Common climate scenario baseline

Deliverable 3.5: Climate projections for multi-hazard and multi-sectoral risk assessment (common baseline across cases – 1. update)

WP3: Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework

Authors: Martin Drews (DTU), Andrea Böhnisch (LMU), Ophélie Meuriot (DTU) and Ralf Ludwig (LMU)

Date: 30/9 2024

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101037424.

Deliverable Number and Name	D3.5 - Common climate scenario baseline
Work Package	WP3 – Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework
Dissemination Level	Public
Author(s)	Martin Drews (DTU), Andrea Böhnisch (LMU), Ophélie Meuriot (DTU) and Ralf Ludwig (LMU)
Primary Contact and Email	Martin Drews, DTU, mard@dtu.dk
Date Due	30/9 2024
Date Submitted	30/09/2024
File Name	ARSINOE_D3.5_fv
Status	Public
Reviewed by (if applicable)	Marino Marrocu, CRS4, marino@crs4.it
Suggested citation	Authors (2024) Common climate scenario baseline. ARSINOE Deliverable 3.5, H2020 grant no. 101037424

This document has been prepared in the framework of the European project ARSINOE. This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 101037424.

TABLE OF CONTENTS

List of abbreviations

AR5/AR6: Assessment Report 'no.' (from IPCC)

CMIP5/6: Coupled model intercomparison project ‘no.’

CORDEX: Coordinated Regional Downscaling Experiment

CRCM: Canadian Regional Climate Model

CS: Case study (in the context of Deliverable 3.5; “cs” is sometimes used for "climate services")

DEM: Digital elevation model

ESD: Empirical statistical downscaling

ESGF: Earth System Grid Federation

ESM: Earth system model

GCM: Global climate model

GDP: Gross domestic product

GHG: Greenhouse gas emissions

GRIB: Gridded Binary or General Regularly-distributed Information in Binary form

IPCC: Intergovernmental Panel on Climate Change

LULCC: Land use and land cover changes

ML: Machine Learning

MSDMF: Multi-System Dynamic Resilience Modelling Framework

NetCDF: Network Common Data Form

RCM: Regional climate model

RCP: Representative concentration pathway

SSP: Shared socio-economic pathway

EXECUTIVE SUMMARY

This is the second of three deliverables aimed at guiding the implementation of systematic and state-of-the-art climate risk assessments across the nine ARSINOE case studies and the project as a whole.

The document updates D3.4 (September 2022) and provides a revised methodology with guidelines for implementing a common climate scenario baseline across case studies. While the release of new CORDEX-CMIP6 climate simulations after several delays is still pending, our revised methodology will instead utilize a novel and complimentary set of climate projections provided by the ClimEx-II project. These simulations were finished in the first part of 2024 and are made available courtesy of LMU.

The report contains three main parts: (i) a description of the ClimEx-II data set, (ii) a list of data needs by the case studies, and (iii) guidelines for carrying out impact modelling at case study levels using simulations drawn from the climate scenario baseline.

In addition to modelling at case study level, supplementary analyses will be carried out at the European and regional scales to support upscaling and cross-evaluation of the results including beyond the project's lifetime.

1.0 Introduction

1.1 Scope of the deliverable

The ARSINOE Multi-System Dynamic Resilience Modelling Framework (MSDMF) framework integrates tools, methods and techniques from different academic disciplines to facilitate a holistic analysis of results. In this light, Task 3.3 defines common climate scenario baselines to facilitate associated projections of multi-hazards and multi-risks within each of the nine diverse Case Studies (CS) in ARSINOE.

Task 3.3 has four main objectives:

- To define common climate scenario baselines ("reference scenarios") to be explored by all CSs;
- To exploit existing/forthcoming data and operational climate services provided e.g., by the Copernicus programme or Horizon 2020, Horizon Europe projects, and to ensure the timely delivery of updated climate information to CS;
- To facilitate distillation of climate risk information at the appropriate scales through e.g., downscaling, process-based and data-driven modelling, statistical methods, and machine learning (ML) (together with Task 3.4);
- To support case studies in assessing compound and cascading climate risks.

This report is the second of three linked deliverables aimed at guiding the implementation of systematic and state-of-the-art climate risk assessments embedded in, across and tailored to the nine ARSINOE CSs, the SustainGraph, and other innovations within the project. The first deliverable (D3.4) was published in Month 18 and the last update will be delivered in Month 42 (D3.6). In addition to these, the scope of the present document is linked to D3.7 (Modular suite of land use response tools) and to D3.10 (Sensitivity/uncertainty analysis report).

Changes to the workplan

As described in D3.4, the intent was to base the ARSINOE climate scenario baseline on the subset of CORDEX-CMIP6 regional climate simulations that was planned for late 2023 – early 2024 (see **Box 1**). Since a number of the simulations had to be re-run and others were delayed, even a limited set of the new CORDEX-CMIP6 regional climate projections are still not available for download (September 2024). Consequently, the current deliverable, originally scheduled for Month 30 (March 2024), had to be pushed to Month 36 (September 2024). Moreover, instead of using CORDEX-CMIP6 simulations a choice was made to adopt climate simulations from the new ClimEx-II set of simulations, which are completed in the Spring 2024 (see **Box 2**). In accordance with the methodology originally outlined (Deliverables 3.4 and 3.10), the ClimEx-II simulations downscale the SSP1-2.6 and SSP3-7.0 shared socio-economic pathways (O'Neill et al. 2016, 2020; Riahi et al. 2017) as means to explore different climatic futures while also providing a sample of the uncertainty. The ClimEx-II set of climate projections are discussed in Chapter 2.

Box 1. **EURO-CORDEX** (Jakob et al. 2020) is the European branch of the international **CORDEX** (Coordinated Regional Climate Downscaling Experiment) initiative, which is sponsored by the **WCRP** (World Climate Research Program). CORDEX aims to advance and coordinate the science and application of regional climate downscaling through global partnerships, including *(i)* to better understand relevant regional/local climate phenomena, their variability and changes, through downscaling; *(ii)* to evaluate and improve regional climate downscaling models and techniques; *(iii)* to produce coordinated sets of regional downscaled projections worldwide; and *(iv)* to foster communication and knowledge exchange with users of regional climate information.

Following the publication of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), CORDEX has maintained an ensemble (CORDEX-CMIP5) of regional climate model simulations downscaling the results of global climate and Earth system models from CMIP5 - Coupled Model Intercomparison Project Phase 5 (Taylor et al. 2012). The CORDEX-CMIP5 ensemble is accessible via the ESGF (Earth System Grid Federation) software and data infrastructure (see https://esgf.llnl.gov/) and via the Copernicus Climate Data Store. While contributions in form of simulations provided by global climate modelling centres are voluntary, several research projects, including the EUCP project (see https://www.eucp-project.eu/) have included contributions to CORDEX. Climate projections from the EURO-CORDEX constitute the most comprehensive source of multi-model regional climate projections for both science and practice in Europe.

The production of a new generation of CORDEX simulations based on the most recent CMIP6 generation of global climate and Earth system models, i.e. CORDEX-CMIP6, has been ongoing since 2022 (see https://wcrp-cordex.github.io/simulation-status/) and has experienced several delays. Originally, a subset of the simulations was planned to be ready via ESGF in late 2023 or early 2024, but this has also been postponed. Currently, there is - to the authors' knowledge at least – no expected date for publication of new CORDEX-CMIP6 simulations, although early 2025 has been mentioned as a possibility.

Box 2. The **ClimEx (Climate Change and Hydrological Extremes)** project is a part of a long-standing collaboration between Bavaria (Germany) and Québec (Canada) on climate change research. It is a collaboration between LMU München, Bayerisches Landesamt für Umwelt, Ouranos - Climate Scenarios and Services Group, Centre d'Expertise hydrique du Québec (CEHQ), École de Technologie Superieure (ETS), Montréal (PQ), and supported by the Leibniz Supercomputing Centre (LRZ), who are contributing high performance computing and storage.

