values allow us to gain consciousness of the actual state of hydric conditions.

4. References

Bentsen, Mats; Oliviè, Dirk Jan Leo; Seland, Øyvind; Toniazzo, Thomas; Gjermundsen, Ada; Graff, Lise Seland; Debernard, Jens Boldingh; Gupta, Alok Kumar; He, Yanchun; Kirkevåg, Alf; Schwinger, Jörg; Tjiputra, Jerry; Aas, Kjetil Schanke; Bethke, Ingo; Fan, Yuanchao; Griesfeller, Jan; Grini, Alf; Guo, Chuncheng; Ilicak, Mehmet; Karset, Inger Helene Hafsahl; Landgren, Oskar Andreas; Liakka, Johan; Moseid, Kine Onsum; Nummelin, Aleksi; Spensberger, Clemens; Tang, Hui; Zhang, Zhongshi; Heinze, Christoph; Iversen, Trond; Schulz, Michael (2019). NCC NorESM2-MM model output prepared for CMIP6 ScenarioMIP. Version YYYYMMDD[1]. Earth System Grid Federation. doi: 10.22033/ESGF/CMIP6.608.

Bi, Daohua, Dix, Martin, Marsland, Simon, O'Farrell, Siobhan, Sullivan, Arnold, Bodman, Roger, Law, Rachel, Harman, Ian, Srbinovsky, Jhan, Rashid, Harun A., Dobrohotoff, Peter, Mackallah, Chloe, Yan, Hailin, Hirst, Anthony, Savita, Abhishek, Dias, Fabio Boeira, Woodhouse, Matthew, Fiedler, Russell, Heerdegen, Aidan, 2020: Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model. Journal of Southern Hemisphere Earth Systems Science, 70, 225, doi:10.1071/es19040.

Cherchi, A., Fogli, P.G., Lovato, T., Peano, D., Iovino, D., Gualdi, S., Masina, S., Scoccimarro, E., Materia, S., Bellucci, A. and Navarra, A., 2019. Global mean climate and main patterns of variability in the CMCC–CM2 coupled model. Journal of Advances in Modeling Earth Systems, 11(1), pp.185-209. https://doi.org/10.1029/2018MS001369.

EC-Earth Consortium (EC-Earth) (2019). EC-Earth-Consortium EC-Earth3-Veg model output prepared for CMIP6 Scenario MIP. Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.727.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev. 9: 1937-1958. doi:10.5194/gmd-9-1937-2016.

Gaitan, E., Monjo, R., Portoles, J., Pino-Otin, M.R., 2019. Projection of temperatures and heat and cold waves for Aragon (Spain) using a two-step statistical downscaling of CMIP5 model outputs. Sci. Total Environ. 650, 2778–2795

Good P., Sellar A., Tang Y., Rumbold S., Ellis R., Kelley D., Kuhlbrodt T. (2019). MOHC UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP ssp245. 1]. Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.6339.

Luque Söllheim A. L., Máyer Suárez P., García Hernández, F., (2024) The digital climate atlas of the Canary Islands: A tool to improve knowledge of climate and temperature and precipitation trends in the Atlantic islands, Climate Services, Volume 34 (http://hdl.handle.net/10553/130655)

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., ... & Zhou, B. (2021). Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2(1), 2391.

Meinshausen, M., Nicholls, Z.R., Lewis, J., Gidden, M.J., Vogel, E., Freund, M.B., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., Montzka, S.A., Rayner, P.J., Reimann, S., Smith, S.J., van den Berg, M., Velders, G.J., Vollmer, M.K., & Wang, H.J. (2019). The SSP greenhouse gas concentrations and their extensions to 2500. Geoscientific Model Development Discussions, 1-77.DOI:10.5194/gmd-2019-222Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., ... & Marotzke, J. (2018). A higher–resolution version of the max planck institute earth system model (MPI–ESM1. 2–HR). Journal of Advances in Modeling Earth Systems, 10(7), 1383-1413.

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, vol. 17, no. 22, pp 179–183

Monjo R, Gaitán, E., Pórtoles, J., Ribalaygua, J., & Torres, L. (2016). Changes in extreme precipitation over Spain using statistical downscaling of CMIP5 projections. International Journal of Climatology, 36(2), 757-769. DOI: https://doi.org/10.1002/joc.438

Monjo R, Pórtoles J, Ribalaygua J. 2013. Detection of inhomogeneities in daily data: a test based in the Kolmogorov-Smirnov goodness-of-fit test. 9th Data Management Workshop of EUMETNET, El Escorial (Madrid), 6th-8th November.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., ... & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global environmental change, 42, 169-180. DOi: https://doi.org/10.1016/j.gloenvcha.2015.01.004

Patiño, J., Collart, F., Vanderpoorten, A., Martin–Esquivel, J. L., Naranjo–Cigala, A., Mirolo, S., & Karger, D. N. (2023). Spatial resolution impacts projected plant responses to climate change on topographically complex islands. Diversity and Distributions, 29(10), 1245-1262.

Ribalaygua J, Torres L, Pórtoles J, Monjo R, Gaitán E, Pino MR. (2013). Description and validation of a two-step analogue/regression downscaling method. Theoretical and Applied Climatology, 114: 253-269. doi:10.1007/s00704-013-0836-x.

Seferian R. (2019). CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6 AerChemMIP hist-1950HC. Version YYYYMMDD[1].Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.4041.Yukimoto S., Koshiro T., Kawai H., Oshima N., Yoshida, K., Urakawa S.; Tsujino H., Deushi M., Tanaka T., Hosaka M., Yoshimura H., Shindo E., Mizuta R., Ishii M., Obata A., Adachi, Y. (2019). MRI MRI-ESM2.0 model output prepared for CMIP6 CMIP. Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.621.

Swart N. C., Cole J. N. S., Kharin V. V., Lazare M., Scinocca J. F., Gillett N. P., Anstey J., Arora V., Christian J. R., Hanna S., Jiao Y., Lee W. G., Majaess F., Saenko O. A., Seiler C., Seinen C., Shao, A., Sigmond M., Solheim L., von Salzen K., Yang D. and Winter B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3), Geosci. Model Dev., 12, 4823–4873, doi:10.5194/gmd-12-4823-2019.

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.

Wu T., Lu Y., Fang Y., Xin X., Li L., Li W., Jie W., Zhang J., Liu Y., Zhang L., Zhang F., Zhang Y., Wu F., Li J., Chu M., Wang Z., Shi X., Liu X., Wei M., Huang A., Zhang Y. and Liu, X. (2019). The Beijing Climate Center Climate System Model (BCC-CSM): the main progress from CMIP5 to CMIP6 , Geosci. Model Dev. 12, 1573–1600. doi:10.5194/gmd-12-1573-2019, 2019.

Zorita E, Hughes J, Lettenmaier D, Storch Hv. 1993. Stochastic downscaling of regional circulation patterns for climate model diagnosis and estimation of local precipitation. Max Planck Institute for Meteorology Technical Report 109.