Common climate scenario baseline

Deliverable 3.4: Climate projections for multi-hazard and multi-sectoral risk assessment (common baseline across cases)

WP3: Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework

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List of abbreviations

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

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

CORDEX: Coordinated regional downscaling project

CRCM: Canadian Regional Climate Model

CS: Case study (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

ML: Machine Learning

MSDMF: Multi-System Dynamic Resilience Modelling Framework

NetCDF: Network Common Data Form

RCM: Regional climate model

RCP: Representative concentration pathway

SRES: Special report on emission scenarios (by IPCC)

SSP: Shared socio-economic pathway

EXECUTIVE SUMMARY

This is the first 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 provides a detailed description of the SSP/RCP framework as defined in the preparation of the Sixth Assessment Report from the Intergovernmental Panel on Climate Change and used as the foundation for the 6th cycle of the Coupled Model Intercomparison Project (CMIP6). A summary of currently available sources of climate projections is included. This information is meant to be used within the ARSINOE project, including recommendations on model and scenario combinations. We have included a set of general guidelines for climate change impact assessments and an overview of the different hazard and impact models used by the different case studies. This overview includes relevant information on the individual climate baselines and climate data that are already available and will therefore be used initially. The document finalizes with a description and rationale for i) The reference SSP/RCP scenarios to be implemented by all case studies (CSs), that is, SSP1-2.6 and SSP3-7.0; ii) Time horizons (near future +30 years and end-of-century) iii) Optional recommendations for specific climate model combinations to be used in the initial phase of the modelling.

1.0 Introduction

1.1 Scope of the deliverable

To quantify, model and manage climate risk in a systematic way through resilience analyses co-created and co-designed with the stakeholders, ARSINOE will develop a Multi-System Dynamic Resilience Modelling Framework (MSDMF). The MSDMF integrates tools, methods and techniques from different academic disciplines and facilitates a holistic analysis of results. To this end, Task 3.3 will define common climate scenario baselines across the project and 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 investigated 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 is the first of three associated 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 as well as the Knowledge Graph. Deliverable 3.5 (Month 30) and 3.6 (Month 42) will update and extend the content of the current deliverable.

Each CS will apply its own suite of models assisted by, e.g., Tasks 3.1-3.4, to evaluate impacts and associated risks, including flooding and water scarcity, related to gradually changing climate conditions like temperature, precipitation, solar radiation, sea level rise; and climate extremes such as drought, extreme rains, storms, heatwaves; and select compound events including storm surges. Initially, most of these models come with existing preferences for specific climate scenarios, e. g. RCP 4.5 and RCP 8.5 (see Table 1), inherited from the current availability of climate data, national (policy or planning) recommendations, stakeholder consultation or simply previous model applications and may depend on local observations for model development, calibration, and/or bias correction. The hazard and impact models used in ARSINOE (see Section 3) span a wide range from simple climate indicator sets and hydrological models of varying complexities to dynamic urban-scale climate modelling using convection-permitting regional climate models. To be able to compare the results and findings of ARSINOE across the diverse modelling approaches and CSs as well as in a broader context, involving other national and international research actions like the "sister" projects IMPETUS and TRANSFORMAR, all CSs will therefore carry out a limited set of reference simulations based on the common scenario baseline (see Section 4) in the second part of the project. A detailed description of these simulations will be included in Deliverable 3.5.

1.2 Overview

This deliverable comprises the following sections

- A description of the (extended) SSP/RCP framework introduced in the preparation phase of the Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC) and used as the foundation for the 6th Cycle of the Coupled Model Intercomparison Project (CMIP6).
- A short summary of currently available sources of climate projections for use in ARSINOE, including optional recommendations on model and scenario combinations to be used in the first phase of the project.
- A set of general guidelines for climate change impact assessments.
- An overview of the different hazard and impact models used within ARSINOE including relevant information on the individual climate baselines and climate data that will be used initially
- A description and rationale for the "reference scenarios" to be implemented by all CS, that is, SSP1-2.6 and SSP3-7.0.

A list of references is provided as an annex.

2.0 Climate scenarios

Scenarios are used to explore how the future may evolve under a range of alternative conditions, and to better anticipate associated impacts. Scenarios represent coherent, internally consistent, and plausible descriptions of possible trajectories of changing conditions and therefore support adaptation decision-making under uncertainty (Kebede et al. 2018, O'Neill et al. 2020). In the following, we provide a description of the SSP/RCP framework and its implications, a brief overview of climate projections and available resources and a set of recommendations for climatic impacts analyses.

2.1 The SSP/RCP framework

Scenarios are commonly represented by global emissions trajectories. The RCP (Representative Concentration Pathways) framework currently used i.e., by the IPCC, was initially introduced in 2011 (van Vuuren et al. 2011). The framework was recently extended to include SSP (Shared Socioeconomic Pathways) combinations (Riahi et al. 2017), and is regularly updated.

2.1.1 Representative Concentration Pathways (RCP)

RCP scenarios include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs), aerosols and chemically active gases corresponding to a set of socioeconomic assumptions, including land use/land cover changes as simulated by global integrated assessment models (IAMs). The word "representative" here means that each RCP represents one out of many possible tracks that could lead to specific radiative forcing characteristics and ultimately a specific warming or cooling of the climate system. The term "pathway" emphasizes that not only the long-term concentration levels are of interest, but also the shape of the trajectory taken over time to reach that outcome (Moss et al., 2010). RCPs are generally named by the combined radiative forcing level in Watts per square meter ($W\ m^{-2}$) in 2100 when aggregating the influence from greenhouse gas emissions (GHGs), aerosols and chemically active gasses in the atmosphere.

The Fifth IPCC Assessment Report (AR5) used four RCPs as basis for the climate predictions and projections (Fig. 1):

- **RCP2.6** A high mitigation scenario. Along this pathway the radiative forcing peaks at approximately 3 $W\ m^{-2}$ before 2100 with a decreasing trend after the peak, reaching 2.6 $W\ m^{-2}$ by 2100.

- **RCP4.5** and **RCP6.0** Two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100.
- **RCP8.5** One high pathway for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some time.

The more recent AR6 extended this with a few more RCPs, however here they are embedded in a framework highlighting the underlying socioeconomic narratives or pathways explicitly.