One of the project's overall themes is to investigate the occurrence and impacts of extreme meteorological events on hydrology in Bavaria and Québec under climate change conditions (Leduc et al. 2019). In the first phase of the ClimEx collaboration (funded by the Bavarian State Ministry for the Environment and Consumer Protection, Grant No. 81-0270-024570/2015), the project delivered a 50-member single-model initial condition (large) ensemble (SMILE) using the Canadian Regional Climate Model version 5 (CRCM5; Martynov et al. 2013; Separovic et al. 2013) to dynamically downscale global climate model (GCM) simulations. In the second phase, the focus is on land use and land cover changes (LULCC) and a main outcome of the project will be a set of regional climate simulations for assessing the role of LULCC on climate variability and extremes on a regional scale under SSP1-2.6 and SSP3-7.0.

1.2 Overview

This deliverable comprises the following material:

- A short description of changes to the workplan and the climate scenario baseline originally described in D3.4 (September 2022), including the rationale for the implemented changes (section 1.1 and chapter 4).
- A description of the ClimEx-II set of regional climate projections, including the implementation of land use scenarios corresponding to the shared socio-economic pathways / reference concentration pathways (SSP/RCPs) be implemented by all case studies: SSP1-2.6 and SSP3-7.0 (section 2.1).
- Preliminary evaluation of the ClimEx-II set of regional climate projections (Section 2.2).
- A technical description of ClimEx-II variables that can be accessed (Section 2.3).

- A preliminary overview of the data requirements by each of the case studies (see D3.4, D3.7 and D6.3 for short descriptions of the different hazard and impact models used within ARSINOE).
- Guidelines for implementing the common climate scenario baselines in case studies (Chapter 4).

A list of references is provided as an annex.

2.0 CLIMEX-II climate projections

Commented [AB1]: Andrea + Ralf – A description of CLIMEX2 experiment, data, and scenarios – feel free to organize the material as you see fit (see the overview 1.2)

[Scope of the ClimEx2 data]

The IPCC Special Report on Climate Change and Land (IPCC 2019) highlights the human impacts on climate through land use and land cover changes (LULCC). This occurs by sources and sinks of greenhouse gas emissions but also by biophysical effects such as surface albedo, roughness, and evapotranspiration, which can have significant impacts locally. On the regional scale, these biophysical impacts resulting from LULCC are likely to affect the local climate to a similar extent as global greenhouse gas emissions (Noblet-Ducoudré et al. 2012). Still, they are comparatively less studied. The Land Use and Climate Across Scales (LUCAS) project explored these effects in regional climate models, finding consistent winter warming due to decreased albedo but variable summer responses (Davin et al. 2020). This highlights the need for accurate LULCC implementation in RCMs for better climate adaptation strategies.

Global climate models (GCMs) generally account for land use changes through dynamic vegetation components but lack a detailed regional representation due to their coarse spatial resolution. Regional climate models (RCMs) offer high-resolution simulations but rarely account for LULCC explicitly. This is for example the case of the CORDEX multi-model regional climate model ensemble (Jacob et al. 2020, Hesselbjerg et al. 2019).

In the ClimEx-II simulations, realistic changes of land use and land cover aligned with the SSP1-2.6 and SSP3-7.0 global narratives were incorporated to assess LULCC impacts on climate variability and extremes on a regional scale. The first results derived from these new simulations were recently published in Asselin et al. 2024, who investigates heatwave attenuation and alteration of precipitation patterns under SSP1-2.6.

2.1 ClimEx-II simulations

The ClimEx-II simulations include aspects of the single-model initial condition (large) ensemble (SMILE) approach used in the first phase of the ClimEx initiative by employing multiple global SSPs, downscaled through regional LULCC, and four ensemble members of the same GCM-RCM chain to sample uncertainties due to GHG or land use forcing and internal variability.

The following sections provide details about the ClimEx-II set of simulations as well as the rationale behind them. Further information may be found in Asselin et al. (2024) (for ClimEx-II) and Leduc et al. (2019) (for the regional SMILE description, section 2.1.1).

2.1.1 Downscaling a global single-model initial condition large ensemble

SMILEs typically consist of multiple simulations of the same model and forcing conditions, but with slightly varying starting values to trigger different climate trajectories. The idea is to create a bundle of simulations located in the same climate, but spanning the range of internal variability.

Most SMILEs consist of global Earth System Models (ESMs). However, internal variability poses a large source of projection uncertainties also and in particular on regional scales. Therefore, some attempts on downscaling global SMILEs to regional scales were recently carried out (e.g., Leduc et al., 2019; Aalbers et al. 2018). Due to the high resolution and typically large member counts, these enterprises result in high computational costs and require large storage systems. Therefore, only few regional SMILEs exist.

One of the few examples is the CRCM5-LE (Large Ensemble), for which the Canadian Earth System Model Version 2 Large Ensemble (CanESM2-LE) was dynamically downscaled by the CRCM5 regional climate model (Leduc et al. 2019). This resulted in 50 equally likely members at high spatial resolution (0.11°, ~ 12 km), each covering the period of 1950-2099 under RCP8.5 (van Vuuren et al. 2011) from 2006 onwards. The CRCM5-LE was the main outcome of the ClimEx-I project.

The benefits of regional SMILEs are reflected in multiple studies on high-resolution climate variability and climate change, originating from this regional SMILE. Most often, the focus has been on hydrometeorological extreme events that can be studied more thoroughly within the enhanced sample size of a SMILE: extreme precipitation over Europe (Poschlod et al. 2021, Wood 2023, Mittermeier et al. 2019), rain-on-snow or hot and dry compound events (Poschlod et al. 2020, Felsche et al. 2024, Böhnisch et al. 2023a), freezing rain in Canada (Mittermeier et al. 2022), European droughts (Böhnisch et al. 2021), and European heatwaves (Böhnisch et al. 2023b, Felsche et al. 2023).

The data was also used as input for impact modelling, e.g., floods in Bavaria or in other parts of Europe (Poschlod et al. 2021, Brunner et al. 2021, Willkofer et al. 2023) or changing fire weather conditions in Bavaria (Miller et al. 2024). In general, the SMILE produced within ClimEx-I has been found to produce results that are similar to analogous results derived from the CORDEX multi-model ensemble.

2.1.2 Multi-scenario (climate and land use) set up

The **ClimEx-II regional climate model ensemble** was produced in the second phase of the ClimEx cooperation. Like in the first phase, the ensemble is based on the CRCM5 regional climate model coupled to the Canadian Land Surface Scheme (CLASS; Verseghy 1991; Verseghy et al. 1993). However, the new ensemble has a different structure than the "typical" regional SMILE described above.

For the ClimEx-II ensemble, the CRCM5 regional climate model is forced by either ERA-5 reanalysis data (Muñoz-Sabater et al. 2021) (the driving data) or the Max Planck Institute for Meteorology Earth System Model version 1.2 Grand Ensemble (MPI-ESM-1.2; Mauritsen et al. 2019, Olonscheck et al. 2023). Specifically, only the first four members (rXi1p1f1, with X=1-4) of the lower-resolution ensemble (MPI-ESM-LR-1.2, Olonscheck et al. 2023) are used. The members vary due to different initial conditions of the simulation. For each of these four members, three different configurations are used: *present* land cover and GHG emissions (**GpLp**, or **control**), *future* GHG emissions but *present* land cover (**GfLp**), and *both future* land cover and GHG emissions (**GfLf**).

