Preliminary draft report on future climate at local scale in each LL

Deliverable 4.1 - version: 3

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REVISION HISTORY

Version	Date	Author/reviewer	notes
v.0	16-07-2024	MeteoGRID Team	first draft
v.1	20.08.2024	Jaime Ribalaygua Batalla	comments on draft
v.2	23.9.2024	MeteoGRID Team	Second draft
v.3 (final version)	30-09-2024	Steering Committee (Peter van der Keur, Magdalena Von Der Thannen, Miguel Potes)	Final version revised

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Summary

Europe has had to cope with different adverse weather and climate events over the last decades. Variations in temperature and rainfall patterns have led to periods of prolonged drought (water scarcity) alternating with flash flooding, endangering the health of water resources. This trend is expected to continue in the coming decades. On the one hand, in the short term, extreme events such as heavy rainfall episodes, heat waves, frost or hail can pose a great threat to vulnerable sectors and lead to significant socio-economic losses. On the other hand, in the long term, the effects of climate change pose a major challenge to society, which must adapt to the new climatic conditions. Overall increases of 2-4°C in temperature and slight changes in the amount of precipitation accumulated annually are expected over the coming decades, but with more intense precipitation events over time, as well as increasingly intense extreme events. To minimise these negative impacts and enhance the positive ones, it is essential to have local-scale climate information based on the microclimatic characteristics of each area, as changes in climate will vary markedly, even between fairly close points, especially in topographically complex areas. It is therefore essential that any activity planned for the coming decades that may be affected by climatic effects should take into account the future climatic conditions on a local scale, and those projections should be adapted to the needs of relevant adaptation or mitigation interventions.

The local future climate information should provide a range of (equiprobable) projections on the basis of which the necessary adaptation measures for the activity under consideration can be established for both the upper and lower ranges of possible future changes.

To meet this challenge, climate change impact analysis is one of the strengths of INTERLAYER and within Task 4.2. Future climate modelling and resilience, in the first months of the project, a preliminary set of future climate projections at the local scale have been generated for each of the four Living Labs (LL) selected in this project. The temperature and precipitation projections have been generated applying a two-step statistical downscaling methodology based on analogue stratification and transfer functions (Ribalaygua et al., 2013) to the outputs of 10 CMIP6 (Coupled Model Intercomparison Project, Phase 6) climate models under 4 SSPs (Shared Socioeconomic Pathways). In total, 40 climate projections have been generated (10 models x 4 SSPs) for each LL. To further explore this impact, a set of 60 indicators (based on

temperature and precipitation) have been simulated to generate an initial view of how future variations in climatic conditions may affect each LL.

This first deliverable provides an initial overview of the projected future climate at each LL involved in the INTERLAYER project. It presents a preliminary characterization of the future climate for each LL, which will serve as a basis, so that project partners can explore the future climate at the local scale for each LL from the very beginning of the project and can orientate their work towards identifying nature-based solutions for slow hydrology taking this information into account.

A more detailed analysis will be provided in subsequent delivery phases and scenarios more adjusted to the specific needs of each Living Lab will be elaborated.

1. Introduction

1.1. Background

The first conclusions presented by the sixth report of the Intergovernmental Panel on Climate Change (IPCC6) (IPCC, 2021a and b), focusing on the physical bases of climate and climate change, present an indisputable reality: the climatic emergency that the planet is experiencing is directly linked to human activity, being one of its main precursors. There is no region of the planet that has not been affected, to a greater or lesser extent, by climate change-related effects such as melting ice, rising sea levels or extreme weather events, among others (IPCC, 2021a, IPCC, 2021b).

This report is categorical in its conclusions: 'It is unequivocal that human activity has warmed the atmosphere, ocean and land surface' and that 'global surface temperature will continue to increase at least until mid-century under all possible emissions scenarios'. In other words, even in a best-case scenario, the temperature will continue to rise as a result of the actions taken and it will take at least 30 years to reverse the damage caused. This is an unknown climate emergency, as many of the observed changes in climate are unprecedented over thousands, if not hundreds of thousands of years (IPCC, 2021a, IPCC, 2021b), consequently the following is advised: 1) large-scale, immediate and forceful mitigation measures to reduce its impact, 2) adaptation measures appropriate to each sector and problem, and 3) using climate research as a tool for adapting to climate change.

Climate change poses a series of risks that affect the development and economy of all countries in the world, which in recent decades have been hit by extreme weather events associated with climate change. It is expected that in the coming decades the temperature (both maximum and minimum) will rise throughout Europe by between 2 and 4 °C and that there will be slight changes in the amount of precipitation accumulated annually, albeit with more concentrated precipitation events over time, as well as increasingly intense extreme phenomena. In other words, events such as heat waves, droughts, extreme precipitation etc. will occur more frequently and the socio-economic risk associated with their occurrence will increase considerably.

In order to assess and/or estimate climate risk, it is necessary to define it according to the extent that climate impacts have on the sector being assessed and/or estimated. It is necessary to take into account that the impact of climate change does not affect all regions homogeneously in the same way, nor all socio-economic sectors in the same way. Therefore, these impacts need to be assessed at the local scale. In order to estimate climate risk, it is necessary to have climate information projected at the local scale (future evolution of basic meteorological variables such as temperature, precipitation or wind), to analyse the impacts and implications of these projections for the sector under study (using indicators adjusted to the needs of that sector) and to identify the possible risks that may occur in the coming decades. Once the impacts have been identified, it is possible to define adaptation measures to deal with them, reducing the negative effects as much as possible and trying to take advantage of the positive ones.

For this reason, this study aims to provide an overview of how climate change affects the evolution of meteorological variables in the coming decades in the Living Labs. In order for this study to serve as an input for local climate information to be considered as a support tool when considering adaptation measures in the face of climate change, a set of basic meteorological variables have been selected to characterize the region climatically. Thus, when making decisions, these should be made on the basis of the new climatic conditions expected in the future and not on the basis of past climatic conditions.

1.2 State of the art in climate modelling

The most powerful tool for climate simulation today is the Climate Model (CM). A CM is a numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and including all or some of their known properties. The climate system can be represented by models of varying degrees of complexity, i.e. for each component or set of components it is possible to identify a spectrum or hierarchy of models that differ in aspects such as the number of spatial dimensions, the degree of explicit representation of physical, chemical or biological processes, or the degree of use of empirical fits.

The most modern climate models are the Earth System Models (ESMs), which describe the processes within and between the atmosphere, ocean, cryosphere, marine and terrestrial biosphere. Process equations capture the physical, chemical and biological mechanisms that govern the elements of the Earth system and also include volcanic eruptions and variations in incoming solar radiation. ESMs include representation of the carbon cycle, allowing interactive calculation of atmospheric emissions of CO2 or similar. They can also include other components, such as atmospheric chemistry, ice sheets, dynamic vegetation, the nitrogen cycle, urban or crop models, etc. The main advance over the General Circulation Models (GCMs) previously used is that they allow the interaction of the system with the carbon cycle and take into account marine biochemistry and biogeology (Figure 1).

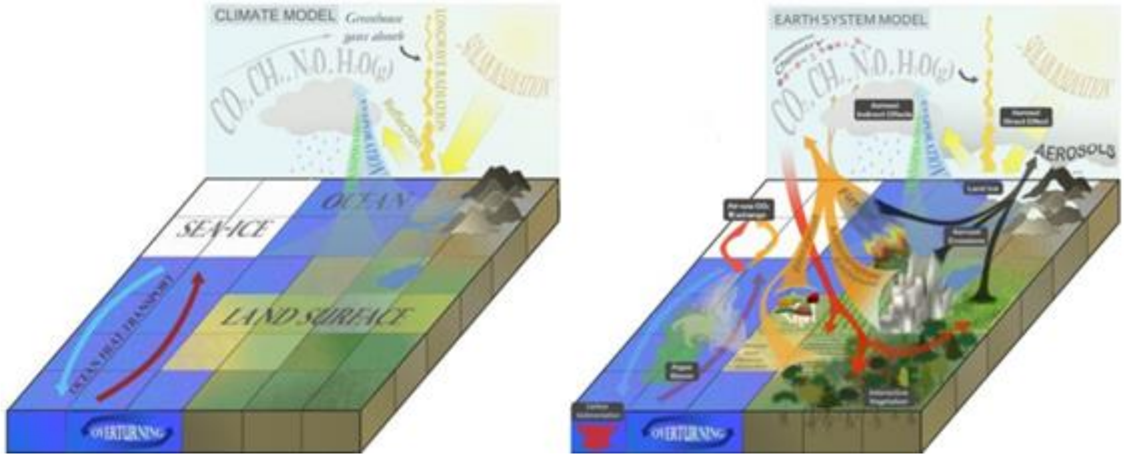

Figure 1. Main features of climate models and Earth System Models (ESMs): ESMs gain in complexity by considering biological and chemical processes that feed back into the physics of climate. Source: Heavens et al. 2013

These CMs are run under different assumptions of future Greenhouse Gas (GHG) concentration, as plausible descriptions of how future socio-economic, technological, energy, land use, GHG and pollutant emissions, etc., will evolve based on a coherent set of assumptions about the driving forces (e.g. demographic and socio-economic development and technological evolution) and the main relationships between them.

Model-generated climate scenarios or projections are plausible, more or less simplified, representations of future climate, based on an internally consistent set of climate relationships explicitly defined to investigate the possible consequences of anthropogenic climate change, and which can be fed as input to impact models.

Efforts to coordinate all matters related to climate change are the responsibility of the Intergovernmental Panel on Climate Change (IPCC). The IPCC is the UN intergovernmental body responsible for producing reports covering 'scientific, technical and socio-economic information relevant to understanding the scientific basis of the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation'. These reports contribute to the work of the United Nations Framework Convention on Climate Change (UNFCCC), the main international treaty on climate change. Its objective is to 'stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system'.

The IPCC is an internationally accepted authority on climate change and produces reports that have the agreement of leading climate scientists and the consensus of participating governments. The IPCC periodically publishes reports that bring together all the advances and studies developed by the scientific community and multi-sectorial experts on Climate Change. The reports for the IPCC's Sixth Assessment Report were published in August of 2022.

In parallel to the IPCC, the Coupled Model Intercomparison Project (CMIP) is a collaborative framework designed to improve understanding of climate change. It was established in 1995 by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WCRP). WGCM has led to a better understanding of past, present and future climate change and variability in a multi-model framework, and also defines protocols for experimentation, forcings and common results. It is developed in phases to promote the improvement of climate models, but also to support national and international climate change assessments. Throughout the different phases of the project, improvements have been made to the quality of climate models up to the current ESMs. Likewise, new emission scenarios have been defined in each of the phases, adjusting to the new adaptation and mitigation needs in the face of climate change.

The CMIP model simulations have also been regularly assessed as part of the IPCC Climate Assessment Reports and various national assessments. The sixth phase of CMIP (CMIP6) is currently underway, with the CMIP models being the most up-to-date to date.

1.3 The need for regionalization or downscaling

CMs are able to simulate very satisfactorily the general atmospheric circulation, but due to their spatial resolution (around 100 km) they are not able to simulate smaller-scale atmospheric phenomena that are of great importance in local climatology. In order to overcome this and other limitations of CMs, regionalisation or downscaling techniques are used. These techniques consist of adapting the outputs provided by CMs to the local scale: they are fed with the so-called predictors (the information that CMs offer with greater reliability, i.e. low-resolution atmospheric configurations, preferably at a certain height in the atmosphere, since CMs simulate poorly in the vicinity of the surface because their low resolution prevents a correct representation of topography, land use, etc.), determining factors of near-surface meteorological conditions; and 'translate' this low-resolution atmospheric information into surface effects (rain, temperature, wind...) with local detail, called predictands (Figure 2).

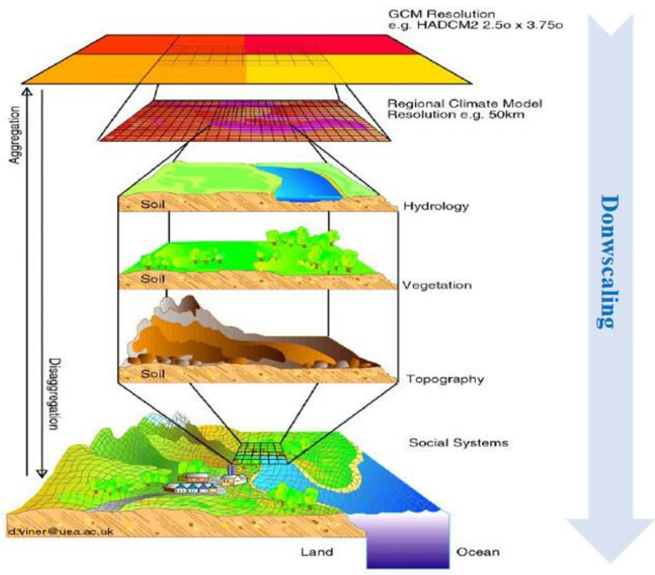

Figure 2. Diagram of the regionalisation process. Source: Climate Research Unit (CRU, 2000)

There are two main approaches to regionalisation: statistical and dynamic, each with its own advantages and limitations. Depending on the working methodology (number of expected climate projections, availability of observed data, orographic complexity of the study area, among others), one or the other will be used. In this study a two-step statistical downscaling methodology called FICLIMA (Ribalaygua et al., 2013) will be applied. This methodology has been developed by the Foundation for Climate Research and verified and validated in multiple national and international projects.

To ensure the reliability and robustness of climate projections, these climate projections are required to meet certain technical requirements, which are shown in Figure 3.