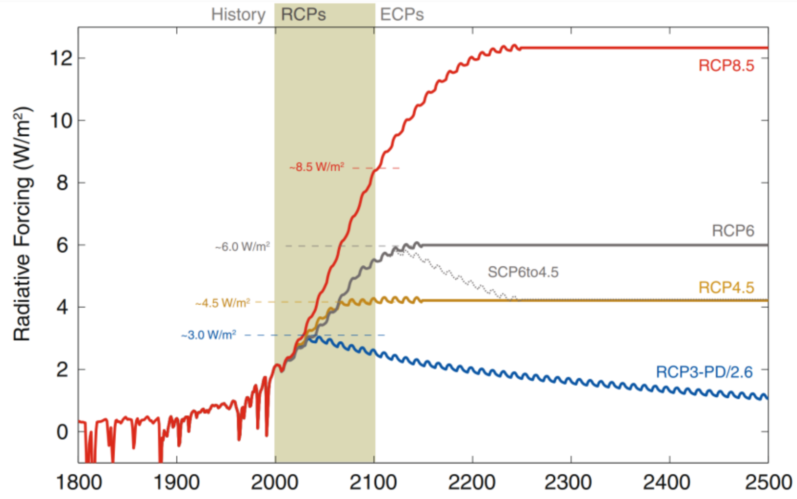

Figure 2.1 Representative Concentration Pathways. Total radiative forcing (anthropogenic plus natural) for RCPs, supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP2.6 (called as well RCP3-PD), RCP4.5 & RCP6, as well as RCP8.5, respectively. Note that the stated radiative forcing levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future radiative forcing levels. Short-term variations in radiative forcing are due to both volcanic forcing in the past (1800–2000) and cyclical solar forcing—assuming a constant 11-year solar cycle (following the CMIP5 recommendation), except at times of stabilization (Meinshausen et al. 2011).

2.1.2 Shared Socioeconomic Pathways (SSP)

The idea of shared socioeconomic pathways (SSPs) extends back to AR5 and has been developed as the basis for describing (global) socioeconomic scenarios and their associated emissions. A SSP is one of a collection of pathways that describe alternative futures of socioeconomic development with varying levels of climate policy intervention. A socioeconomic scenario describes a possible future in terms of population, gross domestic product (GDP), and other socioeconomic factors relevant to understanding the implications of climate change (Fig. 2).

The SSPs explore different ways in which the world might evolve in terms of climate policies. Combined with the mitigation targets of the RCPs, they enable an assessment of the extent to which climate change mitigation could be achieved in different socio-economic states. The SSPs used in AR6 are based on five narratives describing broad socioeconomic trends that could shape future society.

- **SSP1:** The sustainable and “green” pathway describes an increasingly sustainable world. Global commons are being preserved; the limits of nature are being respected. The focus is more on human well-being than on economic growth. Income inequalities between states and within states are being reduced. Consumption is oriented towards minimizing material resources and energy usage.

- **SSP2**: The “middle of the road” or medium pathway extrapolates the past and current global development into the future. Income trends in different countries are diverging significantly. There is a certain cooperation between states, but it is barely expanded. Global population growth is moderate, leveling off in the second half of the century. Environmental systems are facing a certain degradation.
- **SSP3**: Regional rivalry. A revival of nationalism and regional conflicts pushes global issues into the background. Policies increasingly focus on questions of national and regional security. Investments in education and technological development are decreasing. Inequality is rising. Some regions suffer drastic environmental damage.
- **SSP4**: Inequality. The chasm between globally cooperating developed societies and those stalling at a lower developmental stage with low income and a low level of education is widening. Environmental policies are successful in tackling local problems in some regions, but not in others.
- **SSP5**: Fossil-fueled development. Global markets are increasingly integrated, leading to innovations and technological progress. The social and economic development, however, is based on an intensified exploitation of fossil fuel resources with a high percentage of coal and an energy-intensive lifestyle worldwide. The world economy is growing and local environmental problems such as air pollution are being tackled successfully.

Fig. 2 provides an overview of the considered Shared Socioeconomic Pathways (SSP1 to SSP5) projections and their associated a) Development of global population and education, b) urbanization, c) GDP, and d) GDP per capita and Gini index.

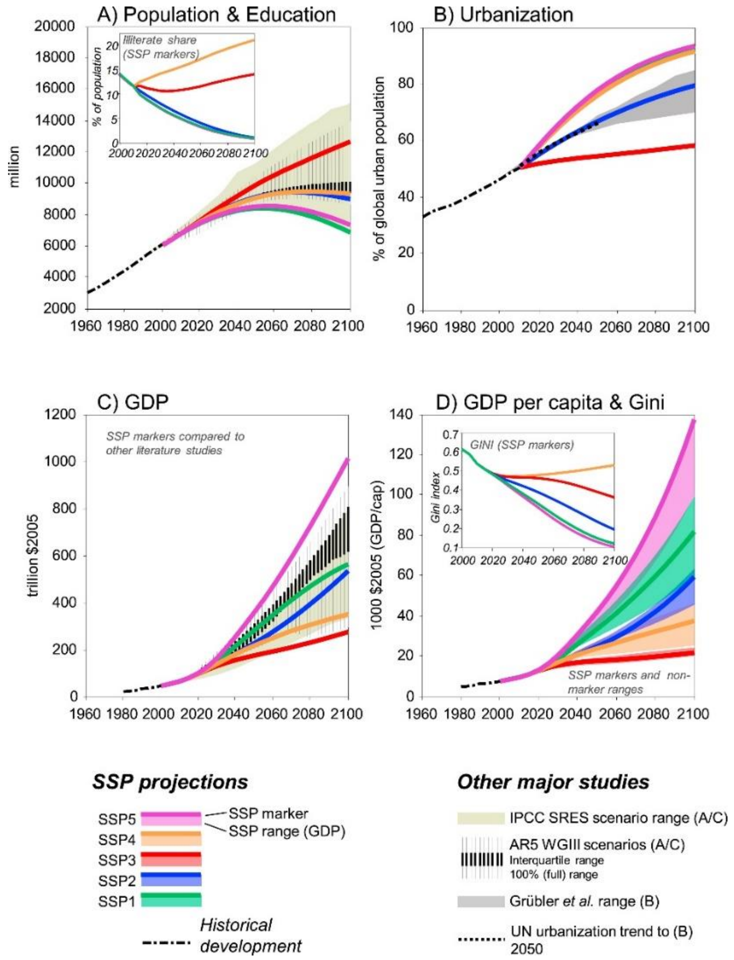

Figure 2.2 Shared Socioeconomic Pathways projections. Development of global population and education (A), urbanization (B), GDP (C), and GDP per capita and the Gini index (D). The inset in panel A gives the share of people without education at age of ≥15 years, and the inset in panel D denotes the development of the global (cross-national) Gini index. The SSPs are compared to ranges from other major studies in the literature, such as the IPCC AR5 (Clarke et al., 2014), IPCC SRES (Nakicenovic and Swart, 2000), UN, and Grübler et al. (2007). The colored areas for GDP (panel D) denote the range of alternative SSP GDP projections (Dellink et al. (2017), Crespo Cuaresma (2017), Leimbach et al. (2017), and Riahi et al. (2017).

