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Report on European Earth System Modelling for Climate Services

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1 Introduction

Changes in climate are affecting many sectors of society and economy. The underlying climate research has shown a strong development during the last decade. The user and stakeholder orientation of many climate research projects, the need to provide "actionable" results, and the development of a European Roadmap on Climate Services have all emphasised the need to strengthen the link between climate change research and users of climate change knowledge and information in all sectors. The European Union formulates ambitions that highlight climate services with "the potential to become the intelligence behind the transition to a climate-resilient and low-carbon society" and "building Europe's capacity to respond and to improve resilience to climate change"

The audience of climate change information, i.e. decision- and policy-makers is so wide and varied that the requirements of varying policy questions can be quite different. There is a growing number of initiatives at the international and European level, from research networks of data providers, operational services, impact assessments, to coordination of government initiatives and provision of policy relevant recommendations; all provided on a wide range of timescales. The landscape of activities is very diverse. Users and providers of climate information currently face significant challenges in understanding this complex landscape.

The overall concept behind the Coordinating Support Action Climateurope[1] is to create and manage a framework to coordinate, integrate and support Europe's research and innovation activities in the fields of Earth-System modelling, infrastructure and observations in one side and climate services in the other. Climateurope will provide a comprehensive overview of relevant activities to ensure that society at large can take full advantage of the investment Europe is making in research and innovation and associated development of services. Climateurope is establishing multidisciplinary expert groups and aims at accessing the state-of-the-art of Earth system modelling and climate services to identify existing gaps, new challenges and emerging needs. This report addresses the first element in the chain towards climate services: Earth system models.

Climate adaptation and mitigation measures are and will be supported by "climate services" that are currently under development in Europe for both the public and private sectors. According to the European Roadmap for Climate Services these concern, among others, the transformation of climate-related data into customised products such as projections, forecasts, trends, economic analysis, assessments, counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for society at large. Climate services can help decision-makers take informed decisions in order to raise resilience and adaptation capacity by addressing existing or emerging risks.

[1] www.climateurope.eu

Climate service products are expected to cover direct consequences of climate change in the atmosphere, ocean, cryosphere and on land, and a range of indirect impacts. Climate change is expected to lead to a range of varied and significant impacts affecting ecosystems and human systems – such as agricultural, transportation, water resources, natural resources, economic activities and health-related infrastructure. Those impacts do not depend only on climate change, but also on other changes in the environment and on the capacity of society and economy to adapt to impacts. To limit risks and identify opportunities associated with the changes, it is helpful for people, society and economic sectors to understand how climate change could affect respective conditions and what can be done and how much should be done to adapt, as well as what can be done to reduce future climate change by reducing global emissions and maintaining greenhouse gas sinks (mitigation). The base for information on future climate for climate services is provided by observations and Earth System Models (ESMs) (section 2), which represent extensions of the classical climate models with biogeochemical cycles. Given the important role of climate services, climate models and ESMs and the way they are interpreted need further attention to strengthen the very base and underpinnings of climate services.

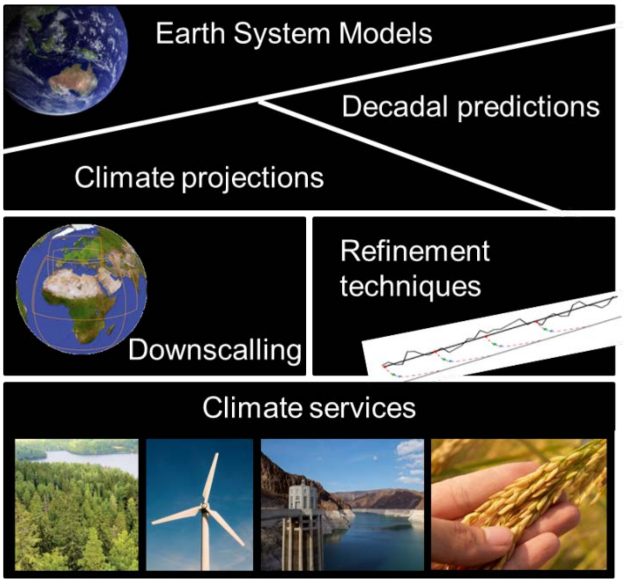


Figure 1.1Structure of Climateurope´ s first report

This report is the first in a row of three Climateurope reports. This first report focuses on the state-of-the-art of Earth System modelling, which forms a key foundation of climate services (Fig. 1.1). The ESMs' ability to perform long-term climate projections (section 3), and seasonal-to-decadal scale predictions (section 4) is scrutinized in relation to uncertainties and opportunities for climate services. Stakeholder-oriented application often requires regionalization of the global climate change signal. Therefore the report is reviewing the state of downscaling efforts in the CORDEX community (section 5). Further refinement techniques such as bias correction and selection techniques are reviewed (section 6). To describe the link between ESMs and climate services, the state-of-the-art of the rising European climate services research is mapped (section 7).

Providers of climate services can play different roles from the supply of data/information for research and analysis to providing the best strategy to achieve goals.

The report series is expected to form the base for forward-looking Climateurope recommendations about coming research and development efforts in Europe. The reports target climate scientists, climate service developers, and a range of policy- and decision-makers. They are envisaged to lead to an improved understanding of the current climate modelling and climate service activities in Europe with the potential to foster new interactions between providers and users of climate model based information and to promote the identification of new spaces for co-development and innovation.

While the focus of this first report is on the ESMs and their usage, forthcoming reports are planned to update this first report and provide progress on the integration of climate services and Earth-system modelling. Climateurope is planning additional reports before 2019. As CMIP6 will reach a mature phase, the reports will cover opportunities in ESM applications during CMIP6, regionalization and evolving links to climate services, including sector-oriented products as well as selection of success stories. Forthcoming reports are also expected to review the process of bundling climate service products from a stakeholder perspective, to identify "unknown knowns" which are the subset of our Earth system knowledge that can be relevant to users, and a validation of the evolving landscape with an emphasis on usability, coordination of dissemination methods, and missing features. The last Climateurope report is anticipated to include even an assessment of the impact of forward-looking recommendations during the Climateurope project. The use of the key scientific projects like CMIP6 and CORDEX as well as operational climate prediction activities for climate services should be evaluated. Experiences with evolving climate services during the first four years of the project are expected to feed back to the ESM and climate prediction community; such feedbacks will be described.

2 What is an Earth System Model in a nutshell?

2.1 The basis

Earth System Models (ESMs) describe the global climate system and its development in time by a combination of coupled physical and biogeochemical cycles. ESMs are numerical computer programs running on the most capable available computers (HPC systems), with climate processes formulated as mathematical equations covering a geographical grid in the atmosphere, the ocean and on the land surface. ESMs represent the most advanced and complex description of the Earth system, providing gridded climate variables in geographical 3D space and in time.

Following established terminology, the classical “climate model” describes the relevant physics of the atmosphere, sea ice, ocean and land surface, while ESMs add processes of ocean biogeochemistry, atmospheric chemical composition and vegetation, which includes carbon cycle feedbacks and other biogeochemical-physical feedbacks (Fig. 2.1). Underlying principles include physical laws of geophysical fluid dynamics in air and water flow, the radiative heating by the sun, the radiative response to that heating, connected thermodynamics, and the flow of carbon and nitrogen through ocean, atmosphere and land surface.

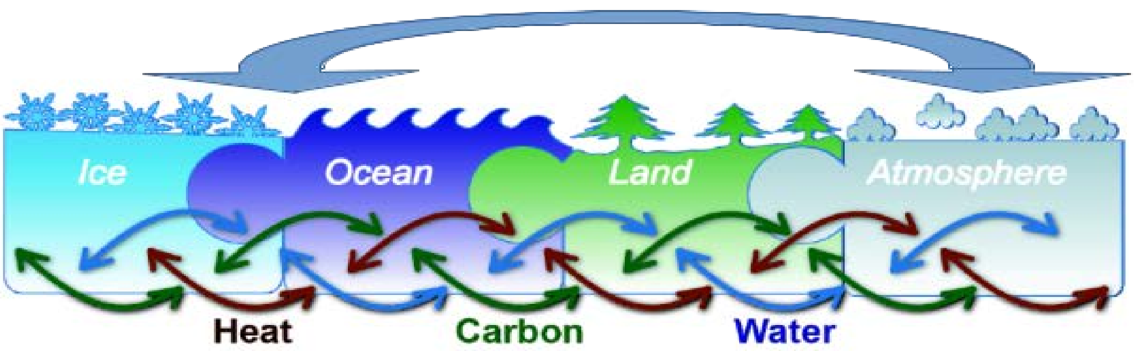


Figure 2.1 Interacting components in an Earth System Model in a simplified sketch (taken from Sandrine Bony, WGCM). All components interact.

Climate models exist since the mid-1970s and have been further developed since then. Starting from basic descriptions on very coarse geographical grids (the numerical mesh), process descriptions have been improved and the mesh has been refined to about 100 km distance between grid points. Processes acting on smaller scales (smaller than resolved by the numerical mesh), such as clouds, precipitation, radiation, swirls in ocean and atmosphere and sea ice processes, need to be described by so-called parameterizations, i.e. empirical observation-based relations between larger scale simulated conditions and smaller scale processes. Major efforts of advancing the abilities of climate models and ESMs have been made on improving such parameterizations. On the way, the number and complexity of processes has been enhanced. Starting from an atmosphere-ocean-land system, sea ice has been added, followed by aerosol processes, biogeochemistry and carbon cycle, land ice sheets, atmospheric chemistry and marine ecosystems. By adding such new components, new feedback processes are enabled, such as a carbon cycle response to greenhouse-gas forced climate warming by changing storage of carbon in the ocean and land surface. Future ESMs might even include aspects of human decision making including feedbacks with greenhouse gas emissions and the type of land use.

A critical step in increasing the confidence in ESM performance by developing process parameterizations is to thoroughly evaluate the representation of these processes against observations.

The rationale for climate models and ESMs is the assumption that coupled representations of climate-relevant processes can describe the combined effects that constitute the overall climate system. When development is focusing on individual processes and their interactions within the climate system, the resulting overall performance will improve.

Systematic intercomparisons of climate models and observations since 1996 has proven the concept and shows increasing accuracy in the representation of the observed climate for individual models and for the average over all participating climate models (Reichler and Kim, 2008).

In comparison with simpler climate models of reduced complexity, ESMs aim at incorporating the full range of relevant processes at the price of not fully understanding all interacting mechanisms and their amplitudes. ESMs are actually used as well to understand processes. A complementary approach targets the better understanding of isolated processes by simplified mathematical descriptions, as part of a hierarchy of climate models, which could facilitate understanding of more complex interactions (Held 2014).

Climate models and ESMs have demonstrated their capability in representing the earth's climate system and its variability. Changes of e.g. the near-surface air temperature can be well described in the global mean, and as continental scale variation patterns. The verification of climate models against real climate conditions is based on observational data and process validation. ESMs need to cover basic global mean quantities ensuring a realistic radiative budget, i.e. a balance (depending on a stable or transient type of climate) between incoming and outgoing heat fluxes at the top of the atmosphere and between model components such as ocean and atmosphere. Furthermore, the correct representation of large-scale patterns and the functioning of specific processes and teleconnections are both systematically verified.

The Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report (AR5) by Working Group 1 (2013) states very high confidence that models reproduce observed large-scale mean surface temperature patterns, with exception of regions of high topography, near ice edges and in certain regions of ocean upwelling (Flato et al., 2013). ESMs are considered to allow for climate policy-relevant calculations such as the level of carbon dioxide emissions compatible with given climate warming targets or calculation of the transient climate response to cumulative carbon emissions.

ESMs are subject to inaccuracies and errors which contribute to the overall uncertainty of climate simulations of the past and possible future climates. Inaccuracies arise from necessary model approximations to real-world processes and limited understanding of those real processes, both leading to limited capabilities of empirical parameterizations to describe sub grid scale processes. Further inaccuracies arise from the numerical translation into computer code and from coding errors.

In an ESM framework for climate change, several ESMs are simulating the climate in a coordinated fashion that allows for mapping of the overall climate simulation uncertainty by analysing differences between model output results. Uncertainties consist of the model errors, natural climate fluctuations and, for future scenario simulations, the uncertainty due to the choice of greenhouse gas emissions scenario. Assessment of uncertainty is a necessity for ESMs productive use in decision making. In the field of climate prediction (section 4), i.e. seasonal to 10-year long simulations, the model initialisation from observed conditions represents as key uncertainty as well.

Optimizing decisions under the conditions of uncertainty is a research field in itself. Applied to climate change assessment by climate modelling, uncertainties of the amplitude of a changing climate need to be translated to risks and even opportunities, which differ between various economical and societal activities. In the context of so-called “robust decision frameworks”, an underutilization of model-generated climate information turns out (Weaver et al. 2013). Future climate services based on climate change projections and predictions (section 7) have the potential to identify policy vulnerabilities under uncertainty about the future, and to propose strategies for minimizing regret in the event of broken assumptions.

Coordinated simulations with several ESMs are carried out under the umbrella of Climate Model Intercomparison Projects (CMIP[2]). Starting in the 1990s, four rounds of CMIP (CMIP1,2,3,5) have been carried out. Under the concept of model comparison, various climate science questions are addressed together with assessing robustness, prediction skill and uncertainty. Climate services related to the future climate generally build on coordinated CMIP simulations and on downstream products such as regionalization and impact modelling products.

2.2 Summary and conclusions

Earth system modelling relies on a system of scientific and technical services of model development, validation systems, high-performance computer systems, post-processing and publication of resulting digital data and climate-science conclusion. All of those chain elements are necessary to enable downstream climate services.

Research into climate change adaptation generally lies one step down the chain of ESM projections – regional downscaling – sectorial impact assessment, with adaptation research needing to factor simulated climate change impacts into the complexity of societal vulnerability to climate change, societal capacity to adapt to the impacts of climate change and other competing stressors on society, external to climate change.

[2] https://www.wcrp-climate.org/wgcm-cmip

Earth system models are at the starting point of this chain of research. The more reliable and comprehensive ESMs are, the more successful each subsequent activity in the chain will ultimately be in supporting informed adaptation planning. Similar arguments hold with respect to climate change mitigation (EMBRACE final report, 2016).

Between IPCC AR4 (2007) and AR5 (2013) a number of physical Global Climate Models (GCMs) have been extended to Earth system models (ESMs), primarily through inclusion of an interactive treatment of the global carbon cycle (Ciais et al. 2013). This has allowed an assessment of the potential response of the Earth's carbon sources and sinks to both a changing climate and changing atmospheric concentrations of carbon dioxide (CO_2). An example is provided below in Box 2.1.

Furthermore, ESMs are beginning to allow investigation of a range of important environmental responses to a warming climate and increasing CO_2 concentrations, some of which may feedback on to global climate change itself. Two examples are wildfires, which alter aerosol concentrations and albedos, and ocean acidification which impacts on biological cycles.

ESMs also form a direct link between climate change and human activities. Near-term mitigation of aerosols, methane and black carbon and long-term emission targets require detailed knowledge of biogeochemical processes and feedbacks which only ESMs can provide. For informed mitigation policy, it is crucial all feedbacks that influence the magnitude of global climate change for a given cumulative human emission of CO_2 are included in models used to make future projections (EMBRACE final report, 2016).

Box 2.1 | Example for post-CMIP5 ESM application

Developments in EU projects on Earth system modelling (such as EMBRACE) have a direct impact on the European climate and Earth system modelling and the broader research community engaged in climate and Earth system science research. A large body of researchers use multi-ESM data sets to analyse and understand climate processes and interactions and their potential sensitivity to future greenhouse gas forcing.

It is crucial that relevant climate feedbacks that influence the magnitude of global climate change are included in models used to make future projections (EMBRACE final report, 2016). An example from the EMBRACE project helps stressing this point: Around 50% of the CO_2 emitted into the atmosphere by human activities is presently taken up by the Earth's natural carbon sinks (split roughly evenly between the oceans and the terrestrial biosphere). If these sink terms become less efficient in the future in response to increasing CO_2 levels and/or the impacts of climate change, then a greater fraction of human-emitted CO_2 will remain in the atmosphere, to warm the climate, and the actual cumulative human emissions available to stay below a target warming threshold (such as 2°C global warming) will be reduced. In CMIP5 most ESM did not include a terrestrial nitrogen cycle. It is now widely expected that in many regions of the world future increases in photosynthetic activity (and thus CO_2 uptake), in response to increased atmospheric CO_2, will be limited by the availability of nitrogen. ESMs that do not include such nitrogen limitation will overestimate future uptake of anthropogenic CO_2, compared to a reality that is nitrogen limited. Most ESMs that now include a nitrogen cycle simulate a reduction in future terrestrial carbon uptake compared to the equivalent models without nitrogen limitation. This results in more CO_2 remaining in the model atmosphere in the nitrogen-limited ESMs and thus less "human emission-space" to stay below a target warming level. Similar arguments hold for Earth system feedbacks that impact marine carbon uptake (e.g. ocean acidification) or cause the release of previously stored natural carbon from either the oceans or land into the atmosphere (e.g. permafrost melt and release of frozen methane). In short, ESMs need to include all key (climate and biogeochemical) feedback processes if they are to support the development of realistic GHG mitigation plans. Model developments such as implementation of nitrogen limitation in the project ESMs or an improved representation of CaCO3 dissolution in the oceans, all contribute to more complete models that can better support mitigation planning.

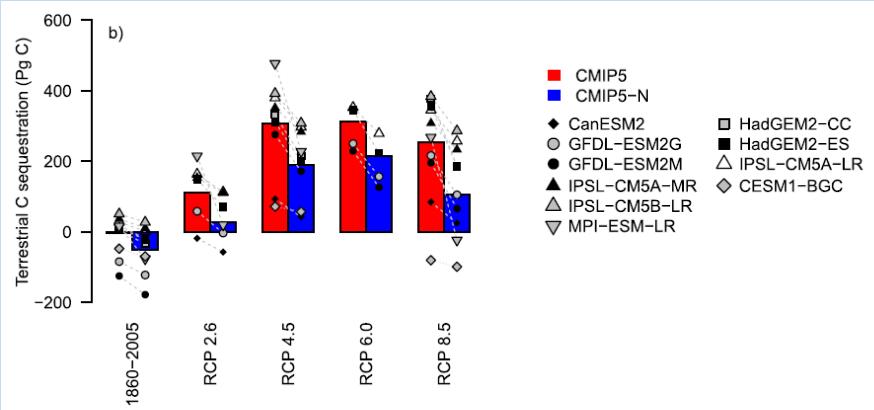


Figure B2.1.Ensemble median of terrestrial C sequestration for the historical (1860–2005) and scenario (2006–2100) period with (CMIP5-N) and without (CMIP5) taking N constraints into account. Points mark the median result for each model and scenario. N limitation reduced the projected CMIP5 net land C uptake by 37% (median for RCP 2.6) and 58% (median for RCP 8.5), with a larger difference between models than across scenarios. (Zaehle et al., 2015).

3 State of the art of European Earth System modelling for climate projections

3.1 Robustness of Earth System Models

Climate and Earth System models are built on basic physical principles, and they reproduce many important aspects of the observed climate (IPCC AR5 WG1 report, 2013). Climate projections and predictions of possible future climates need to be complemented by a quantification of result robustness as a key measure before applying results. In a framework with multiple ESMs for assessing climate change, as used e.g. for the IPCC assessment, the models span a range of different climate simulation outcomes, interpreted as uncertainty of climate simulations. Major components of uncertainty relate to:

- ESM errors and inaccuracies (uncertainty due to limited knowledge about the climate system
- simulated natural climate fluctuations that express themselves differently within a range of models, and
- for future climate scenario simulations: the uncertainty due to the choice of greenhouse gas emissions scenario (uncertainty about the socio-economic developments).

Knowledge about uncertainties is needed in order to provide relevant information for decision making, supported by climate simulations. Relevance of decisions increases once uncertainties are weighted in. Users of the climate information should actively consider uncertainties for the respective user case. This requires an provision of uncertainty information in a user-friendly way.