In view of the original ClimEx-II objectives, the range of downscaled climate projections only covers the period 2064-2100, while the simulated present-day period is 1979-2015. This was done to save CPU time while allowing for as many ensemble members as possible to be simulated. The main objective of the data set is to allow joint evaluation of different GHG and/or land use scenarios between a future and a present time slice. While the first few years essentially represent a model spin-up period, it is recommended to use 2070-2099 for analyses.

The land cover maps are based on the Land Use Harmonized Dataset Version 2 (LUH2; Hurtt et al., 2020). By means of the land-use translator by Hoffmann et al. (2023), land cover maps based on land use transitions for the year 2100 in SSP1-2.6 and SSP3-7.0 (Hoffmann et al., 2022) were derived from LUH2. The land use change maps provide fractions of 16 plant-functional types (PFTs) over Europe in 2015 which were simplified to 6 land cover categories for the ClimEx-II experiments. **Figure 1** shows spatially distributed land use change (LUC) by classes (broadleaf trees, needleleaf trees, crops, urban, grasslands and shrubs) under SSP1-2.6.

The three configurations in the ensemble allow for studying the effects of LUC and GHG emission scenarios both in isolation and in combination (for details see Asselin et al. 2024). All simulations are produced in 0.11° (~12 km) spatial resolution over two domains, North-Eastern North-America and Europe, as defined by the CORDEX protocol. The European domain covers all of the ARSINOE case studies, except for the Canary Islands and the southern part of Cyprus.

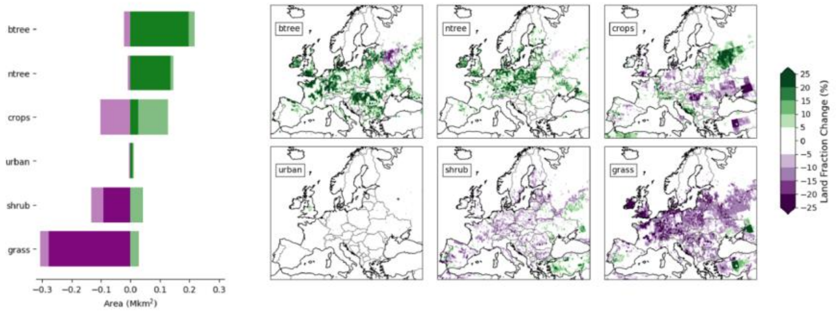

Figure 1: Land-use change (LUC) between the present (2015) and the end of the century (2100) under the "sustainability scenario", SSP1-2.6 (Reinhart et al., 2022b; Hoffmann et al., 2023). The bar graph shows the sums of all positive (pale green) and all negative (pale purple) changes as well as the net change (dark green or purple). In the individual LUC maps, the color bar leaves out regions with LUC of a magnitude lower than 5%. This defines the threshold of significant LUC, over which all spatial integration or averaging are carried out (see details in section 7.5 of Asselin et al. 2024). SSP1-2.6 is characterized by a strong forestation signal at the expanse of grasses and shrubs. Figure and caption text is adapted from Asselin et al. 2024 [Broadleaf trees: btree; needleleaf trees: ntree].

2.2 Preliminary evaluation

As mentioned above, the related ClimEx-I ensemble, which is also based on the CRCM5 regional climate model has been extensively compared to CORDEX simulations and found to yield largely similar results for the RCP8.5 representative concentration pathway. Here, we evaluate different combinations under SSP1-2.6 (Asselin et al. 2024). Further preliminary analyses (not shown) indicate that under SSP3-7.0, GHG-driven trends tend to outpace LUC effects with respect, e.g., heat extremes.

In the following, preliminary evaluation results are shown for heat extremes and precipitation. A more comprehensive evaluation of the ClimEx-II performance will appear in Deliverable 3.6.

2.2.1 Heat extremes under climate change and land use scenarios

Asselin et al. 2024 investigated the biophysical effects of land-use changes (LUC) over Europe that are compliant with the SSP1-2.6 shared socio-economic pathways, which is roughly aligned with the Paris Agreement. Their results are summarized in **Figure 2**.

Results based on ClimEx-II simulations indicate that under this heavily mitigated scenario, LUC comprised primarily of broadleaf (af)forestation may significantly reduce summertime heat extremes over Europe. In fact, under SSP1-2.6 the cooling caused by LUC compensates for the warming caused by GHG and even leads to a substantial decrease in heat extremes by 2100 compared to today (> 1°C for the heat metric under consideration; **Figure 2**). Parts of the cooling pattern clearly follow LUC features (e.g., the forestation line stretching across southwestern Russia), hinting at highly local effects of heatwave attenuation (Asselin et al. 2024).

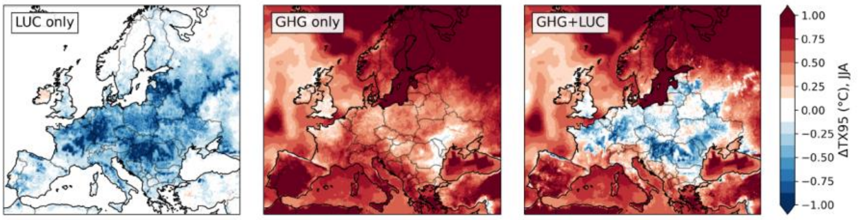

Figure 2: (adapted from Asselin et al. 2024) LUC trump GHG in mitigating summer heat extremes. From left to right the panels show the respective contributions of land-use change (ΔLUCTX95, left panel), greenhouse gas emissions (ΔGHGTX95, middle panel) and their sum (ΔGHG+LUCTX95, right panel) to summer heat extremes, defined by the 95th percentile of maximum daily temperature (TX95) over the months of June, July and August (JJA). See Asselin et al. 2024 for further details.

The cooling effect follows an increase in latent heat flux and evapotranspiration (net evaporative cooling), which offsets GHG warming.

2.2.2 Hydrometeorological implications of LUC

Figure 3 depicts the projected impact of LUC on evaporation, precipitation and runoff based on ClimEx-II. Under strong afforestation, the shift towards latent heat flux during heat extremes enhances evapotranspiration and precipitation, but also reduces runoff, leading to decreased net water availability and drying in some regions (**Figure 3**). While evapotranspiration (left panel) indicates strong local responses in some places (strongly related to the LUC patterns), changing precipitation patterns hint at non-local effects as well (left, center panel).

The additional water evaporated by "new" forests is mostly drawn from soil moisture, in particular, from the deeper layers that can be accessed by the tree roots. This results in more green water (by evapotranspiration), but less blue water in soil, streams, reservoirs and aquifers. Blue water resources are essential to support European communities and ecosystem services. Hence, the implications of the projected changes on water cycles and heat extremes highlight a critical trade-off between cooling benefits and potential water scarcity related to ambitious forestation.

As indicated by the dotted areas on Figure 3, the inter-member variability is large in some areas and needs to be accounted for when assessing the magnitude of the signals and thereby the robustness of conclusions.

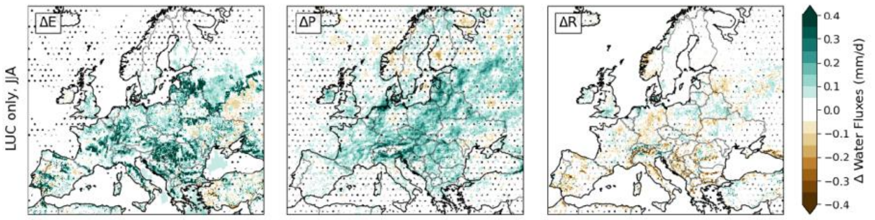

Figure 3: (adapted from Asselin et al. 2024) LUC drive widespread increases in evapotranspiration and precipitation, but the latter signal is significantly more non-local and diffuse. The resulting run-off change is more patchy. The ensemble-average values of LUC-induced changes in the summertime water fluxes (E: evapotranspiration; P: precipitation; R: run-off) are displayed in color. Zones of disagreement in the sign of changes, meaning that 2 of the

members show a positive sign while the other 2 show a negative sign, are dotted and can be considered an indication of uncertainty.