2.1.3 SSP/RCP-Framework

The AR6 uses a combined SSP/RCP framework, which, as already mentioned, combines alternative socioeconomic development pathways (SSPs) yielding with different atmospheric concentration pathways (RCPs) and ultimately their associated climate change outcomes.

The primary goals of the framework is to (O'Neill et al. 2020):

- support climate change-related research globally across research communities and be extendable to other scales, sectors and issue areas
- facilitate research that integrates climate and societal futures by providing more detailed socioeconomic and political conditions as inputs to studies of impacts, adaptation and mitigation
- foster consideration of uncertainty in future climate and societal conditions by describing a wide range of plausible futures

- encourage more coherent synthesis in scientific assessments by improving the consistency of climate and societal assumptions in the literature; and
- support research and analysis to inform policy

The IPCC/AR6 has recently given special attention to the following SSP/RCP scenarios:

- **SSP5-8.5:** With an additional radiative forcing of 8.5 W/m² by the year 2100, this scenario represents the upper boundary of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 scenario RCP8.5, now combined with socioeconomic reasons.

- **SSP3-7.0:** With 7 W/m² by the year 2100, this scenario is in the upper-middle part of the full range of scenarios. It was newly introduced after the RCP scenarios, closing the gap between RCP6.0 and RCP8.5.

- **SSP2-4.5:** As an update to scenario RCP4.5, SSP245 with an additional radiative forcing of 4.5 W/m² by the year 2100 represents the medium pathway of future greenhouse gas emissions. This scenario assumes that climate protection measures are being taken.

- **SSP1-2.6:** This scenario with 2.6 W/m² by the year 2100 is a remake of the optimistic scenario RCP2.6 and was designed with the aim of simulating a development that is compatible with the 2°C target. This scenario, too, assumes climate protection measures being taken.

In addition, AR6 and the preceding IPCC Special Report on the impacts of global warming of 1.5 °C introduced a set of so-called “overshooting scenarios”, e.g. SSP5-3.4-OS, in which the GHG concentration in the atmosphere temporarily exceeds some pre-defined, “dangerous” threshold before being reduced to non-dangerous levels. An “overshoot” lets global temperatures temporarily rise above 1.5°C or higher and then uses e.g. carbon capture to bring them back down in a few decades.

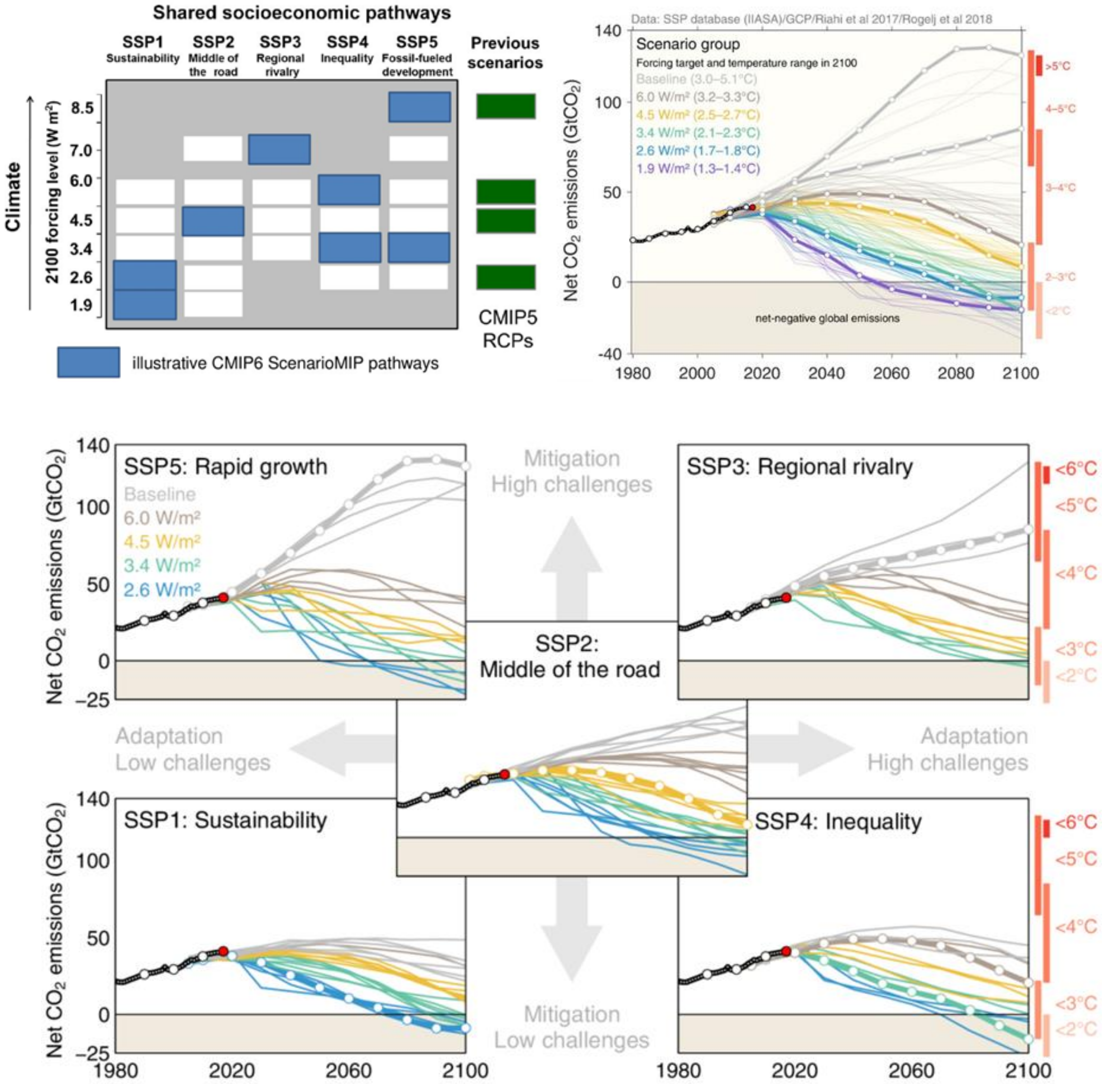

Figure 2.3 Overview of SSP/RCP scenarios (CMIP6, ScenarioMIP – Tier 1, adapted from O'Neill et al. (2016)) and the associated net CO_2 emissions (Riahi et al. 2017, Rogelj et al. 2018).