Technical requirements for climate projections

Need to use the most recent Climate Models

Need to work with information at local level

Need to work with information at daily scale

Need to manage uncertainties appropriately

Need for extensive verification and validation processes

Figure 3.Requirements for climate projections. Source: MeteoGRID

Meeting these requirements ensures that the set of climate projections generated is robust and based on verified and validated techniques that allow uncertainties to be quantified and taken into consideration when interpreting future scenarios.

2. Study Area

INTERLAYER project set up four Living Labs (LL) in four contrasting European watersheds to include and compare different European edaphoclimatic regions with different geologic characteristics, see Figure 4.

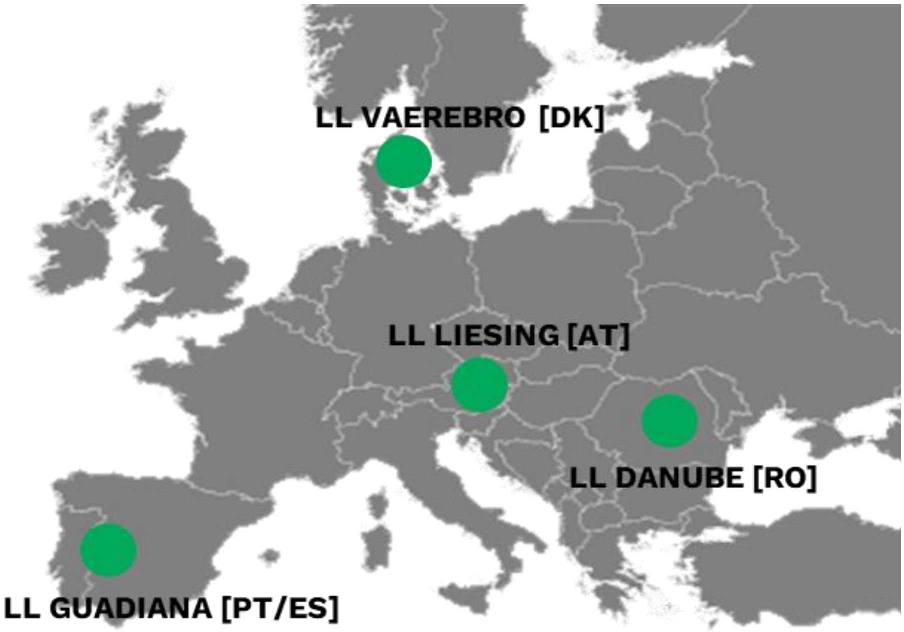

Figure 4. INTERLAYER's four LL's, located in contrasting watersheds in different regions of Europe

Vaerebro River [DK] - The catchment of river Vaerebro is 153 km^2 and the river itself is 35 km long and one of the longest rivers in the capital region of Denmark, having its source in a biodiversity rich bog area, passing through mixed land use with small and medium sized villages, many spare-time farmers, often horse-hobby, and some agriculture, before discharging to Roskilde Fjord. This LL is set in a rural area within the peri-urban matrix in a regional context and allows a source-to-see approach, in a region with a continental humid with warm summer climate. A mature formalized LL is established and ready for engagement.

Liesing River [AT] - The Liesing river is beside the Danube and the Wien River one of the main water courses in the city of Vienna. It flows 30 km through strongly populated regions in the south of Vienna. The catchment can be divided into a forest dominated area followed by an urban river section. This LL is set in a peri-urban and urban regional context, with high potential for replication due to stakeholder involvement rates (capitalized from other projects), in a region with a continental humid with warm summer climate.

Guadiana River Watershed [PT/SP] - The Guadiana watershed has a total surface area of 66 800 km^2 and is shared between Spain (83%) and Portugal (17%). Guadiana River is 810 km long, with 260 km in Portugal and 110 km along the border between the two countries. This LL will be set up in an international river with hot summer Mediterranean climate, encompassing the biggest artificial lake in Europe (Alqueva reservoir), as well as smaller reservoirs, rivers and streams. Flash-flood events and temporary streams are characteristic of the system. The LL allows for source-to-see approach.

Danube River [RO] - A stretch of the former floodplain of the Danube River, between Salcia and Maglavit villages consisting of 200 ha along the corridor at Salcia, with abandoned fish farm, arable land with mix uses, including planted forest and pasture. This LL is set up in a continental humid with a hot summer climate. The area has high potential for improvement of lateral connectivity through Nature-based solutions (NBS) implementation in order to re-connect the surface and groundwater to increase resilience and reduce the impact of drought.

As the LLs are located in different and contrasting European regions, they show different processes and settings in the landscape as well as various microclimatic, hydrological and geological characteristics. It is a great chance to observe four different watersheds. In contrast, it is also a challenging process to find common characteristics and methodologies fitting to all four LLs in order to generate comparable results.

3. Methodology and data bases

The FICLIMA methodology (Ribalaygua et al., 2013) has been applied in the generation of climate projections of temperature and precipitation.

3.1. Two-step statistical downscaling methodology: FICLIMA

This project has used a two-step statistical regionalisation methodology developed by the Foundation for Climate Research (Ribalaygua et al. 2013) and widely tested in many national and international projects (Gutierrez et al., 2019). This methodology has been applied to the variables: temperature (both maximum and minimum) and precipitation.

The methodology requires a prior selection of fields to be used as predictors and, once these have been selected, it performs a treatment based on the analogue's methodology. In general terms, the methodology follows the following scheme: for a certain problem day 'X', whose atmospheric fields (geopotentials, temperatures at different pressure levels...) of low resolution are known (through the outputs of the Climate Models for day 'X'), the aim is to estimate the value of the surface meteorological variables (maximum and minimum temperatures, precipitation...) for day 'X' at a specific point in the territory (observatory) from these known fields. The method works in two successive steps:

The first step, called analogue stratification, consists of selecting, from a reference data bank, those n days with atmospheric configurations most similar to those of the problem day 'X'. The similarity measure used compares the resemblance between the predictor variables used to characterise the atmospheric synoptic situations (as for example, geopotential or wind); these variables determine the synoptic forcing causing the descents and ascents of air, which generate cloudiness and precipitation. The aim is also to provide information on the surface wind direction, which allows us to study the effects that topography has on the rising air masses and, therefore, on the spatial distribution of cloudiness and precipitation.

The second step applies different methods depending on the variable to be calculated:

- To estimate daily minimum and maximum temperatures, a multiple linear regression with automatic forward and backward predictor selection is performed for each variable. The data population will consist of the n (analogue) days selected in the previous step. As potential predictors, on the one hand, the values of atmospheric variables related to temperature forcings (such as the thickness of the air layers) in the vertical of the point for which the surface temperature is to be estimated, and on the other hand, predictors related to other temperature forcings, such as an indicator of the duration of the day in question (related to the radiative warming potential) and a weighted average of the temperatures of the previous days (which considers the effect of the thermal inertia of the ground) are offered. Once the linear relationship between the selected predictors and the predictand (minimum, maximum temperature) has been established, this relationship is applied to the predictor values for day 'X' to estimate the value of the predictand on that day.
- In the case of precipitation, precipitation is obtained by averaging the k analogous days most similar to 'X'. In addition to estimating the amount of rainfall, this method allows obtaining the probability of rain or dry weather. Figure 5 illustrates the methodology described graphically.

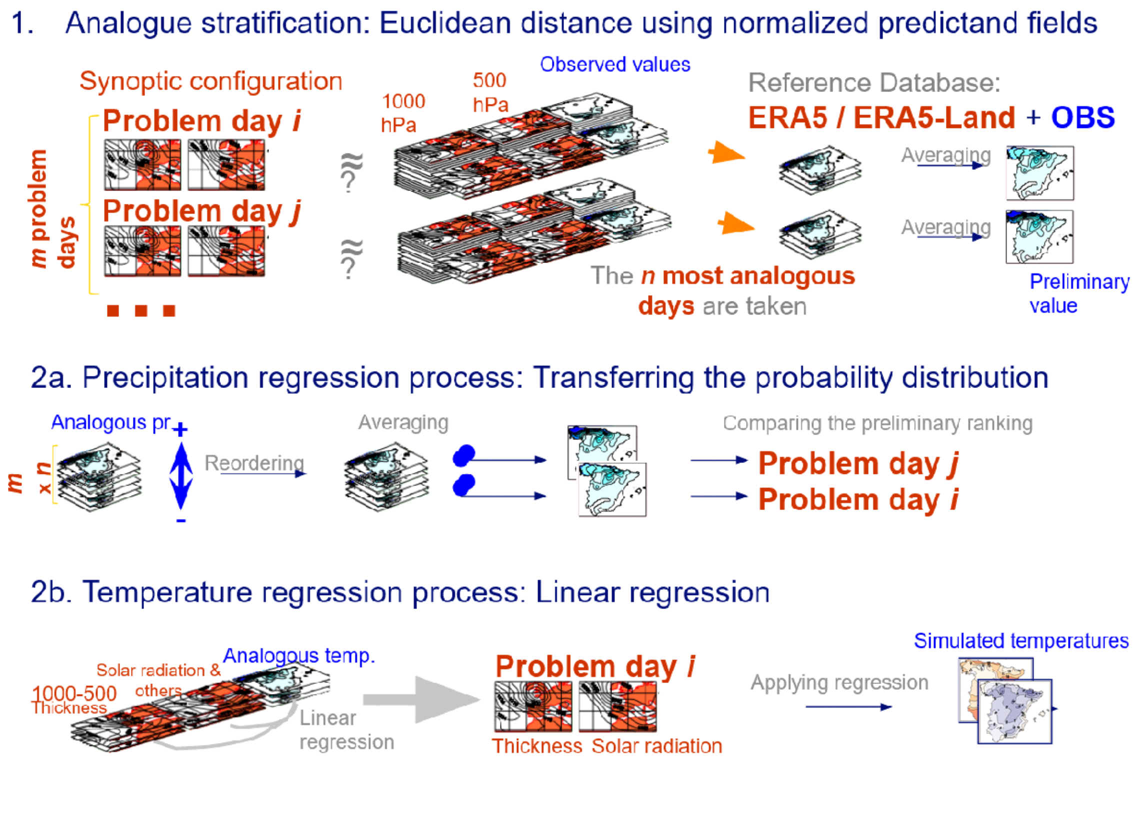

Figure 5. Key features of the FICLIMA statistical downscaling

3.2. Databases

In order to carry out the regionalisation process, it is necessary to have a set of data, which are summarised in Figure 6.

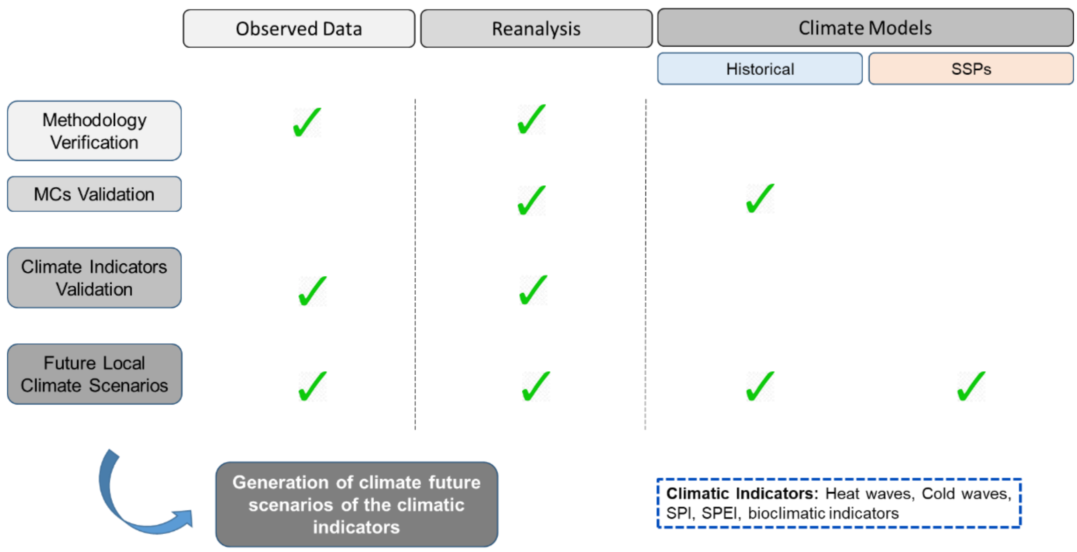

Figure 6. Outline of data required for the study.

3.2.1 Observed data

For each of the Living Labs, the observatory closest to the study area with sufficient data to be used for regionalisation studies has been selected in this first phase. All information on the observed data sources used is detailed in Section 4. In the course of the project, the number of observatories used will be completed and, if necessary, their spatialisation will be carried out.

3.2.2 Climate data

- ERA5 and ERA5-Land Reanalyses

We have chosen to work with the reanalyses belonging to the European Centre for Medium-Range Weather Forecasts (ECMWF): ERA5 (atmospheric) and ERA5-Land (surface) and they have been selected for several reasons: 1) as they are developed by the ECMWF they cover the area of the Segura River Basin; 2) they are the most current versions of the European reanalyses, which means an improvement in spatial and temporal resolution with respect to the previous ones; and 3) they can be downloaded free of charge through the Copernicus programme (Climate Change Service: DOI: 10. 24381/cds.adbb2d47).

ERA5-Land is the version for surface variables, covering only terrestrial terrain and providing data for up to 50 different variables. The coverage of ERA5-Land is a global grid with a spatial resolution of 0.073 x 0.073 degree (approx. 9km x 9km). Its vertical coverage ranges from 2 metres above surface level to a ground depth of 289 cm and 4 levels of the ECMWF surface model. ERA5-Land provides hourly data from January 1951 to the present (data are updated monthly with a lag of about three months behind the actual date).