2.3 Data availability

This section provides an overview of the different LUC/GHG combinations and availability in ClimEx-II. The ClimEx-II ensemble consists of 48 ensemble members/simulations comprising a total data amount of 464 TB. **Table 1** summarizes the characteristics of the ensemble simulations. Note that the SSP-driven simulations are not transient but cover two periods: 1979-2015 (present GHG and Land Cover) and 2064-2100 (combinations of SSP/present land cover and SSP GHG). Simulation names indicate *member-GHG-land cover* combinations. For member acronyms, the first letter indicates the member (e, f, g, h), the second letter provides the GHG scenario (p - present, o - SSP1, t - SSP3) and the third letter the land cover scenario (p - present, o - SSP1, t - SSP3). For ERA5-driven runs, *er* indicates "ERA5", and the third letter refers again to the land cover scenario (p - present, o - SSP1, t - SSP3).

Examples:

- erp: ERA5-driven run in the present (1979-2020) [er] using present land cover (2015) [p]
- ett: Run forced by member #1 of the MPI-ESM-LR (r1i1p1f1) [e] at the end-of-century (2064-2100) under the SSP3-7.0 scenario [t] with land cover consistent with end-of-century (2100) SSP3-7.0 [t].

Table 1: CRCM5 simulations over Europe.

Simulation	Forcing	Member	Land Cover	GHG	Period	Domain
erp	**ERA5**	**x**	**Present**	**Present**	**1979-2020**	**EU**
erh	ERA5	x	Historical	Present	1979-2020	EU
ero	ERA5	x	SSP1	Present	1979-2020	EU
ert	ERA5	x	SSP3	Present	1979-2020	EU
epp	**MPI-ESM**	**r1i1p1f1**	**Present**	**Present**	**1979-2015**	**EU+**
eop	**MPI-ESM**	**r1i1p1f1**	**Present**	**SSP1**	**2064-2100**	**EU+**
eoo	MPI-ESM	r1i1p1f1	SSP1	SSP1	2064-2100	EU+
etp	**MPI-ESM**	**r1i1p1f1**	**Present**	**SSP3**	**2064-2100**	**EU+**
ett	MPI-ESM	r1i1p1f1	SSP3	SSP3	2064-2100	EU+
fpp	**MPI-ESM**	**r2i1p1f1**	**Present**	**Present**	**1979-2015**	**EU+**
fop	**MPI-ESM**	**r2i1p1f1**	**Present**	**SSP1**	**2064-2100**	**EU+**
foo	MPI-ESM	r2i1p1f1	SSP1	SSP1	2064-2100	EU+
ftp	**MPI-ESM**	**r2i1p1f1**	**Present**	**SSP3**	**2064-2100**	**EU+**
ftt	MPI-ESM	r2i1p1f1	SSP3	SSP3	2064-2100	EU+
gpp	**MPI-ESM**	**r3i1p1f1**	**Present**	**Present**	**1979-2015**	**EU+**
gop	**MPI-ESM**	**r3i1p1f1**	**Present**	**SSP1**	**2064-2100**	**EU+**
goo	MPI-ESM	r3i1p1f1	SSP1	SSP1	2064-2100	EU+
gtp	**MPI-ESM**	**r3i1p1f1**	**Present**	**SSP3**	**2064-2100**	**EU+**
gtt	MPI-ESM	r3i1p1f1	SSP3	SSP3	2064-2100	EU+
hpp	**MPI-ESM**	**r4i1p1f1**	**Present**	**Present**	**1979-2015**	**EU+**
hop	**MPI-ESM**	**r4i1p1f1**	**Present**	**SSP1**	**2064-2100**	**EU+**
hoo	MPI-ESM	r4i1p1f1	SSP1	SSP1	2064-2100	EU+

htp	MPI-ESM	r4i1p1f1	Present	SSP3	2064-2100	EU+
htt	MPI-ESM	r4i1p1f1	SSP3	SSP3	2064-2100	EU+

The simulations marked in green indicate climate simulations carried out for the baseline period of 1979-2015 (2020). The simulations marked in orange indicate climate simulations carried out in the same way as CORDEX simulations, that is, with fixed land use and land cover. For each scenario (GHG) there are four ensemble members (i.e. eop, fop, gop and hop for SSP1-2.6 and etp, ftp, gtp and htp for SSP3-7.0).

The remaining ensemble members employ variant land cover and land use information that essentially downscale the global shared socio-economic pathways to regional scale as described above.

Invariant (geophysical) fields like land cover fractions are also available.

A selection of variables produced as sub-monthly time series are shown in **Table 2.**

Commented [AB2]: Actually, there are many more variables available on monthly scales, though most likely not of interest to the case studies (monthly average of northward wind on different geopotential height levels, anyone? 😜). Therefore, I'd like to stick to the table shown here. Upon request, we may still check for the more exotic variables.

Table 2: ClimEx-II output variables.

Variable	Description	Temporal resolution	unit
capei	Atmospheric convective available potential energy	*3 hourly*	J kg-1
dds	Near-surface dewpoint depression	*3 hourly*	K
evspsbl	Evaporation	*3 hourly*	kg m-2 s-1
hfls	Surface Upward Latent Heat Flux	*3 hourly*	W m-2
hfss	Surface Upward Sensible Heat Flux	*3 hourly*	W m-2
hurs	Near-Surface Relative Humidity	*3 hourly*	%
huss	Near-sfc Specific Humidity	*3 hourly*	1
mrso	Total soil moisture content	*3 hourly*	kg m-2
mrsos	Moisture in Upper Portion of Soil Column	*3 hourly*	kg m-2
pr	Precipitation	*hourly*	kg m-2 s-1
prc	Convective precip	*3 hourly*	kg m-2 s-1
prlp	Liquid precipitation	*3 hourly*	kg m-2 s-1
ps	Surface air pressure	*3 hourly*	Pa
psl	Sea-level pressure	*3 hourly*	Pa
rsds	Surface Downwelling Shortwave Radiation	*3 hourly*	W m-2
sfcWindmax	Daily Maximum Near-Surface Wind Speed	*Daily*	m s-1
snd	Snow thickness	*3 hourly*	m
tas	Near-surface air temp	*3 hourly*	K
tasmax	Daily Maximum Near-Surface Temperature	*Daily*	K
tasmin	Daily Minimum Near-Surface Temperature	*Daily*	K
ts	Surface temperature	*3 hourly*	K
tsmax	Maximum Near-Surface Temperature	*3 hourly*	K
tsmin	Minimum Near-Surface Temperature	*3 hourly*	K
tso	Sea-surface temperature	*3 hourly*	K
uas	Surface Eastern wind	*3 hourly*	m s-1
vas	Surface Northern wind	*3 hourly*	m s-1

zg	Geopotential Height	*3 hourly*	m

The regional climate model data mentioned above are available in NetCDF or GRIB file formats, which are file formats for storing multidimensional scientific data such as temperature, humidity, air pressure, and wind speed. Facilities exist for processing these special file formats, including CDO (LINUX or Windows/Cygwin shell), R, Fortran and Python codes/libraries and MATLAB. For less experienced users, NetCDF/GRIB files can be viewed in e.g., IDV or Panoply. Also, the KNMI ClimateExplorer (https://ClimExp.knmi.nl) provides simple procedures for processing of climate model data and for providing visualizations and download options.

A comprehensive list of tools for processing NetCDF and GRIB files may be found at

https://www.unidata.ucar.edu/software/netcdf/software.html.