ESM inaccuracies and errors contribute to the overall uncertainty. They arise from model approximations to real-world processes, programming bugs and from limited understanding of the natural processes that hinders numerical implementation into models, and from missing feedbacks in less complex climate models such as in models without carbon feedback. The collected issues lead to limited capabilities of empirical parameterizations to describe the effect of subgrid scale processes on the coarser numerical grid. The challenge is addressed by a permanently ongoing model improvement with targeted observations as reference for parametrizations, by developing numerical methods for the dynamical cores, and by intensifying software testing procedures during development, following IT standards. Progress between model generations is quantified by climate performance metrics, a process that itself is subject to increasing standardization and further development. Structural issues with insufficient parameterizations can be addressed by empirical-stochastic approaches that could lead to reduced biases, increased variability and a more complete representation of uncertainty (Berner et al. 2012). Such approaches acknowledge parameter uncertainties and vary those stochastically within the limits of a given statistical distribution.

Climate variability, natural fluctuations and oscillations of the global and regional climate exist in reality and in climate simulations, although simulated intensity and timing differs between models and in comparison with observations. Climate simulations might thus be biased during times despite a general ability to describe relevant coupled processes. For that reason, climate change assessments need to be built on an ensemble of simulations which span the range of effects of different timing for a given simulation time. Ensemble members start from a set of different initial conditions or are carried out with a range of parameterization configurations. Multi-model ensembles give a sight on the amplitudes of simulated natural fluctuations. Ensembles of ESMs and climate models are typically produced as international Climate Model Intercomparison Projects (CMIP).

In order to assess possible future climate change, different emission scenarios are projected. Those were first based on a set of standardised socio-economic scenarios for demography, economic development, and environmental policy (known as the SRES scenarios for Special Report on Emission Scenarios). Since AR5, a different approach has been followed based on Representative Concentration Pathways (RCPs) associated with different policy scenarios. When run under these different emission and land use scenarios, climate models project different change in climate, highly dependent on the amplitude of the greenhouse gas concentrations in the emission scenario. Fig. 3.1 illustrates the development of the different uncertainty components in time. While the uncertainty due to natural simulated variability remains constant, the model uncertainty increases slightly, and the uncertainty due to the choice of emission scenario grows strongly. In the second half of the 21st century, the scenario uncertainty is dominating the overall uncertainty (e.g. Sillmann et al. 2013). This uncertainty associated with the choice of scenarios implies that policy has very different options and can respond to alternative expected climate change amplitudes, whereby all uncertainties need to be weighed in.

Indeed, for each emission scenario, the climate change amplitude will, as described above, depend on models (first level of uncertainty) and natural fluctuations. Each emission scenario is associated with a range of global mean temperature increase and other changes of climate variables, arising from the use of different models or different parameterization. One main source of uncertainty between models is due to clouds representation which differs from one model to the other and leads to a different response of sensitivity of climate models to CO_2 increase, referred to as climate sensitivity (see box 3.1). Climate sensitivity represents the overall response of a climate model to a doubling of atmospheric CO_2 concentrations compared to preindustrial conditions. The equilibrium global-mean temperature change in recent (CMIP5) climate models ranges from 1.9 to 4.4 degrees (Vial et al. 2013), which is within the range estimated by the IPCC based on various methods and sources, model-based and observational.

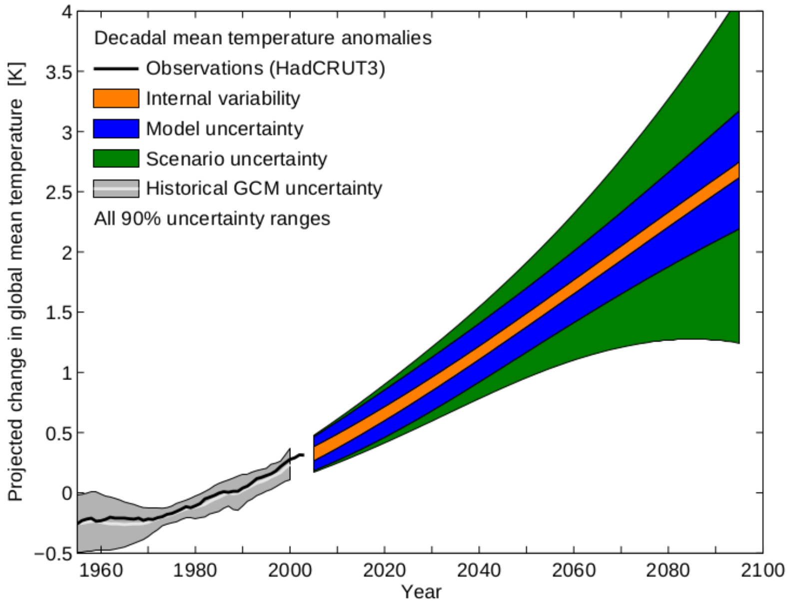


Figure 3.1 The total uncertainty in CMIP3 global mean, decadal mean projections for the 21st century separated into its three components: internal variability (orange), model uncertainty (blue) and scenario uncertainty (green). The grey regions show the uncertainty in the 20th century integrations of the same GCMs, with the mean in white. The black lines show an estimate of the observed historical changes. Temperature, with observations from HadCRUT3 (Brohan et al., 2006). All anomalies are calculated relative to the 1971-2000 mean, except for the precipitation observations, for which a 1979-2000 mean is used. Appendix B describes how the components of standard deviation were scaled from the estimated variances. Figure taken from Hawkins and Sutton (2011)

Box 3.1 | Climate sensitivity

Projections of climate change are strongly dependent on the ESM's climate sensitivity, defined as the global mean surface air temperature warming in response to a doubling of the atmospheric CO_2 concentration from pre-industrial levels.

An important distinction is made between:

- the transient climate response (TCR) : defined as the warming at the point of CO_2 doubling in a model simulation in which CO_2 increases at 1% yr−1 which is a measure of the rate of warming while climate change is evolving; and
- the equilibrium climate sensitivity (ECS): the rate of warming the climate system has reached a new steady state, i.e. after a new equilibrium between the oceans and the atmosphere is reached after a few decades to centuries.

Climate sensitivity cannot be measured directly, but it can be estimated from recent climate events (including volcanic eruptions) during the short instrumental period of earth observations, from paleo-geological and paleo-biological proxy observations covering time scales from millenium to millions of years, and from Earth System model experiments. IPCC AR5 (2013) estimates the ECS between 1.5 and 4.5°C. Equilibrium sensitivities estimated by ESMs and GCMs range from 1.9 to 4.4°C, while the transient climate responses are smaller, ranging 1.0-2.5°C. Climate sensitivity is the largest source of model uncertainty in projections of climate beyond a few decades. This sensitivity depends primarily on the amplitude of various feedback effects, both positive and negative, that either reinforces (positive feedback) or counteracts (negative feedback) the climate forcing. There are three primary feedback effects — clouds, water vapor and sea ice. Recent research suggests that higher climate sensitivities are to be expected for a warmer climate due to a reducing ability of ocean and biosphere to sequester anthropogenic carbon (Previdi et al., 2013).

3.2 Evaluation of Earth System Models

Evaluation of ESMs is the process to quantify a model's overall ability to simulate combined processes and the resulting climate. Together with a standard model bias evaluation, in terms of averages, extremes and variability, the ability of climate models to represent specific physical processes must be addressed. Evaluation is carried out by model groups individually, and in multi-model comparisons. Building confidence in climate models and their projections involves quantitative comparisons of simulations with a diverse suite of observations. Climate modellers often consider information from well-established tests and comparisons among existing models to help decide on a new model version among multiple candidates (Gleckler et al. 2016).

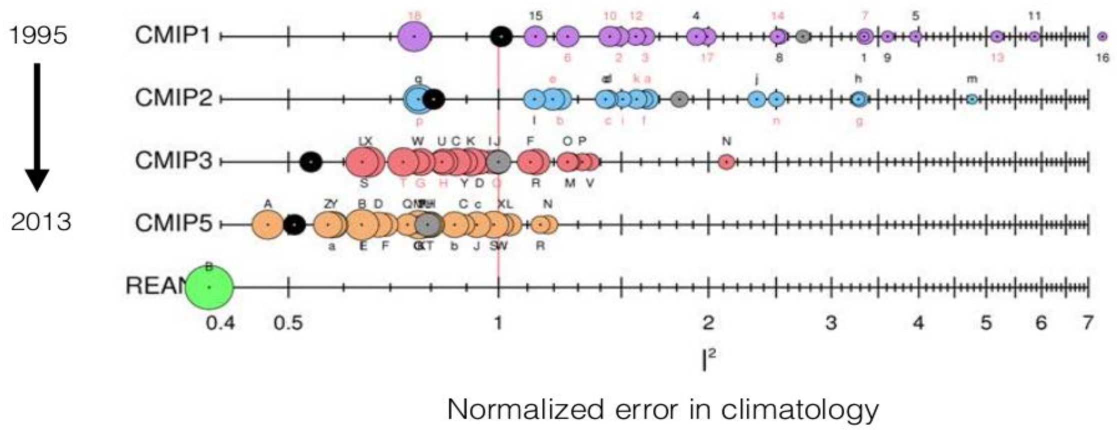


Figure 3.2 Normalized error based on a range of global climate variable's standard deviation error (based on Reichler and Kim, 2008). Average model errors have been reduced with time.

Fig. 3.2 illustrates progress in reducing model error over the last decades. Thus, there is clear reason for growing confidence in using climate models for quantitative future predictions and projections. However, as IPCC points out, "in general, there is no direct means of translating quantitative measures of past performance into confident statements about fidelity of future climate projections. However, there is increasing evidence that some aspects of observed variability or trends are well correlated with inter-model differences in model projections for quantities such as Arctic summertime sea ice trends, snow albedo feedback, and the carbon loss from tropical land. These relationships provide a way, in principle, to transform an observable quantity into a constraint on future projections, but the application of such constraints remains an area of emerging research. There has been substantial progress since the IPCC AR4 (2007) in the methodology to assess the reliability of a multi-model ensemble, and various approaches to improve the precision of multi-model projections are being explored. However, there is still no universal strategy for weighting the projections from different models based on their historical performance." (IPCC, 2013)

IPCC evaluated CMIP models in a holistic sense taking into account processes, resulting climate variables and the corresponding confidence of assessment as defined by the calibrated language of IPCC[3]. Results are summarized in Fig. 3.3. Examples of model features with high and very high confidence, combined with high model performance are: Large scale surface air temperature (TAS), regional scale surface air temperature (TAS-RS), Meridional heat transport (MHT), Global ocean carbon sink ($fgCO_2$), Sea surface temperature (SST), Seasonal cycle Arctic sea ice extent (ArcSIE), Zonal mean zonal wind stress (Z-taux), Trend in Arctic sea ice extent (ArcSIE-t), Surface air temperature trends (TAS-t), Global distributions of surface air temperature extremes (TAS-ext). It is interesting to note that even model features with low and medium performance can give high confidence for assessment.

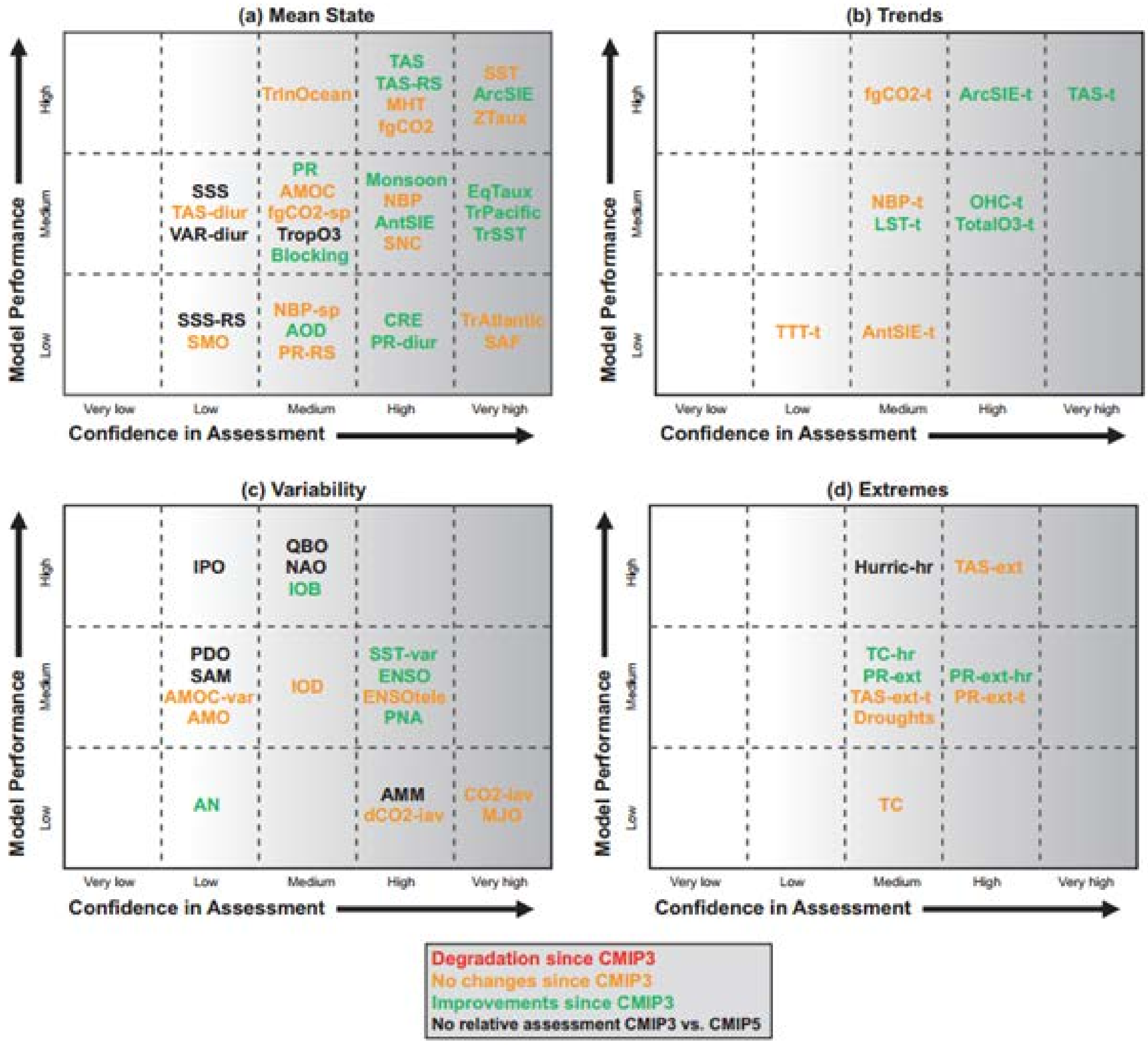


Figure 3.3 Summary of findings with respect to how well the CMIP5 models simulate important features of the climate of the 20th century. Confidence in the assessment increases towards the right as suggested by the increasing strength of shading. Model performance improves from bottom to top. The colour coding indicates changes since CMIP3 (or models of that generation) to CMIP5. The assessment of model performance is expert judgment based on the agreement with observations of the multi-model mean and distribution of individual models around the mean, taking into account internal climate variability. (taken from IPCC AR5 WG1, 2013)

[3] https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

Concerning ESMs and their new component models (e.g. for vegetation and carbon cycle), the evaluation has lagged behind that of physical climate processes. To catch up, ongoing projects (e.g. EU-CRESCENDO) are developing crucial process-based techniques to evaluate even biogeochemical schemes. The complexity of ESMs means that improved parameterization must first be evaluated in a constrained model configuration, driven by observations (e.g. for a vegetation parameterization, running experiments with the land-only component of an ESM driven by observed atmospheric forcing). Targeted observations can then be used to evaluate the realism of the actual processes being simulated and assess the sensitivity of processes to a range of input variables defined from, and evaluated against, observations. Often referred to as process-level or bottom-up evaluation, the CRESCENDO project is developing a range of such methods to evaluate new ESM processes focussing on descriptions for terrestrial and marine biogeochemistry and natural aerosols[4].

How to measure the added value of increasing complexity in ESM? The fact that the CMIP5 ensemble compares more favourably than CMIP3 with observations might be an indication that the development strategy of investing progressively more and more computing resources to add complexity to the models has been successful in better representing the climate system (Knutti et al., 2013). The increased resolution (not only in terms of spatial resolution but also in terms of coupling frequency between the model components) with respect to CMIP5 model generation, provides more realistic tools to investigate projected changes in extreme events, on different frequencies (Scoccimarro et al. 2015), from the daily to the hourly.

To better understand climate changes arising in response to changes in radiative forcing, a concept based on multiple models has been initiated as Climate Model Intercomparison Project (CMIP) during 1995 under the auspices of the Working Group on Coupled Modelling (WGCM[5]). Comparing models with each other and with observations provides information and understanding of the model's abilities, variability, simulation uncertainties and quality of representation of climate processes. The CMIP6[6] concept (Fig.3.4) includes assessments of model performance during the historical period and quantifications of the causes of the spread in future projections. Idealized experiments are also used to increase understanding of the model responses. In addition to long time scale responses, experiments are performed to investigate the predictability of the climate system on various time and space scales as well as making predictions from observed climate states, as explained in section 4. An important goal of CMIP is to make the multi-model output publically available in a standardized format, which is the primary source of model data for climate services.

[4] https://crescendoproject.eu/research/theme-2
[5] https://www.wcrp-climate.org/wgcm-cmip/54-unifying-themes/unifying-themes-modelling/modelling-wgcm/219-modelling-wgcm-overview
[6] https://www.wcrp-climate.org/wgcm-cmip

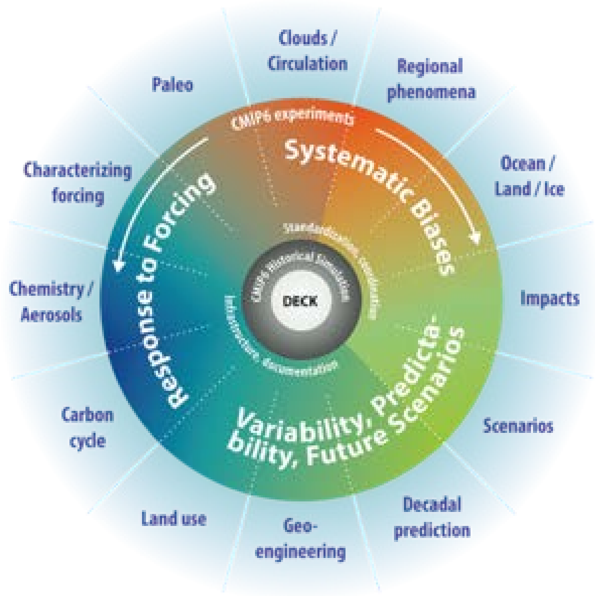


Figure 3.4 The concept of CMIP6 experiments.

Another contribution to our understanding of the climate system is given by exploring multiple models performance in terms of their ability to reproduce important teleconnections for the correct reasons (Cherchi et al, 2014), through statistics and linking processes.

In comparing models' performance, the question of the actual diversity among models in terms of components emerges as a crucial aspect, especially in the context of the European climate community, where many ESMs share the same component models. Sharing components might represent an advantage (for example in sensitivity experiments, where having common components might provide insight into the response of the models) as well as a limitation (for example in terms of multi-model ensemble skill). In a study dedicated to the genealogy of CMIP3 and CMIP5 models, Knutti et al.(2013) concluded that sharing model components is not necessarily a shortcoming; rather it can be used to explore the climate system.

3.3 Usage of ESMs

When CMIP started in 1995, the first set of common experiments was comparing the model response to an idealized forcing - a constant rate of increase which was accomplished using a CO_2 increase of 1% per year compounded. Since then, the CMIP experiments have evolved, but continue to include integrations using idealized forcings to facilitate understanding (so called DECK experiments). They now also include integrations forced with estimates of the changes in the historical radiative forcings as well as estimates of the future changes. In addition to the major experiments, CMIP has also included a series of smaller model intercomparison efforts, called the Coordinated CMIP Experiments, designed to understand specific aspects of the model response.

With the Grand Science Challenges of the World Climate Research Programme (WCRP) as its scientific backdrop, the current CMIP6 (2017-2020) will address three broad questions (Eyring et al. 2016):

- How does the Earth system respond to forcing?
- What are the origins and consequences of systematic model biases?
- How can we assess future climate changes given internal climate variability, predictability, and uncertainties in emission scenarios?