ERA5 is the latest atmospheric reanalysis published by ECMWF. Available from July 2019, it is the most accurate reanalysis available to date. It works with a huge set of data and observations from weather stations, soundings, satellites and other different reanalyses (such as oceanic) as input at different atmospheric and marine levels. In this way, ERA5 tries to reproduce as accurately as possible the actual values that defined the atmospheric situation at a given time in the past. Due to its high quality input requirements, only post-release data from satellites are available. ERA5 covers the entire European land area with a regular spatial resolution of 0.25 degrees (approx. 30 km).

The reanalysis has to undergo a quality process to remove inconsistent values such as negative precipitation, areas with no data, relative humidity higher than 100% or minimum temperatures higher than maximum temperatures.

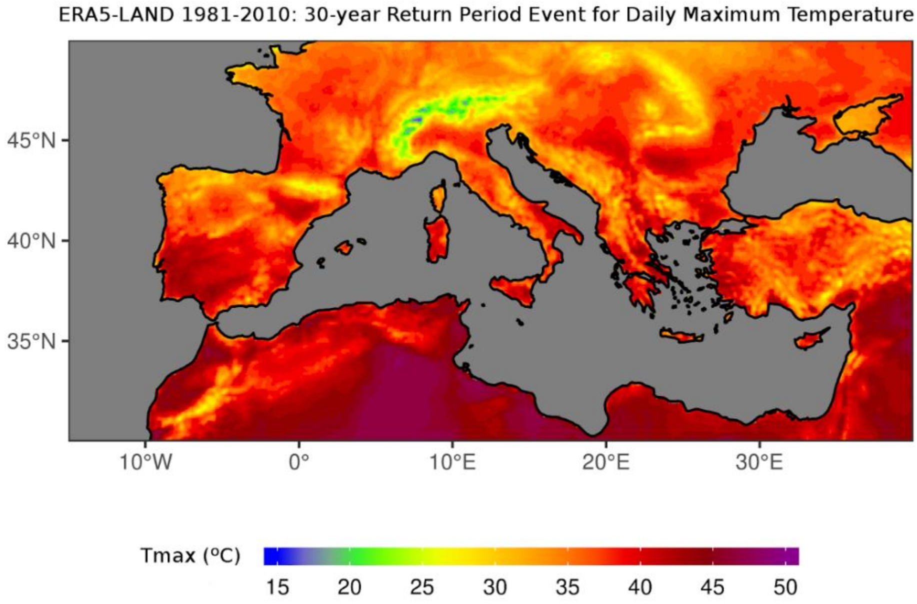

Figure 7. Example of the spatial representation of ERA5-Land reanalysis, representing a 30-year return period event for daily maximum temperature. (Source: C3S)

➢ Climate Models

The last set of data required are the climate models. Specifically, we have worked with the climate models belonging to the 6th phase of the CMIP (CMIP6) as well as the emission scenarios defined within this phase, the SSPs (Shared Socioeconomic Pathways). Statistical techniques, due to their computational speed, allow working with a large number of climate models (n) and SSPs (m), so that a set of (n x m) climate projections will be obtained. The climate models are run continuously from the past into the future, once the control period is simulated, the run is separated into as many runs as SSPs are considered. For each climate model there is therefore a control simulation called 'Historical' for the period 1951-2014 and 4 SSPs for the period 2016-2100 (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5).

Using these new CMs is important, given that relevant novelties have been introduced in CMIP6, related to the World Climate Research Programme (WCRP) Grand Science Challenges: Clouds, Climate Circulation and Sensitivity, Changes in the Cryosphere, Climate Extremes, Regional Sea Level Rise, Water Availability, Short-Term Climate Prediction and Biogeochemical Cycles and Climate Change.

Also new is the way in which future GHG concentration scenarios are considered, now through so-called SSPs (Shared Socioeconomic Pathways), instead of the RCPs (Representative Concentration Pathways) used in CMIP5. The new SSP scenarios cover a similar range as the RCPs, but fill critical gaps such as the role of certain forcings (land use and short-lived species or air quality), the effect of peak and trough forcings, and the consequences of limiting warming to below 2 °C (Eyring et al., 2016).

SSPs are scenarios of global socio-economic changes projected up to 2100 that describe alternative socio-economic developments. Each of the SSPs describes a line of evolution (Figure 8):

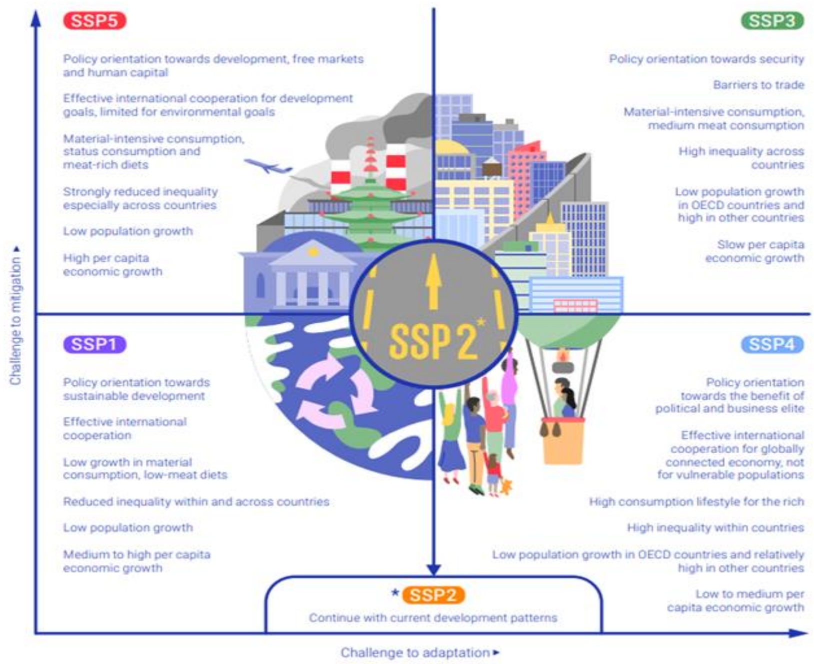

Figure 8. Shared Socioeconomic Pathways (in the Figure, OECD stands for Organizations of Economic Co-operation and Development). Source: Figure adapted from O'Neill et al., 2017.

CMIP6 has established SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 as main scenarios (referred to as Tier 1). CMIP6 extends Tier 1 from 2 to 4 scenarios (Figure 9).

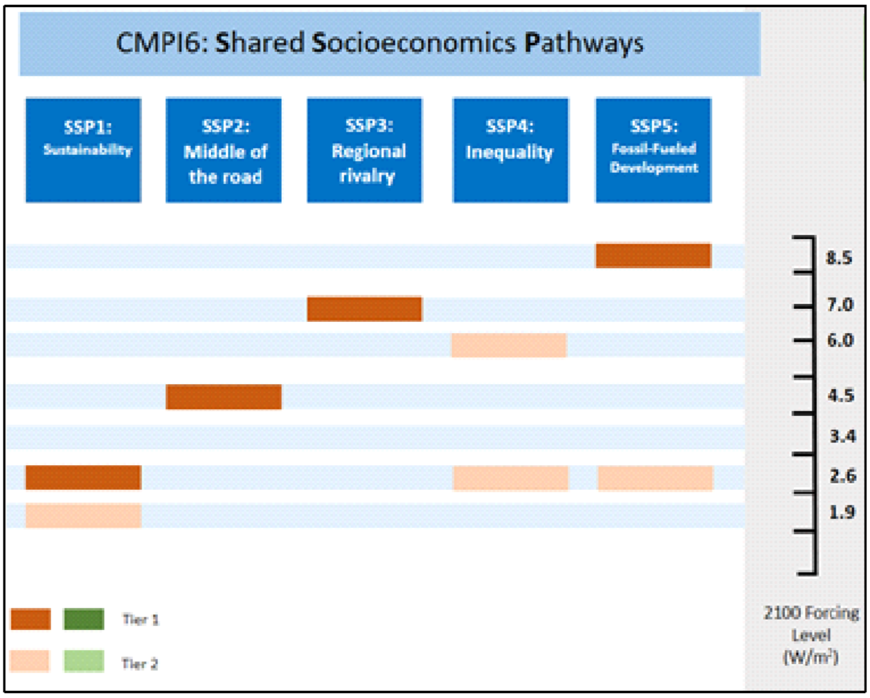

Figure 9. Scenarios defined in CMIP6. Level 1 and level 2 are defined as the scenarios to be provided as mandatory and optional, respectively, by all climate models that are part of each CMIP phase. Source: Figure adapted from O'Neill et al., 2016

In this study, 10 daily resolution climate models have been used, collected within the CMIP6 (Table 1). Throughout the different phases of this project, improvements have been made to the quality of the climate models up to the current Earth System Models (ESM). Furthermore, new emission scenarios have been defined in each of the phases, adjusting to the new adaptation and mitigation needs in the face of climate change. CMIP6 has a common set of future scenarios covering land use and emissions, as required for future SSPs (Eyring et al., 2016).

Table 1. Information on 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

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)

4. Analysis and Results

For each of the LLs, a set of 60 climate indicators has been simulated (Figure 10) in order to get a first idea of how the climatic characteristics of the LLs will evolve in the coming decades. Given the enormous amount of information generated, this has been compiled in annexes 1 to 4 corresponding to the results obtained for the Vaerebro River, Liesing River, Guadiana River Watershed and Danube River, respectively. A summary of the main preliminary results obtained for each of them has been included in this document.

The definition of each indicator together with the results obtained in graphical format can be found in Annexes 1 to 4. In order to facilitate possible consultations on each of the indicators, their definition has been included in Annex II of this document, as well as the interpretation of the graphs attached with the preliminary results (Annex I).

4.1. Results obtained in the Living Lab: Vaerebro River (Denmark)

According to the climate change local scenarios generated for this case study (see in the Figure 10 the location of the observatory used), **we can expect an increase in temperatures** across all scenarios, time horizons, and periods of the year. However, **no significant changes are expected in terms of precipitation** by mid-century for any of the scenarios or periods of the year although there would be significant increases by the end of the century, especially during the summer and spring seasons.

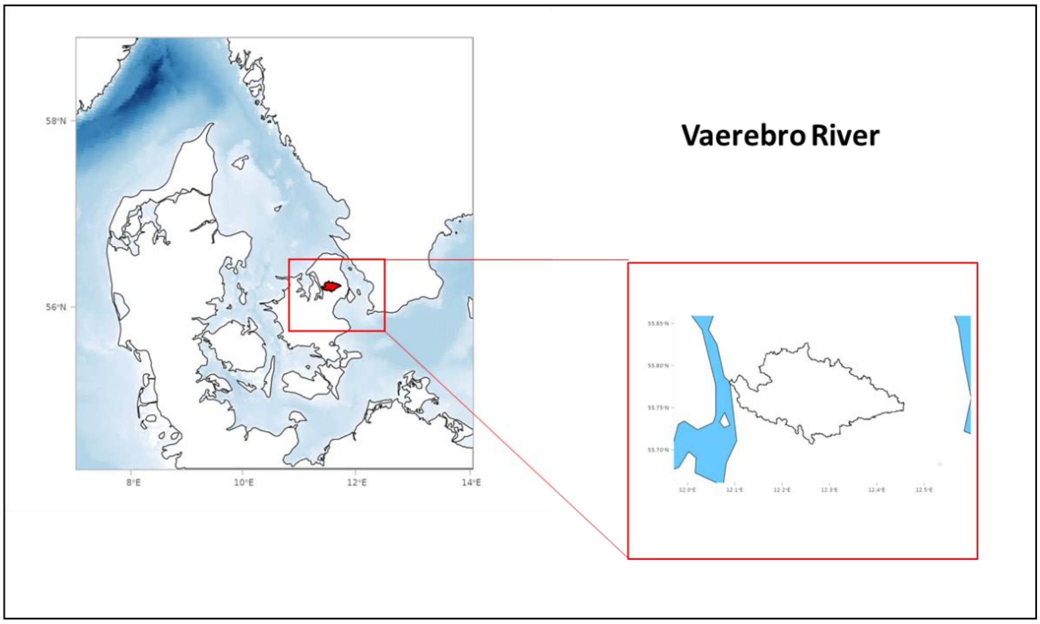

Figure 10. Location of the observatory with temperature and precipitation data used in the preliminary study for Vaerebro River.

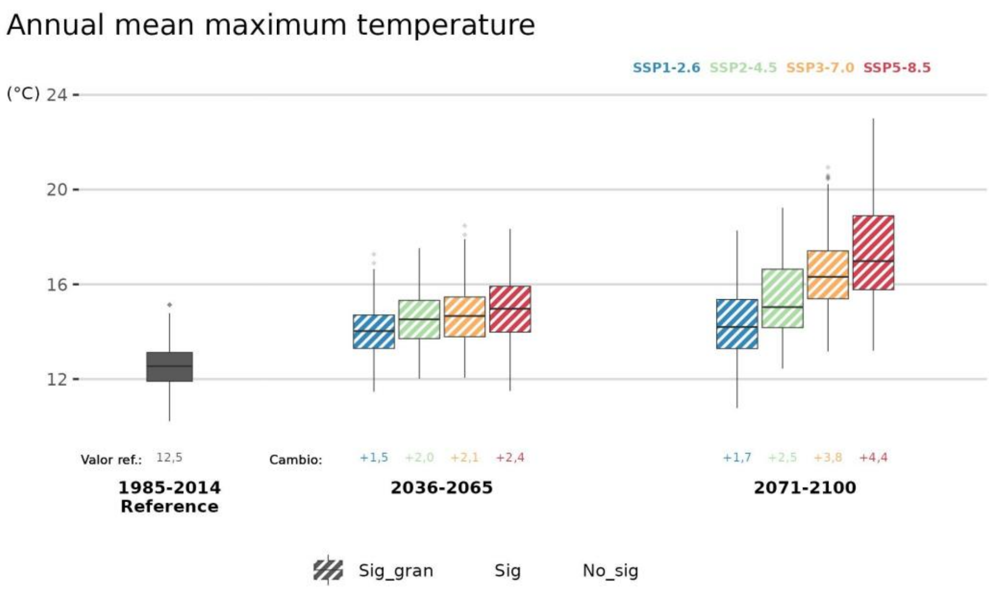

Figure 11. Expected evolution for the annual mean maximum temperature variable for Vaerebro River.