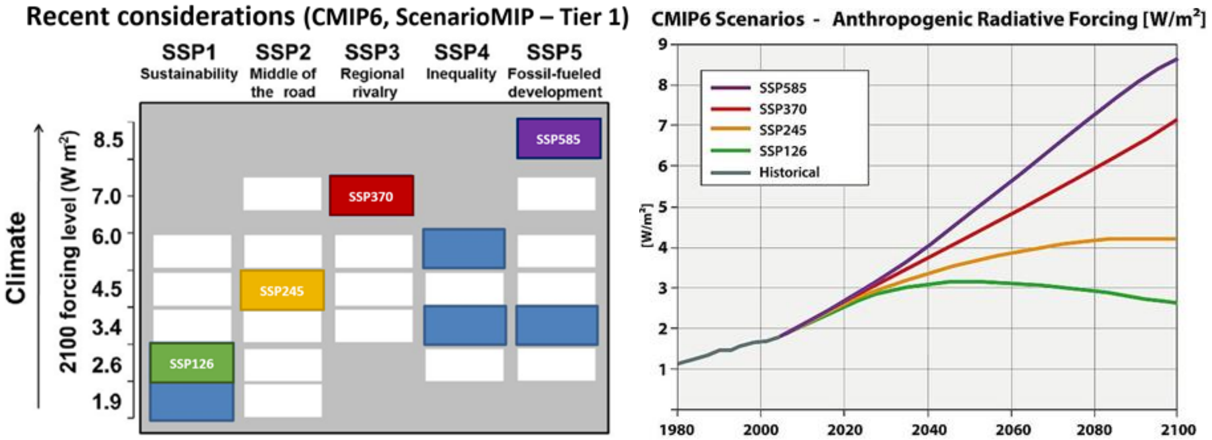

Figure 2.4 Overview of recent considerations of SSP/RCP scenarios adapted from O'Neill et al. (2016). a) Combinations of RCPs and SSPs that have been recently considered are highlighted; b) CMIP6 scenarios and the associated anthropogenic radiative forcing.

2.2 Climate projections

2.2.1 Available data sources

Recent IPCC assessments generally rely on the concerted efforts of the **Coupled Model Intercomparison Projects (CMIP)**. The CMIPs somewhat defines the common procedure and scenarios (see above) used by global climate modelling groups worldwide to ensure the consistency and validation of the results feeding into IPCC assessments and, more generally, the scientific community. The thousands of simulations included in the CMIP climate model ensembles are openly published by and can be downloaded from the **Earth System Grid Federation (ESGF)** network of data servers. The AR5 used global circulation models (GCMs) and Earth System Models (ESMs) from the 5th CMIP cycle (CMIP5), while AR6 features results from more than 100 distinct state-of-the-art climate models included in CMIP6.

Climate predictions and projections from global climate models in general provide information on scales of a hundred km's or coarser. In order to obtain information on smaller scales as needed for e.g., climate risk and adaptation assessments, regional climate models (RCM) and empirical statistical downscaling (ESD) can be applied over a limited area, driven by (nested within) the GCMs. The World Climate Research Programme's **Coordinated Regional Downscaling Experiment (CORDEX)** provides downscaled climate projections from a wide range of state-of-the-art RCMs produced by leading climate science centres around the world. The CORDEX climate model ensembles spans 14 strategically located regional domains across the world, which are generally resolved at 50 km horizontal resolution. For some regions, including Europe (e.g. EuroCORDEX) climate projections are available down to 11 km horizontal resolution or even finer.

The CORDEX RCMs typically use re-analysis or GCM as boundary forcing data. In general, simulations cover, the historical period from 1979-2017 when forced by re-analysis data and 1950 to 2005 when forced by GCM data. Future projections are mainly available towards year 2100 (for technical reasons some stop in 2099) but some runs also cover the period until 2300. Most currently available CORDEX runs employ CMIP5 data as GCM forcing and spans the RCP2.6, RCP4.5 and RCP8.5 scenarios. The temporal resolution ranges from sub-daily to monthly values. Current efforts are made to downscale the new global CMIP6 runs, however since this is an uncoordinated effort there is not exact timeline. It is expected that a large number of new simulations forced by CMIP6 models will populate the CORDEX database within 2023. This will imply a transition of scenarios from RCPs towards SSPs, with a priority for Tier 1 scenarios including SSP1-2.6 and SSP3-7.

From the combination of CMIP and CORDEX runs or from CMIP runs alone, multi-model ensembles are often employed as means to estimate specific measures and metrics of robustness or to, more simply, provide an estimate of the output range, with the main intent of addressing cross-model variability. The internal climate model variability has also been addressed in a number of single-model ensemble studies employing perturbation techniques or testing the influence of setup specific criteria. One of the most extensive data repositories that enables the assessment of single model variability stems from the **CLIMEX** project, where the CANESM2 GCM is used to force the CRCM5 RCM from 1950-2100 for 50 ensemble members across a large subset of key variables. Beyond year 2006, RCP8.5 is used. Model output using the forcing from ERA-Interim (re-analysis data) from 1980-2013 is also available for model evaluation purposes.

2.2.2 Tools

Climate model data is most often 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.

2.3 Guideline to climate change assessments

The appropriate framework for a climate change assessment is dependent on the specific application. In the following, we describe some common guidelines based on scientific best practices. The inherent uncertainties in climate model simulations are briefly discussed and some recommendation for a variety of applications are given.

In the previous sections, it was highlighted that there are different climate scenarios, which entail different trajectories of global warming. Likewise, different climate models project low/high levels of change under the same forcing scenario due to model uncertainty. In general, uncertainty associated with future climate projections can be partitioned into the three major sources: scenario uncertainty, model uncertainty, and internal climate variability. See Lehner et al. (2020) for a comprehensive discussion and partitioning of uncertainties. Due to the inherent uncertainties, it is critically important to communicate and discuss these uncertainties in order to draw meaningful conclusions from any climate change analysis. The analysis of a single climate simulation is inadequate for robust climate change assessments.

Scenario uncertainty, or radiative forcing uncertainty, describes the uncertainty related to the unknown future levels of greenhouse gas concentrations. Since these scenarios are socioeconomic what-if scenarios, they can be considered an irreducible source of uncertainty (at least from a climate science perspective). The scenario uncertainty can somewhat be quantified using members from a single- or multi-model ensemble (i.e., CORDEX, CMIP5/6) representing different RCP or SSP-RCP emission scenarios.