The latter two questions gained importance throughout the history of CMIP projects.

Climate projections of possible future climates are carried out under the CMIP6 Scenario Model Intercomparison Project (Scenario-MIP) with ESMs. Projections play a fundamental role in improving understanding of the climate system as well as characterizing societal risks and response options. “The Scenario-MIP provides multi-model climate projections based on alternative scenarios of future emissions and land use changes” (O'Neill et al. 2016). “The Scenario-MIP design is one component of a larger scenario process that aims to facilitate a wide range of integrated studies across the climate science”, impacts, adaptation, and vulnerability communities, and will provide an important part of the evidence base in the forthcoming IPCC assessments.

In addition, the Scenario-MIP “will provide the basis for investigating a number of targeted science and policy questions that are especially relevant to scenario-based analysis, including the role of specific forcings such as land use and aerosols” (O'Neill et al. 2016), the consequences of scenarios that limit warming to below 2^{o}C, the relative contributions to uncertainty from scenarios, climate models, and internal variability, and long-term climate system outcomes beyond the 21st century. Scenario-MIP simulations will form the base of upcoming climate services on the future climate. Currently developed climate service pilot projects need to be based on the previous CMIP5 data set.

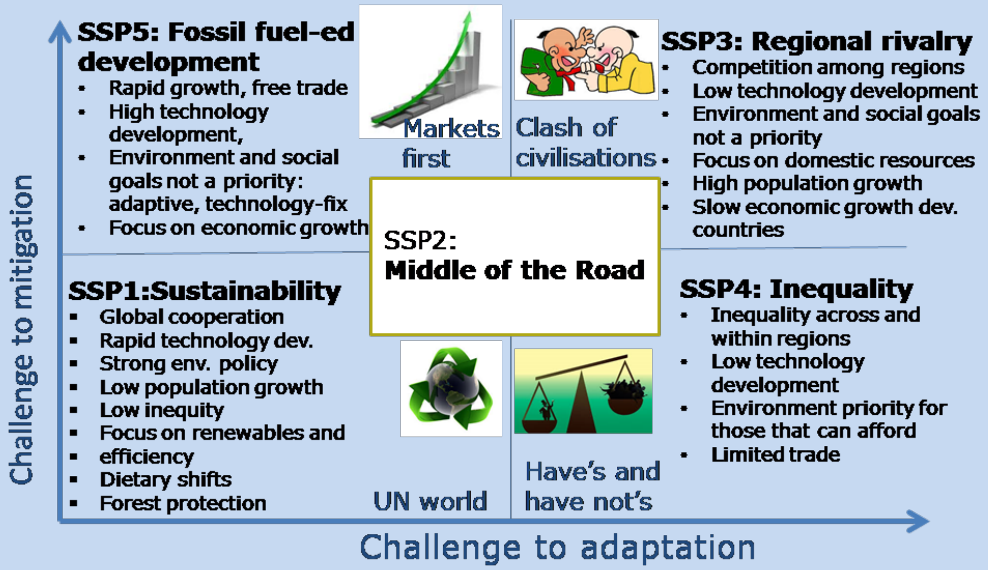
The greenhouse gas emissions scenarios used in CMIP5 are based on Representative Concentration Pathways (RCPs) associated with different policy scenarios. For CMIP6, the concept is extended by new Shared Socio-economic Pathways (SSPs (see box 3.2)), which describe alternative evolutions of future society in the absence of climate policy. Those are combined with a range of mitigation levels and land use options, which span a matrix of possible pathways into the future, associated with alternatives for policy decisions.

The overall ensemble of CMIP climate scenario simulations shows a spread due to different kinds of uncertainty (see section 3.1). Climate services build on a range of simulations, but often cannot make use of all ensemble members due to practical limitations (e.g. computational capacity). Therefore, a limited number of model simulations is selected. Criteria for selection of model simulations are a very relevant topic before feeding model results into climate services or assessment studies. The choice needs to represent a large part of the range of possible outcomes. One of the main considerations for choosing ensemble members is the performance of the model, its skill to reproduce historical observations for a given variable in a given region. Indeed, the model’s performance can be strongly dependent on the localisation and global and regional assessments that is to be carried out. A problem is that the ability of a model to produce results comparable with observations does not necessarily guarantee that this model will be exactly as well performing under new forcing in the future (Knutti et al. 2010), but is a reasonable requirement for selection. Consideration of models with well simulated past trends and variability makes the selection more reasonable. This conceptual potential problem becomes less important when more observations for model evaluation become available. Besides model selection, most climate services, e.g. for hydrological applications, need to reduce possible model biases by empirical corrections. Section 6 describes selection and bias correction methods in more detail.

Box 3.2 | Shared Socio-economic Pathways (SSPs)

The Shared Socioeconomic Pathways (SSPs) are part of a new scenario framework, established by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi, K., et al., 2017). For modelling purposes the SSPs are combined with the former Representative Concentration Pathways (RCPs) forming a scenario matrix architecture.

The SSPs are based on five narratives describing alternative socio-economic developments: sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil-fueled development (SSP5



), and middle-of-the-road development (SSP2).

Figure B3.2. SSP narratives are designed to span a range of futures in terms of the socioeconomic challenges they imply for mitigating and adapting to climate change. Two of the SSPs describe futures where challenges to adaptation and mitigation are both low (SSP1) or both high (SSP3). In addition, two “asymmetric cases” are designed, comprising a case in which high challenges to mitigation is combined with low challenges to adaptation (SSP5), and a case where the opposite is true (SSP4). Finally a central case describes a world with intermediate challenges for both adaptation and mitigation (SSP2). (from D. van Vuuren’s presentation at H2020 CRESCENDO’s General Assembly, Rome 28th Oct 2016).

Global climate models and ESMs provide the large scale structure of the climate and the climate change signal. Regional interpretation of that signal requires higher spatial resolution than global models can effort (typically 100-200 km for global models, and increasing for

CMIP6) in a computational sense. Regional conditions such as steep orography, and landscape heterogeneities are strongly affecting the signal and its extremes. To address that limitation in global models, regional climate models (RCMs), climate models in spatially limited domains, are applied to downscale ESMs and GCMs with enhanced grid resolution that allows for a much more realistic regional climate response. The rationale and use of RCMs in the value chain from ESMs to climate services are described in section 5.

Potential climate change mitigation methods can be tested by ESM or GCM experiments with different assumptions on the type of land use and on the timing of negative emissions. Both experiments are considered necessary to inform the process towards emission pathways compatible with a global warming below $2^{o}C$ as politically agreed in the Paris Agreement 2015. Non-physical ESM components including a carbon cycle are especially important to address these questions. Experiments are designed in CMIP6 and beyond to find optimal emission pathways.

Accessing model results from the coordinated CMIP experiments requires a strong international infrastructure organisation. For the last phase, CMIP5, a large distributed database had been established, with 2 petabytes used by over 20 000 registered users all around the world. Europe contributes to this database, the Earth System Grid Federation (ESGF), with support from the European climate modelling research infrastructure (EU-IS-ENES-1 and-2 projects), initiated by the European Network for Earth System modelling (ENES). This is only possible thanks to defining a range of standards for naming, storing, describing data and experiments so that they can unambiguously be used worldwide. Twenty-seven modelling centres from Europe, Canada, USA, China, Korea, Japan, Australia run a large set of model experiments and shared them within ESGF. This collaboration required strong national support for computing and human resources to run and evaluate the climate models as well as to adopt the international standards to disseminate output. These climate model results have been widely used within the 5th Assessment report in 2013 and for many climate studies, impact analyses and serve as a reference base for climate services.

The ESM projections and predictions residing on the ESGF data nodes are increasingly utilized by climate services via data networks. This usage of the research data base for long term climate services raises challenges for the climate modelling research infrastructure. Existing infrastructure elements, such as common standards for data and metadata, as well as quality control methods are used. For developed climate services, sustained and reliable ESM data service (i.e. more than temporary, project based), and tools to facilitate its usage and computing facilities for calculating standard indices will be necessary.

The content of the ESM data, e.g. climate projections, is in need of a larger range of scenarios ensembles and needs bias correction for several applications (section 6) and user guidance on a sustained organizational basis. Current limitations exist in the possibilities to create sustained long-term infrastructure elements that underpin the evolving climate services.

As prototypes and models for upcoming data links into climate services, several portals have been built as project activities. In order to facilitate the access to the ESGF database for impact studies, a dedicated portal and platform has been developed in Europe by EU-IS-

ENES and further supported to include impact indices by the Copernicus CLIP-C project. Users can access guidance on how to best use model results, as well as browsing and visualisation of results. CMIP6 is aiming at "ESGF super nodes" which could even hold interactive tools to assess climate performance of model simulations. This is a necessary step to avoid download of large data volumes.

The *climate4impact* portal[7], part of the ENES data infrastructure, represents an example of a link between ESGF and a user community. It is oriented towards climate change impact modellers, impact and adaptation consultants, as well as other experts using climate change data. Climate4impact provides access to data and quick looks of global and regional climate models and downscaled higher resolution climate data, with data transformation tooling and mapping & plotting capabilities and guidance. Additional climate modelling data portals are listed in section 7. A future sustained infrastructure for climate service needs to further develop such approaches.

3.4 Summary and conclusions

Climate and Earth System models are built on basic physical principles. Robustness and uncertainty of climate simulations in general and in particular for climate scenarios and predictions, are mapped by interpreting multi-model coordinated simulations such as recently CMIP5 and the upcoming CMIP6. Decision making with respect to climate adaptation and mitigation needs to relate to uncertainty. Relevance of decisions increases once uncertainties are weighted in.

For climate scenarios of the 21st century, the uncertainty due to natural simulated variability remains about constant with time, the model-error related uncertainty increases slightly, and the uncertainty due to the choice of emission scenario grows strongly. In the second half of the 21st century, the scenario uncertainty is dominating the overall uncertainty. This uncertainty associated with scenarios implies that governance has very different options and can respond to alternative expected climate change amplitudes.

Based on model evaluation efforts on historical climate simulations since the mid 1990s, there is growing confidence in climate models for quantitative future predictions and projections. Many aspects of physical performance has been evaluated and judged using the calibrated IPCC language. Evaluation of ESMs with their additional component models (e.g. for vegetation and carbon cycle) has lagged behind that of physical climate processes, and is currently gaining in focus and importance.

In general, the direct translation of physical model performance from historical simulations into confident statements about fidelity of future climate projections is limited due to incomplete observation of changing past climate conditions. However, evaluation successes with growing observed climate time series showing trends and variability are very well motivating climate services. Additional potential is seen in techniques constraining model results. Standard techniques are described in section 6. New evidence is increasing that observed variability or trends are partly well correlated with inter-model differences in model

[7] https://climate4impact.eu/impactportal/general/index.jsp

projections. These relationships allow transforming an observable quantity into an “emergent” constraint on future projections. The application of such constraints would reduce the uncertainty from a user perspective, and is a growing area of research and method development.

New climate projections of possible future climates are to be carried out under the CMIP6 Scenario Model Intercomparison Project (Scenario-MIP) during 2017-2019. The greenhouse gas emissions scenarios used in CMIP6 extend the concept of RCPs with socio-economic pathways (SSPs) which describe alternative evolutions of future society in the absence of climate change or climate policy. Those are combined with a range of mitigation levels and land use options, which span a matrix of possible optional pathways into the future, associated with alternatives for policy decisions.

Elements of an ESM infrastructure to link climate modelling with climate services exist partly in the form or temporary projects. Efforts to sustain such an infrastructure will be necessary to support long term climate services.

4 European seasonal to decadal climate prediction systems

4.1 Robustness of Earth System Models

Subseasonal-to-decadal (S2D) prediction, also known as climate prediction, has been a central research theme in climate science for the last thirty years. The reason behind the interest is twofold. On the one hand, a growing need has recently emerged from a suite of stakeholders including public decision makers, (re)insurance companies, the tourism industry and the agricultural sector, to name just a few, to benefit from more accurate climate information at time scales ranging between a few weeks to a decade into the future, a range where management and relatively short-term (up to a few years) planning is crucial. On the other hand, the scientific development behind S2D prediction benefits from progress in aspects involving both weather forecasting and long-term climate change assessment, covering a wide range of topics. The recent developments in those two fields (increased resolution, inclusion of new components, better observations, etc.) have brought a leap forward in the quality of the climate information provided by the operational climate prediction systems.

Climate prediction aims at issuing statements about the future evolution of climate on S2D time scales (Doblas-Reyes et al., 2013). The seasonal time scale deals with forecasts for future times ranging between more than one month and slightly longer than one year. Shorter time scales are dealt with by weather and sub-seasonal forecasting, while climate predictions for future times beyond the first forecast year and up to 30 years are covered by decadal prediction.

The statements formulated by climate predictions are accompanied by two fundamental estimates: of the forecast uncertainty and of the forecast quality. As it will be explained below, and following similar arguments to those used in the formulation of climate projections (see section 3), climate predictions are intrinsically uncertain due to the lack of perfect knowledge of the observations used to generate the initial conditions, the inability to perfectly reproduce the relevant processes in the climate system (model uncertainty or inadequacy) and the lack of knowledge about the evolution of the atmospheric composition even in short time scales. Besides, users of climate forecasts require robust estimates of the quality of the predictions to decide the weight they can give to the climate information in their decision process.

The feasibility of climate prediction largely rests on the existence of slow, and predictable, variations in the soil moisture, snow cover, sea-ice, and ocean surface temperature, including how the atmosphere interacts and is affected by these boundary conditions. For instance, at seasonal time scales the El Niño-Southern Oscillation (ENSO) is the main process that contributes to the forecast quality. At the sub-seasonal time scale the main process considered as a source of skill is the Madden-Julian Oscillation (MJO), which allows making accurate predictions of intraseasonal tropical variability, tropical cyclones and extratropical weather types. For the decadal time scale the main source of predictability is associated with the ocean circulation and thermal conditions of the North Atlantic. The initialisation is the first critical stage to be addressed in climate prediction. For instance, the skill associated to the persistent behaviour of the sea-ice encourages its correct initialization. The information about the state of the atmosphere, ocean, sea-ice cover, snow, soil moisture, etc. is needed to phase in the model with the best estimate of state of the climate system at the start date of a forecast. Each component of the model needs to be appropriately initialised, and in the case of empirical-statistical methods, the predictor variables need to use a similar kind of information. This is done in a process known as analysis which, using procedures of various degrees of complexity (like data assimilation), attempts to obtain a physically balanced, optimal (in the sense of an objective metric) extrapolation of the observations onto the grid where the model equations are resolved. In addition, the observed evolution of temperature and other climate variables at the S2D time scale can also be considered as externally forced low-frequency variability due to human-induced changes in greenhouse gas and aerosol concentrations, land-use changes as well as natural variations in solar activity and volcanic aerosol, superimposed on the natural variability of the system. Hence, climate prediction is not just an initial-value condition problem of the internal variability of the whole climate system, but also a boundary-condition problem (Fig. 4.1).

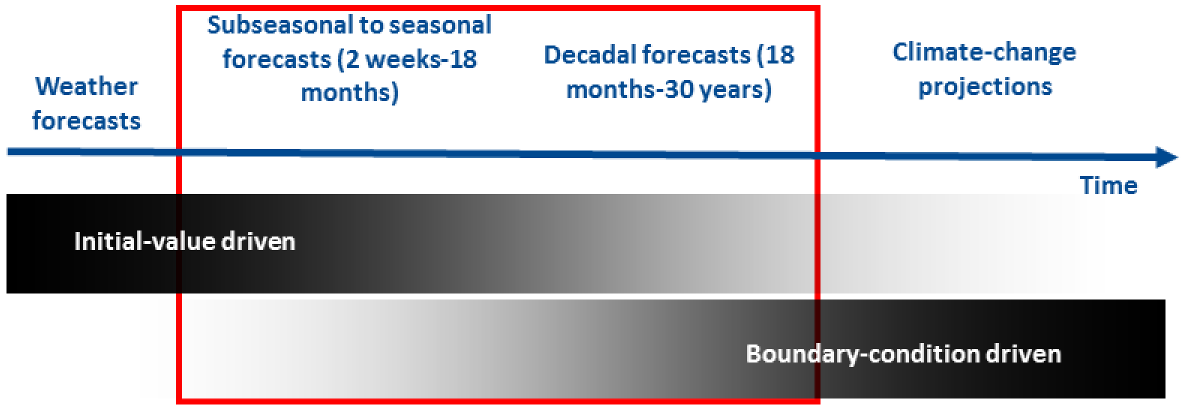


Figure 4.1 Schematic illustrating the progression from initial value problems with daily weather forecasts at one end, and multidecadal to century projections as a mainly forced boundary condition problem at the other, with subseasonal, seasonal and decadal prediction in between. Climate predictions are encompassed within the red box. Adapted from Meehl et al. (2009).

4.2 Performing climate predictions

Two types of prediction methods, those based on either statistical-empirical approaches or on process-based, dynamical models, are used to perform climate predictions (Suckling et al., 2017). Both methods are complementary because advances in statistical-empirical climate prediction are often associated with enhanced understanding, which usually leads to improved dynamical prediction, and vice versa. Both techniques rely heavily on the availability of observations, although with different constraints. The application of the statistical-empirical approach to long-lead prediction requires a careful use of conventional statistical modelling techniques, in particular, due to the relatively short history of the observed database and the existence of long-term changes in a non-stationary climate system. Dynamical predictions use climate models (see chapter 2), developed using observational and theoretical results, and started being explored in the early 1980s to predict ENSO events. The main differences in the way climate models are used for climate-change projections (see chapter 3) and climate predictions are that the former make an increasing use of Earth system models (ESMs), which include processes like the biogeochemistry that are deemed less relevant for formulating climate predictions, and the need to initialise the latter with the best information from observations of the climate system at the time of formulating the prediction (the initialisation stage described above).

Due to the chaotic nature of the climate system and the systematic errors of current forecast systems, quantifying forecast uncertainty plays a central role in climate prediction. Two of the main sources of uncertainty in dynamical climate prediction are the lack of perfect knowledge of the initial conditions of the climate system and the inability to perfectly model this system, and hence its evolution. Climate predictions are typically formulated in a probabilistic way, which is achieved by using a probabilistic formulation in statistical-empirical approaches and with the ensemble method in dynamical forecast systems, which requires an additional statistical model that transforms the discrete solutions from the ensemble into a probability distribution. The probabilistic form of the climate predictions is not the only way to quantify forecast uncertainty, but it tends to be the most frequently used. In any case, dealing with uncertainty is a necessary condition for decision makers to take any action given the probability forecast of an event.

Dynamical climate forecast systems have relatively large systematic errors in their representation of the mean climate, the climate variability, and their interaction. These systematic errors, which are shared with the climate models used to perform climate change projections, are indicative of problems in the model formulations. It has been suggested that systems with larger systematic errors tend to have lower forecast quality. But there is more in-depth specifics about systematic errors in climate prediction. The systematic error tends to be different depending on the time of the year the simulations are initialized in. The variations of the systematic error with the forecast time illustrate the model drift, i.e. the tendency of the predictions to evolve from the observed climate corresponding to the initial conditions to the dynamical model climate. The drift might be complicated by initial-condition inhomogeneity, such as sudden changes in the analyses from which the initial conditions are taken (known as “shock”). The occurrence of the drift also means that in climate prediction simulations the model is a non-stationary state, with a mean climate that changes as the forecast progresses. Process-based evaluation and metrics that allow identifying the main physical processes responsible for the systematic error in seasonal prediction have recently started by exploring the sensitivity of the model adjustment to the drift.

The presence of the drift requires for a climate prediction experiment or forecast system to produce a sufficiently large sample of retrospective predictions (also known as re-forecasts or hindcasts) in order to be corrected for their systematic biases against observations (the selected period should have observations for both initialising and validating the forecasts). These hindcasts, along with the need to run ensembles of simulations, makes dynamical climate prediction a particularly expensive computational exercise. These hindcasts are also used to estimate the forecast quality, as it will be explained below. Finally, the hindcasts also allow to postprocess the forecasts via either calibration (also known as bias correction, see section 6) or downscaling, or both. These processes lead to forecast information that is usable by different decision makers, removing the effect of the drift a posteriori.