3.0 Data needs by case study

The nine case studies in the ARSINOE project span a wide range of climate challenges ranging from water resources management (Main River Basin, Ohred/Prespa Lakes, Canary Islands and Sardinia), flooding (Canary Islands, Southern Denmark, Torbay and Devon County), heat-related stressors (Athens, Ports), marine conditions (Ports), to other rare extremes and compound events (Main River Basin, Southern Denmark). Consequently, the need for climate projections of key hydro-meteorological quantities varies between CSs.

Table 3 summarises the current and future climate data needs by each CS for implementing the common climate scenario baseline (Chapter 4). The first two columns identify the different CS (number and name), followed by a short description of the local model, which will be use the climate data as input (column 3). For a detailed description of the land surface response tools used within ARSINOE, we refer to D3.7. The fourth and fifth columns indicate the local (reference) climate scenarios, and the time horizon(s) implemented by the different CS until Month 36 in alignment with stakeholder needs and data availability. As indicated in **Table 3**, most CS (except Canary Islands) employ (EURO-) CORDEX or a similar source of climate projections downscaling CMIP5 global scenarios (RCP4.5 and RCP8.5). The sixth column summarizes the key hydro-meteorological variables that will be derived from the CLIMEX-II ensemble (Chapter 2) and used by the case study modelling teams. Finally, the last column lists the expected outcomes in terms of new climate data sets provided by each CS.

An updated description of each CS (including the broader data needs: Table 5) can be found in D6.3.

Table 3: Overview of climate data needs by each CS (variables, current climate, future projections under different climate scenarios). The table was partly reproduced from D3.4, D3.7 with updates from Table 5 in D6.3.

#	CS	Description	Local scenarios	Local time horizon	Climate data (input)	Analysis (output)
1	Metropolitan Athens	Climate indicators	CMIP5: RCP2.6, RCP4.5, RCP8.5	2031-2050 2081-2100	Temperature, relative humidity (daily)	Daily minimum/maximum temperature Daily humidex (compound index of temperature and relative humidity) Derived indices (e.g., number of days per year with maximum temperature >35C, number of days per year with humidex >38C)
2	Ports (Valencia,	Climate indicators	Not specified (CMIP5 RCMs: CNRM-ALADIN /	2040-2060 2080-2100	Precipitation, wind, wind surface, relative humidity, sea level	Waves

	Piraeus, Limassol)		ALADIN-Climat, DMI-HIRHAM5, SMHI-RCA4			
3	Main river	Water Flow and Balance Simulation Model Hydrological model (WaSiM)	CMIP5: RCP8.5	2041-2060 (2041-2071) 2081-2100 (2071-2100)	Temperature, precipitation, radiation, relative. humidity, wind, topography, land use, soils	Streamflow, precipitation, radiation, temperature, humidity, wind, evapotranspiration, soil moisture, groundwater recharge, snow storage, direct runoff, interflow
4	Prespa/Ohrid lakes	Hydrological and integrated water management model across sectors (climate – water –energy – food)	CMIP5: RCP2.6, RCP8.5	2021-2100	Temperature, precipitation (daily) (local hydrological data - inflows)	Water level in the lakes, pprecipitation, temperature, radiation, humidity, wind, evapotranspiration, soil moisture, groundwater recharge, snow storage/melt, direct runoff, interflow
5	Canary Islands	Groundwater models (insular) (GW-EH-LP + FEFLOW)	CMIP5: RCP4.5 and RCP8.5	2022-2100	Maximum temperature, minimum temperature, precipitation (daily), Sea level rise	Water production cost (economic damage cost) Water quality production (saltwater intrusion)
5	Canary Islands	Hydrodynamic h2d	CMIP5: RCP4.5 and RCP8.5	2015-2046 2080-2100	Wind and sea level	Free surface
6	Black Sea	Hydrology (HEC-HMS)	CMIP5: RCP4.5 and RCP6.0	2040-2060	Precipitation, temperature (daily)	Streamflow
6	Black Sea	3D Coupled Hydrodynamic – Biogeochemistry Model	CMIP6: SSP2-4.5 and SSP5-8.5	2020-2040 2080-2100	Meteorological forcing (daily)	Temperature, salinity, sea surface height, velocity, etc.
7	Southern Denmark	Climate projections of extremes	CMIP5: RCP4.5 and RCP8.5	2041-2060, 2081-2100	Temperature, precipitation, wind, sea level pressure, sea level rise (tide)	Downscaled precipitation statistics (sub-daily), regional sea level rise, extreme sea level statistics, drought indicator (SPEI)
7	Southern Denmark	Flood model (SCALGO Live)	CMIP5: RCP4.5 and RCP8.5;	2041-2060, 2081-2100	Precipitation statistics, extreme sea level statistics	Flood depth and extent
8	Torbay and Devon County	Flood model (CAFlood)	CMIP5: RCP2.6, RCP4.5, RCP6.0, RCP8.5 CMIP6: SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	2021-2040, 2061-2080	Precipitation, design rainfall, downscaled UK climate projections	Water depth, flood extent, flood duration for the modelled domain, water depth hydrograph at selected locations
9	Sardinia	Crop modelling (CERES-Wheat model)	RCP4.5 and RCP8.5 CMIP6: SSP1-2.6, SSP2-4.5, SSP4-6.0, SSP5-8.5	2050 (2026-2075), 2080 (2076-2099)	Maximum and minimum temperature, total precipitation, global solar radiation (daily), soil data	Crop phenology and crop yield Water and nutrient balances
C9	Sardinia	Crop modelling (AQUACROP-OS and AQUACROP-OSPy)	ERA5 LAND + RCP4.5 and RCP8.5	1950-2023 & 2024-2050	Daily maximum and minimum temperature, precipitation, potential evapotranspiration (daily), crop and soil characteristics	Crop yield Maximum yield and Net Irrigation

4.0 Implementing the ARSINOE climate scenario baseline

4.1 Rationale (updated from D3.4)

The nine ARSINOE CSs are designed to span a portfolio of challenges related to climate resilience in the context of green and sustainable development. They rely on a variety of modelling approaches with associated requirements for current and future climate data. Establishing a common climate scenario baseline across the different cases is needed not only to enable systematic evaluation across different domains but also to facilitate transferability and upscaling of lessons learned beyond the lifetime of the project and in the context of other European projects, for example in terms of being in line with content published by Climate-ADAPT (https://climate-adapt.eea.europa.eu/en).

To estimate the deep uncertainties related to both future socio-economical and reference concentration pathways and to climate model simulations, it is in general necessary to consider and simulate many combinations of SSPs and RCPs using a large number (ensemble) of climate models. Regional downscaling and impact models add additional complexities. For many practical applications, such an approach is therefore computationally expensive and not possible to implement along a full modelling chain from global to local scales, i.e. considering different SSP/RCP scenarios, global model-based climate projections, regional downscaling using RCMs and/or empirical-statistical downscaling, impact models (including hydrological models), economic and adaptation models, and so on. The alternative approach, which is often relevant in case of lower data availability, is to analyse only *a few representative examples* that are found to be relevant and fit-for-purpose. This is the approach we adopted in ARSINOE (D3.4).

Selecting a representative sample of climate simulations can be done in a variety of ways, for example:

- If the objective is to explore the difference between different climate scenarios and their underlying narratives often simulations that represent the "mean" of the available global or regional climate projections (e.g. the ensemble mean), driven by a specific scenario, are used for impact and integrated assessment studies. This somewhat carries the underlying assumption that the projected "mean" represents the more robust result given the uncertainties associated with climate models.
- The number of climate scenarios considered (e.g. SSP/RCM combinations) can be further reduced by considering only a few scenarios, e.g. analysing a high and a low mitigation scenario.
- For many types of extremes, including precipitation extremes like floods and droughts, climate model uncertainty is generally more important than scenario uncertainty. In such cases, it may be useful to base analyses on a selection of climate scenarios/projections that can be shown to represent the spread of the combined ensemble in order to sample the full range of uncertainty. This can for example be done by selecting representative simulations from a set of climate projections that is forced by an "extreme" (non-mitigated) scenario like RCP8.5.
- For very short time horizon, i.e. the coming few decades, the natural climate variability dominates together with climate model uncertainty and the choice of climate scenario can be neglected.