The uncertainty from **internal climate variability** arises from the chaotic nature of the Earth system induced by natural processes in the atmosphere-ocean-land-biosphere-cryosphere system. This can be considered an irreducible source of uncertainty, which is present at any given point in the future or past. The current best practice of quantifying internal climate variability are long control simulations (under the assumption of stationarity in the quantity of internal variability) or from single model initial condition ensembles (including non-stationarity in the response of internal variability under external forcing).

Model uncertainty, or climate response uncertainty, are determined by differences between the climate models (e.g. structural differences, differences in the representation of key climate processes), leading to differences in the model's response to external forcing. The differences between the models thus arise from differences in model components and the setup/tuning of the model. Since these differences can be boiled down to model errors, they can be considered as a reducible uncertainty under constant improvements of the models. In order to distinguish between model uncertainty and internal climate variability, the model's true forced response (i.e., the model's response to external forcing under a given emission scenario) needs to be robustly quantified. A robust estimate of the forced response can be quantified by averaging of simulations from a single model initial condition ensemble.

The fractional contribution from all three sources of uncertainty are dependent on the projected time horizon in future (i.e., short-term (10-30 years), long-term (>50 years)), but is also highly dependent on the geographic region, regional extent (global vs. local), season, and target variables among others. To exemplify, **Error! Reference source not found.** showcases the fractional contribution of each uncertainty source to decadal projections of temperature and precipitation on global and regional scales. The figure is taken from Lehner et al. (2020).

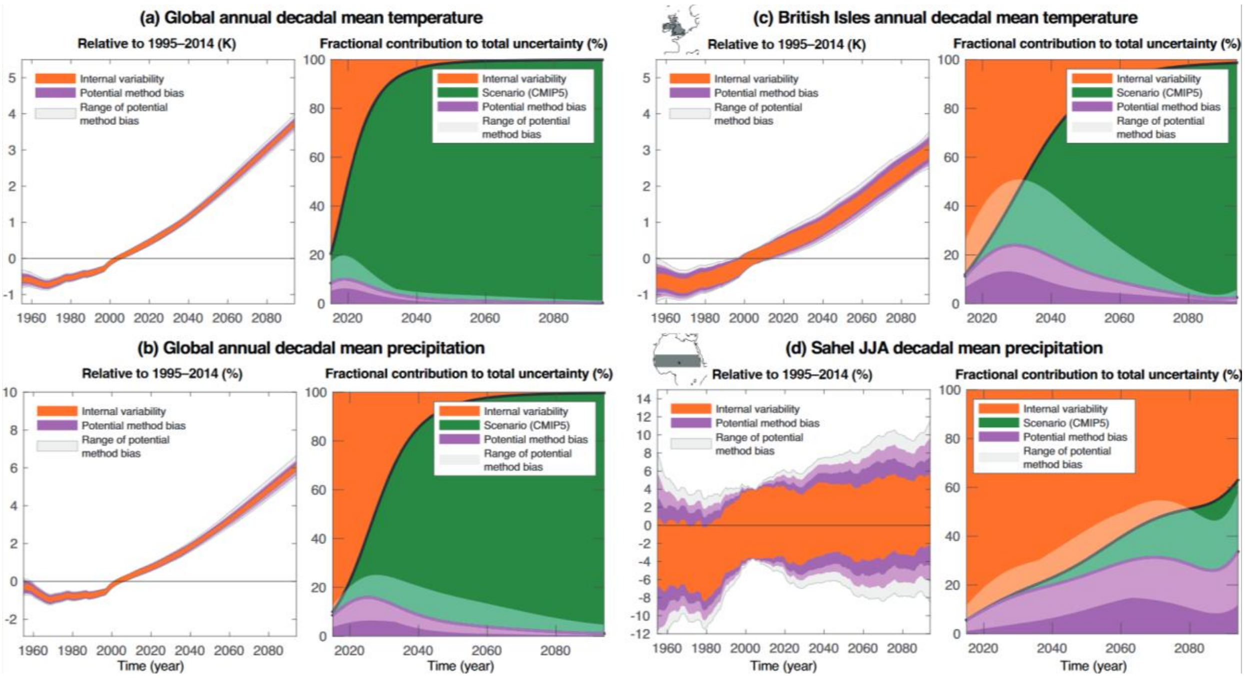

Figure 2.5 Decadal mean projections from SMILEs and fractional contribution to total uncertainty (using scenario uncertainty from CMIP5) for (a) global mean annual temperature, (b) global mean annual precipitation, (c) British Isles annual temperature and (d) Sahel June–August precipitation […] (from Lehner et al. (2020)).

In the following, a few common topics of climate change studies are discussed and the current best practice is summarized.

Extreme events including multivariate hazards and compound events

Extreme events or low-likelihood events (i.e., floods of any kind, droughts, heatwaves, etc.) are by definition rare occurrences that are difficult to capture within observations or single climate simulations. These events are strongly influenced by internal climate variability. Hence, robust statistical quantification of many kinds of extreme events and their change inherently requires large sample sizes. In the context of "compound" events i.e. events where two climate hazards (e.g. a wind storm and a cloudburst) are co-located in time and space, or "cascading" events where the impact of one hazard (e.g. a flood) is affected by a preconditioning event(s) (e.g. a land slide or wild fire), their dependence structure can only be robustly quantified or even detected by very large sample sizes. The current best practice to obtain physically consistent large sample sizes are by large model ensembles, including single model initial condition large ensembles. For an overview of applications using large ensembles see Maher et al. (2021) and Deser et al. (2020). The added-value of using large ensembles for assessing extreme return levels of river discharge has been highlighted in van der Wiel et al. (2019) and Brunner et al. (2021). Most large ensemble consists of GCMs (e.g. CMIP 5/6), however for Europe there are a few regional large ensembles available (see: Leduc et al. (2019), Aalbers et al. (2018), Addor and Fischer (2015)).

Box 1. Extreme events including multivariate hazards and compound events

For the analysis of low-likelihood events or of compound events (univariate or multivariate) the use of large (regional or global) climate model large ensembles is recommended. Since in the context of extreme events the most severe consequences should be adverted, the focus should be given to the high-end scenarios (e.g. RCP8.5).