All climate forecasts, as any other forecast, have to be systematically compared to a reference, preferably observations, in a multifaceted process known as forecast quality assessment (see box 4.1). The multifaceted nature of forecast quality dictates that no single metric is sufficiently comprehensive to single-out the best forecast system. Forecast quality is fundamental to the prediction problem because a prediction has no value without an estimate of its quality based on past performance.

As in climate projections, generally, predictions from different sources are combined into a single climate prediction to reduce the uncertainties that arise from the errors in the simulation of the relevant dynamical/physical processes. The most common approach to do this is the multi-model, in which a number of forecast systems are combined into a single prediction. The resulting predictions increase different aspects of the forecast quality (Athanasiadis et al., 2016). Fig. 4.2 illustrates this point in the combination of two multi-model ensembles, one from a research exercise (ENSEMBLES) and an operational one (APCC). The figure also gives an idea of the limited accuracy current forecast systems have at the seasonal time scale. Skill for temperature and other variables (sea level pressure, tropical cyclone frequency, Arctic sea ice) is higher than for precipitation, which has been chosen to offer a sober picture of what users can expect. It is important to bear in mind that in many instances of climate prediction a warming trend is the main, though not the only, source of skill in temperature forecasts. This figure is not representative of the accuracy for forecast systems at other time scales, or for other variables, for which the forecast quality varies widely as a function of the forecast time (predictions close to the initial conditions have larger skill), the variable and the region. Unfortunately, a comprehensive comparison of the latest forecast systems across time scales is currently not available.

Box 4.1 | Forecast quality assessment

The forecast quality assessment where the predicted and observed values are compared is a fundamental step in climate prediction (Jolliffe and Stephenson, 2012). It assesses to what measure the combination of different forecast systems leads to an improved forecast or if a forecast system improves when compared to previous versions. Due to the high dimensionality of the problem of forecast verification, it is very important to take into account multiple verification measures to obtain richer and more robust conclusions about the quality and/or value of the forecast systems. Several measures are typically used to assess the quality of the predictions. For probability forecasts the Brier skill score (BSS) and its decomposition in reliability and resolution components are used to assess the forecast quality for binary events. Reliability is a particularly important characteristic for users (Fig. B4.1) and represents the ability of the forecasting system to match the observation frequencies. Ideally, the nominal rates and the observed frequencies would be the same and, as a consequence, the points would be aligning with the diagonal. Other scores for continuous probability forecasts are the continuous ranked probability skill score (CRPSS) and the ignorance skill score. The reference forecast to obtain the skill scores tends to be the naïve forecast base on the climatological distribution estimated from the historical observations, although other references based on the persistence of the anomalies observed immediately before the start date of the forecast are also used. A particular verification data set is just one of many possible samples from a population, and therefore, verification measures need to be shown together with an indication of the sampling uncertainty, which is estimated using either parametric or non-parametric methods.

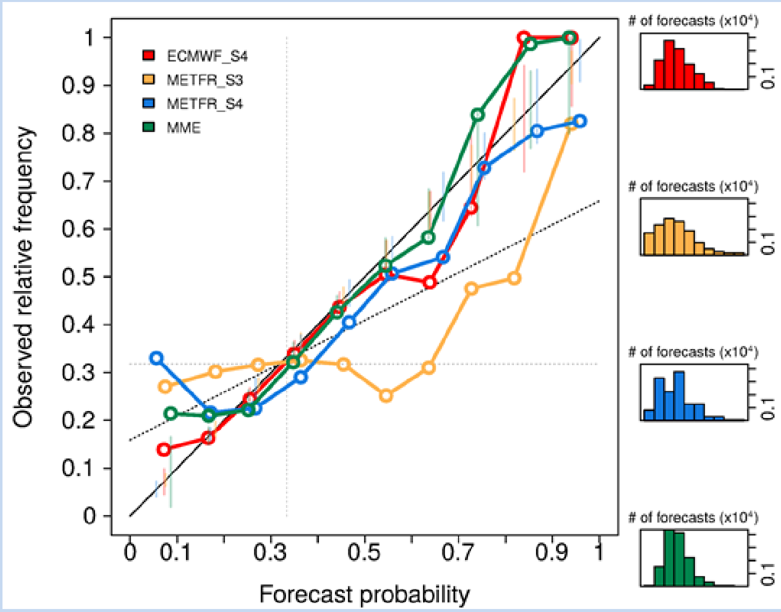


Figure B4.1: Reliability diagrams of 10-metre wind speeds forecasts from ECMWF System 4, Météofrance Systems 3 and 4 and the multi-model built from the three of them using ERA-Interim reanalysis as reference. The predictions are for boreal winter (DJF) with one-month lead time and have been initialized on the first of November for the period of 1991-2012. The reliability diagram is drawn for probability forecasts of categorical events. In this case, the event shown corresponds to the "anomalies above the upper tercile", which means that the observed probabilities are computed as zero or one depending on whether each year the observed value is above the climatological tercile estimated from the observational reference dataset. The proportion of ensemble members with values above the tercile estimated from all the hindcasts available gives the forecast probabilities. In the case of the multi-model ensemble, the probabilities given by each forecast system are averaged. The right-hand-side panels show the sharpness diagrams with the distribution of the forecast probabilities for each probability bin considered. The consistency bars, which give the 95% interval for a perfectly reliable system to deviate from the diagonal by random variations, have been represented as vertical lines to illustrate how likely the observed relative frequencies are under the assumption that predicted probabilities are reliable.

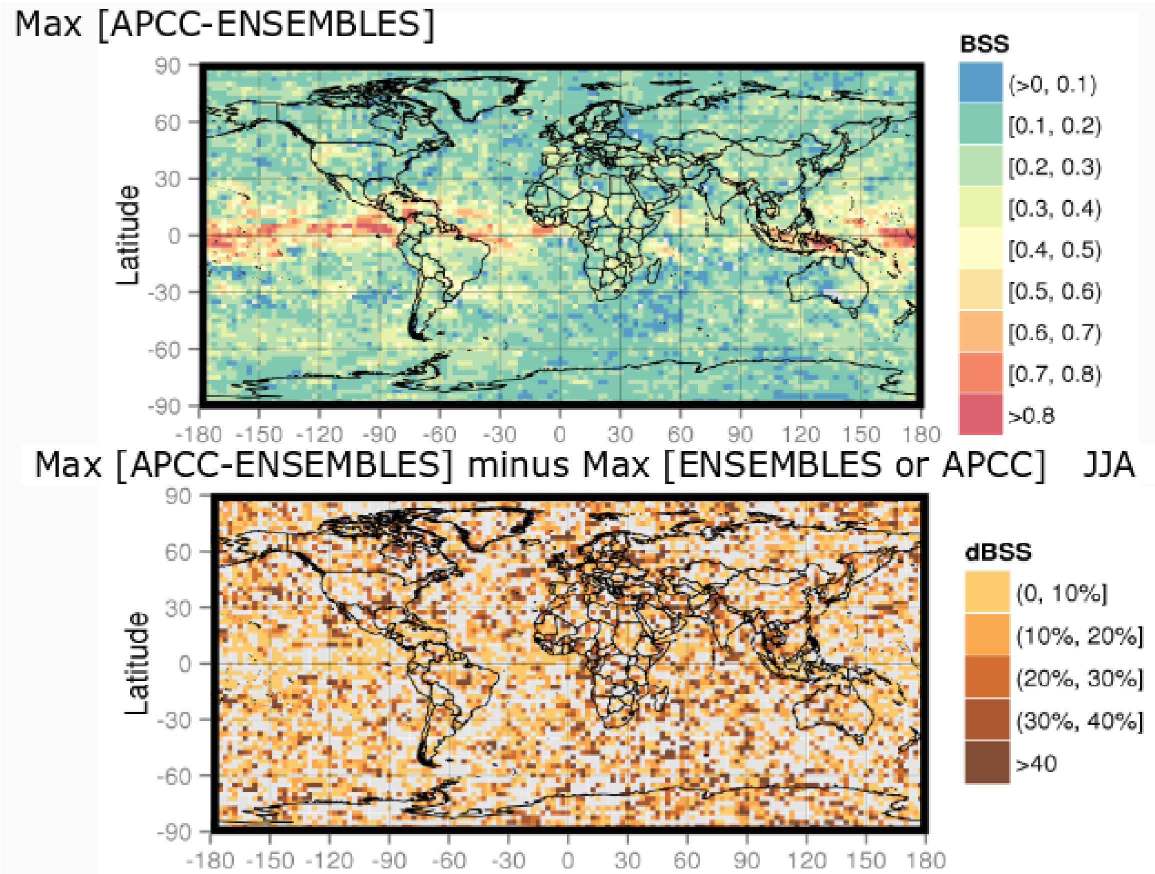


Figure 4.2 Brier skill score (BSS) for the one-month lead boreal summer precipitation multi-model forecasts from the ENSEMBLES and APCC multi-model ensembles (top) and difference with the maximum skill score obtained from either the ENSEMBLES or APCC multi-model ensembles (bottom).In the top panel, positive BSS values indicate that the climate predictions are more informative than a naïve climatological probability forecast. In the bottom panel, grey areas correspond to those where the APCC-ENSEMBLES multi-model does not improve over the best of the individual ENSEMBLES or APCC multi-models. Adapted from Lee et al. (2013).

The number of systems to be included in a multi-model forecast in order to imply that implies a better forecast quality is not well known, as demonstrated in the European projects DEMETER and ENSEMBLES (Weisheimer et al., 2009). The inclusion of a few systems with relatively poor forecast skill may limit the skill of the multi-model ensemble, which has led to the concept of climate filter, which weights the forecast systems on the basis of some metrics that depend on part performance, for the optimisation of the information in multi-source climate predictions (Lee et al., 2013).

Many stakeholders require climate information at regional and/or local spatial scales. This is sometimes readily available with statistical-empirical forecast systems. However, global forecast systems used to generate dynamical climate predictions are typically unable to provide information at the spatial scale required. This is the case in spite of the planned increases in horizontal resolution and, hence, regionalisation or downscaling methods are necessary. Although there are both empirical and dynamical approaches to downscaling, local-scale seasonal predictions usually have explored the empirical or statistical methods due both to the enormous amount of hindcasts to be downscaled to estimate the model systematic error and the necessary forecast quality (necessary to formulate a prediction), and to the large computational demands of dynamical downscaling. The merits of empirical or statistical downscaling consist mainly in providing climate information for specific locations and with much reduced systematic error, but with only a marginal increase of the forecast quality, and even at times a degradation. In spite of the cost of having to downscale all the hindcasts, dynamical downscaling of climate predictions can be justified because local feedbacks between processes, such as soil moisture, clouds, and precipitation are locally important, in particular in summer. However, until now, no clear advantages in terms of forecast quality of dynamically downscaled predictions have been found.

4.3 The future of climate prediction

Three main obstacles are currently hindering the development of skilful and reliable S2D predictions: a) limited computational resources to carry out the predictions with the new systems, b) a lack of efficient communication between the scientific community and the community of users of climate information to identify the priorities for joint development, and c) the quality of the prediction system themselves to satisfy the increasing user demands.

Computational resources are one of the main bottlenecks because climate model complexity is continuously increasing, and usually a substantial number (between 20 and 60) of past forecasts have to be issued to properly characterise the probability that some climate event will occur in the future. High-performance computing (HPC) and novel strategies for optimizing climate model code should make possible reducing the time to solution of these experiments to cope with the increase in climate model complexity and resolution. Communication is an essential facet of S2D prediction, and since scientific research should always lead to some application. The inherent probabilistic character of a climate forecast has proven to be a particularly difficult aspect to communicate to stakeholders, who are used to deterministic statements. In addition, stakeholders generally need tailored information that is not originally present in the prediction systems; this requires an ad-hoc interface and continuous exchanges between the scientist and the user. The Copernicus programme[8] is one of the most visible initiatives in this direction which at this stage is considering the dissemination of tailored multi-model seasonal forecasts and might disseminate in the future other types of climate predictions. Finally, forecast systems themselves are still in need of (large) improvement. Climate model bias and forecast drift remain major barriers that prevent converting predictability estimates into skill. The crude parameterization of some processes (e.g., clouds, sea ice) are susceptible to be the origin of model errors, an aspect that might be alleviated with increases in resolution (Prodhomme et al., 2016), although more serious and ambitious work to include relevant new components (interactive chemistry for aerosols or vegetation) and more realistic processes will still be needed.

[8] www.copernicus.eu

4.4 Climate services based on climate predictions

It has been shown that the best forecasts from the user perspective can ultimately be obtained by optimally combining all predictions available to provide better guidance for decision support (Doblas-Reyes et al., 2013). However, as explained above, an open issue is how to efficiently transfer this information to the range of users interested in using climate information based on predictions. It is already accepted by the community that there is a significant gap between how climate information is communicated (regardless on which time scales are considered) and how it is perceived and used by stakeholders.

One of the aspects that require particular attention is the way users access data and products. Climate predictions can be obtained from a variety of sources. Decadal predictions are made available from the CMIP5 repositories (see section 3), in a similar way as climate projections are. There is a recent effort to make decadal predictions an operational activity guided by World Meteorological Organisation (WMO) standards and following on examples that provide some information in real time[9,10]. The producers warn that these forecasts are still in the development stage and that should be understood as an experiment and not used as a basis for decisions yet.

Subseasonal and seasonal forecast data are made available either in research mode, like from the S2S multi-model database[11] or the CHFP repository[12], or from operations. Many of the research datasets are produced by international initiatives with limited duration and coordinated by programmes or working groups of the World Weather Research Programme (WWRP) or World Climate Research Programme (WCRP, e.g. the Working Group on Intraseasonal to Interdecadal Prediction). While the value of research databases is unquestionable, the character of subseasonal-to-seasonal predictions, which can be verified very soon after they have been formulated (because they have forecast horizons ranging between a few weeks and a year), makes the access to the real-time forecasts invaluable. Although the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble[13] collects a subset of the real-time seasonal (and in the future also subseasonal) forecasts released by the existing 15 global producing centres, the outcome is not made publicly available. Something similar occurs with the subseasonal forecasts disseminated by the S2S project, which provide the forecasts with several weeks delay so that they cannot be used in an operational context. Although this situation of limited access to the data might change in the future, in the short term users are forced to access the real-time forecasts from the individual producing centres, who use a wide range of protocols and policies (many of them with

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9 https://www.fona-miklip.de/service/news/news/news/first-experimental-decadal-climate-forecasts-in-online-interactive-tool/

10 http://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/decadal-fc

11 https://software.ecmwf.int/wiki/display/S2S/Models

12 http://chfps.cima.fcen.uba.ar/

13 https://www.wmolc.org

restricted access) to disseminate their data. Depending on the amount of data required by the user, different download protocols may be used, ranging from http/ftp download via a web browser to serial batch download requests launched from dedicated nodes at weather centres. The complexity of the ecosystem and the political restrictions are a clear barrier to reduce the communication gap.

Users can also access the real-time forecast products in graphical form. As with the data, there are important issues that prevent an efficient access. Current approaches to the visual communication of probabilistic climate forecast information are unsatisfactory (Davis et al., 2015). A visual communication protocol for such forecasts does not currently exist. Global producing centres show their own probabilistic forecasts with limited consistency in communication between different centres, which complicates how end users understand and interpret the products. A communication protocol that encompasses both the visualisation and description of climate forecasts can help to introduce a standard format and message, facilitating the improvement of decision-making processes that rely on climate forecast information.

As a consequence, despite the strong dependence of certain sectors (e.g. energy, health, agriculture, tourism and insurance) on reliable and accurate predictions of climate variability, and the success of several initiatives (e.g. the EUPORIAS and SPECS European projects) towards demonstrating the added benefits of integrating probabilistic climate forecasts into decision-making processes, climate information based on predictions is still underutilised.

4.5 Summary and conclusions

Climate prediction aims at issuing statements about the future evolution of climate on S2D time scales. These statements are always made along with estimates of the forecast uncertainty and of the forecast quality. All three aspects (the forecast statement, the forecast uncertainty and the forecast quality) are huge challenges on their own and, although provided operationally to a range of users, still require a substantial amount of research. Climate prediction is expected to address a long list of challenges to produce climate information that responds to the expectations of both existing and future climate services. Some of the challenges are briefly described below.

A reduction of the forecast drift and systematic error, and an increase of both accuracy and reliability by better understanding and representing the physical processes at the origin of the climate predictability over land areas (where most of the users have their interests) have been a priority for many years. Solutions to rapidly alleviate the systematic error problem have been elusive, progress up to now having been incremental. Above all, it seems important that the climate prediction community takes advantage of the substantial efforts that take place in both the weather

and climate-change communities to improve current Earth system models, in addition to making progress in the aspects specific to the climate prediction problem, such as the initialization and the ensemble generation.

Thanks to the ever-increasing computational resources available and the increased attention paid to model computational efficiency, it is expected that better (both in the sense of forecast quality and interest to the users) prediction systems (i.e. with improved representation of processes and at higher resolution, started from more trustworthy initial conditions and running larger ensembles) will be available within the next years. Various studies have suggested that increasing the complexity of a prediction system by for instance increasing its resolution is generally paired with an improvement of predictions themselves (Scaife et al., 2014; Prodhomme et al., 2016). This future objective is also related to the need to critically examine the role of coupling between components, particularly between the atmosphere and ocean, to more realistically represent such coupling over a wide range of spatial scales (including down to the scales of the sharp SST gradients associated with ocean fronts), and to better observe and more realistically represent fluxes in models.

As the user is increasingly playing a central role, the climate prediction community needs to consider a process-based verification approach and propose solutions that include modelling the mechanisms responsible for high-impact events (not necessarily extreme and with a multivariate perspective), which are arguably the ones that concern most users. Along the same line, the reliable and accurate information should be made available at local-to-regional scales, which can be achieved via the combination and calibration of the information from different sources and the implementation of state-of-the-art regionalisation tools (see section 5).

5 Review of the role of the downscaling efforts for climate services

5.1 Why downscaling?

Global climate models (GCMs) and ESMs provide the large-scale picture of the climate and the climate change signal as well as interactions between the components of the global earth system. Robust assessment of that signal at regional to local scales necessary for development of climate services requires higher spatial resolution than global models can provide. Regional features such as steep orography, varying soil and vegetation properties, and small-scale landscape heterogeneities such as urban areas and coastlines are strongly shaping the signal, associated climate events and short-term extremes. Processes like convection (100 m – km scale vertical movements) are not explicitly represented in ESMs. To address those limitations in global models, regional climate models (RCMs), climate models in spatially limited domains are applied downstream of the GCMs with enhanced grid resolution that allows for a much more realistic regional climate response. To an extent, also statistical models are applied. Those RCMs are driven by the large-scale circulation and physical conditions from global models at their lateral boundaries. RCMs typically cover continental regions such as Europe (Fig. 5.1), the Mediterranean region or Africa, which can be resolved with 10-25 or 50 km instead of the typical 80-200 km for GCMs. The value of downscaling for impact applications generally increases with resolution.

RCMs generally apply the same dynamical equations as global models, but differ in physical parameterizations. For resolutions finer than 10 km, even the dynamic equations need to be adjusted to better account for so-called convective processes involving vertical movement. Reviews about RCMs are given, for instance, by Rummukainen (2010) and Rockel (2015).

In recent years demands for local climate information in support of climate impact assessments and the development of regional to local-scale adaptation strategies has grown quickly. In particular, interest is high when dealing with small-scale extreme events such as local floods caused by short-term, heavy precipitation (e.g. spring floods 2016 in UK). These events can only be captured by climate models with high (10-25 km) or very high (1–10 km) spatial resolutions. Even higher resolutions are required when events are characterized by deep convection, occur in the presence of complex topography and/or involve steep frontal gradients. These resolutions of 3 km and finer are called “convection permitting” or “convection resolving”. The information demands can at present only be addressed by RCMs either embedded in, or driven by, GCMs and global ESMs. (Rummukainen et al. 2014, Jacob et al., 2013, Prein et al., 2015). Limited computational resources do not permit to perform long term climate simulations at convection permitting resolution on a global scale.