Maximum temperature increases are expected to range from 2 to 2.4 degrees Celsius by mid-century and from 2.5 to 4.4 by the end of the century in the SSP2-4.5 and SSP5-8.5 respectively. This change would be especially significant in the summer and autumn months when the change would be up to 2.6 and 2.8 degrees respectively by mid-century in the most pessimistic scenario.

Additionally, the increase in temperatures will affect the occurrence of extreme weather events such as heat waves. Therefore, the length, intensity, and frequency of both heat waves and cold waves must be analysed to characterize these extreme weather events.

Regarding the heat waves, the main change is expected to occur in the annual number of events, which will increase significantly in every scenario and time horizon. By mid-century, it is expected to increase from 1 event to 2 in the two most optimistic scenarios and 3 in the two most pessimistic scenarios. For the same time horizon, no significant changes are expected in the average length or average intensity of heat waves.

The annual number of days with maximum temperatures higher than the 95th percentile of the warmest months in the reference period is expected to increase significantly in every scenario and time horizon. Specifically, by mid-century, the average number of these days would be increased from 4 days to 11 or 16 days in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The mean annual temperature and minimum annual temperature are expected to increase in the same magnitude than the maximum temperatures in absolute values. The change in minimum temperatures will lead to a **decrease in the number of frost** days from 62 days per year to 28 and 8 days in the worst case by mid- and end-century. The change in minimum temperatures will also lead to a **significant increase in the occurrence of tropical nights** (those with Tmin>22º). This change is expected to be significant not by mid-century, but by end-century the increase is expected from no tropical nights in the reference period to 3 and 17 for SSP2-4.5 and SSP5-8.5, respectively. **Regarding cold spells, no significant changes are expected to occur.**

The annual number of days with minimum temperatures lower than the 5th percentile of the coldest months of the reference period is expected to decrease significantly in most scenarios and in all time horizons. Specifically, by mid-century, the median number of these days would be decreased from 7 days to 1 or 0 day in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The **temperatures of the coldest and warmest months are expected to increase** for all time horizons and scenarios. Mean and maximum temperatures of the warmest month would probably increase from 2.6 to 3.2 degrees and from 2.8 to 3.3 respectively for the SSP2-4.5 and SSP5-8.5. Mean and minimum temperature of the coldest month is expected to rise from 1.7 to 2.4 degrees and from 1.8 to 2.4 respectively for the SSP2-4.5 and SSP5-8.5.

Subsequently, different indicators related to the water balance of the case study are analysed. As was already mentioned, slight significant changes are expected in terms of precipitation for any of the scenarios, and periods of the year by end-century. However, **concerning the annual evapotranspiration, significant increases are expected for all time horizons and scenarios and almost all times of the year**, mainly caused by the rise of temperatures. The annual reference evapotranspiration would increase 41.8 mm to 54.5 mm in the SSP2-4.5 and SSP5-8.5 scenarios respectively, so the absolute value would rise from 539.3 mm to 581.1 mm or 593.8 mm, by mid-century. This increase would be mainly distributed in the summer and autumn seasons.

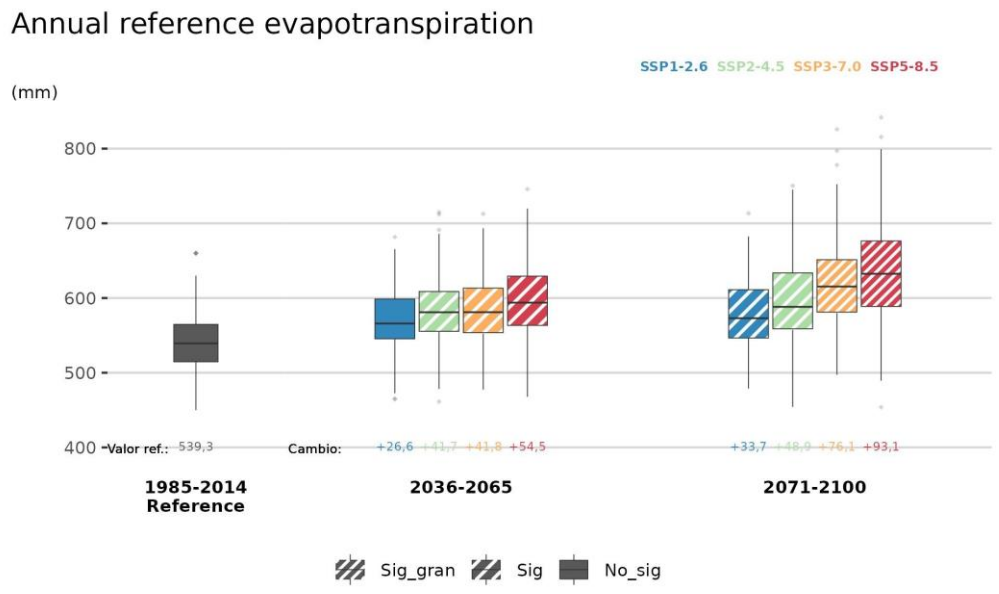

Figure 12. Expected evolution for the annual potential evapotranspiration variable for Vaerebro River.

Water balance, meaning, the difference between the accumulated precipitation minus the calculated evapotranspiration for each month, **is not expected to change** in general terms. Only summer water balance is expected to be slightly reduced in every scenario already by mid-century, this decrease will be 25.9 mm in the higher GHG emissions scenario by mid-century. In this case, the historically negative water balance is going to be reduced from –25.9 mm to –34.4 mm in this scenario.

Annual water surplus is expected to change in any scenario by the end of the century. However, some decreases are expected in the annual water deficit. Seasonally, this change would be mainly concentrated in the summer season. This indicates a potential increase in aridity during the summer season. Also, **there are no expected changes in the number of months with a positive water balance**, neither on an annual basis nor in any season.

Regarding the **aridity index analysed, no significant changes are expected on it in general by mid-century.** Also, no significant changes are expected on the Martonne and Lang aridity indices by the mid-century in any scenario. Thus, the climate classification according to Martonne and Lang indices would remain semi-arid by mid-century.

Attending to **the Thornthwaite humidity index,** climate projections in general do not indicate any significant change in the Thornthwaite humidity index in annual or neither seasonal periods by mid-century.

To end the future climate **droughts characterization**, there are not expected changes in the intensity of droughts in any scenario.

The Figures of all the indicators associated with Living Lab Vaerebro River, can be found in the document “D4.1_Annex1_Vaerebro River.pdf”.

4.2. Results obtained in the Living Lab: Liesing River (Austria)

According to the climate change local scenarios generated for this case study (see in the Figure 13 the location of the observatory used), **we can expect an increase in temperatures** across all scenarios, time horizons, and periods of the year. However, **no significant changes are expected in terms of precipitation** by mid-century for any of the scenarios although there would be slight increases by the end of the century under the SSP5-8.5 scenario.

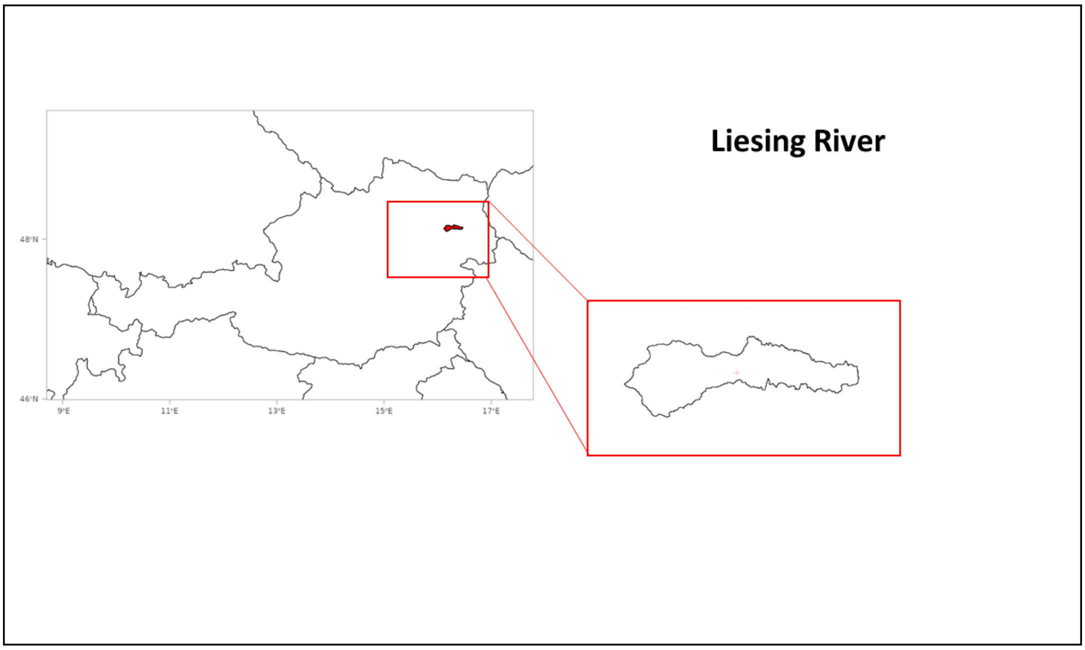

Figure 13. Location of the observatory with temperature and precipitation data used in the preliminary study for Liesing River.

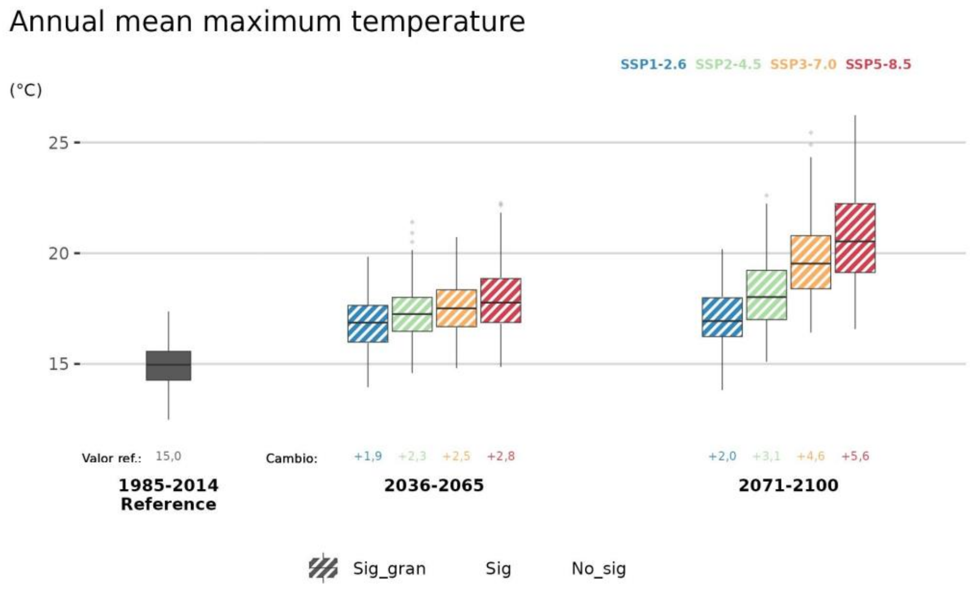

Figure 14. Expected evolution for the annual mean maximum temperature variable for Liesing River.

Maximum temperature increases are expected to range from 1.9 to 2.3 degrees Celsius by mid-century and from 2.5 to 4.4 by the end of the century in the SSP2-4.5 and SSP5-8.5 respectively. This change would be especially significant in the summer and autumn.

Additionally, the increase in temperatures will affect the occurrence of extreme weather events such as heat waves. Therefore, the length, intensity, and frequency of both heat waves and cold waves must be analysed to characterize these extreme weather events. These events may pose a threat to wetland ecosystems.

Regarding the heat waves, the main change is expected to occur in the annual number of events, which will increase significantly in every scenario and time horizon. By mid-century, it is expected to increase from 1 event to 3 in the two most pessimistic scenarios. For the same time horizon, slight changes are expected in the average length or average intensity of heat waves.

The annual number of days with maximum temperatures higher than the 95th percentile of the warmest months in the reference period is expected to increase significantly in every scenario and time horizon. Specifically, by mid-century, the average number of these days would be increased from 5 days to 20 or 26 days in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The mean annual temperature and minimum annual temperature are expected to increase in the same magnitude than the maximum temperatures in absolute values. The change in minimum temperatures will lead to a **decrease in the number of frost days.** By mid-century, a decrease of 30 to 36 is expected for SSP2-4.5 and SSP5-8.5, respectively. This represents one of the major changes identified, and as a result, the annual number of frost days is expected to disappear. The change in minimum temperatures will also lead to a **significant increase in the occurrence of tropical nights** (those with Tmin>22º). This change is expected to be significant at every time horizon and scenario, from no tropical nights in the reference period to 3 and 6 for SSP2-4.5 and SSP5-8.5, respectively by mid-century.