Changes in the mean climate

Compared to extreme events, robust changes in the mean climate can be quantified by much fewer simulations (Tebaldi et al. (2021), Milinski et al. (2020)). Hence, at medium to longer timescales the projections are mainly subject to model and scenario uncertainty. A multi-model framework spanning different emission scenarios is an ideal choice for assessing changes in the mean climate.

Conversely, at shorter timescales of a few decades, climate projections are often dominated by internal climate variability. For example, if you are looking at temperature trends for the next few decades it is very likely that some climate models show negative trends even under progressing climate change (Maher et al. (2020)), which can lead to potential misconceptions. For lead times of only a few decades (i.e. “decadal predictions”), climate models generally have little or no robust prediction skill, however, the use of large model ensembles can help quantify the role of internal climate variability.

Box 2. Changes in the mean climate

For the analysis of changes in the mean climate state at medium to long future periods, multiple models under different emission scenarios should always be used. In the ideal case, we recommend using an ensemble suite, e.g. CORDEX.

Changes in variability on interannual to decadal timescales

Studying changes in the variability on interannual to decadal timescales is inherently more complex than changes in the mean climate state. The quantification of interannual to decadal variability typically relies on larger scale modes of variability (such as El Niño or La Niña), and is therefore strongly influenced by internal climate variability. In many cases, even state-of-the-art climate models have difficulties in representing larger scale modes of variability in the Earth system. For example, Wood et al. (2021) have shown that the projected changes in precipitation variability exhibit large model uncertainties. Quantifying robust changes in large-scale modes is generally only possible using sufficiently large ensembles of climate models (Maher et al. (2018)) or by using alternative techniques (which is beyond the scope of this document).

Using climate data to dynamically drive impact models

The above cases are valid for the analysis of the climate component as well as for any subsequent impact model assessment, since uncertainties from the climate model propagate through the entire modelling chain. The use of climate model data to drive an impact model (e.g., hydrological/hydraulic model, crop model, etc.) is an advanced case of a climate change assessment. Since impact models often have native spatial and temporal resolutions that are much higher than the current “standard” for “high-resolution” regional climate models (~11 km, daily), climate model outputs require further post-processing steps (i.e., spatial downscaling) prior to feeding the data into the impact model data stream. In addition, some impact models – in particular hydrological models - often require a parameterization or calibration in order to capture the local processes correctly. That is, they are optimized for an observed climate (i.e., seasonal cycle, daily cycle). Climate models regularly show model biases in the magnitude but also in the distribution of e.g. temperature and precipitation. In order to ensure physical consistency between the climate data and your model setup, a bias-correction is thus often needed prior to statistical downscaling and/or running climate impact simulations. It is always recommended to do a detailed evaluation of climate model output against observations prior to using the simulations for impact models. It is advisable to dismiss climate simulations in case neither the distribution, magnitude or spatial patterns match the observed climatology.

Box 3. Using climate data to dynamically drive impact models

For the purpose of driving an impact model with climate model data, it is recommended to always use as many simulations as you can afford to run.

Depending on your underlying research question, the complexity of your modelling framework and the spatial scale of your application, one or both of the following post-processing should be considered.

- Bias-correction: In case of the importance of multivariate dependencies (e.g., precipitation and temperature for the built-up/melt of a snow cover) we recommend using a multivariate bias correction method (e.g., Cannon (2018)). Most methods can also be applied univariately.
- Statistical downscaling: Depending on your spatial scales and relevance of topography, an additional level of downscaling may be needed. The statistical downscaling method will typically depend on the availability of observations and the complexity of the case study.

3.0 Models in ARSINOE

The set of hazard and impact models used in ARSINOE entails a variety of typologies: from climate models, GIS based tools, hydrological and hydrodynamic models, to crop and traffic modelling, and damages assessment software. Table 1 summarizes the models used in ARSINOE by CS.

From the available model information, we find that 87% of the models used in the project are currently working with the RCP4.5 and RCP8.5 climate scenarios from CMIP5. Additionally, 50% of these models are also using RCP2.6 (CMIP5). The CSs that are already working or planning to implement CMIP6 scenarios generally agree to apply SSP1-2.6, SSP3-7.0, and SSP5-8.5. The targeted time horizons can be divided in short and long-term horizons, with a consensus of mid-century and end of the century horizons (with their associated time span).

The input and output datasets are relatively broad but can be synthesized as follows:

- Meteorological forcing datasets
- Digital elevation models (DEM)
- Soil properties
- Land cover, land use
- Crop data

Additional related datasets included e.g., green urban areas, population density, infrastructure, hydrological variables, particularly flood descriptors, such as water depth, flood extent, and flood duration, and management practices.

Some interdependencies among models are clearly present. This implies that in order to set up or run some of the models, the results from other models need to be available to be used as input. All in all, the similarities of the datasets as well as their interconnections (e.g., same or very similar input data required, output as input data for other models) highlights a high potential interplay among models even across CS. This opens a window of opportunity to exchange or couple models and underlines envisaged collaboration between the ARSINOE case studies.

Table 3.1 Overview of models used in the ARSINOE project by the different case studies. The first column shows the case study, followed by the model's name and a short description, scenarios currently used and planned to be implemented within the project, associated time horizon, input and output data. The last column indicates whether the described model has any dependencies, which implies that the output of a different model previously used by the case study is used as input for the described model.

CS	Name of model	Description	Scenarios (current/planned)	Time horizon	Data needed (input)	Data produced (output)	Depend. (Y/N)
CS1	Climatic indicators	climate projections	CMIP5: RCP2.6 - RCP4.5 - RCP8.5	2031-2050 2081-2100	Observations (e.g.: T), climate model data	• Daily data of minimum/maximum temperature, relative humidity • Daily humidex (compound index of temperature and rel. humidity) values • Derived indices (e.g., number of days per year with maximum temperature >35C, number of days per year with humidex >38C)	N
CS1	ArcGIS	Citizens' Accessibility to Green Urban Areas (15-minutes city concept)	CMIP5: RCP2.6 - RCP4.5 - RCP8.5	2031-2050 2081-2100	Green urban areas, Open spaces, Road network, Population, Social and urban infrastructure: residential density, mobility, inequality, refugees, jobs	• Accessibility of green urban areas • Number of citizens with and without accessibility to green urban areas, • Social characteristics in relation to the accessibility to green urban areas	N
CS1	GIS-GuidosToolbox	Connectivity of Protected Areas	CMIP5: RCP2.6 - RCP4.5 - RCP8.5	2031-2050 2081-2100	Protected areas Land use	Landscape fragmentation	N
CS1	EPISODE-CityChem (v1.5)	chemistry/transport simulations of reactive pollutants (air quality)	CMIP5: RCP2.6 - RCP4.5 - RCP8.5 CMIP6: SSP3-7.0 - SSP5-8.5	Tbd	Initial and boundary air pollution conditions (surface and atmospheric input) Anthropogenic emissions Meteorological (and land) parameters	NO_2, NO, CO, O_3, SO_2, $PM_{2.5}$, PM_{10}, VOCs, etc.	N
CS1	MINKA, MECODA	Trees- Citizen Science	-	2022-2025	Date, picture, geometry, species	Trees and tree attributes	N
CS1	Multilayer network (GIS tools)	Complex Network Analysis for the simulation of the Urban Heat Island effect	CMIP5: RCP2.6 - RCP4.5 - RCP8.5	2031-2050 2081-2100	Daily humidex (compound index of temperature and rel. humidity), Daily data of minimum/maximum temperature, relative humidity, wind speed, land uses: Landscape fragmentation including protected areas, Green & Blue infrastructure, Building heights	Average Surface Temperature Difference between Average Surface Temperature at the target location and the peri-urban, which operates as an indicator for the Urban Heat Island effect	Y