To ensure that a limited number of simulations indeed presented the range of uncertainties, climate projections could be drawn from a large ensemble of model runs. Currently, the EURO-CORDEX-CMIP5 multi-model ensemble comprise more than 70 members. Conversely, the ClimEX-II SMILE has 48 ensemble members representing not only different climate scenarios but also different assumptions with respect to land use (Chapter 2).

ClimEx-II vs. CORDEX-CMIP5

Unlike CORDEX, The ClimEx-II dataset provides the means to assess the simultaneous effects of LULCC on climate change, natural climate variability, and hydro-meteorological extremes. This is in addition to “standard” regional climate projections. Since ClimEx-II uses the same domain with the same spatial resolution (~12 km) as CORDEX, ensemble members are interchangeable between the two ensembles. Both CORDEX and ClimEx-II allow for regional-level analyses though not necessarily at single-grid point level.

While the ClimEx-II experiment is designed for great flexibility, the number of ensemble members that accommodate a specific analysis is moderate. When assessing uncertainty in climate change projections due to internal variability, there are 4 different members of the same model (using the same forcing-LUC combinations); when carrying out a similar analysis with a focus on climate scenarios, the ensemble comprises 2 different SSPs with 4 members per LUC. Finally, there are 3 different LUC scenarios, with 4 members each per SSP, for analyses with respect to land cover.

It is essential to acknowledge that

1) ClimEx-II is a *single-model initial-condition ensemble*, i.e. there is but one model chain (MPI-ESM and CRCM5, including the land use scheme named CLASS) which “cannot capture the breadth of plausible outcomes, even within a specific scenario” (Asselin et al. 2024),
2) SSP1-2.6 and SSP3-7.0 represent two possible futures among many,
3) Land cover projections used in this set-up are contingent on the translator (Hoffmann et al. 2022) and the assumptions made for their projection,
4) While 4 members are a good starting point for assessing internal variability, it is theoretically insufficient (e.g. Asselin et al. 2024).

While the new CORDEX-CMIP6 climate projections, downscaling global climate models and scenarios from the Sixth Assessment Report of the IPCC (IPCC 2023), remain unavailable, climate projections from the ClimEx-II ensemble will be used within the scope of the ARSINOE project as means realize a common climate scenario baseline across CSs and to provide climate / extremes indicators or time series of key variables for the local modelling activities. A protocol for implementing the climate scenario baseline in CS may be found in Section 4.2.

Box 3. Climate indicators, model evaluation, and bias correction

Task 3.3 will support the implementation of the common climate scenario baselines in CSs by facilitating access to and / or providing the appropriate forcing data corresponding to SSP1-2.6 and SSP3-7.0 to CS modelling teams as indicated in Table 3.

For applications of the ClimEx-II data that require bias correction, Task 3.3 will perform bias correction of the data using, e.g. quantile-quantile mapping, and or advise CS partners in this regards. When performing a bias correction of the climate data, challenges with regards to the different land cover scenarios may arise. Hence, in general we recommend a focus on the “present-day” land cover members that are also compliant with CORDEX scenarios. For CS wishing to explore varying land cover scenarios, this will be handled on a case-by-case basis.

To support the upscaling and transferability of the results of the CS, several “standard” climate indicators, including indicators for temperature- and precipitation-related extremes (heatwaves, droughts, extreme precipitation, runoff, etc.) will be calculated at European and specifically at case study level and compared to indicators calculated from CORDEX-CMIP5 and ClimEx-I data.

All of the above will be reported in D3.6 (Month 45).

4.2 Protocol for implementation in case studies

A principal objective for carrying out joint modelling activities based on the same climate scenario baselines (see **Box 4**) is to be able to compare across different European domains and to facilitate the sharing of lessons learned from the ARSINOE project also beyond the scope of the project (Task 6.5). The outcomes of the joint modelling study will feed into Deliverable 6.7 (Resilience Assessment for all the Case Studies, Month 45).

On this background, the following protocol will guide the additional modelling that will be carried out within the CSs:

Scenarios: All CS should run simulations using the SSP1-2.6 and SSP3-7.0 narratives. They represent a (moderately) high mitigation scenario and a contrasting scenario with little or no mitigation to assess the spread of the potential outcomes.

Climate model projections: To evaluate climate model uncertainty and to allow for subsequent benchmarking of results against climate projections from CORDEX-CMIP6, when they become available, it is recommended that all CS (expect CS5 - Canary Islands, which is not covered by the EURO-CORDEX domain, and thereby will be using a different set of projections based on the abovementioned climate scenarios) will run simulations using the *4 ensemble members that represent “present day” land cover* for the baseline as well as for the future climate scenarios (SSP1-2.6 and SSP3-7.0). It is *optional* for CSs to explore also the ensemble members that employ the future downscaled land uses and land cover scenarios aligned with SSP1-2.6 and SSP3-7.0.

Time horizon: ARSINOE has defined two time horizons. The “near future” is defined as the time horizon of 2041-2060 (present day + 30 years) whereas the “future” or “end-of-century” is defined as 2081-2100. These time slices are largely compliant with what it is used by the IPCC and other studies. As indicated in Table 3 *most of the CS have already explored both of these time scales in the first phase of the modelling activities at CS level*.

In view of the (lack of) availability of climate projections from CORDEX-CMIP6 to implement the common climate scenario baseline, the subsequent delays, and the limited coverage of ClimEx-II (2064-2100), *only the end-of-century (2081-2100) time slice* will be included in the second phase of modelling at CS level that will be carried out between Month 37 and Month 45. That is, existing simulations for downscaled future CMIP5 scenarios will only be repeated for CMIP6 scenarios for the late time slice 2081-2100. Since projections for the “near future” (2041-2060) are expected to resemble the “present-day” and be dominated by natural variability and model rather than scenario uncertainty (D3.4, D3.7), it is thus probable that the new simulations would resemble the existing experiments.

In summary, the following climate projections should ideally be considered by all case studies:

Simulation	Forcing	Member	Land Cover	GHG	Period	Domain
erp	ERA5	X	Present	Present	1979-2020	EU
epp	MPI-ESM	r1i1p1f1	Present	Present	1979-2015	EU+
eop	MPI-ESM	r1i1p1f1	Present	SSP1	2081-2100	EU+

etp	MPI-ESM	r1i1p1f1	Present	SSP3	2081-2100	EU+
fpp	MPI-ESM	r2i1p1f1	Present	Present	1979-2015	EU+
fop	MPI-ESM	r2i1p1f1	Present	SSP1	2081-2100	EU+
ftp	MPI-ESM	r2i1p1f1	Present	SSP3	2081-2100	EU+
gpp	MPI-ESM	r3i1p1f1	Present	Present	1979-2015	EU+
gop	MPI-ESM	r3i1p1f1	Present	SSP1	2081-2100	EU+
gtp	MPI-ESM	r3i1p1f1	Present	SSP3	2081-2100	EU+
hpp	MPI-ESM	r4i1p1f1	Present	Present	1979-2015	EU+
hop	MPI-ESM	r4i1p1f1	Present	SSP1	2081-2100	EU+
htp	MPI-ESM	r4i1p1f1	Present	SSP3	2081-2100	EU+

In CSs where it will be necessary to reduce the number of simulations further, this will be agreed between Task 3.3 and the individual case studies.