Regarding cold waves, no significant changes are expected to occur. The average length would continue to be 4 days per year, and maximum and average intensities would slightly increase. Furthermore, the annual number of cold waves in a median year would decrease from 1 to 0 already by mid-century.

The annual number of days with minimum temperatures lower than the 5th percentile of the coldest months of the reference period is expected to decrease significantly in most scenarios and in all time horizons. Specifically, by mid-century, the median number of these days would be decreased from 7 days to 2 or 1 day in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The **temperatures of the coldest and warmest months are expected to increase** for all time horizons and scenarios. Maximum temperatures of the warmest month would probably increase from 3.3 to 4.4 degrees and from 4 to 7.8 respectively for the SSP2-4.5 and SSP5-8.5. Minimum temperature of the coldest month is expected to rise from 2.1 to 2.7 degrees and from 2.6 to 4.9 respectively for the SSP2-4.5 and SSP5-8.5. Regarding the annual temperature range, no significant changes are expected in any of the scenarios and time horizons.

Subsequently, different indicators related to the water balance of the case study are analysed. As was already mentioned, no significant changes are expected in terms of precipitation for any of the scenarios, and periods of the year by mid-century. However, **concerning the annual evapotranspiration, significant increases are expected for all time horizons and scenarios and almost all times of the year**, mainly caused by the rise of temperatures. The annual reference evapotranspiration would increase 78.1 mm to 95.1 mm in the SSP2-4.5 and SSP5-8.5 scenarios respectively, so the absolute value would rise from 816.7 mm to 894.8 mm or 911.8 mm. This increase would be mainly distributed in the summer and autumn seasons.

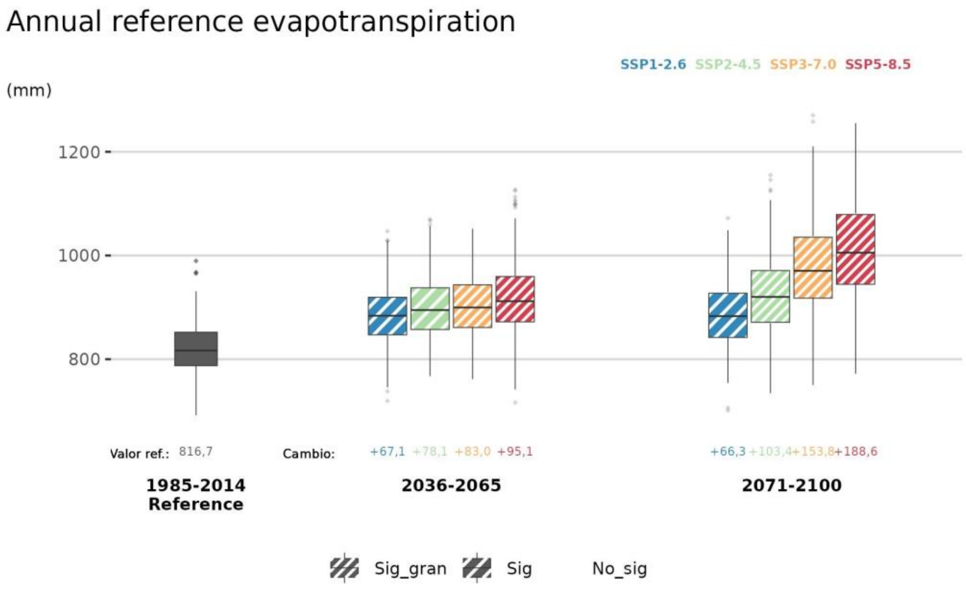

Figure 15. Expected evolution for the annual potential evapotranspiration variable for Liesing River.

Water balance, meaning the difference between the accumulated precipitation minus the calculated evapotranspiration for each month, **is not expected to change** in general terms. Only summer water balance is expected to be significantly reduced in every scenario already by mid-century, this decrease will be 68.4 mm in the higher GHG emissions scenario by mid-century. In this case, the historically negative water balance is going to be reduced from –187.5 mm to –255.9 mm in this scenario.

Annual water surplus is not expected to change in any scenario and time horizon. However, significant decreases are expected in the annual water deficit only by end-century. Also, **there are no expected changes in the number of months with a positive water balance**, neither on an annual basis nor in any season.

Regarding the **aridity index analysed, no significant changes are expected on it in general by mid-century.**

Attending to the **Thornthwaite humidity index**, climate projections in general do **not indicate any significant change** in the Thornthwaite humidity index in annual or neither seasonal periods by mid-century.

To end the future climate droughts characterization, the intensity of droughts is not expected to change significantly by mid-century.

The Figures of all the indicators associated with Living Lab Liesing River, can be found in the document "D4.1_Annex1_Liesing River.pdf".

4.3. Results obtained in the Living Lab: Guadiana River Watershed (Portugal)

According to the climate change local scenarios generated for this case study (see in the Figure 16 the location of the observatory used), **we can expect an increase in temperatures** across all scenarios, time horizons, and periods of the year. However, **no significant changes are expected in terms of precipitation** by mid-century for any of the scenarios or periods of the year although there would be significant decreases by the end of the century, especially during the summer and spring seasons. It is worth noting that an increase in aridity is probable, especially during the summer and spring seasons especially towards the end of the century, due to these significant decreases.

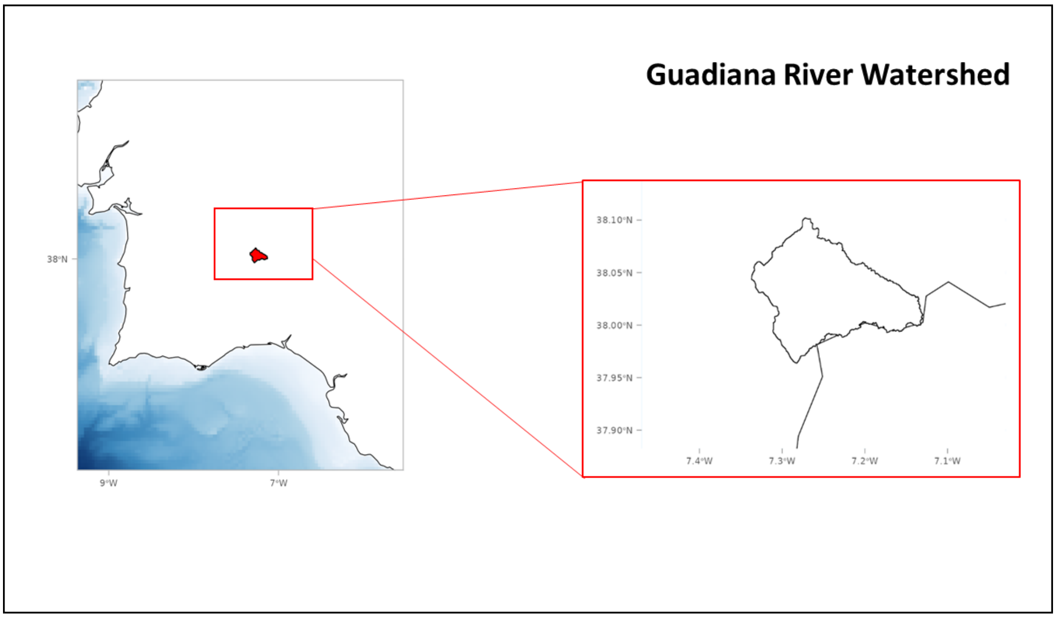

Figure 16. Location of the observatory with temperature and precipitation data used in the preliminary study for Guadiana River.

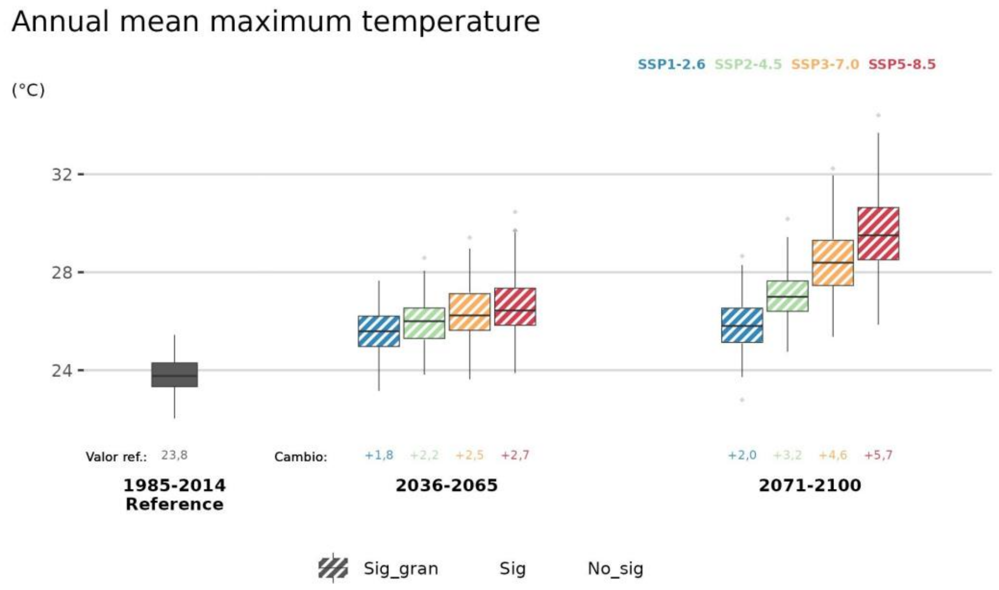

Figure 17. Expected evolution for the annual mean temperature variable for Guadiana River.

Maximum temperature increases are expected to range from 2.2 to 2.7 degrees Celsius by mid-century and from 3.2 to 5.7 by the end of the century in the SSP2-4.5 and SSP5-8.5 respectively. This change would be especially significant in the summer and autumn.

Additionally, the increase in temperatures will affect the occurrence of extreme weather events such as heat waves. Therefore, the length, intensity, and frequency of both heat waves and cold waves must be analysed to characterize these extreme weather events. These events may pose a threat to wetland ecosystems.

Regarding the heat waves, the main change is expected to occur in the annual number of events, which will increase significantly in every scenario and time horizon. By mid-century, it is expected to increase from 1 event to 2 in the most optimistic scenarios and 4 in the two most pessimistic scenarios. For the same time horizon, no significant changes are expected in the average length or average intensity of heat waves.

The annual number of days with maximum temperatures higher than the 95th percentile of the warmest months in the reference period is expected to increase significantly in every scenario and time horizon. Specifically, by mid-century, the average number of these days would be increased from 5 days to 20 or 27 days in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The mean annual temperature and minimum annual temperature are expected to increase slightly less than the maximum temperatures in absolute values. The expected rise will be from 2 to 2.5 in the first case and from 1.9 to 2.3 for the second variable for the SSP2-4.5 and SSP5-8.5 respectively by mid-century.

The change in minimum temperatures will lead to a **decrease in the number of frost days.** During the reference period (1985-2014), the mean annual number of frost days was 26. By mid-century, a decrease of 14 and 16 is expected for SSP2-4.5 and SSP5-8.5, respectively. This represents one of the major changes identified, and as a result, the annual number of frost days is expected to disappear. The change in minimum temperatures will also lead to a **significant increase in the occurrence of tropical nights** (those with Tmin>22º). This change is expected to be significant at every time horizon and scenario, from no tropical nights in the reference period to 5 and 8 for SSP2-4.5 and SSP5-8.5, respectively by mid-century.

Regarding cold waves, no significant changes are expected to occur. The average length would continue to be 4 days per year, and maximum and average intensities would slightly increase. Furthermore, the annual number of cold waves in a median year would decrease from 1 to 0 already by mid-century.

The **annual number of days** with minimum temperatures lower than the 5th percentile of the coldest months of the reference period is expected to decrease significantly in most scenarios and in all time horizons. Specifically, by mid-century, the median number of these days would be decreased from 8 days to 2 or 1 day in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The **temperatures of the coldest and warmest months are expected to increase** for all time horizons and scenarios. Mean and maximum temperatures of the warmest month would probably increase from 2.1 to 2.9 degrees and from 2.4 to 3.4 respectively for the SSP2-4.5 and SSP5-8.5. The mean and minimum temperature of the coldest month is expected to rise from 1.3 to 1.9 degrees and from 2.2 to 3.7 respectively for the SSP2-4.5 and SSP5-8.5. Regarding the annual temperature range, no significant changes are expected in any of the scenarios and time horizons

Subsequently, different indicators related to the water balance of the case study are analysed. As was already mentioned, no significant changes are expected in terms of precipitation for any of the scenarios, and periods of the year by mid-century. However, **concerning the annual evapotranspiration, significant increases are expected for all time horizons and scenarios and almost all times of the year**, mainly caused by the rise of temperatures. The annual reference evapotranspiration would increase 129.8 mm to 171.3 mm in the SSP2-4.5 and SSP5-8.5 scenarios respectively, so the absolute value would rise from 1556.5 mm to 1686.3 mm or 1727.8 mm.