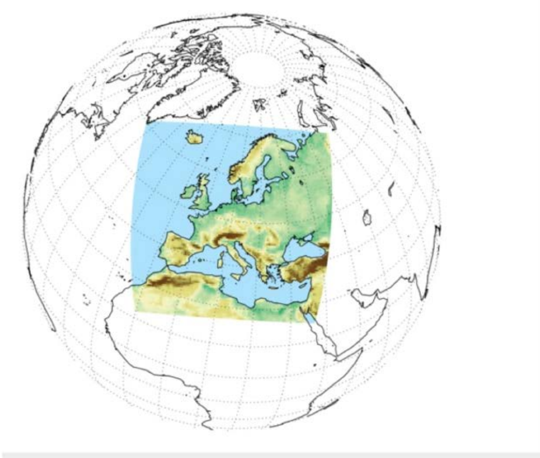

Figure 5.1 The EURO-CORDEX regional climate model domain

As an alternative to dynamical downscaling with RCMs, empirical-statistical downscaling (ESD) can be applied to regionalize global model signals. It is a procedure that first establishes empirical relations between observed large-scale fields (such as circulation patterns) and local climate variables (such as air temperature and precipitation) and then applies the established relations to simulated climate change signals from global climate models. Similar to dynamical models, results are subject to uncertainty, which in this case depends on the chosen strategy or method behind the empirics (Benestad et al. 2015).

While RCMs have the fundamental advantage to build on physical principles, ESD is based on empirical statistical relations. RCM problems relate to the full realization of the principle advantage, while ESD problems exist due to a limited valid range of the empirics. ESD can generally not account for non-stationary relationships between the large-scale and local climate. ESD also tends to reduce the variance of local climate (Benestad et al. 2008). Both methods depend critically on the climate performance of the global climate models, which are to be downscaled. Both approaches are used complementarily, with the RCM approach more widespread due to its general applicability and smaller dependence on regional observations.

As in the case of global models, regional dynamical models of the atmosphere can be coupled to compartmental model systems, e.g., of the ocean, sea-ice, vegetation, subsurface and surface hydrology or bio-geochemistry, towards fully two-way coupled multi-physics and geo-bio-chemistry regional climate system models. The more realistic representation of the complex Earth system with its large internal variability has the potential for a better understanding of feedbacks and interaction processes for different scales and under natural and anthropogenic forcing scenarios.

Added value is, e.g., found in RCMs coupled to regional oceans (Gröger et al. 2015 for the Baltic Sea, and Feser et al. 2011 for the North Sea), sea ice and dynamic vegetation and lakes, which are incorporating more sources of local-to-regional scale coupled feedback, and have more user value. Examples are the impact of climate change on marginal sea's bio-chemistry and Mediterranean air-sea interactions including exchange of gases.

Incorporation of lakes generally improves local temperature variability and enhances precipitation due to induced local circulation. Inclusion of dynamic vegetation feedbacks enhances warming trends over e.g. the Scandinavian Mountain range due to forest expansion in a warming climate and subsequent reduction of the albedo (Wramneby et al. 2010). It also allows quantifying land-based albedo feedbacks (additional winter and spring warming) and evapotranspiration feedback (summertime cooling), as well as methane releasing effects in the Arctic under climate change (Zhang et al. 2014).

By incorporating more complex physics-based groundwater and surface hydrology model systems, the water cycle from catchment to continental scales can be better represented. Via its connection with soil moisture land surface processes such as latent and sensible heat flux, groundwater significantly influences land-atmosphere feedback processes and in turn also the atmospheric boundary layer evolution, extreme events such as heat waves and or precipitation (Keune et al., 2016). Furthermore, the inclusion of groundwater allows for a comprehensive assessment of water resources in the context of land cover and land use change including irrigation and water extraction.

5.2 The added value of regional downscaling

The expectation to downscaling is to add value to coarse resolution global climate simulations. Clear potential advantages due to higher resolution can be expected, although the actual added value can be defined in various ways, either in terms of physical model performance statistics or as process-oriented, or both. Di Luca et al. (2015) discuss the definition of added value. In a practical sense, targeting climate services, added value is seen in a more correct and reliable description of the regional and local climate in mean values and extremes and improved representation of physical and dynamical processes. While RCMs deliver the tool to accomplish this, there remain barriers to realizing their full potential. Among the major limitations to achieve robust estimates (across models, model versions and climate state) of added value are: limited ability to represent internal variability, regional model errors, and incorrect global model fields at the lateral boundaries of the RCM. As a result, added value can be seen in some regions, but can be absent for others. Therefore, the extent of the added value of regional downscaling has long been a topic of scientific argument.

Summarizing this discussion, Rummukainen (2016) concludes that, "Regional climate modelling adds value to the output of GCMs". Added value in a climate modelling sense "aligns itself with quantified measures of skill improvements compared to relevant large-scale data", i.e. climate fields are generally better represented in higher resolution.

The needs of model development and usage of model results motivate an interpretation of added value from a pure climate modelling point of view and from a user point of view. Both are linked by the provision of physically meaningful enhanced spatial and temporal detail that adds value by refining information for applications such as analyses, impact studies, and other climate services.

Considering downscaling of recent climate from large-scale best estimates (observations and reanalysis), there is ample evidence of added value for temperature, precipitation, and wind information, for mean and extremes. Scientific literature is relatively scarce on other climate variables; however, examples exist e.g. for snowfall and extremes (e.g., Prein et al., 2016). "Such added value is traceable to physical mechanisms that come to play in RCMs thanks to their higher resolution in comparison to what is feasible in GCMs. In particular, RCMs add value to GCMs' outputs in regions with variable topography and variable land cover characteristics including snow and ice. RCMs add value to GCMs' outputs also when considering phenomena characterized by small scales and short timescales in the free troposphere as well as surface climate, such as sub daily characteristics of precipitation and extremes" (Rummukainen, 2016). "RCMs do not, however, add value across the board in all regions, seasons, and configurations compared to GCM outputs. Whether regional climate modelling adds value to climate change projections has only more recently come under study. RCMs have been found to modify climate change signals projected by GCMs. When this corresponds to physical features resolved in the RCMs but not in the GCMs, it can be taken as an indication of added value as it coincides with real mechanisms and factors being accounted for. Again, examples of demonstrated added value often coincide with features and measures characterized by higher resolution than what is practically attainable in GCMs" until now.

"The answer to whether regional climate modelling provides added value is yes, but its degree and nature varies with the model, variable, scale, region, experiment set-up including boundary conditions (GCM, reanalysis), and also applications using RCM output." (Rummukainen, 2016) Thus, it is necessary to further on focus on which variables and processes can be improved and how different regions respond to downscaling.

The relevant literature on RCM downscaling is extensive, but to a large extent it consists of studies that are based on different models, configurations, regions, periods, and appropriate metrics. To address that issue, the CORDEX community (see below) is planning for so called CORE coordinated experiments (Gutowski et al. GMD 2016) with more comparable results in terms of climate variables and processes.

Studies from all fields of climate modelling (RCM, GCM, ESM, climate prediction) strongly indicate that there is potential for further improvement of climate simulation performance (e.g. EMBRACE final report, 2016). In the case of RCM downscaling, improved added value by continued model development, including increased resolution, can be expected (Kendon et al. 2014), and will be necessary for the emerging European climate services.

5.3 CORDEX and its potential for climate services

The international framework for advancing the science and application of dynamical regional downscaling is provided by the "Coordinated Regional Downscaling Experiment" (CORDEX[14]) (Giorgi et al. 2006). CORDEX is a component of the World Climate Research Programme (WCRP) and was established in 2013 under the Working Group on Regional

[14] http://wcrp-cordex.ipsl.jussieu.fr

Climate (WGRC), which interacts with both the physical climate science community and the users of climate information.

CORDEX provides an internationally coordinated framework to improve regional climate scenarios for many regional domains. This includes harmonization of model evaluation activities in the individual modelling centres and the generation of multi-model ensembles of regional climate projections for the land-regions worldwide (e.g. EURO-CORDEX, described below).

Climate services are driven by societal needs to support sustainable development throughout societal sectors by enhancing understanding of projections of future climatic conditions. As such, climate services must integrate and convey sets of projections at multiple scales including the regional and local scale, where the climate change impact is felt and adaptation needs exist. CORDEX simulations are providing coordinated sets of regional downscaled projections for most regions of the world (Fig. 5.2). Further needs down the value chain towards climate services are related to bias correction and models selection (see section 6) methods and user guidance.

Present activities of CORDEX include the design of the CORE experiment and the Flagship Pilot Studies (FPS). The CORE experiment aims at the creation of a consistent ensemble of regional climate simulations at high spatial resolution for all major land-areas of the world using a given set of RCMs. The FPS are aiming at investigating regional climate processes and phenomena and improving their representation in regional climate models (see Box 5.1 for a more detailed description).

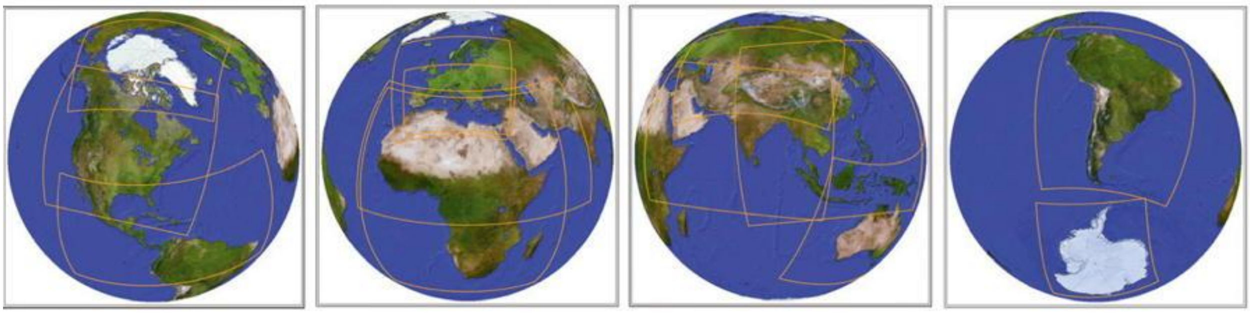

Figure 5.2 Various CORDEX domains for RCM downscaling of recent climate and future climate scenarios

5.3.1 EURO-CORDEX

As a part of the global CORDEX framework the EURO-CORDEX[15] initiative provides regional climate projections for Europe at 50 km (EUR-44) and 12.5 km (EUR-11) resolution. The following link gives an overview on the planned, running, and finished dynamical regional climate simulations.

EURO-CORDEX is actively supported by 31 modelling groups and is coordinated by the Climate Service Center (GERICS) in Germany, together with the co-coordinators from the Aristotle University of Thessaloniki in Greece and from the Bjerknes Centre for Climate

[15] www.euro-cordex.net

Research in Norway. EURO-CORDEX aims to improve the robustness of climate projections at regional scales and at high spatial and temporal resolution in order to enable the European society to better adapt to unavoidable climate change and to design more efficient mitigation strategies. The output from EURO-CORDEX serves, and will continue to serve, as the scientific basis for climate services in Europe. Besides creating and providing an unprecedented ensemble of regional climate simulations at high resolution over Europe, EURO-CORDEX aims at improving RCMs and developing new statistical methods for downscaling and analysis. In addition, in order to facilitate the usage of the ensemble of simulations by the Vulnerability, Impact, Adaptation and Climate Services (VIACS) community and other potential users, EURO-CORDEX guidelines are being created, providing practical and background information. They will be available via the EURO-CORDEX webpage[16]. Furthermore, as a service for the VIACS community, bias-adjusted data is created and documented.

In its initial phase, the focus of CORDEX was on the evaluation of various aspects of the regional simulations of present-day climate. In Vautard et al. (2013), the ability of the EURO-CORDEX ensemble (EUR-11 and EUR-44) to accurately simulate heat waves at the regional scale of Europe was evaluated. Kotlarski et al. (2014) documented the performance of the EURO-CORDEX models in representing the basic spatio-temporal patterns of the European climate, with respect to near-surface air temperature and precipitation for the period 1989–2008.

Over the last years, a new coordinated high-resolution regional climate change ensemble with a horizontal resolution of 12.5 km has been established for Europe (Jacob et al. 2014). The regional simulations were downscaling CMIP5 global climate projections (Taylor et al. 2012). 26 modelling groups were contributing with 11 different regional climate models, partly in different model configurations. Current efforts are focusing on methods to enhance synergies between the RCM and empirical statistical downscaling (ESD) activities, and with GCM projections, in the context of the Working Group on Regional Modelling' s (WGRM) distillation challenge.

Analysis of EURO-CORDEX hindcast simulations confirms the ability of RCMs to capture the basic features of the European climate, including its variability in space and time (Kotlarski et al. 2014). But it also identifies deficiencies of the simulations for selected metrics, regions and seasons. Seasonally and regionally averaged temperature biases are mostly smaller than 1.5 °C, while precipitation biases are typically located in the ±40% range. The biases limit direct use of climate model results in most impact models due to many nonlinear relations in these. Therefore bias correction is needed to reduce biases (see section 6). Some bias characteristics, such as a predominant cold and wet bias in most seasons and over most parts of Europe and a warm and dry summer bias over southern and south eastern Europe reflect common model biases. For seasonal mean quantities averaged over large European sub-domains, no clear benefit of an increased spatial resolution (12 vs. 50 km) can be identified. The bias ranges of the EURO-CORDEX ensemble mostly correspond to those of earlier activities (in the EU-ENSEMBLES simulations), but specific improvements in model performance can be identified (e.g., a less pronounced southern European warm summer bias). The temperature bias spread across different configurations of one individual

16 www.euro-cordex.net

model can be of a similar magnitude as the spread across different models, demonstrating a strong influence of the specific choices in physical parameterizations and experimental setup on model performance. Based on a number of reproducible metrics, Kotlarski et al. (2014) quantify the currently achievable accuracy of RCMs used for regional climate simulations over Europe and provide a quality standard for future model developments. Vautard et al. (2013) evaluated the ability of the EURO-CORDEX ensemble (EUR-11 and EUR-44) to accurately simulate heat waves at the regional scale of Europe. Future climate change is investigated e.g. by Jacob et al. (2014), with the first set of high-resolution simulation (EUR-11). A list of publications related to EURO-CORDEX can be found here: http://euro-cordex.net/060380/index.php.en.

The major EURO-CORDEX achievements so far are:

- EURO-CORDEX provides a coordinated model evaluation and climate projections framework and is an interface to the applicants of the climate simulations in climate change impact, adaptation, and mitigation studies (the VIACS activity, e.g. by bias documentation). Seven annual meetings have been held to discuss ongoing research and future plans. To bring convergence between different modelling activities, three working groups have been established: dynamical downscaling; empirical statistical downscaling and climate information distillation.
- A comprehensive EURO-CORDEX database is being published and distributed via the Earth System Grid Federation (ESGF) under the project name "CORDEX". The regional climate model simulations for the European domain are conducted at two different spatial resolutions of 0.44 degree (EUR-44, ~50 km) and the finer resolution of 0.11 degree (EUR-11, ~12.5km) for different emission scenarios defined by IPCC.
- Guidance for the VIACS community and other users is provided bilaterally and via the EURO-CORDEX Guidance document.
- To date EURO-CORDEX has resulted in 18 peer-reviewed publications with more in preparation.

Current efforts are concentrated on developing phase 2. The EURO-CORDEX community is involved in the leadership of two FPS projects on convection permitting modeling and land-use land-cover change, respectively. The VIACS community will profit from the improved regional climate models and their capability to simulate climate events at regional to local scale at very high resolution.

5.3.2 MED-CORDEX

Another CORDEX domain relevant for Europe is MED-CORDEX domain. Proposed by the Mediterranean climate research community as a coordinated contribution to CORDEX, the MED-CORDEX[17] initiative is supported by HyMeX[18] and MedCLIVAR[19] programs. Currently 20 research groups from 11 countries participate in the initiative which makes use of regional climate system models to increase the reliability of past and future regional climate information (Ruti et al., 2016) with focus on Mediterranean Sea and surrounding land. Within

[17] www.medcordex.eu
[18] www.hymex.org
[19] www.medclivar.eu

the online database, regional coupled runs can be found together with runs of stand-alone components (ocean-only and atmosphere-only), giving users a unique opportunity to explore the impact of coupling on different models results.

Similarly to EURO-CORDEX, in its initial phase the MED-CORDEX focus was on the evaluation of regional models under so called perfect boundary condition experiment using ERA-Interim for initial and latterly boundary condition (Fantini et al., 20016; Dell'Aquila et al., 2016). The majority of available runs are provided on 50 km resolution but there are also runs on 12.5 km resolution. The second stage was dedicated to CMIP5 global climate projection downscaling (to be published in special issue of Climate Dynamics journal in early 2017). In the context of future activities, MED-CORDEX research community will participate in three FPS that are already endorsed by CORDEX.

Scientific achievements within the MED-CORDEX initiative can be clustered in three groups. The first group covers results related to the atmospheric processes in the Mediterranean area, more specifically cyclogenesis processes and extremes associated with Mediterranean cyclones, such as intense precipitation and wind events. Improving the resolution from 50 to 12.5-km grid spacing gives increased accuracy of extreme rainfall events. Several studies found benefits from coupled systems in comparison to stand-alone models. Atmosphere-ocean coupling results in improved representation of SST in coupled system simulations, that has an enhanced impact on the Mediterranean cyclones (cyclogenesis, lifetime, and intensity) compared to atmosphere-only runs, which use low-resolution SST, taken from GCM or reanalysis as a lower boundary condition. In addition, it was found that high-frequency atmosphere-ocean coupling significantly influences the extreme event intensity and position. A second group of scientific achievements emerges from other climate system components such as river discharge and aerosols. It was found that decreasing trend in aerosols over the past decades in the region to some extent contributed to the corresponding positive SST trend in Mediterranean basin, and that a clear added value exists in using coupled regional climate system models with respect to SST-driven RCMs for the correct simulation of this interconnection between aerosols concentration and SST. Finally a third group of achievements is strengthening the link with the vulnerability, impacts, and adaptation research community through the establishing of connection between climate modelling groups and key impact sectors. More details on this findings and corresponding references can be found in Ruti et al. (2016) and MED-CORDEX publication web page[20] .

[20] https://www.medcordex.eu/publications

Box 5.1 | CORDEX Flagship studies

During the International Conference on Regional Climate - CORDEX 2013, a number of scientific challenges were identified, including the need for:

- More rigorous and quantitative assessment of the added value of regional downscaling;
- Better understanding of processes and phenomena relevant for regional climate change;
- Moving towards very high resolution, convection permitting models;
- A broader and more process-based assessment of downscaling techniques and models;
- Development of coupled regional earth system models;
- Distillation of actionable information from multiple sources of downscaled projection information.

Since addressing these scientific challenges could be problematic within the general CORDEX framework that employs standard sets of simulations for large domains (often encompassing entire continents), more targeted experimental setups, called Flagship Pilot Studies (FPS), were requested. These will enable the CORDEX communities focusing on sub-continental-scale targeted regions, addressing key scientific questions and the needs of the VIACS (Vulnerability, Impacts, Adaptation and Climate Services) community (Ruane et al. 2016).

A total of Five FPS proposals, out of nine, were selected from the first round of submissions and announced at the ICRC-CORDEX 2016:

- Extreme precipitation events in South-eastern South America: a proposal for a better understanding and modelling
- Convective phenomena at high resolution over Europe and the Mediterranean
- Impact of land use changes on climate in Europe across spatial and temporal scales
- Role of the natural and anthropogenic aerosols in the Mediterranean region: past climate variability and future climate sensitivity
- Role of the air-sea coupling and small scale ocean processes on regional climate.

Results of the FPS studies will potentially impact on forthcoming CORDEX Common Regional Experiment framework (CORE) experiments. The motivation of CORE is the need for eliminating inhomogeneity in information and simulations across domains and to improve on the often relatively coarse resolution in relation to the upcoming CMIP6 global climate model effort. The CORDEX community is currently developing detailed plans for the CORE experiments.

5.4 How do users currently access downscaling data

5.4.1 Use of RCM Information

Information derived from RCM downscaling under the coordination of CORDEX is the primary input to emerging European climate services. Already today, EU-FP7 and EU-H2020 research projects are addressing ways to utilize the downscaling information. Here we give selected examples.