CS1	*WRF*	*Nature based Solutions (NbS) selection and microclimate simulations (WRF)*	*CMIP5: RCP4.5 - RCP8.5* *CMIP6: SSP1-2.6, SSP3-7.0 - SSP5-8.5*	*Tbd*	*Initial and boundary conditions (surface and atmospheric input), Static input (topography, land use, soils), Accessible green areas, Landscape fragmentation, Areas of low air quality, Trees distribution, Areas of thermal stress and UHI effect*	*air temperature, precipitation, relative humidity, surface temperature, soil moisture, PBL height, etc.*	*Y*
CS2	ALADIN63	Regional Climate model (RCM): CNRM-ALADIN or ALADIN-Climat. Application in Valencia and Piraeus/Limassol	Not specified	2040-2060 2080-2100	Precipitation, Wind, Wind surface, Wave, Humidity, Sea level	Atmospheric and oceanographic climate variables	N
CS2	DMI-HIRHAM5	RCM based on HIRLAM and ECHAM models. Application in Valencia and Piraeus/Limassol	Not specified	2040-2060 2080-2100	Precipitation, Wind, Wind surface, Wave, Humidity, Sea level	Atmospheric and oceanographic climate variables	N
CS2	SMHI-RCA4	RCM. Application in Valencia and Piraeus/Limassol	Not specified	2040-2060 2080-2100	Precipitation, Wind, Wind surface, Wave, Humidity, Sea level	Atmospheric and oceanographic climate variables	N
CS3	WaSiM	Water Flow and Balance Simulation Model Hydrological model	CMIP5: RCP4.5 and RCP8.5, CMIP6: SSP1-2.6, SSP3-7.0, SSP1 SSP5-8.5	2041-2060 (2041-2071) 2081-2100 (2071-2100)	Meteorological forcing (T, P, radiation, rel. Humidity, wind) Topography, land use, soils Water management structures (reservoirs, water transfer)	Streamflow, Precipitation, Temperature, radiation, humidity, wind, Evapotranspiration, Soil moisture, groundwater recharge, snow storage, direct runoff, interflow	N
CS4	IWaMM (Integrated Water Management Model)	Hydrological and integrated water management model across sectors (climate – water – energy – food)	CMIP5: RCP2.6, RCP8.5	2021-2100	Meteorological forcing (Temperature, Precipitation); Hydrological data (inflows), Climate scenarios Static information on land use (agriculture) and water use Information on water consumption by users (households, agriculture, industry, hydro power)	Water level in the lakes Precipitation, temperature, radiation, humidity, wind Evapotranspiration, soil moisture, groundwater recharge, snow storage/melt, direct runoff, interflow, etc. Water consumption per consumer type	N

CS5	GW-EH-LP + FEFLOW	Groundwater models (insular)	CMIP5: RCP4.5 and RCP8.5	2022-2100	Maximum temperature Minimum temperature Precipitation Sea level rise	Water production cost (economic damage cost) Water quality production (saltwater intrusion)	N
CS5	Hydrodynamic Model h2d	hydrodynamic	CMIP5: RCP4.5 and RCP8.5	2015-2046 2080-2100	Wind and sea level	Free surface	N
CS6	HEC-HMS	hydrological	CMIP5: RCP4.5 and RCP6.0	2040-2060	Canopy storage, Constant rate of initial and constant loss correspond to saturated hydraulic conductivity, Meteorological data (precipitation, temperature, etc.) Surface slope - EU-DEM	Streamflow	N
CS7	DTU Damage Cost Model	GIS-based tool	CMIP5: RCP4.5 and RCP8.5	2050, 2100	Flood depth (height above ground) Land use	Cross-sectorial damage costs Localization of flooded assets including non-monetary ones	N
CS8	CAFlood	Flood model	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	LiDAR DEM Precipitation Design rainfall Land cover UK Climate change allowance Downscaled UK climate projection	Water depth, flood extent, flood duration for the modelled domain Water depth hydrograph at selected locations	N
CS8	SUMO (Simulation of Urban Mobility)	traffic modelling software	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	Road Network Data Traffic Count Data Flood Data	Time-Series Graphs showing Traffic Loading in Network/Cross comparison of Traffic Flows under Dry and Flooded Conditions, Traffic Congestion Maps Emergency Response Service Zone Maps	Y
CS9	CERES-Wheat model (implemented in DSSAT software)	Crop modelling	RCP4.5 and RCP8.5 CMIP6: SSP1-2.6, SSP2-4.5, SSP4-6.0, SSP5-8.5	2050 (2026-2075), 2080 (2076-2099)	Daily data of maximum and minimum temperature, total precipitation, and global solar radiation Soil data (texture, pH, soil organic carbon, etc..) Crop and management data	Crop phenology and crop yield Water and nutrient balances	Y

4.0 ARSINOE climate scenario baseline

The nine ARSINOE CS span a variety of climatic zones and socio-economic, environmental and social conditions. They represent a portfolio of interrelated challenges related to climate change in the context of a green and sustainable development and employ a variety of modelling approaches and data requirements (see Section 3). Establishing a common climate scenario baseline across the different cases is needed not only to enable systematic evaluation across the ARSINOE CS but also to facilitate upscaling of the lessons learned and "pooling" of the results beyond the project. This will include collaboration with the "sister" EU Green Deal projects REGILIENCE (coordination and support action), TRANSFORMAR and IMPETUS. For this aim, an inter-project working group has been established and is coordinated by REGILIENCE.