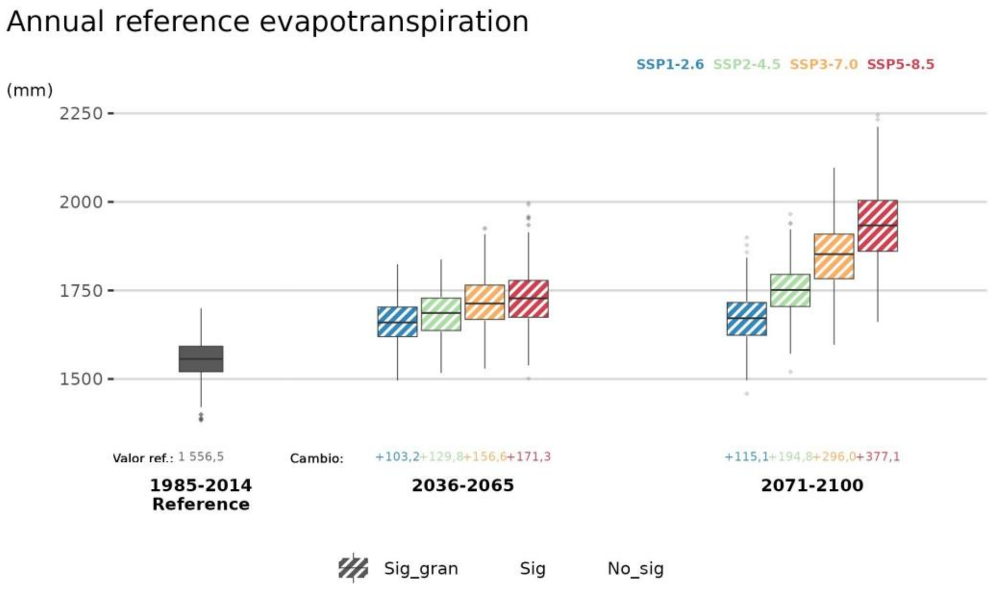

Figure 18. Expected evolution for the annual potential evapotranspiration variable for Guadiana River.

Water balance, meaning, the difference between the accumulated precipitation minus the calculated evapotranspiration for each month, **is not expected to change** in general terms by mid-century but by end-century is expected to decrease slightly.

Annual water surplus is not expected to change in any scenario and time horizon. However, significant decreases are expected in the annual water deficit, from a value of -1208.6 mm in the reference period to –1391.6 mm in the worst scenario by mid-century. Seasonally, this change would be mainly concentrated in the summer and autumn season. This indicates a potential increase in aridity during the summer season. Also, **there are no expected changes in the number of months with a positive water balance**, neither on an annual basis nor in any season.

Regarding the **aridity index analysed, no significant changes are expected on it in general by mid-century.** Also, no significant changes are expected on the Martonne and Lang aridity indices by the mid-century in any scenario.

Attending to the Thornthwaite humidity index, climate projections in general do not indicate any significant change in the Thornthwaite humidity index in annual or neither seasonal periods by mid-century.

To end the future climate droughts characterization, the intensity of droughts is expected to decrease significantly by mid-century at annual, spring, and winter scales in every scenario. By the end of the century, this significant decline would extend to all seasons except autumn.

The Figures of all the indicators associated with Living Lab Guadiana River Watershed, can be found in the document "D4.1_Annex1_Guadiana River Watershed.pdf".

4.4. Results obtained in the Living Lab: Danube River (Romania)

According to the climate change local scenarios generated for this case study (see in the Figure 19 the location of the observatory used), **we can expect an increase in temperatures** across all scenarios, time horizons, and periods of the year. However, **no significant changes are expected in terms of precipitation** by mid-century for any of the scenarios or periods of the year although there would be significant decreases by the end of the century, especially during the summer and spring seasons.

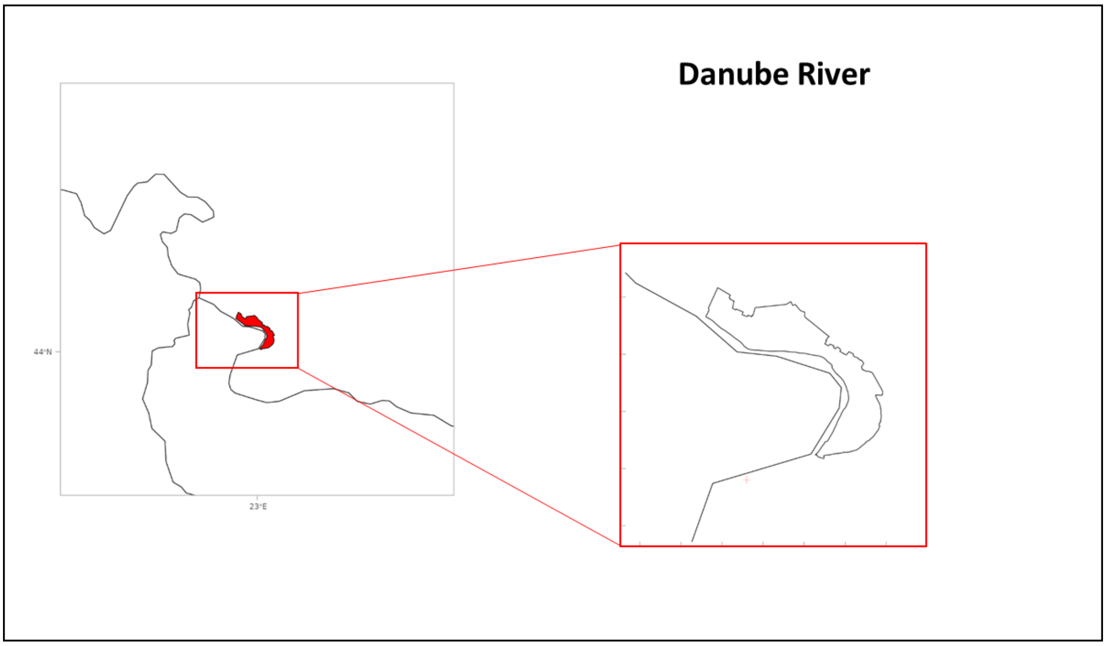

Figure 19. Location of the observatory with temperature and precipitation data used in the preliminary study for Danube River.

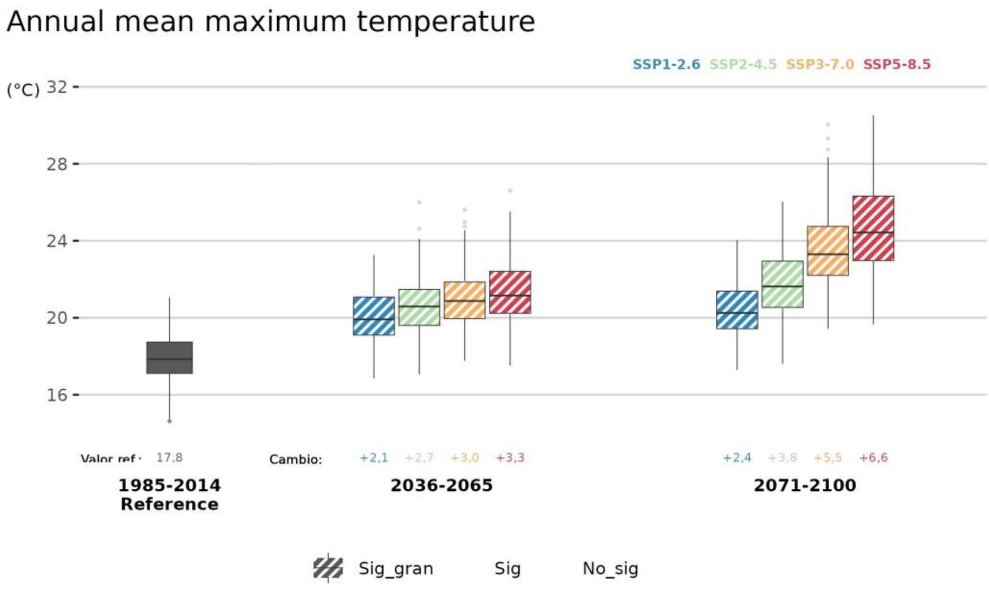

Figure 20. Expected evolution for the annual mean temperature variable for Danube River.

Maximum temperature increases are expected to range from 2.7 to 3.3 degrees Celsius by mid-century and from 3.8 to 6.6 by the end of the century in the SSP2-4.5 and SSP5-8.5 respectively. This change would be especially significant in the summer and autumn months.

Additionally, the increase in temperatures will affect the occurrence of extreme weather events such as heat waves. Therefore, the length, intensity, and frequency of both heat waves and cold waves must be analysed to characterize these extreme weather events. These events may pose a threat to wetland ecosystems.

Regarding the heat waves, the main change is expected to occur in the annual number of events, which will increase significantly in every scenario and time horizon. By mid-century, it is expected to increase from 1 event to 3 in the two most optimistic scenarios and 4 in the two most pessimistic scenarios. For the same time horizon, no significant changes are expected in the average length or average intensity of heat waves.

The annual number of days with maximum temperatures higher than the 95th percentile of the warmest months in the reference period is expected to increase significantly in every scenario and time horizon. Specifically, by mid-century, the average number of these days would be increased from 4 days to 25 or 33 days in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The mean annual temperature and minimum annual temperature are expected to increase slightly less than the maximum temperatures in absolute values. The expected rise will be from 2.5 to 3.1 in the first case and from 2.2 to 2.8 for the second variable for the SSP2-4.5 and SSP5-8.5 respectively by mid-century. Also, is relevant to consider that mean temperature and minimum temperature increases will be especially concentrated in the spring and winter seasons.

The change in minimum temperatures will lead to a **decrease in the number of frost days.** During the reference period (1985-2014), the mean annual number of frost days was 79. By mid-century, a decrease of 29 to 35 is expected for SSP2-4.5 and SSP5-8.5, respectively. This represents one of the major changes identified, and as a result, the annual number of frost days is expected to disappear. The change in minimum temperatures will also lead to a **significant increase in the occurrence of tropical nights** (those with Tmin>22º). This change is expected to be significant at every time horizon and scenario, from no tropical nights in the reference period to 15 and 23 for SSP2-4.5 and SSP5-8.5, respectively by mid-century.

Regarding cold waves, no significant changes are expected to occur. The average length would continue to be 4-5 days per year, and maximum and average intensities would slightly increase.

The annual number of days with minimum temperatures lower than the 5th percentile of the coldest months of the reference period is expected to decrease significantly in most scenarios and in all time horizons. Specifically, by mid-century, the median number of these days would be decreased from 7 days to 2 or 1 day in the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The **temperatures of the coldest and warmest months are expected to increase** for all time horizons and scenarios. Mean and maximum temperatures of the warmest month would probably increase from 3.1 to 3.9 degrees and from 3.3 to 4.3 respectively for the SSP2-4.5 and SSP5-8.5. The mean and minimum temperature of the coldest month is expected to rise from 2.6 to 3.2 degrees and from 2 to 3.2 respectively for the SSP2-4.5 and SSP5-8.5. Regarding the annual temperature range, no significant changes are expected in any of the scenarios and time horizons

Subsequently, different indicators related to the water balance of the case study are analysed. As was already mentioned, no significant changes are expected in terms of precipitation for any of the scenarios, and periods of the year by mid-century. However, **concerning the annual evapotranspiration, significant increases are expected for all time horizons and scenarios and almost all times of the year**, mainly caused by the rise of temperatures. The annual reference evapotranspiration would increase 123.3 mm to 152.1 mm in the SSP2-4.5 and SSP5-8.5 scenarios respectively, so the absolute value would rise from 1081.6 mm to 1204.9 mm or 1233.7 mm. This increase would be mainly distributed in the summer and autumn seasons.

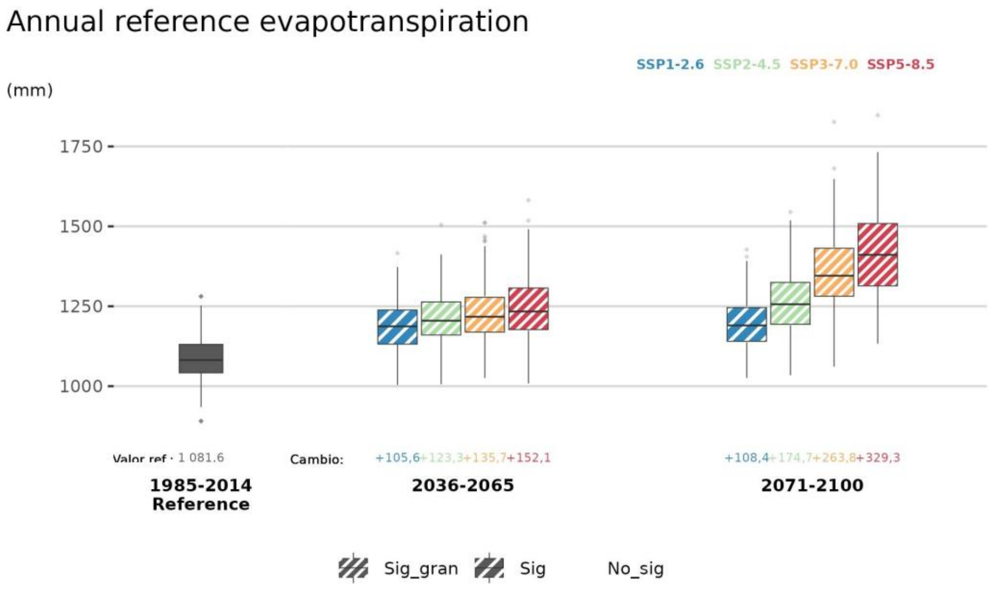

Figure 21. Expected evolution for the annual potential evapotranspiration variable for Danube River.

Water balance, meaning, the difference between the accumulated precipitation minus the calculated evapotranspiration for each month, **is not expected to change** in general terms **scenario by mid-century but decrease slightly by end-century**.

Annual water surplus is not expected to change in any scenario and horizon. However, significant decreases are expected in the annual water deficit, from a value of -657.3 mm in the reference period to –796.3 mm in the worst scenario by mid-century. Seasonally, this change would be mainly concentrated in the summer season. Also, **there are no expected changes in the number of months with a positive water balance**, neither on an annual basis nor in any season.