Box 4. Climate scenario baseline in ARSINOE (updated from D3.4)

ARSINOE employs a *two-phased approach*, recognizing that regional downscaling of the most recent generation of climate models and (SSP/RCP) scenarios, i.e. CMIP6 models, were not available at the beginning of the project. Instead, in the first phase, CS are "free" to define their modelling setup, i.e. their choice of climate scenarios and climate models to use (Section 3). In many cases, this entails using RCP4.5 and RCP8.5 scenarios and one or more regional climate model projections from CORDEX forced by CMIP5 GCMs.

In the second phase, all CS will redo/update their model simulations within a common "workspace" given by the following global "reference scenarios" (shared socio-economic pathways):

- SSP1-2.6
- SSP3-7.0

Anthropogenic climate change is not just happening at a defined pace and magnitude; its severity depends on the underlying society, behaviour and development. That said, there are various pathways of future climate and societal development that may be equally likely; also, it is more complicated than picking what we believe is realistic. In terms of global emissions, the mentioned scenarios represent different "ends" of the scale. **SSP1-2.6** is a **high mitigation scenario** that aligns with the goals of the Paris Agreement, while **SSP3-7.0** is a "new" **low mitigation scenario** where the projected warming in 2100 will be of the order of 3-6.5C compared to pre-industrial levels. According to IPCC AR6, CMIP6 climate models on average give rise to slightly higher levels of warming than CMIP5 models, and hence the projected warming under CMIP6 and SSP3-7.0 is comparable to projected levels of warming under CMIP5 and RCP8.5.

The narrative of SSP1-2.6 is a "green" socio-economic pathway that aligns with the targets of the European Green Deal and the Sustainable Development Goals. Contrastingly, SSP3-7.0 represents "a rocky road" that resembles a business-as-usual scenario with high mitigation and high adaptation challenges. Downscaling the global SSPs to regional levels may be challenging, since there is currently no standardized methodology for downscaling SSPs. If necessary, this can therefore only be done within each CS on a case-by-case basis, bearing in mind that regional and local policies and developments may not follow global or even national trends. The CLIMEX-II ensemble explicitly considers land use and land cover changes aligned with the SSP1-2.6 and SSP3-7.0, these are *optional to use* by the CSs.

For each of the two "baseline scenarios", we recommend carrying out multiple simulations to account for the climate projection uncertainty and subsequent comparative benchmarking against CORDEX-CMIP6 model simulations. Based on Section 3 of this deliverable and interactions with the individual CS, **appropriate forcing data corresponding to SSP1-2.6 and SSP3-7.0 will be made available to CS modelling teams from around M38**.

In terms of time horizons, ARSINOE defines the "**near future**" as the time horizon of **2040-2060 (present day + 30 years)** as well as the **end-of-century 2081-2100**. These time slices are largely compliant with what it is used by the IPCC and other studies. Note that only the **end-of-century 2081-2100** time slice will be included in the second phase of modelling at CS level. *This is a deviation from D3.4.*

4.3 SSP1-2.6 and SSP3–7.0

In the following, the SSP1-2.6 and SSP3–7.0 narratives are briefly summarized:

SSP1: Sustainability – Taking the green road

- The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.
- Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society.
- Educational and health investments accelerate the demographic transition, leading to a relatively low population.
- Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being, even at the expense of somewhat slower economic growth over the longer term.
- Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries.
- Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term.
- Increased investment, financial incentives and changing perceptions make renewable energy more attractive.
- Consumption is oriented toward low material growth and lower resource and energy intensity.
- The combination of directed development of environmentally friendly technologies, a favorable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand results in **relatively low challenges to mitigation**.
- At the same time, the improvements in human well-being, along with strong and flexible global, regional, and national institutions imply **low challenges to adaptation**.

SSP3: Regional Rivalry – A rocky road

- A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
- Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets.
- Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies.
- Investments in education and technological development decline.

- Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. There are pockets of extreme poverty alongside pockets of moderate wealth, with many countries struggling to maintain living standards and provide access to safe water, improved sanitation, and health care for disadvantaged populations.
- A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. The combination of impeded development and limited environmental concern results in poor progress toward sustainability.
- Population growth is low in industrialized and high in developing countries.
- Growing resource intensity and fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply **high challenges to mitigation**.
- The limited progress on human development, slow income growth, and lack of effective institutions, especially those that can act across regions, implies **high challenges to adaptation** for many groups in all regions.

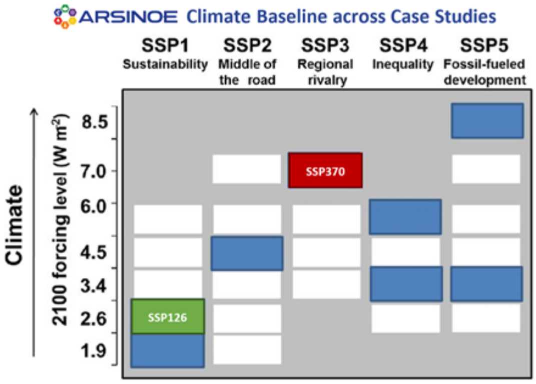

Fig. 4. ARSINOE Climate baseline across case studies: SSP1-2.6 and SSP3-7.0.

4.4 Summary

The current report is the second deliverable produced by Task 3.3 and updates D3.4. Following the consistent delay of new regional climate projections from EURO-CORDEX based on CMIP6, a revised methodology for implementing a common climate scenario baseline across ARSINOE CSs is introduced. Our revised methodology utilizes a novel set of climate projections provided by the ClimEx-II project, which is described in Chapter 2. These simulations were finished over the Spring and Summer 2024 and complement past and planned CORDEX simulations. Task 3.3 will support the integration of these climate projections in the CS and provide supplementary analyses to support upscaling and cross-evaluation of the results including beyond the scope of the project. Results from local (CS) modelling studies using the common climate scenario baseline will feed into the resilience assessment in all case studies, reported in Month 45 (D6.7).

ANNEX: References

Commented [MD3]: To be updated

Aalbers, E. E., Lenderink, G., van Meijgaard, E. & van den Hurk, B. J. J. M. (2018): Local-scale changes in mean and heavy precipitation in Western Europe, climate change or internal variability? Climate Dynamics, 50, 4745-4766.

Asselin, O., Leduc, M., Paquin, D., Noblet-Ducoudré, N., Rechid, D., Ludwig, R.: Blue in Green: Forestation Turns Blue Water Green, Mitigating Heat at the Expense of Water Availability, accepted for publication in Environmental Research Letters, 2024.

Böhnisch, A., Mittermeier, M., Leduc, M., & Ludwig, R. (2021). Hot spots and climate trends of meteorological droughts in Europe–assessing the percent of normal index in a single-model initial-condition large ensemble. Frontiers in Water, 3, 716621.

Böhnisch, A., Felsche, E., Mittermeier, M., Poschlod, B., Ludwig, R. (submitted): Future hotspots of compound dry and hot summers emerge in European agricultural areas. Submitted to Earth's Future

Böhnisch, A., Felsche, E., & Ludwig, R. (2023). European heatwave tracks: using causal discovery to detect recurring pathways in a single-regional climate model large ensemble. Environmental Research Letters, 18(1), 014038

Brunner, M. I., Swain, D. L., Wood, R. R., Willkofer, F., Done, J. M., Gilleland, E., & Ludwig, R. (2021). An extremeness threshold determines the regional response of floods to changes in rainfall extremes. Communications Earth & Environment, 2(1), 173.

Christensen, J. H., Larsen, M. A. D., Christensen, O. B., Drews, M., & Stendel, M. (2019). Robustness of European climate projections from dynamical downscaling. Climate Dynamics, 53(7-8), 4857–4869. https://doi.org/10.1007/s00382-019-04831-z

Davin, E. L. and Coauthors, 2020: Biogeophysical impacts of forestation in europe: First results from the lucas (land use and climate across scales) regional climate model intercomparison. Earth System Dynamics, 11, 183–200, doi:10.5194/esd-11-183-2020.