- IMPACT2C: The data simulated within the EURO-CORDEX initiative were used to investigate a climate change of +2°C global warming, and the corresponding impacts, risks and adaptation in Europe, as well as key vulnerable hot spot regions of the world. This was the main objective of the EU FP7 IMPACT2C project. IMPACT2C was a multi-disciplinary international project, running from 2011 to 2015, which was funded by the European Commission's 7th Framework Programme under the grant agreement No. 282746. The key findings of the project are summarized in the IMPACT2C atlas[21].

- Assessment reports for the North Sea and Germany: Climate change show wide regional variability. Decision-makers, national and local authorities need information on the climate change particularly in their region to cope responsibly with the impacts of climate change. For this reason, the North Sea Region Climate Change Assessment -NOSCCA- was initiated to provide climate change assessment of the North Sea region (Quante et al. 2016).
- GLOBAQUA, aims to improve the scientific knowledge regarding the relationships between multiple stressors, including climate change, to freshwater systems so as to identify potentially synergistic linkages, and to assess how these interactions determine changes in the chemical and ecological status of water bodies.
- CLIPC provides access to climate information of direct relevance to a wide variety of users, from scientists to policy makers and private sector decision makers. Information includes data from satellite and in-situ observations, climate models and re-analyses, as well as transformed data products to enable impacts assessments and composing of climate change impact indicators. The platform focuses on datasets which provide information on climate variability on decadal to centennial time scales from observed and projected climate change impacts in Europe, and provides a toolbox to generate, compare and rank key indicators.

In addition to research projects, first pilot projects under the COPERNICUS climate change service program have been started. Those make active use of downscaling products. Examples are:

- UrbanSIS (Climate information for European Cities): The purpose is to produce high-resolution meteorological, air quality and hydrological data for urban climate change impact assessment, initially based on CMIP5 downscaled climate scenarios on high resolution. A range of Essential Climate Variables (ECVs) will be produced with 1x1 km2 resolution in 150x150 km2 domains covering European cities. From the ECVs, key impact indicators will be calculated to assist planners and decision makers. Impacts focus mainly in infrastructure and health and the concept will be demonstrated in Stockholm, Bologna and Amsterdam/Rotterdam. Various end-users involved in the project will evaluate the products using local models.
- SWICCA (Service for Water Indicators in Climate Change Adaptation): The aim of this service is to provide data and guidance for climate impact assessments in the water sector. The main target group is consulting engineers (so called Purveyors) working with climate change adaptation in the water sector. By using indicators, climate impact assessments can be done without having to run a full production chain from raw climate model results – instead the indicators can be included in the local workflow with local methods applied, to facilitate decision-making and strategies to meet the future. Working with real users will ensure that useful data is inserted into the Climate Data Store (CDS).

A complete catalogue of Sectorial Information Systems is available under COPERNICUS[22].

[21] www.atlas.impact2c.eu

5.4.2 Databases

The majority of CORDEX simulations are available to users today via the Earth System Grid Federation (ESGF) ESGF data base. Additional data bases exist for specific CORDEX regions, for specific data types and for long term archiving. Relevant databases are listed in table 5.1

Table 5.1 Databases relevant for regional downscaling information and data

Database	*Data Type*	*Description*	*Links*
Earth System Grid Federation (ESGF)	Data from climate research generated for and within climate model intercomparison projects: global model output (e.g. CMIP5), regional model output (e.g. CORDEX – see special section for more details) and selected observational data (e.g. obs4MIPs)	ESGF is a worldwide federation for climate data with data nodes in Europe, USA, Canada, China, Japan and Australia. User registration is easy and immediately effective. Registration and data download are free of charge. Most data are also accessible for other purposes than research, even for commercial use.	http://esgf-data.dkrz.de/
Med-CORDEX database	Data from climate research generated for and within MED-CORDEX climate model intercomparison project.	Online database provide access to the results of regional Earth system models that participate in MED-CORDEX initiative. Both coupled and stand-alone components results are available. Registration and data download are free of charge.	https://www.medcordex.eu/medcordex.php https://www.medcordex.eu/simulations.php
EURO-CORDEX database	Data from climate research generated for and within EURO-CORDEX climate model intercomparison project.	The CORDEX regional climate model (RCM) simulations for the European domain (EURO-CORDEX) are conducted at two different spatial resolutions, the general CORDEX resolution of 0.44 degree (EUR-44, ~50 km) and additionally the finer resolution of 0.11 degree (EUR-11, ~12.5km).	Links to European datanodes: esgf-data.dkrz.de http://esgf-index1.ceda.ac.uk/ http://cordexesg.dmi.dk/ http://esgf-node.ipsl.fr/ http://esg-dn1.nsc.liu.se/ **Mailing List** EURO-CORDEX to stay informed about updates, events and discussions: gerics-it@hzg.de
World Data Center for Climate / CERA at DKRZ (WDCC)	Earth system model data (incl. AR4 IPCC) and related observations, data for and from climate research	The services of the WDCC focus on climate data collection, long-term preservation, and dissemination through DKRZ's operational CERA data and information system.	http://cera-www.dkrz.de http://www.dkrz.de/daten-en/cera/portal

[22] http://climate.copernicus.eu/sectoral-information-system

IS-ENES - Infrastructure for the European Network for Earth System Modelling (ENES)	Climate data	The ENES data services will help you to find and access climate data provided by the distributed data centers within the ENES data federation. Information on the different climate models and tools developed in Europe and on European high performance computing facilities is also provided.	https://verc.enes.org/data
IPCC Data Distribution Centre	Data underlying the IPCC Assessment Reports	The IPCC DDC provides climate, socio-economic and environmental data, both from the past and also in scenarios projected into the future. Within the IPCC-DDC, the WDCC/DKRZ hosts the Reference Data Archive for the climate model output data underlying the IPCC Assessment Reports.	http://www.ipcc-data.org/sim/index.html http://ipcc.wdc-climate.de

5.5 Summary and Conclusions

Climate services include the integration and provision of climate projections at multiple scales including the regional and local scale, where the climate change impact is felt and adaptation needs exist. Regional climate simulation efforts, especially those of the CORDEX communities are providing coordinated sets of regional downscaled climate projections.

Regional downscaling is clearly adding value to the underlying global climate projections, with the degree and the nature of the added value varying with the climate model, climate variable, geographical region and other factors. Downscaling is a critical component and basis for downstream development of climate services. However, outstanding scientific questions need to be answered in order to obtain robust estimates of regional change. Therefore, the regional downscaling community, for Europe especially EURO-CORDEX and Med-CORDEX, is focusing on further improving climate modelling, related processes and information integration methods, such as fine-scale process-level changes in the climate system and robust assessment of regional change via the CORDEX FPS and CORDEX CORE simulations. Those efforts are expected to further improve downstream climate services. EURO-CORDEX and Med-CORDEX are valuable expert communities on both the benefits and limitations of regional downscaled climate information. They give guidance to user communities and are actively engaged in interdisciplinary efforts with distributors such as Copernicus Climate Change Services and other downstream developers of climate services.

6 Refinement Techniques

6.1 Introduction

Climate models and ESMs are the main source of information for assessing the potential impact of climate change on human activities and livelihoods, at global or regional scale. The output from the climate models can be used as input data for different impact algorithms such hydrological models, crop simulations etc. Given uncertainty in climate model projections and predictions (sections 3 and 4), impact studies must be based on an ensemble of climate simulations. Climate impact assessment should not be carried out based on a single climate simulation.

The extent of simulation data is beyond the capacity of many impact groups using climate model output. The number of global climate models (GCMs) available is increasing. These models often generate multiple ensemble members, which increase the number of available runs (Lutz et al. 2016). However, limitations appear when using available data. Computational capacity, if increasing, is not infinite and only a limited selection of models and model runs can be used in a given study. As large discrepancies in future changes can be observed amongst the models for the different variables (Overland et al. 2011), criteria for how and which models are selected is of primary importance for the results of any impact assessment study.

Large and systematic biases can be observed between the climate simulations and the observations, despite continuous improvements over the past decades. Such biases have a strong impact on the result of hydrological studies and thus need to be reduced before the impact application. It has been shown that the use of a non-bias-corrected output from a GCM for a hydrological simulation will lead to unrealistic results, at seasonal (Hansen et al., 2006) or longer timescales (Sharma et al. 2007). These results will be of limited use for the wide range of sectors that need to adapt to future changes in freshwater resources such as water management, energy, and agriculture (see section 4 for examples specific to climate prediction). The same limitations applied to crop simulations (Macadam et al. 2016). For this reason, an adjustment of correction has to be applied to climate model output before its use for impact assessment. This correction aims at reducing the bias in the modelled data with regard to a reference (usually observations) in order to obtain a more useable dataset for impact assessment.

Also other methods exist for translating climate model output into relevant input for impact models. So called “delta-methods” modify observations with the help of information on simulated climate changes, and also statistical weather generators can be used.

In this section we will describe some of the main methods for selecting and correcting climate data highlight their strengths and limitations and investigate the potential for improvement.

6.2 Model selection and inter-model uncertainties

An increasing number of global climate models are becoming available for climate change impact studies. IPCC AR4 (IPCC, 2007), based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive (Meehl et al. 2007), uses the outputs from 25 GCMs, whereas the fifth IPCC AR5 (IPCC, 2013), based on the CMIP5 archive (Taylor et al. 2012), uses 61 models. Moreover, a varying number of simulations are available for the different GCMs. Some groups are submitting a single simulation while other institutes propose an ensemble of simulations for a single model. Similar large datasets exist for climate predictions, both in research and operational modes (section 4).

Large differences can be found in the projected changes across different models and the spread in model projections represents a large proportion of future climate uncertainty (McSweeney & Jones 2016). Considerable differences can be observed in the model's performance and output, at global or regional scale and sometimes without obvious reasons (e.g. Overland et al. 2011). There simply is no one best model (Gleckler et al. 2008). To assess the range of potential impacts of climate changes, the range of plausible scenarios has to be investigated. A multi-model approach, involving a large number of GCMs should be ideally used, representing the range of projected outputs. However, the number of simulations used is limited in practice by data accessibility and computational capacity and specific user needs. For this reason, most impact studies are restricted to a subset of GCMs, RCMs and the selection method has a strong effect on the impact scenarios that are generated and the potential decisions that will follow.

It is also worth noting that impact models are often fed with downscaled data that can be obtained through a dynamical process from a regional climate model (RCMs, see section 5) or by statistical downscaling. We focus here on the selection of global models but the same discussion and methods apply for the selection of regional models used for downscaling.

6.2.1 Model selection methods

In the literature and in practise, the selection of models is usually highly subjective and/or determined by practical reasons such as model availability or computing capacity. According to Masson & Knutti (2011) the selection must be designed to maximise model diversity in order to capture uncertainty yet ensuring good model performance. No universal method has been applied for models selection, even though some approaches have been proposed, which share common key points (e.g. Overland et al. 2011; Cannon 2015; Mendlik & Gobiet 2016, Wilcke and Bärring 2016). In the field of seasonal to decadal climate prediction the problem is slightly different because, as explained in section 4, objective combination methods can be used assuming that the forcing in the forecast time is similar to the forcing active during the hindcasts, saving the users the need to select the models. However, the previous assumption is not always valid, as explained in 6.3.4.

One of the main considerations is the performance of the model, its skill to reproduce historical observations and trends for a given variable in a given region. Indeed, the model's performance can be strongly dependent on the localisation and global and regional assessments should be carried out. However, this parameter should not be used alone, as correlations between past performance and future climate change have been shown to be sometimes weak (Knutti et al. 2010). The ability of a model to produce results comparable with observations does not mean that this model will be as performing under new forcing in the future but is a first requirement for selection. This performance assessment should therefore be used to eliminate poorly-performing models rather than to select best ones.

After having reduced the number of models, the remaining ones should be evaluated and a subset can be chosen. This has been done by selecting only the most extremes simulations (Cannon 2015) or by assessing the performance of each model for the region and variables of interest. One should be interested in selecting models that capture a broad range of responses to climate change. The size of the subset may be the main limitation, given computational capacity. Many works rely on a small subset of a few simulations, up to five. According to McSweeney & Jones (2016), a subset of five models might be insufficient to represent the range of projected changes globally in temperature and precipitations, which can lead to an underestimation of the uncertainty in future climate change. A strategic approach is needed, with the selection of regionally-optimised subsets, in order to capture the range of projected changes. This is especially true for small-size subsets.

Before selection, an evaluation of a broad range of climate variables in all climate models should be done. Then, depending on the question in an impact study, a selection of the available model runs can be made based on the relevant climate variables. E.g. in some cases the distribution of the precipitation over the year in a country may be much more important than the total annual rainfall. In that case e.g. the range of seasonal rainfall should be the selection criterion and not the annual rainfall. Depending on the variation (and the aim of the study) a selection can be made.

Whatever selection method is applied, it is useful to provide information on the spread across the selected models and across the available models. The idea (for future research) is to quantify which portion of the range of projections is captured by the subset. This could help policy-makers to consider a plausible range of projections and inform about uncertainties of climate projections and their use.

6.2.2 Model dependence

Even though the different models can produce very different results for future climate, an agreement can be observed across some of them. This agreement should be considered with caution, as it might result from the fact that some models use similar simplifications, because institutes share knowledge or datasets (Abramowitz & Bishop 2015). This means that some models share the same systematic errors or skills. Selecting two similar models would result in a double-counting problem where the same result is counted twice, which can lead to a bias in the overall results. A down-weighting of similar models could avoid these statistical biases in the models subset (Knutti et al. 2013).

Mendlik & Gobiet (2016) propose a method for model selection based on principal components analysis (PCA) to find common patterns of climate change and sampling models from each cluster to generate a subset of models that captures the range of change. This method accounts for model similarity and dependence. Abramowitz & Bishop (2015) have developed a mathematical post-processing method to reduce model dependence in CMIP ensembles.

Independent of the methods chosen, users of multi-model ensembles need to take model interdependency into account before selecting a subset of GCMs for investigating climate projections.

6.2.3 Greenhouse gas emission and concentration scenarios

Climate models are used to generate climate projections with respect to a large range of drivers, amongst which the emissions of greenhouse gases (GHG) is the most widely-known. GHG concentrations are used as an input to climate models to investigate the impact of climate change and potential mitigation solutions. To ensure consistency across the scientific community and a better understanding by the audience, a common set of emissions scenarios has been adopted by the IPCC AR5 (2013) and has been used for climate change simulations. These emission scenarios are referred to as “representative concentration pathways” (RCPs, see also section 3) representing four GHG concentration trajectories under a set of socioeconomic assumptions. They describe four climate futures, covering the range of plausible scenarios. The four RCPs are named after the expected radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5W/m2, for RCP2.6, RCP4.5, RCP6, and RCP8.5, respectively, Fig. 6.1). For a given model, climate simulations will produce different projected changes for different emission scenarios.

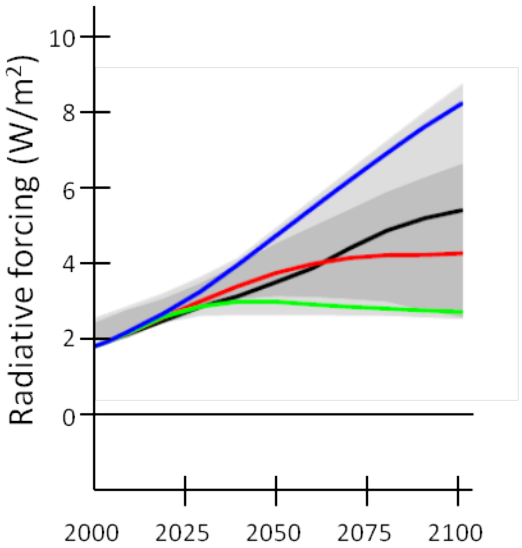

Figure 6.1 Trends in radiative forcing. Grey area indicates the 98th and 90th percentiles (light/dark grey)of the literature (modified from van Vuren et al., 2011)

As the largest contribution for projection uncertainty after the first 20-30 years is given by the choice of emission scenario (section 3), their selection for any climate change assessment is as important as the model selection. There is no universal solution for this selection, as it depends almost entirely on the nature of the study and the message that will be created and disseminated. One might be interested in exploring the range of plausible future, hence using the most extremes scenarios (RCP2.6 and 8.5), whereas other studies might try to highlight the potential differences between two scenarios (e.g. Hannah et al. 2013). In any case, the selection of the scenarios should be detailed and well-argued and its implications described.

Moreover, the importance of this selection is dependent on the timescales; as the four RCPs often produce comparable results for the first half of the 21st century, the choice of the emissions scenario is especially important for the second part of 21st century.

6.3 Bias adjustment

A general definition for bias adjustment (or bias correction) applied to climate models could be a method to reduce the model bias with respect to a “true” reference dataset. In practice, this reference is often an observational dataset or reanalysis that will be used to correct climate modelled data in order to use it as input for an impact study (“bias-correction” methods). Also “delta-methods” methods are used, where observational data is modified with information on changes from climate model runs.

Correcting gridded model output with observation or reanalysis often leads to a spatial and/or temporal scaling, the model and the observation presenting different resolutions. For this reason, bias adjustment methods are often applied for statistical downscaling (section 5) as well as for bias reduction. In this section, we focus only on the “correction” aspect of bias correction, without describing its use for downscaling.

Climate models output such as temperature and precipitation data can exhibit large and systematic errors (biases) when compared to observations (Teutschbein & Seibert 2012). This may be due to imperfect conceptualisation, discretisation and spatial averaging within grid cells, simplified physics and thermodynamic processes, numerical schemes or incomplete knowledge of climate system processes. This might, for example, result in an over-estimation of the number of wet days with low intensity or incorrect seasonal variations of precipitation, with consequences for information usage via climate services.

These data are the main input in many impact models, whether it is for hydrological simulations for water resources management (Piani et al. 2010) or for crop models for agriculture (Macadam et al. 2016), or other types of impact models. Refinement techniques such as bias adjustment can be applied for their use in any impact assessment study.

In the following we will describe some of the most commonly used bias correction methods. When using the terms bias correction or bias adjustment, we refer here to any method that aims to reduce or avoid the bias between model and observations in order to be able to compare historical, present and future scenarios. This will include for example the delta change approach which may or may not be considered as a bias adjustment for some authors (e.g. Räty et al. 2014). Bias adjustment methods for climate predictions are briefly described in section 4 and in 6.3.4 below.

6.3.1 Delta change

The delta change approach consists in working with changes instead of working directly with climate data points (Fig. 6.2). This method has been widely used to assess potential changes in climate and related impacts, especially for hydrological purposes (Graham et al. 2007). The climate models' present-day values (baseline) are subtracted from the future simulated values, resulting in future climate anomalies. These anomalies are then added to the present day observations in order to generate a future climate dataset (Tabor & Williams 2010). This correction is usually done on a monthly basis. The mathematical method used to correct each variable might differ; for example, the biases in temperature and precipitation might not be corrected the same way (Teutschbein & Seibert 2012). If this is an efficient method to obtain information on the mean changes, the delta approach does not typically affect changes in variability between baseline and future simulations (Graham et al. 2007).