Regarding the **aridity index analysed, no significant changes are expected on it in general by mid-century.** Also, no significant changes are expected on the Martonne and Lang aridity indices by the mid-century in any scenario.

Attending to the **Thornthwaite humidity index**, climate projections in general do not indicate any significant change in the Thornthwaite humidity index in annual or neither seasonal periods by mid-century.

To end the future climate droughts characterization, the intensity of droughts is expected to decrease significantly by mid-century at annual, spring, and winter scales in every scenario.

The Figures of all the indicators associated with Living Lab Danube River, can be found in the document “D4.1_Annex1_Danube River.pdf”

ANNEX I. CLIMATE CHANGE FIGURES INTERPRETATION

The expected temporal evolution of the provided variables is represented by box-and-whisker plots, which illustrate the expected changes in these variables throughout the 21st century in relation to the chosen reference period (1985-2014) (e.g., see Figure AI.1). The temporal evolution is displayed along the X-axis in the form of three sets of box-and-whisker plots, with each set corresponding to a different time period, from left to right: the reference period (1985-2014), mid-century (2036-2065), and end of the century (2071-2100). The Y-axis displays the values of the simulated variable, in this case, the mean annual temperature.

These plots provide a statistical representation of the distribution of the obtained values, allowing for observation of both the median (the value at the centre of the distribution) and the dispersion of the other values, which enables the identification of the sample variability and the most expected and/or atypical values of the sample. The central horizontal line within each box represents the median (2nd quartile or 50th percentile). This value indicates that 50% of all values obtained for each year within the period and for each of the climate models considered within each scenario are above that value, and the remaining 50% are below that value. The lower and upper limits of the box correspond to the 1st and 3rd quartiles, respectively, or the 25th and 75th percentiles. The lower limit indicates that 25% of the values are below it, and the upper limit indicates that 75% of the values are below it. Thus, it can be said that 50% of the values lie within the box, which represents the most expected values. Finally, the whiskers determine the limit for detecting outliers in the distribution, which are shown as isolated points aligned with the whiskers (lower and upper limits).

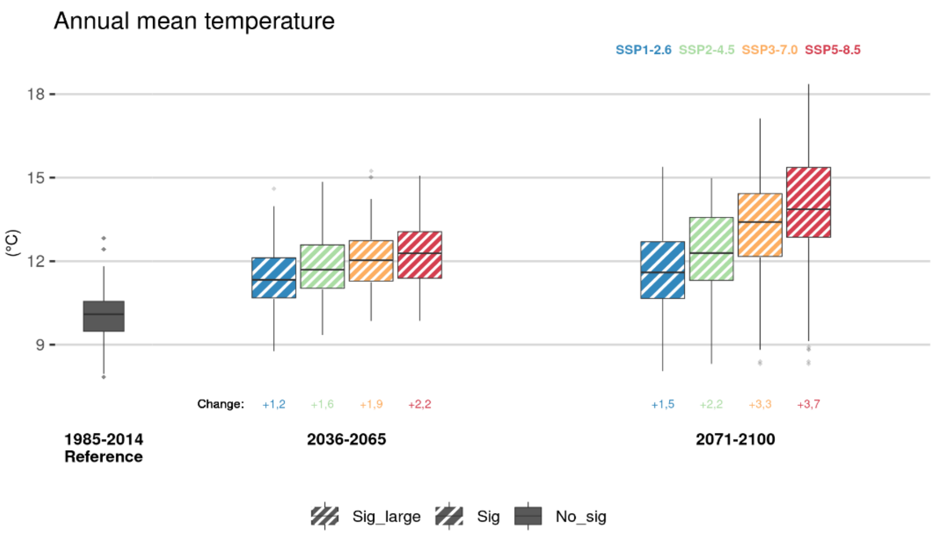

Figure AI.1. Graphic example: Expected evolution for the annual mean temperature variable.

On the X-axis, three-time blocks are displayed with a different number of box and whisker diagrams, as well as various colours and patterns. The reference period is represented by a single diagram in a greyish colour, which corresponds to the values of the variable obtained using the historical simulation of the different CMIP6 models used in this study. For mid- and end-century, four box-and-whisker plots are shown. Each plot represents the values of the variable under different emission scenarios, projected by the CMIP6 models used in this study. The scenario names are a combination of two indices: a baseline socio-economic trajectory "index" (ranging from SSP1: sustainability to SSP5: fossil fuel development), and the level of radiative forcing in 2100 (ranging from 2.6 to 8.5 W/m2) (O'Neill et al., 2016).

The results obtained for each of the 4 scenarios considered are arranged in order of pessimism: from the most optimistic to the most pessimistic scenario. The order is the same for both the middle and the end of the century: SSP1-2.6 in blue, SSP2-4.5 in green, SSP3-7.0 in yellow, and SSP5-8.5 in red. Each of these box plots corresponding to future developments can present three different patterns depending on whether the expected change in the variable is significant or not with respect to the values obtained in the reference period according to the Wilcoxon Mann Whitney test. They also depend on whether the difference in size between the two series of values is small, moderate or, large according to the Wilcoxon size effect. Thus, the box-and-whisker plots of those changes that are considered non-significant or small-scale significant will show no pattern at all. Those that are considered moderate-scale significant will show a pattern of low-density diagonal lines. Finally, those that are considered large-scale significant will show a pattern of high-density diagonal lines (as is currently the case for all expected changes for both mid- and end-century).

Finally, the expected values of change at mid- and end-century are specified for each of the future emission scenarios. These values are obtained by calculating the difference between the median value of the future scenario in question with respect to the median value of the reference period. They are represented numerically (showing increases or decreases) below the diagrams corresponding to each emission scenario and future period.

ANNEX II. CLIMATE CHANGE INDICATORS

In this annex, all the indicators that have been calculated and analysed to characterise future climate are described.

1. Climate

1.1. Mean maximum temperature

The mean maximum temperature for each period and time range - where the time ranges considered have been both annual and seasonal - has been obtained by calculating the average of the daily maximum temperatures for each year of the specific time range of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the daily maximum temperature data associated with the time range of interest (annual or seasonal) is taken, and the average is calculated.

1.2. Mean minimum temperature

The mean minimum temperature for each period and time range - where the time ranges considered have been both annual and seasonal - has been obtained by calculating the average of the daily minimum temperatures for each year of the specific time range of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the daily minimum temperature data associated with the time range of interest (annual or seasonal) is taken, and the average is calculated.

1.3. Mean temperature

The Mean temperature for each period and time range - where the time ranges considered have been both annual and seasonal - has been obtained by calculating the average of the daily mean temperatures for each year of the specific time range of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the daily mean temperature data associated with the time range of interest (annual or seasonal) is taken, and the average is calculated.

1.4. Mean temperature of warmest month

The mean temperature of the warmest month is assessed annually for each year of the period in question. The value of the average daily temperature of the month in which the maximum of the average monthly maximum temperatures was recorded is taken.

1.5. Mean temperature of coldest month

The average temperature of the coldest month is assessed annually for each year of the period in question. The value of the average daily temperature of the month in which the lowest of the average monthly minimum temperatures was recorded is taken.

1.6. Mean maximum temperature of warmest month

The average maximum temperature of the warmest month is assessed annually for each year of the period in question. The value of the highest monthly average maximum temperature of the year is taken.

1.7. Mean minimum temperature of coldest month

The average minimum temperature of the coldest month is assessed annually for each year of the period in question. The value of the lowest monthly average minimum temperature of the year is taken.

1.8. Annual temperature range

The Annual temperature range is a variation of the Thermal Oscillation in which other parameters are considered in its calculation: the average of the maximum temperatures of the warmest month and the average of the minimum temperatures of the coldest month. By not dealing now with the global average of the selected months, but with the averages of the minimum temperature of the coldest month and the maximum temperature of the warmest month, we can consider aspects such as areas with strong thermal inversions in winter (and very low minimum temperatures) that were blurred when computing the daily maximum, or real heat pans in summer in rural areas where it cools down at night. This allows us to know the total thermal oscillation of the year at each point, which is a very useful value for the continentally of an area.

1.9. Tropical nights

The number of tropical nights per year has been obtained as the sum of the number of days in which the daily minimum temperature is greater than or equal to 22ºC for each year of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the number of times that the daily minimum temperature exceeds or equals 22ºC is counted.

1.10. Frost days

The number of frosts (strictly speaking, the number of frost days) has been obtained as the sum of the number of days in which the daily minimum temperature is less than or equal to 0ºC for each year of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the number of times that the daily minimum temperature equals or falls below 0ºC is counted.

1.11. Heat summation over 7.5 ºC

Heat summation means a continuous sum of values above a certain threshold or between two values, in this case of temperature. This can be done in a continuous way by having data with an almost continuous frequency, but in general it is developed as a sum of discrete values (hourly, daily, monthly...) with respect to the base threshold point taken as a reference. In our case, the calculation has been developed from daily data as follows:

$$HS = \sum_{D_1}^{D_n} \left(\underline{T} - T_0 \right)$$

Where D_1 is the first day to be taken into account, D_n the final nth day, T is the average temperature of the day, and T_0 the threshold temperature. The resulting unit will be ºC/time, where time will be the time unit taken as reference (day, month, year...). Note that negative integrals are not considered, so any value of $T < T_0$ must be neglected or equated to T_0 in order to obtain a difference of 0.

In this case, the heat summation is a variable that defines an accumulation of thermal energy in the plant environment, and its value is correlated with the phenological evolution of many species. As such, we have taken as a reference threshold the value of 7.5ºC, a temperature above which photosynthesis is potentially active. The calculation is based on the available daily scale and aggregated to both seasonal and annual scales.

1.12. Simple continentally index or annual mean temperature range

The simple continental index (Ci) or annual mean temperature range expresses in degrees Celsius the difference or oscillation between the mean temperature of the warmest month $Tmean_{wm}$ and that of the coldest month of the year $Tmean_{cm}$ for each year of the period in question:

$$Ci = Tmean_{wm} - Tmean_{cm}$$

1.13. Thermicity index

The thermicity index (Ti) is a value that weights the intensity of cold, a limiting factor for many plants and plant communities. It is the sum in tenths of a degree of the mean annual temperature, the mean minimum temperature of the coldest month and the mean maximum temperature of the coldest month. Thus:

$$T_i = (T + T + T) \cdot 10$$

Where T is the mean annual temperature, Tmin and Tmax of cm are the mean minimum and maximum temperature of the coldest month, respectively.

The correlation between the values of this index and vegetation is quite satisfactory in warm and temperate climates.

1.14. Compensated thermicity index

The Compensated Thermicity Index attempts to weight the value of the thermicity index, due to the "excess" of cold or temperance that occurs during the cold season in the territories located in the extratropical zones (north and south of the 23rd parallel N and S), so that their continentally can be comparable:

1) If the simple continentally index (Ci) is between 8 and 18, the value of Cti is considered equal to that of Ti:

$$Cti = Ti$$

2) Conversely, if the simple continentally index (Ci) does not reach or exceed the above values, the thermicity index must be compensated by adding or subtracting a compensation value (C):

$$Cti = Ti \pm C$$

   a) If the simple continentally index is less than 8, the compensated thermicity index (Cti) is calculated by the formula:

$$Cti = Ti - [10 \cdot (8 - Ci)]$$

   b) If the simple continentally index is between 18 and 21, the value of the compensated thermicity index is calculated by the following formula:

$$Cti = Ti + [5 \cdot (Ci - 18)]$$

c) If the simple continentally index is between 21 and 28, the compensated thermicity index is calculated by the following formula:

$$Cti = Ti + [15 + 15 \cdot (Ci - 21)]$$

d) If the simple continentally index is between 28 and 46, the compensated thermicity index is calculated by the following formula:

$$Cti = Ti + [120 + 25 \cdot (Ci - 28)]$$

e) If the simple continentally index is between 46 and 65, the compensated thermicity index is calculated by the following formula:

$$Cti = Ti + [570 + 30 \cdot (Ci - 46)]$$

1.15. Ombrothermic index

The ombrothermic Index is an indicator that relates rainfall and temperature in order to help establish a relationship between vegetation and climate, a bioclimatic classification. It relates total monthly rainfall and mean monthly temperature only in those months where both have a positive value (>0), creating a scenario conducive to vegetation development and growth. It is measured in mm/ºC.

The Ombrothermic Index is calculated by developing the following expression:

$$Io = 10 \cdot \frac{Pr}{\underline{T}} \Leftrightarrow Pr, \underline{T} > 0$$

where, as already mentioned, Pr is the total monthly precipitation of those months whose average temperature exceeds 0\degree C, and $\underline{T}$ is the average temperature of the month expressed in tenths of a degree, as long as it exceeds 0ºC. This index is obtained on an annual scale by calculating the sum of all the months that meet the imposed condition of total monthly precipitation and mean monthly temperature, for each of the 30 years of each period in question.

1.16. Heat waves

Heat wave events (i.e., a period of consecutive days with extreme maximum temperatures) have been calculated according to the definitions proposed by the Spanish State Meteorological Agency (AEMET), by the World Meteorological Organization (WMO, 2010) and by the IPCC, on the basis of which the criteria for calculating and evaluating a heat wave have been established (Gaitan et al., 2019).

Thus, a heat wave takes place when for at least three consecutive days the daily maximum temperature is higher than the 95th percentile of the daily series of maximum temperature corresponding to the months of June to September for a historical reference period, in this case the period 1985-2014 has been selected as the reference period.

A heat wave episode is analysed based on its duration, average intensity and maximum intensity reached during the heat wave episode. The average number of heat wave episodes per year is also included.