Felsche, E., Böhnisch, A., & Ludwig, R. (2023). Inter-seasonal connection of typical European heatwave patterns to soil moisture. npj Climate and Atmospheric Science, 6(1), 1.

Felsche, E., Böhnisch, A., Poschlod, B., Ludwig, R. (2024): European hot and dry summers are projected to become more frequent and expand north-wards, Communications Earth & Environment, 5, 410, https://doi.org/10.1038/s43247-024-01575-5

Hoffmann, P., Reinhart, V., and Rechid, D.: LUCAS LUC future land use and land cover change dataset for Europe (Version 1.1), https://doi.org/10.26050/WDCC/LUC_future_EU_v1.1, 2022.

Hoffmann, P., Reinhart, V., Rechid, D., de Noblet-Ducoudré, N., Davin, E. L., Asmus, C., Bechtel, B., Böhner, J., Katragkou, E., and Luyssaert, S.: High-resolution land use and land cover dataset for regional climate modelling: Historical and future changes in Europe, Earth System Science Data, 15, 3819–3852, 2023.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., et al.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geoscientific Model Development, 13, 5425–5464, 2020.

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H.

Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

Jacob, D., Teichmann, C., Sobolowski, S. et al. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. Reg Environ Change 20, 51 (2020). https://doi.org/10.1007/s10113-020-01606-9

Leduc, M. and Coauthors, 2019: The ClimEx Project: A 50-member Ensemble of Climate Change Projections At 12-km Resolution Over Europe and Northeastern North America With the Canadian Regional Climate Model (CRCM5). Journal of Applied Meteorology and Climatology, 58, 663–693, doi:10.1175/JAMC-D-18-0021.1.

Martynov, A., R. Laprise, L. Sushama, K. Winger, L. Separovic, and B. Dugas, 2013: Reanalysis-Driven Climate Simulation Over Cordex North America Domain Using the Canadian Regional Climate Model, Version 5: Model Performance Evaluation. Clim Dyn, 41, 2973–3005, doi:10.1007/s00382-013-1778-9.

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., et al.: Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1. 2) and its response to increasing CO2, Journal of Advances in Modeling Earth Systems, 11, 998–1038, 2019.

Miller, J., Böhnisch, A., Ludwig, R., Brunner, M. I. (2024): Climate change impacts on regional fire weather in heterogeneous landscapes of Central Europe. Natural Hazards and Earth System Sciences, 24, https://doi.org/10.5194/nhess-24-411-2024

Mittermeier, M., Braun, M., Hofstätter, M., Wang, Y., & Ludwig, R. (2019). Detecting climate change effects on Vb cyclones in a 50-member single-model ensemble using machine learning. Geophysical Research Letters, 46(24), 14653-14661.

Mittermeier, M., Bresson, E., Paquin, D., & Ludwig, R. (2022). A deep learning approach for the identification of long-duration mixed precipitation in Montréal (Canada). Atmosphere-Ocean, 60(5), 554-565.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., ... & Thépaut, J. N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth system science data, 13(9), 4349-4383.

Noblet-Ducoudré, N. de and Coauthors, 2012: Determining robust impacts of land-use-induced land cover changes on surface climate over north america and eurasia: Results from the first set of lucid experiments. Journal of Climate, 25, 3261–3281, doi:10.1175/JCLI-D-11-00338.1.

Olonscheck, D., Suarez-Gutierrez, L., Milinski, S., Beobide-Arsuaga, G., Baehr, J., Fröb, F., et al. (2023). The new Max Planck Institute grand ensemble with CMIP6 forcing and high-frequency model output. Journal of Advances in Modeling Earth Systems, 15(10), e2023MS003790. https://doi.org/10.1029/2023MS003790.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model

Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., . . . Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. Nature Climate Change, 10(12), 1074-1084. doi:10.1038/s41558-020-00952-0

Poschlod, B., Zscheischler, J., Sillmann, J., Wood, R. R. & Ludwig, R. (2020): Climate change effects on hydrometeorological compound events over southern Norway. Weather and Climate Extremes, 28, 100253.

Poschlod, B., Ludwig, R., & Sillmann, J. (2021). Ten-year return levels of sub-daily extreme precipitation over Europe. Earth System Science Data, 13(3), 983-1003.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Separovic, L., A. Alexandru, R. Laprise, A. Martynov, L. Sushama, K. Winger, K. Tete, and M. Valin, 2013: Present Climate and Climate Change Over North America As Simulated By the Fifth-Generation Canadian Regional Climate Model. Clim Dyn, 41, 3167–3201, doi:10.1007/s00382-013-1737-5.

Taylor, K.E., R.J. Stouffer, G.A. Meehl, An overview of CMIP5 and the experiment design, Bull. Amer. Meteor. Soc., 93, 485-498, DOI:10.1175/BAMS-D-11-00094.1, 2012.

Reinhart, V., Hoffmann, P., Rechid, D., Böhner, J., and Bechtel, B.: High-resolution land use and land cover dataset for regional climate modelling: a plant functional type map for Europe 2015, Earth System Science Data, 14, 1735–1794, 2022.

van Vuuren, D.P., Edmonds, J., Kainuma, M. et al. The representative concentration pathways: an overview. Climatic Change 109, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

Verseghy, D., McFarlane, N., and Lazare, M.: CLASS—A Canadian land surface scheme for GCMs, II. Vegetation model and coupled runs, International journal of climatology, 13, 347–370, 1993.

Verseghy, D. L.: CLASS—A Canadian land surface scheme for GCMs. I. Soil model, International Journal of Climatology, 11, 111–133, 1991.

Willkofer, F., Wood, R. R., & Ludwig, R. (2023). Assessing the impact of climate change on high return levels of peak flows in Bavaria applying the CRCM5 Large Ensemble. EGUsphere, 2023, 1-31.

Wood, R. R. (2023). Role of mean and variability change in changes in European annual and seasonal extreme precipitation events. Earth System Dynamics, 14(4), 797-816.

Systems Innovation Approach (SIA) addresses the growing complexity, interdependencies and interconnectedness of modern societies and economies, focusing on the functions of the cross-sectoral system as a whole and on the variety of actors. The Climate Innovation Window (CIW) is the EU reference innovations marketplace for climate adaptation technologies. ARSINOE shapes the pathways to resilience by bringing together SIA and CIW, to build an ecosystem for climate change adaptation solutions. Within the ARSINOE ecosystem, pathways to solutions are co-created and co-designed by stakeholders, who can then select either existing CIW technologies, or technologies by new providers (or a combination) to form an innovation package. This package may be designed for implementation to a specific region, but its building blocks are transferable and re-usable; they can be re-adapted and updated. In this way, the user (region) gets an innovation package consisting of validated technologies (expanding the market for CIW); new technologies implemented in the specific local innovation package get the opportunity to be validated and become CIW members, while the society (citizens, stakeholders) benefits as a whole. ARSINOE applies a three-tier, approach: (a) using SIA it integrates multi-faceted technological, digital, business, governance and environmental aspects with social innovation for the development of adaptation pathways to climate change for specific regions; (b) it links with CIW to form innovation packages by matching innovators with end-users/regions; (c) it fosters the ecosystem sustainability and growth with cross-fertilization and replication across regions and scales, at European level and beyond, using specific business models, exploitation and outreach actions. The ARSINOE approach is show-cased in nine widely varied demonstrators, as a proof-of-concept with regards to its applicability, replicability, potential and efficacy.

ARSINOE
CLIMATE-RESILIENT REGIONS THROUGH SYSTEMIC SOLUTIONS AND INNOVATIONS