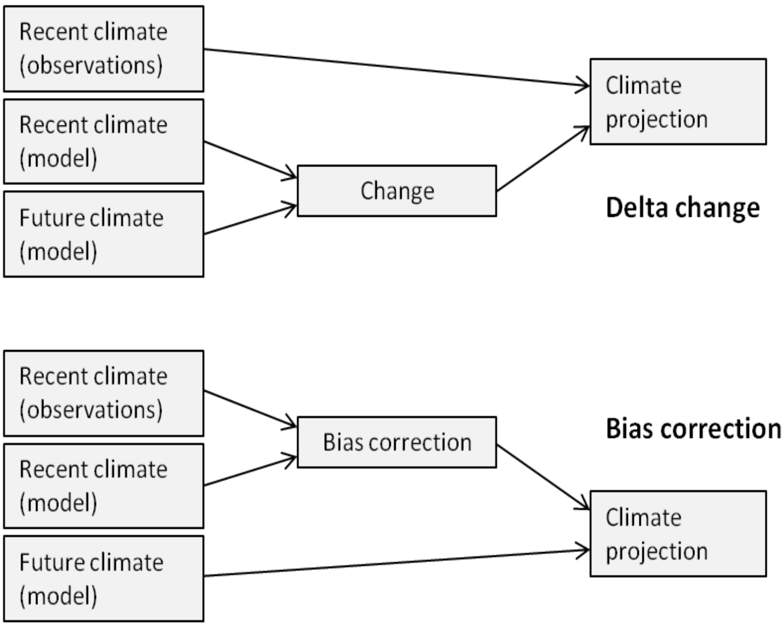

Figure 6.2 A schematic presentation of delta change and bias correction approaches (modified from Räty et al., 2014)

6.3.2 Scaling approach

Another way to adjust model data to observations is to use a scaling method as a variant of the delta approach.. The modelled data are corrected with scaling factors that are based on the differences between a simulated, control run and the observations. A simple example would be the correction of temperature by an additive term based on the difference of long-term monthly mean observed and control run data (Teutschbein & Seibert 2012).

The scaling process can involve a linear approach (in which case the differences in variance are not corrected) or more complicated methods such as power transformation or variance scaling. A more detailed description and examples can be found in Teutschbein & Seibert (2012).

6.3.3 Distribution mapping

Delta approach and simple scaling methods can perform well for certain variables such as temperature mean conditions, but a more sophisticated approach is needed for other parameters (e.g. precipitation) and extreme conditions from a climate service perspective. In most cases extremes are very important for impact assessment. Distribution-based methods have been shown to generally perform better than simpler techniques for precipitation (Themeßl et al. 2011; Teutschbein & Seibert 2012).

Whether the method is called 'distribution mapping' (Ines & Hansen 2006), 'quantile mapping' (Maraun 2013), 'statistical downscaling' (Piani et al. 2010) or 'histogram equalization' (Rojas et al. 2011), the main idea is to correct the distribution of simulated climate data to agree with the observed distribution. This is done by creating a mathematical function, called transfer function that transforms the simulated distribution into the observed one. The cumulative probability of a given simulated event is estimated using a theoretical (Piani et al. 2010) or empirical (Themeßl et al. 2011) cumulative probability distribution for the model and is replaced with the event with equal cumulative probability from the observed distribution (Fig. 6.3).

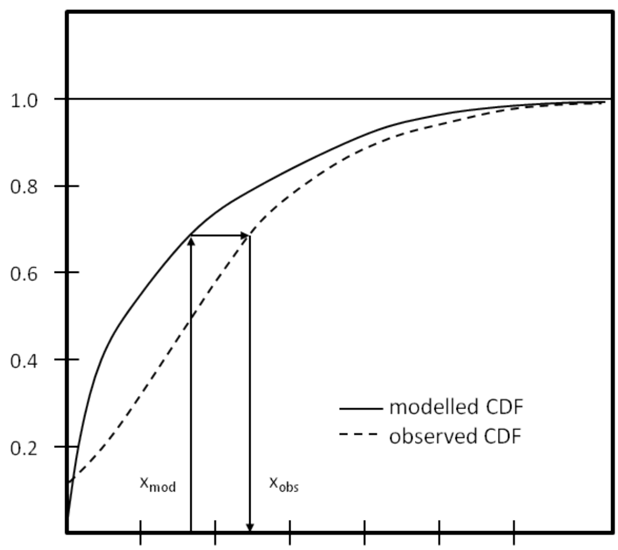

Figure 6.3 A simple presentation of a distribution mapping method (modified from Piani et al., 2010). The simulated value is replaced by the observed value corresponding to the same cumulative probability

The "Cumulative Distribution Function-transform" (CDF-t) method (Vrac et al. 2012) can be seen as a variant of the traditional distribution mapping. It differs from it in the fact that CDF-t takes into account the change in the CDF from the baseline to future period, whereas the quantile mapping corrects the historical and future simulated data according to the same observational distribution. In the CDF-t case, the transform function (which transforms the historical simulated distribution into the corrected observed one) is applied to the future simulated distribution in order to generate a future distribution (Fig. 6.4). A distribution (or quantile) mapping is then applied between the two future distributions.

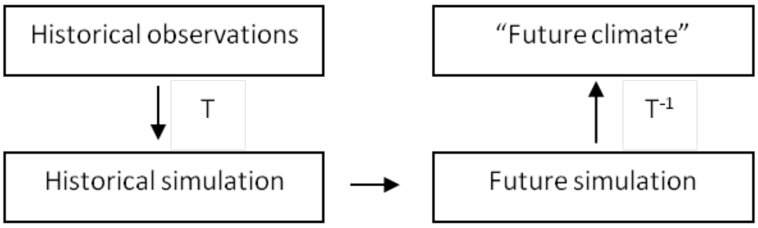

Figure 6.4 A simplified representation of the CDF-t approach

6.3.4 Bias adjustment of seasonal-to-decadal predictions

The adjustment techniques described above focus mainly on long-term climate timescales. However, seasonal-to-decadal predictions present a different problem as they are initialised from observations (section 4). A model being not defined to exactly reproduce the observations at a given time, but initialized with observations, is not in its "natural", preferred model state. It will then tend to go back to this preferred state, which leads to a drift in the modelled data over time (Fig. 6.5). This means that the bias between the model and the observations is not constant through time, even at short forecast time scales, but is a function of the forecast lead time (i.e. the time since the model initialisation). A different correction needs to be applied for each time step and the evolution of the bias through time, i.e. the drift of the model with respect to the observations has to be quantified. Different methods can be applied, including a calculation of a specific bias for each lead-time (non-parametric approach, ICPO 2011) or a fit to reproduce the lead-time dependent bias (parametric approach, Kruschke et al. 2015). The latter approach will be more consistent if the drift itself is not consistent through time (fig 6.5b).

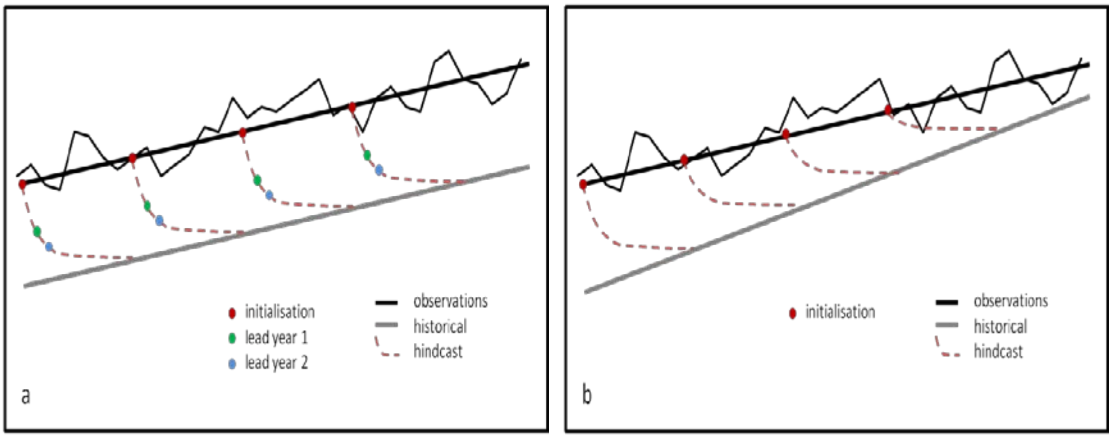

Figure 6.5 Illustration of the drifting of seasonal-to-decadal prediction for a) a consistent drift and b) a drift varying through time (modified from Grieger et al., 2016).

6.3.5 Multivariate correction

So far we have described techniques for the bias removal of one variable at a time. In most cases, each variable is indeed independently corrected, the most common example being the one-dimensional correction of temperature and precipitation for climate change impact studies. However, this approach raises the question of the link between the different variables. Temperature and precipitation, to keep the same example, have been shown to be correlated (e.g. Trenberth & Shea 2005) and the application of a univariate correction (i.e. individual and independent for each variable), whatever methods is used, might strongly degrade the physical relationship between the variables. This will lead to statistically comparable distributions but one might question the physical consistency of such an approach. To overcome this problem, multivariate adjustment methods are being developed. These can be based on copulas, which are a comprehensive graphic representation of the statistical link between two variables (Vrac & Friederichs 2015). Multidimensional analogs of the quantile mapping method (Cannon 2016) and resampling-based techniques (Sippel et al. 2016) have also been investigated. More detailed descriptions of the recent methods briefly described above can be found in the references.

6.3.6 Limitations and challenges

Bias adjustment methods have been widely used to correct climate simulated data, especially for climate change impact studies, since in most cases it is essential to produce useful information on the impact of climate change. However, the relevance of the development and the use of such techniques is still discussed (Ehret et al. 2012). The application of bias adjustment relies on many assumptions, amongst which:

- time-invariance: the correction method can be applied in the same way to both baseline and future simulations
- effectiveness: the correction does not add unwanted side effects. It has been indeed shown that the choice of a bias correction is an additional source of uncertainty (Haerter et al. 2011)
- reliability: the question is here to assess the suitability of an imperfect climate model (i.e. that needs to be corrected) to simulate the effect of climate change

Despite these imperfections, and even though efforts are devoted towards the development of better models, the current consensus is that there are no realistic alternative for improving climate simulations (Argüeso et al. 2013). The main statement from the IPCC AR5 Breakout group (BOG) on Bias Correction (IPCC, 2015) is that “Bias correction (alternatively: bias adjustment or bias reduction) is a computationally inexpensive and pragmatic tool which, however, is also prone to misuse due to its mathematical simplicity.” Bias adjustment should then be applied with caution, and only with an understanding how the adjustment relates to the bias causes. Common errors in its application include the lack of cross-validation (the validation is carried out with the same dataset as the calibration) or the use of too many parameters for the fitting process, leading to an overfitting.

Even when used cautiously, bias correction presents some unavoidable issues (IPCC, 2015):

- The introduction of physical inconsistencies between corrected and non-corrected variables
- The skill of the model is usually unchanged, while some aspects of climate predictions are clearly improved (this point may not be true for seasonal forecasts).

- The simulated climate signal may be affected, which may or may not be desirable.
- Temporal biases are usually not corrected (e.g. seasonal onset)
- Specific classes of BC methods are required to correct for climate pattern offset
- Even when cross-validation is carried out, forecast skill is hard to estimate
- Multivariate corrections may maintain inter-variable correlation, but hinge on sufficient data availability
- The method used, e.g. bias correction, delta method, statistical weather generator, and whether a simple or a sophisticated method is used, affects the time series that result for the future (and for the bias correction and the statistical weather generator also for the current climate). Therefore, impact studies based on the same model runs, but with different “bias correction” methods may result in different impacts. This is introducing some additional uncertainty.

6.4 Summary and conclusions

Climate models are the main sources of future climate data for use in assessing the potential impacts of climate change in impact science and via climate services. The output of such models needs to be handled with care before being translated into services, whether it is for climate prediction or longer timescales. The uncertainty brought by the large discrepancies across the growing range of climate models needs to be considered. The selection of a subset of models as well as the choice of the emissions scenario(s) needs to be the results of a thorough, strategic approach. Information about the range of projected changes captured by the subset can be important for decision-making.

Moreover, the output from the selected models needs to be corrected for the biases, whether it is used at global or regional scale. Bias adjustment techniques are being developed, from simple scaling to multidimensional approaches. They are now an integral part of pre-processing of climate simulations for use in impact modelling studies. If these few pages did not detail all the current available methods and the science that underpins them, the reader should now be aware of potential issues raised by biases in climate models. A growing literature is now available for further understanding of these crucial and sometimes neglected issues.

Bias adjustment as a statistical approach introduces a new unexplored level of uncertainty to the chain of uncertainties. In order to explore that level, a Bias Correction Intercomparison Project (BCIP) has been recently established. The BCIP addresses following topics: i) to quantify what level of uncertainty bias adjustment introduces to workflow of climate information, ii) to advance bias-adjustment techniques, iii) to provide the best practice on use of bias-adjusted climate simulations and iv) to make bias-adjusted simulations available on the Earth System Grid Federation (ESGF). It can be expected that future climate services benefit from that effort.

7 State of the art of the rising European climate services research and its links to the climate adaptation community

7.1 Definition of Climate Services

In the European Roadmap for Climate Services a broad meaning is attributed to the term "Climate Services": the transformation of climate-related data — together with other relevant information — into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and Disaster Risk Management (DRM) (EU, 2015).

Other definitions exist. Most have the following common elements (e.g. WMO[23], WCSP[24], GFCS[25], ERA4CS[26], CSP[27], AMS[28]; NRC, 2001; EU, 2015):

- An ambition to be user driven, indicated by words such as: customized, co-production, strong partnerships, consult with users;
- Services are for decision making or to support adaptation, mitigation and disaster risk management;
- Transfer/dissemination or guidance in the use of "science based (climate) information" or "reliable climate data", or "knowledge on the climate, climate change and its impacts"

In this Climateurope report we limit the description of climate services to those that utilize climate observations, climate model data or Earth System Model (ESM) data directly.

7.2 Types of climate services

The definitions of climate service types are very broad and regularly the term is also used for weather services or climate research (often the differences between those are not that clear either). Therefore, the use of the term climate services can be confusing for potential users (Vaughan & Dessai, 2014; Capela Lourenco et al., 2015). There are hardly any efforts so far to describe the various types of services. Divisions can be made e.g. between those services that provide data and information about the current and future climate, about the

23 https://www.wmo.int/pages/themes/climate/climate_services.php
24 http://public.wmo.int/en/programmes/world-climate-services-programme
25 http://www.gfcs-climate.org/sites/default/files/GFCS_3-fold_flyer_July2014_EN.pdf
26 http://www.jpi-climate.eu/media/default.aspx/emma/org/10869130/ERA4CS_joint+call_04march.pdf
27 http://www.climate-services.org/about-us/what-are-climate-services/
28 https://www.ametsoc.org/ams/index.cfm/about-ams/ams-statements/archive-statements-of-the-ams/climate-services/

current and future climate impact and adaptation and mitigation options, that provide support for decisions and implementation, for communication and dissemination and for monitoring. Only climate adaptation services are mentioned explicitly in literature (e.g. Goosen et al., 2013).

Providers of climate services can play different roles from the supply of data/information (research and analyse) to providing the best strategy to achieve goals (Fig. 7.1) (advise strategically; Mayer et al., 2004; Reinecke, 2015).

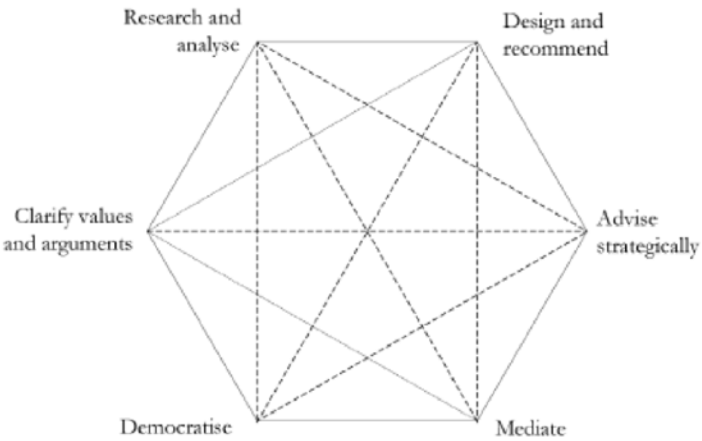

Figure 7.1 Overview of the six policy analysis styles (Mayer et al. 2004).

Climate services can alternatively be subdivided into more general services and tailored services. More general services are often made for broader target groups, and no direct personal contact is needed for use. Examples are climate scenarios at national level (Skelton et al, 2016), portals that give access to data and processing tools (e.g. C3S[29], CLIPC[30], Climate4impact[31]) or information on adaptation (e.g. ClimatAdapt[32]). They can be developed first as tailored services or in close contact with various users. These services are often freely available and financed (partly) by national governments or the EU. Commercial providers can also provide services to governments that become publicly available (e.g. reports, presentations, films, campaign for creating public awareness). Tailored climate services are services that are developed for a specific user (e.g. government, company) and often in close contact with this user. During the direct contact with the user advice and guidance is given on the interpretation and use of the product. These services more often require a fee and are provided more often by commercial climate service providers. In a next report more information will be given on the type of products provided by the various climate service providers.

[29] https://climate.copernicus.eu
[30] www.clipc.eu
[31] https://climate4impact.eu
[32] http://climate-adapt.eea.europa.eu

7.3 Relation between Earth System Models and Climate services

Earth System Models (ESMs) describe the climate system and its development in time by a combination of coupled physical and biogeochemical components. For the current and past climate, often observations are used for climate services Climate models and ESMs are the very base of climate services for possible future climates and seasonal-decadal climate prediction. Confidence in using climate models for quantitative predictions and projections is growing (section 3 and 4). Research of climate change impacts and adaptation generally lies down the chain of ESM projections – regional downscaling – sectorial impact assessment. Adaptation research needs to factor in simulated climate change impacts into the complexity of societal vulnerability to climate change, societal capacity to adapt to the impacts of climate change and other competing stressors on society.

Climate services are regularly developed with direct interaction with users. This assumes a bottom-up- approach. However, this bottom-up approach cannot exist without information on the current and future climate. Developing and running climate models takes a lot of time, and therefore cannot be started when there is a question from a user. A more top-down approach exists, where basic material for the bottom-up climate services (e.g. climate model or ESM runs, downscaled runs) is developed (e.g. Berkhout et al., 2014). The demand-driven projects and climate services (bottom-up) rely on climate information provided in these more top-down (science driven) projects, as presented in Fig. 7.2. However, the further development of climate/ESM models (Section 3 and 4) and the processing of the results (Section 5 and 6) is often indirectly influenced by user requirements, such as the request for higher spatial resolutions by downscaling techniques.

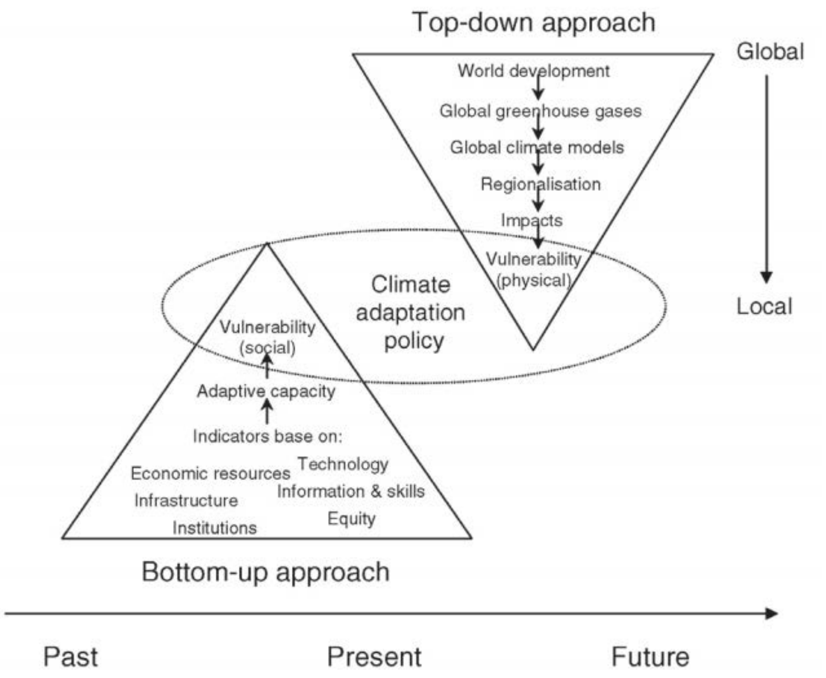

Figure 7.2'Top-down' and 'bottom-up' approaches used to inform climate adaptation policy(Source: Dessai & Hulme, 2004).