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. 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. In the case of more than one heat wave in the same year, the value is obtained as the average of all cases

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. In the case of more than one heat wave in the same year, the value is obtained as the average of all cases.

Number of Heat Waves

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.

1.17. Cold waves

Cold wave (spells) events (i.e., a period of consecutive days with extreme maximum temperatures) have been calculated according to the definitions proposed by the Spanish State

Meteorological Agency (AEMET), by the World Meteorological Organization (WMO, 2010) and by the IPCC, on the basis of which the criteria for calculating and evaluating a heat wave have been established (Gaitan et al., 2019).

Thus, a cold wave takes place when for at least three consecutive days the daily maximum temperature is lower than the 0th percentile of the daily series of maximum temperature corresponding to the months of November to April for a historical reference period, in this case the period 1985-2014 has been selected as the reference period.

A cold wave episode is analysed based on its duration, average intensity and maximum intensity reached during the cold wave episode. The average number of cold wave episodes per year is also included.

Average length of Cold Waves

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

Average intensity of Cold Waves

The average intensity of a cold wave episode is the average of the minimum temperature values recorded on the days constituting the cold wave episode. It is calculated for each of the 30 years of each period in question. In the case of more than one cold wave in the same year, the value is obtained as the average of all cases.

Maximum intensity of Cold Waves

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

Number of Cold Waves

The average number of cold 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.

1.18. Number of days with maximum temperatures over Heat Wave threshold

The number of days with Tmax > T(P95) [1985-2014 JJAS] expresses the number of days per year where the daily maximum temperature is higher than the 95th percentile obtained for the reference period 1985-2014 between the months of June to September (inclusive). In this way it is possible to quantify the number of days in which the temperature threshold necessary to consider a Heat Wave episode is exceeded, although it is not considered as such because it does not reach the minimum number of consecutive days with a maximum temperature above the established threshold value. It is calculated for each of the 30 years of each period in question.

1.19. Number of days with minimum temperatures under Cold Wave threshold

The number of days with Tmin < T(P05) [1985-2014 NDJFMA] expresses the number of days per year in which the daily minimum temperature is lower than the 05th percentile obtained for the reference period, in this case, the months of November to April (inclusive) 1985-2014. In this way it is possible to quantify the number of days in which the temperature threshold necessary to consider a Cold Wave episode is exceeded, although it is not considered as such because it does not reach the minimum number of consecutive days with a minimum temperature below the established threshold. It is calculated for each of the 30 years of each period in question.

2. Water balance

2.1. Precipitation

The accumulated precipitation for each period and time range - where the time ranges considered have been both annual and seasonal - has been obtained by calculating the sum of the daily precipitation for each year of the specific time range of the period in question. For example, for the reference period 1985 - 2014, for each of the 30 years considered, the daily precipitation data associated with the time range of interest (annual or seasonal) are taken, and the sum is calculated.

2.2. Potential or reference evapotranspiration

Potential evapotranspiration (PET) is the amount of evaporation and transpiration that would occur if a sufficient water source were available. Reference evapotranspiration (ETo) is the amount of evaporation and transpiration from a reference vegetation of grass. They are usually considered equivalent.

This value is calculated using the Hargreaves equations (SPEI rstudio package), from which monthly values are obtained. Then, for the annual and seasonal calculation, the sum of the PET value of all the months of that year (for the annual calculation) or months of each season of the year (for the seasonal calculation) is added up. It is calculated for each of the 30 years of each period in question.

2.3. Water balance

The water balance is calculated as the difference between the accumulated precipitation in month m minus the calculated evapotranspiration for the same month.

$$WB = \sum_{m=1}^{12} (P_m - ETo_m)$$

Where P_m is the cumulative precipitation in month m and ETo_m is the reference evapotranspiration of month m, calculated using the Hargreaves equations (SPEI rstudio package).

For the annual and seasonal calculation, the sum of the WB value of all the months of that year (for the annual calculation) or months of each season of the year (for the seasonal calculation). It is calculated for each of the 30 years of each period in question.

2.4. Water surplus

From the point of view of the water regime, it is important to characterize for each point not only the Water Balance, but also throughout the year the relationships between the excess or deficit of precipitation and its accumulations since these values also denote the nature of the aridity of a territory according to the time of year. These values are defined with the indices of sum of surpluses (SUR) and sum of deficits (DEF) of water and are often used for the definition of bioclimates or the study of the potential distribution of plant species.

In the case of SUR, we obtain the value of this index using the following expression:

$$SUR = \sum_{m=1}^{12} (P_m - ETo_m) \iff (P_m - ETo_m) > 0$$

That is, SUR is the sum over the year (for the annual case) or season (for the seasonal case) of the difference, for each month, of the monthly precipitation and its reference evapotranspiration equivalent, if and only if this difference is positive (surplus). Its units are "mm". It is calculated for each of the 30 years of each period in question.

2.5. Water deficit

In contrast to the previous SUR, water deficit (DEF) is defined as the sum of deficits by the following expression:

$$DEF = \sum_{m=1}^{12} (P_m - ETo_m) \quad \Leftrightarrow \; (P_m - ETo_m) < 0$$

That is, DEF is the sum over the year (for the annual case) or season (for the seasonal case) of the difference, for each month, of the monthly precipitation and its reference evapotranspiration equivalent, if and only if this difference is negative (deficit); its units are "mm". It is calculated for each of the 30 years of each period concerned.

2.6. Months with positive water balance

In a very simple way and starting from the previously obtained values of the water balance (WB) for all the months of the year, we have proceeded to count the total of those months with a WB > 0 throughout the year. It is calculated for each of the 30 years of each period in question.

2.7. Aridity index

While drought is a natural transient anomaly (although sufficiently prolonged), aridity is a natural structural situation of a region and therefore "permanent", although it can change over very long periods. It is therefore of interest to determine whether the region will become more arid or more humid, regardless of the changes that may occur with respect to periods of water scarcity (drought).

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

$$AI = \frac{P}{ETo}$$

This formula has been applied directly to each point of interest by entering the accumulated precipitation in the time interval in question and the corresponding ETo. It is a dimensionless index, which reaches values $0 < AI < 1$ depending on how arid a point is, and $AI > 1$ if, on the contrary, the point is "wet".

This index is calculated at annual and seasonal level, then the reference (or potential) precipitation and evapotranspiration value accumulated in a year (for the annual case) or in each season (for the seasonal case) are considered. It is calculated for each of the 30 years of each period in question.2.8. Lang aridity index

The Lang aridity index is defined as the ratio of annual rainfall to mean annual temperature:

$$L_i = \frac{P}{T}$$

where P is the mean annual precipitation (mm) and T is the mean annual temperature (ºC). It is calculated for each of the 30 years of each period in question.

The Table AII.1 lists the types of climate defined by this index:

Table AII.1. Climate classification depending on Lang aridity index.

Index values	**Climate types**
L_i < 20	Arid
20 < L_i < 40	Semi-arid
40 < L_i < 70	Semi-humid
70 < L_i < 100	Humid
L_i > 100	Per-humid

2.9. Martonne aridity index

The Martonne aridity index is expressed by the following formula:

$$M_i = \frac{P}{T + 10}$$

Where P is the mean annual precipitation (mm) and T is the mean annual temperature (ºC). It is calculated for each of the 30 years of each period in question.

With this index the climatic regions are classified as shown in Table AII.2. A value of 20 is the boundary between humid and semi-arid areas, and values of 15 and below correspond to arid regions.

Table AII.2. Climate classification depending on Martonne aridity index.

Index values	Climate types	Vegetation types	Meaning
M_i < 5	Per-arid	Absolute desert	No cultivation
5 < M_i < 10	Arid	Desert	No cultivation without irrigation
10 < M_i < 20	Semi-arid	Steppe or savannah	Irrigation required for crops requiring moisture
20 < M_i < 30	Semi-humid	Natural meadow	Irrigation generally not necessary
30 < M_i < 40	Humid	Forest	Trees are playing an increasingly important role in the landscape
M_i > 40	Per-humid	Predominant forest	Cereal crops tend to be replaced by grassland

2.10. Thornthwaite humidity index

The Thornthwaite humidity index (HI) expresses the percentage excess or deficiency of the annual cumulative precipitation with respect to the annual cumulative reference evapotranspiration (ET_0). If $P > ET_0$ the index is positive and if $P < ET_0$ it is negative. It should be noted that the potential evapotranspiration PET is always assumed to be equivalent to the reference evapotranspiration ET_0. The annual value of Thornthwaite's potential or reference evapotranspiration is used in the calculation of this moisture index because it belongs to the same author. However, in this case the ET_0 or PET value obtained by the Hargreaves methodology is used for consistency with the results of the whole analysis.

$$HI = 100 \cdot \frac{Pr - ETo}{ETo}$$

This index is calculated on an annual basis for each of the 30 years of each period in question.

Depending on the value obtained for this index, five moisture regions, some of them diversified, are recognised (Table AII.3).

Table AII.3. Climate classification depending on Thornthwaite humidity index.

Climate types	**HI thresholds**
Per-humid	HI > 100
Very humid	80 < HI < 100
Highly humid	60 < HI < 80
Moderate humid	40 < HI < 60
Low humid	20 < HI < 40
Moist sub-humid	0 < HI < 20
Dry sub-humid	-20 < HI < 0
Semi-arid	-40 < HI < –20
Arid	-60 < HI < –40

2.11. Drought intensity

As a complementary indicator to those already described above for the characterization of aridity at a point, the drought intensity index (DI) expresses the magnitude of drought at a location, being expressed mathematically by:

$$DI = \sum_{m=1}^{m=12} \left(P_m - \underline{T_m}\right) \iff DI < 0$$

i.e., DI is the sum of the values of each month resulting, provided they are negative, from the difference between the monthly precipitation and the average temperature of the month, expressed as (mm-ºC). This value is obtained at both annual and seasonal levels.

2.12. Standardised Precipitation Index (SPI)

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 fallen 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 in sections related to the character of the precipitation (Table AII.4). 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. It is based on two assumptions:

1) The variability of precipitation is greater than that of temperature and potential evapotranspiration (PET).
2) All other variables are stationary over time.

It is one of the most widely used indices in recent decades as it has a solid, robust and versatile basis. It can be calculated at different scales, so that the SPI at 3 months will represent the short and medium term, e.g. seasonal precipitation; at 6 months it represents the medium term, e.g. potential precipitation deficit; and at 12, 24 and 60 months it represents long-term precipitation patterns with impact on water supplies.

Table AII.4. Climate classification depending on Standardized Precipitation Index (SPI).

Climate type	**SPI Thresholds**
Extremely wet	SPI ≥ 2.0
Severely wet	1.50 ≤ SPI < 2.00
Moderately wet	0.50 ≤ SPI < 1.50
Normal	-0.50 ≤ SPI < 0.50
Moderately dry	-1.50 ≤ SPI < -0.50
Severely dry	-2.00 ≤ SPI < -1.50
Extremely dry	SPI < -2.00

2.13. Standardized Precipitation Evapotranspiration Index (SPEI)

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 AII.5).

Table AII.5. Climate classification depending on Standardized Precipitation Evapotranspiration and Precipitation Index (SPEI).

Climate type	SPI 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

3. Biodiversity

3.1 Bioclimatic indices

Bioclimatic indices are variables calculated from monthly temperature and precipitation values and are of interest from a biological point of view. They are often used in species distribution modelling and related ecological modelling techniques. Bioclimatic variables represent annual trends (e.g. mean annual temperature, annual precipitation); seasonality (e.g. annual range of temperature and precipitation) and extreme or limiting environmental factors (e.g. temperature of the coldest and warmest month, precipitation of wet and dry quarters). The Table AII.6 shows the definitions of the 19 calculated bioclimatic indices.

Table AII.6: Definition of the 19 calculated bioclimatic indices.

Index	Description	Unit
1	Average annual temperature	°C
2	Average daily range	°C
3	Isothermality	%
4	Seasonality of temperature	adim
5	Maximum temperature of the warmest month	°C
6	Minimum temperature of the coldest month	°C
7	Annual temperature range	°C
8	Average temperature of the wettest trimester	°C
9	Average temperature of the driest trimester	°C
10	Average temperature of the hottest trimester	°C
11	Average temperature of the coldest trimester	°C
12	Annual precipitation	mm
13	Precipitation of the wettest month	mm
14	Precipitation of the driest month	mm
15	Seasonality of precipitation	adim
16	Precipitation in the wettest trimester	mm
17	Precipitation in the driest trimester	mm
18	Precipitation in the hottest trimester	mm
19	Precipitation in the coldest trimester	mm

4.2 Average temperature during the growing season Average temperature for the growing season calculated as the average daily temperature for the period between April and October.

4.3 Minimum temperature during the growing season

Minimum temperature for the growing season calculated as the average daily minimum temperature for the period between April and October. Damage to the vines normally occurs at temperatures below-3°C.

4.4 Maximum temperature of the growing season

Maximum temperature for the vegetative period calculated as the average daily maximum temperature corresponding to the period between April and October. The consequences of high temperatures on the vine are diverse depending on their duration, water resources, vegetation stage and genotype but it can be considered that, above 35°C, the photosynthesis capacity of the vine decreases and the anthocyanin content of the grape is affected.

4.5 Minimum temperature of the growing dormant period

Minimum temperature for the dormant period calculated as the average daily minimum temperature for the period from November to March. Above a threshold, irreversible damage to the viability of the buds or the entire vine may occur. Although it depends on the plant material and the strength of the vine, the threshold of vine resistance to low temperatures ranges from-15°C to-25°C. (During (1997); Lisek et al. (2009))

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