4.1 Rationale

Ideally, to consider both uncertainties related to future socio-economical and reference concentration pathways (see Section 1), and climate simulations (see Section 2) simultaneously, it is necessary to consider and simulate many combinations of SSPs and RCPs using a large number (ensemble) of climate models. Regional downscaling and impact models will add additional complexities. For practical applications, such an approach is extremely computationally expensive and therefore not possible to implement along a full chain of modelling from global to local scales, i.e. considering different SSP/RCP scenarios, global model-based climate projections, regional downscaling using RCMs and/or ESD, impact models (including hydrological models), economic and adaptation models, and so on. The alternative and more common approach, including in cases of lower data availability, is to analyse only a few representative examples that are found to be relevant and fit-for-purpose. This can be done in a variety of ways, for example:

- If the focus is on 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.

Box 4. Climate scenario baseline in ARSINOE

In ARSINOE we will employ a two-phased approach, recognizing that regional downscaling of the most recent generation of climate models and (SSP/RCP) scenarios, i.e. CMIP6 models, are not currently available. Instead, in the first phase, CS will be “free” to define their modelling setup, i.e. their choice of climate scenarios and climate models to use (see Section 3). In many cases, this will entail using RCP4.5 and RCP8.5 scenarios and one or more regional climate model projections from CORDEX forced by CMIP5 models. For those CS that do not come with a preferred modelling setup and climate baselines, Section 4.3. provides scenario and climate model recommendations for phase 1.

In the second phase, all CS will redo/update their model simulations within a common “workspace” given by the following “reference scenarios”:

- 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, these 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. This will 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.

For each of the two “baseline scenarios”, we recommend to carry out simulations based on *at least three different (regional) climate simulations* using different GCM-RCM model combinations from CORDEX, CMIP6 to account for the climate projection uncertainty. While an exact timeline cannot be set, the CORDEX repository is expected to host an increasing number of CMIP6 downscaling simulations at least by M24 of ARSINOE. 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 M30**.

In terms of time horizons, ARSINOE will define the “**near future”** as the time horizon of **2040-2060 (present day + 30 years)** as well as the **end-of-century 2080-2100**. These time slices are largely compliant with what it is used by the IPCC and other studies.

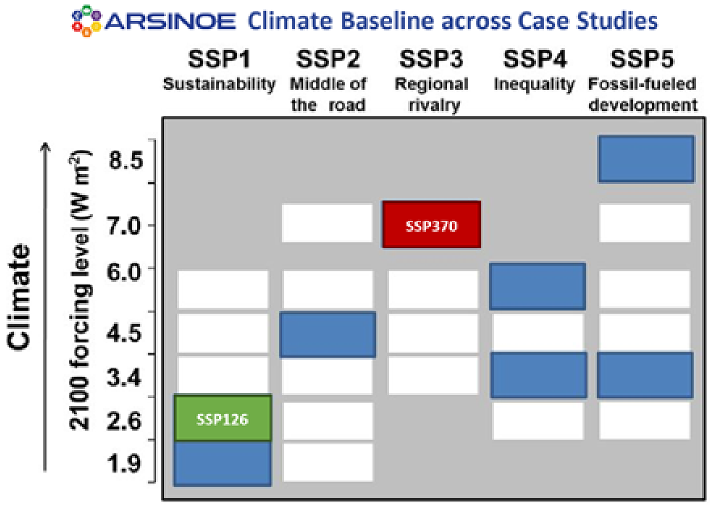

Figure 3.1 ARSINOE Climate baseline across case studies: SSP1-2.6 and SSP3-7.0.

4.2 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.

4.3 Recommendations for phase 1 (optional)

The following recommendations apply to modelling carried out within the CS until regionally downscaled scenarios become available:

- **Scenarios:** If possible, always use two scenarios: a (moderately) high mitigation scenario and contrasting scenario with little or no mitigation to assess the spread of the potential outcomes. The use of the RCP4.5 and RCP8.5 scenarios should be prioritised as is already the case for most of the models listed in Section 3.
- **Climate model projections:** To take climate model uncertainty into account, it is generally recommended to base analyses on *at least three different climate model simulations* and preferably the (GCM/RCM) combinations provided in Table 2 below. The reasoning for the choice of models is provided in Table 3 and is based on recent scientific literature and on providing a spread regarding future projections for precipitation and temperature. For reference periods or other relevant analysis designs, the RCM runs can be forced by re-analysis, e.g. ERA5, or observations can be used.

Table 4.1 Instructions on forcing data, scenarios and GCM/RCM models to use in the first "phase" 1 of ARSINOE across CS. The low/mid/high levels reflect projected levels from literature studies for the variables of precipitation (P) and temperature (T) (across yearly means, seasons and extremes). *Note – if the model applied uses both precipitation and temperature inputs, please use select models consistently from either the T or P column, depending on the scope of the study, to ensure physical consistency across inputs.

		Phase 1 (CMIP5)	
Forcing / scenario	**Historical / reference period**	Observations *or* ERA5 reanalysis	
	Future scenarios	RCP4.5 *and* RCP8.5	
Data input / models (GCM/RCM)	**Low**	T: EC-Earth-RACMO22*	P: HADGEM2 - REMO2015*
	Mid to high	T: EC-Earth-HIRHAM5*	P: MPI-REMO2009*
	High	T: MIROC-RCA4* (if not available then: HADGEM2-RACMO22*)	P: EC-Earth-HIRHAM5*

Table 4.2 Literature basis for the GCM/RCM model instructions in Table 4.1.

	Study	
	Temperature	**Precipitation**
Yearly levels	Kotlarski et al. (2014): Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev., 7, 1297–1333. doi: 10.5194/gmd-7-1297-2014.	Sapez and Larsen (2022, submitted): Projected future European energy sector water usage across power scenarios and corresponding trends in water availability.
Drought / extreme lows / HWMId-WSDI indexes	Molina, Sánchez and Gutiérrez (2020): Future heat waves over the Mediterranean from a Euro-CORDEX regional climate model ensemble. Scientific reports. doi: 10.1038/s41598-020-65663-0.	
Extreme (low)		Sapez and Larsen (2022, submitted): Projected future European energy sector water usage across power scenarios and corresponding trends in water availability.
Extreme (high)		Berg et al. (2019): Summertime precipitation extremes in a EURO-CORDEX 0.11° ensemble at an hourly resolution. Nat. Hazards Earth Syst. Sci., 19, 957–971. doi: 10.5194/nhess-19-957-2019.

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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

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