7.4 Overview of initiatives and projects on climate services

Vaughan & Dessai (2014) give a short history of the development of climate services. The research and observational programmes that support many user-oriented climate services exist already for more than a century. User-oriented climate information or research also exists for a considerable time (e.g. climate normals, statistical analysis of extreme events, tailored climate research), however they were often not called Climate Services until less than a few decades ago (NRC, 2001). Generally, users weren't involved that directly in the development of most products, although many of the products were relating to societal needs. With the notion of climate change, new requests came up and new methods were developed. Scientists, decision makers and other users of climate data realized that it was important to "evolve from the concept of useful information to the concept of usable information" (Lemos et al., 2012). Even in the case of connections between the climate data providers and users, the providers (e.g. the climate modelling community) often did not fully understand the context in which the users apply the climate information (Vaughan & Dessai, 2014). This led to much more emphasis on user engagement/co-production/user-driven information especially after 2010.

In the FP7 European Union's Research and Innovation funding programme for 2007-2013 there was already attention for Climate Services (e.g. ECLISE[33], CLIMRUN[34], EUPORIAS[35], IMPACT2C[36]), and in the Horizon 2020 research programme for 2014 to 2020 there are more projects related to it (e.g. IMPREX[37], Climateurope[38], CIRCLE-2 ERA-net[39]; see also Table 7.2 for links of platforms). In 2009 the Global Framework for Climate Services was endorsed by WMO. In the same year an initiative was started to explore the potential of Joint Programming to pool national research efforts related to climate, including a working group on climate services (later called JPI-Climate[40]), resulting in 2016 in the ERAnet for Climate Services (ERA4CS[41]). The first International Conference on Climate Services was held in New York in 2011. The European Union's Copernicus Climate Change Service (C3S) was launched in a pre-operational mode in November 2014. (EU, 2014; Strahlendorff et al., 2016).

[33] www.eclise-project.eu
[34] www.climrun.eu
[35] www.euporias.eu
[36] https://www.atlas.impact2c.eu/en
[37] www.imprex.eu
[38] www.climateurope.eu
[39] www.circle-era.eu
[40] www.jpi-climate.eu/
[41] www.jpi-climate.eu/ERA4CS

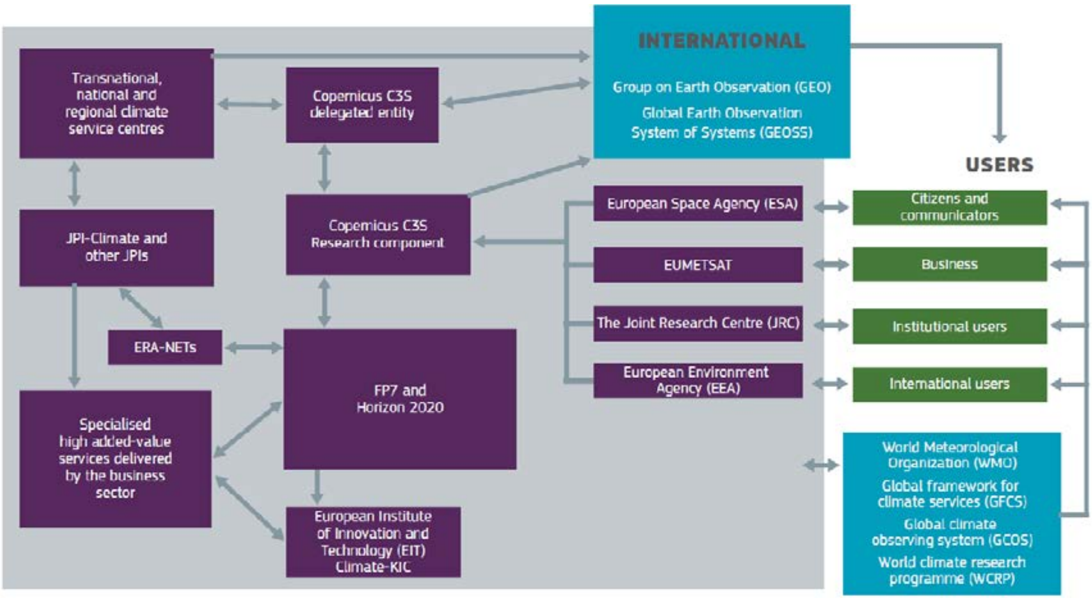

Figure 7.3 Relationships within the European Climate Services landscape (Source: EU, 2015)

Fig. 7.3 summarizes the various groups of projects and initiatives related to climate services. In the text above only examples of these groups are mentioned (Copernicus C3S, FP7/Horizon2020 and JPI-s; a glossary with the acronyms and other definitions is available in Annex I - Glossary). These are grouped especially based on the various initiatives and financing sources, but the focus of the various projects differs:

- Focused especially on understanding the climate system and improving/extending the available climate data for the past and future (climate science driven). Examples are projects such as ENSEMBLES (FP6)[42], CORDEX[43], EURO4M[44], CMIP5/6[45], CRESCENDO[46], PRIMAVERA[47] (H2020), sometimes including case studies for specific sectors.
- Focused especially on the development of infrastructure to get access to climate and impact data and information, visualization and processing: e.g. IS-ENES2, most projects under C3S[48], IMPACT2C, ECA&D[49], and Climate-ADAPT.
- Focused especially on climate change impact/adaptation research, including decision support (more demand- driven, mostly including case-studies): e.g. CIRCLE-2 (FP7), ECLISE (FP7), CLIMRUN (FP7), ISIMIP[50], projects financed by specific sectors (e.g. national Road Authorities (CEDR[51]:): RIMAROCC, ROADAPT, EWENT, WATCH, INTACT), C3S SIS-projects, projects under ERA4CS.

[42] http://ensembles-eu.metoffice.com
[43] www.cordex.org
[44] www.euro4m.eu
[45] https://www.wcrp-climate.org/wgcm-cmip
[46] https://crescendoproject.eu
[47] https://www.primavera-h2020.eu
[48] https://climate.copernicus.eu/tenders/copernicus-c3s511-quality-assessment-ecv-products-prior-information-notice
[49] www.ecad.eu
[50] https://www.isimip.org
[51] http://www.cedr.fr/home/index.php?id=226

- Focused especially on user requirements and market opportunities: Climate-KIC[52], SECTEUR (C3S[53]), MARCO (C3S), EU-MACS (C3S[54]), some calls under H2020-SC5.

7.5 Challenges in Climate Services

7.5.1 Overview of available data, users' requirements, portals, climate service providers

- User requirements

Many inventories on users' requirements have been generated in projects. General information on user requirements (e.g. the climate variables, time horizon, spatial resolution, area) is available in the inventories already executed. Differences in requirements exist between sectors (for tourism different information is needed than for coastal protection), but the differences between countries for the same sector are rather limited and linked often to the tools/models used and the norms. Therefore, more inventories about these general aspects are often of limited added value. More difficult is it to get an overview of the context, perception, current use and intended use of the climate information by the users and the consequences for climate services (Bley et al, 2017; Buontempo et al., 2014; Lemond et al., 2011). Systematic analyses of case studies on climate services focusing on the influence of the context, perception, background knowledge, etc. on the requirements for the climate services would be interesting, to see whether more general lessons can be learned from them for making existing climate services more relevant or develop new climate services that bridge the gap between science and practice. Several finished and ongoing projects have case studies that could be used for that. Also experiences from weather services and current ways of managing weather extremes could be very useful and inspiring for the development of climate services for the future (Van den Hurk et al., 2016).

- Climate data portals and user friendly access

Ample climate data sets are available (observations, re-analysis, climate model runs), but many users do not have an overview on the available data, and the pros and cons of the various datasets (Goddard, 2016). There are several initiatives to provide overviews of available data (e.g. ECA&D, Climate Explorer, Climate4impact, CLIPC, C3S), but most often no guidance or very limited guidance is available for users to make a selection. The use of ensembles is considered state of the art in climate science (Section 6), but generally not an option for most users/purveyors. Potential users are typically aware of only one or a few of these portals. A better overview (and access) of existing portals and datasets is needed, coupled to information about the portals' objectives, target groups, advantages, disadvantages, and links between the various portals. Besides overviews, a more user-friendly access to climate data is also a challenge (Overpeck et al., 2011; Hewitt et al., 2012). Users generally are not experts in climate data and do not have good insight in the limitations, uncertainties, etc. Better assess and overview of climate services may help to get

52 http://www.climate-kic.org
53 https://climate.copernicus.eu/secteur
54 http://eu-macs.eu

the information to the (end-) users, but further research into the motivation of users to use climate services is also needed.

- Climate service providers

Within JPI-Climate a first effort was made to provide some overview of climate service providers in Europe. Within ERA4CS this is further elaborated. Part of this information can be found through the Climate Knowledge Hub[55]. Although the response from the various European countries differs a lot, it is clear that there are considerable differences between countries in the providers and provided climate services and what are considered climate services. The inventory within the ERA4CS programme may give some indications on the causes for these differences such as what is provided through governmental organisations and the activities that they are allowed to do.

7.5.2 Integrated research across science disciplines

Users of climate services often require information that is based on various disciplines (Changdon et al., 1990; Goddard, 2016; Goosen et al., 2013; Buontempo et al., 2014; Brasseur & Gallard, 2016; Harrison et al., 2016): e.g. impact and adaptation options (VIA research) and risks (economic research) for several climate scenarios (climate science). Often the context, framing and communication are important too (social sciences). Although providers from various disciplines regularly work together, integration could be much better and the various disciplines could profit much more from each other's expertise. For example, impact/adaptation researchers often use climate data, but they generally have limited knowledge and overview of available data, sometimes resulting in improper use or interpretation of the data. Working together in projects, good guidance materials and courses could help in these cases. Climate researchers, on the other hand, could potentially profit much more from the social sciences for understanding user requests and communicating results (e.g. von Storch, 2009; Capela Lourenco et al., 2015).

7.5.3 Quality

Quality control/quality is often mentioned as important in Climate services (e.g. SRIA JPI-Climate, EU 2015, Street 2016; Hewitt et al., 2012), Several documents mention that it is difficult to produce Climate services with a "one-size-fits-all" approach. Tailoring for each client or sector is generally needed, and this includes customizing of the climate data choice, but also of how information is communicated and/or framed (JPI-Climate Workshop Brussels[56] April 21/22, 2015, Adaptation Futures workshop 2016[57]). This is e.g. translated into a Sectoral Information System in the Copernicus Climate Change Service (C3S).

Elements that are often mentioned in relation to quality are:

1. "fit for purpose"/relevance and user driven: including timing, framing, the way information is communicated (user perspective). It is important to ensure that the data

[55] http://www.climate-knowledge-hub.org
[56] http://www.jpi-climate.eu/media/default.aspx/emma/org/10862050/Report+JPI+Climate+Workshop+on+Enhancing+Decision+Making.pdf
[57] http://www.adaptationfutures2016.org/gfx_content/documents/SP%2010.4%20meeting%20report.pdf

and the information provided is both user-relevant and user actionable. Engaging with the users in the definition of the service can be an effective way of ensuring such relevance. Given that the quality of the underpinning climate data is critical to the success of a service, other factors are as important., E.g. poor timeliness, unreliable availability or ambiguities in the information provided can easily lead to user dissatisfaction. An operational environment which maintain standard, provide reliable user support and timeliness of the delivery are crucial to service delivery. For example information about the possible occurrence of high-impact events have no value if reaching the users after the event happened (personal comm. Jean-Noel Thépaut, Carlo Buontempo; Brasseur & Gallardo, 2016)

2. Quality of basic data, including traceability, information on uncertainties, best methods for processing (scientific quality, (climate) science perspective; maturity matrix): The quality of a climate service depends on the quality of the information provided. On the one hand, this is naturally linked to the compliance with specific standards and metadata structure; on the other hand this has to do with the intrinsic attributes of the information itself. For example, a perfectly formed NetCDF file providing seasonal prediction in a timely manner for Europe can still be of limited use because of the limited predictive skill that the respective prediction model has. Availability of good, stable and consistent metadata is also an aspect of quality. This can significantly reduce ambiguity and minimize the risk of misuse. Appropriate metadata is also a way to ensure full traceability of the information being provided something that in turns can generate trust among users (personal comm. Jean-Noel Thépaut, Carlo Buontempo).

3. Integration (of climate data) with other relevant data: This can include impact/adaptation research, but also integration with e.g. socio-economic data (science and user perspective?). Propagation of uncertainties is one of the aspects that often receives limited attention. For example, when several climate scenarios are used but only one impact model, a limited view on the uncertainties for the future is obtained. The above aspects of quality aren’t always easy to measure. When the information is “fit for purpose” (what the user asked for), it is not automatically of good scientific quality. Combining excellent quality basic datasets does not automatically result in a good quality combined product. Quality of Climate services should include all of the above mentioned elements.

Other aspects that are often mentioned in relation to the quality of climate services are:

1. Salience: refers to relevant and timely knowledge.
2. Credibility: refers to solid and unbiased knowledge.
3. Legitimacy: refers to the need for a fair and transparent process of designing and producing knowledge.

During the JPI-Climate workshop (Brussels April 21/22, 2015) it was indicated that those three aspects are necessary, but not sufficient conditions for a good policy uptake. In addition, the role the provider (related to credibility and legitimacy) needs to be clarified.

7.6 Journals and other platforms

Not mentioned directly under “challenges” (section 7.5) is the challenge to organize the exchange of experiences with and knowledge of climate services. Examples and some lessons learned on climate services are published in peer-reviewed journals (Table 7.1),

Table 7.1Journals that (sometimes) publish articles/commentaries about climate services

Journal Title	*Objective*
Bull. Am. Meteorol. Soc. (BAMS)	Development of the atmospheric, oceanic, and related sciences in research and development education informed and innovative application of these sciences in public service and private enterprise
Climatic Change	interdisciplinary, international journal devoted to the description, causes and implications of climatic change and climate variability
Climate policy	all aspects of climate policy, including policy and governance, adaptation and mitigation, policy design and development and programme delivery and impact
Climate Services	interface between climate research and application, connect natural and socio-economic research with practice research, stakeholders and practitioners, all sectors
Climate risk management	production and use of climate and climate-related information in decision and policy making from the near- to long-term
Earth's Future	transdisciplinary, challenges and opportunities associated with regional and global change, e.g. water, air, food, energy, hazards, climate, ecosystems, human health and demographics
Environ. Res. Lett.	observations, numerical modelling, theoretical and experimental approaches to environmental science, and especially science relevant to policy, impacts, and decision-making, interdisciplinary
Environmental Science and Policy	interdisciplinary research of policy relevance on environmental issues such as climate change, biodiversity, environmental pollution and wastes, renewable and non-renewable natural resources, sustainability, and the interactions among these issues
Eos	news and research on the relationship of geoscience to social and political questions
Glob. Environ. Change	human and policy dimensions of global environmental change drivers, consequences and management of changes in: biodiversity and ecosystem services, climate, coasts, food systems, land use and land cover, oceans, urban areas, and water resources
Nat. Clim. Change	research across the physical and social sciences, strives to synthesize interdisciplinary research
Nat. Geoscience	all the disciplines within the geosciences

However much material is not published probably for the following reasons:

- Climate services are often not seen as research, but just as implementation or practical extension
- Climate services are often inter/multi-disciplinary and those working on it do not have complete knowledge on available literature from the other sciences (e.g. a climate scientist often does have limited knowledge about available peer reviewed literature from the social/human sciences to set his/her experiences in a broader context). When examples of climate services are published, often only those aspects are described that are in the expertise of the respective scientists. This means that e.g. the "technical" construction of climate scenarios is described, but often not how user information and interaction is included.

The journal "Climate Services" is currently the only journal that mentions climate services explicitly in its focus/objective. In addition, several journals exist, which publish article related to climate services in addition to another respective focus (see table below; after searching with google for "climate services"). There may be many more articles on climate services, however, not all is labelled explicitly as climate service. The social/human sciences also provide useful information for climate services, but for a non-social scientist it is often difficult to obtain an overview of available relevant information (let alone translation to the practice of climate services).

Journals are not the only way to exchange information/experiences related to climate services (Table 7.2). There are several platforms (websites, regular conferences, etc.) where experiences are exchanged. In the table below some that work on an international level are mentioned (the elements that focus on a two-way exchange/interaction are underlined). The exchange of knowledge on climate services is less well organized than for climate modelling and observations, although there is a lot of attention for climate services especially after the start of the GFCS.

Table 7.2 Other international platforms for exchange of information and experiences related to climate services

Platform/Website	*Link*	*Content of the website, other tools*
Climate4impact	https://climate4impact.eu/impactportal/general/index.jsp	Climate data discovery, background information on use of climate data, options for processing, visualizing
Climate Knowledge brokers	http://www.climateknowledgebrokers.net/success-stories/climate-search/	Access to climate data (climate search) Events, workshops, newsletter
Climate knowledge hub	http://climate-knowledge-hub.org/	Information on climate service providers in Europe
Climate Services Partnership	http://www.climate-services.org/	Portal including case studies Newsletter Annual conference
Climateurope	https://www.climateurope.eu/	Portal with overview projects, stories, events calendar Newsletter, Festivals, webinars, communication platform
ECCA (European Climate change Adaptation)	http://ecca2017.eu/conference/themes/	Several sessions/themes that implicitly/explicitly deal with climate services
EGU	http://meetingorganizer.copernicus.org/EGU2016/pico/20080	Sessions on climate services and/or impact assessments
European climate adaptation platform	http://climate-adapt.eea.europa.eu/	Website with case studies, events, Newsletter
European Conference on Applied Climatology	http://meetingorganizer.copernicus.org/ems2016/sessionprogramme	Sessions on climate services
Global Framework for Climate Services	http://www.gfcs-climate.org/	Projects, documents Newsletter, Workshops
Green Growth Knowledge Platform	http://www.greengrowthknowledge.org/	Website with information per sector, theme, global databases, learning products, blog Newsletter
PLACARD	http://www.placard-network.eu/	PLAtform for Climate Adaptation and Risk reduction, blog, policy briefs, workshops
weADAPT	https://www.weadapt.org/	Online 'open space' on climate adaptation issues Learning, sharing and connecting
World Bank Climate Change Knowledge Portal	http://sdwebx.worldbank.org/climateportal/	Access to data Learn about climate data Other Climate Data Sources, adaptation tools

7.7 Summary and discussion

In this Climateurope report we limit the description of climate services to those that utilize climate observations, climate model or Earth System Model (ESM) data directly.

The definition of climate service is very broad. The term is often used without further specification and, therefore, it can be confusing for potential users. A future advancement towards a system to characterize the various climate services would be beneficial to users in order to make clear what can be expected and in order to compare climate services. Many users and decision-makers also ar not aware of the kind of climate services that are available, where to find them, how to use them. Further development of the research-provider–user partnership will be essential to create useful climate services (more detailed information on user requirements) but also to stimulate broader use of climate services (more overview and guidance).

Climate services exist already for more than a century, but the term is used only since about two decades ago. Nowadays there are a wealth of projects and initiatives related to Climate Services which makes it challenging to keep an overview, although there are initiatives to attempt partial overarching views. This lack of overview may result in duplications or underutilization of options to integrate results and to extract lessons learned. An example is the large number of projects with digital inventories of user requirements. They hardly add to what is known already about the general user requirements. Information about the current use of climate information and perception can only be obtained with interviews or by joint projects involving users.

Integration of disciplines would in most cases add to the value of climate services, since users of climate services often require information that is based on various disciplines. Although in many research projects on climate services there is a limited integration of disciplines (e.g. climate and impact/adaptation research), this integration can potentially be extended and improved.

Quality is an important aspect of climate services, but there is an ongoing discussion on how quality of climate services should be determined and measured. Elements that are often mentioned in relation to quality are: “fit for purpose”, relevance for a sector or question, quality of basic data, and integration (of climate data) with other relevant data. Those aspects of quality are generally difficult to measure. When the information is “fit for purpose” (what the user asked for), it is not automatically of good scientific quality. Combining excellent quality basic datasets does not automatically result in a good quality combined product.

Exchange of experiences with climate services is far less organized than for other parts of climate science (modelling, observations). There is a need for a better overview of journals and other platforms to publish results, examples, experiences, overviews, etc. related to climate services to promote the exchange of knowledge and to promote discussion on the challenges. In this section in Tables 7.1. and 7.2 already several journals and platforms are mentioned.

8 Summary and conclusions

The past decade has shown a strong development of climate change research and knowledge. At the same time, many research projects where strengthening its user and stakeholder orientation, and are increasingly focusing on providing actionable results. Consistently, the “Roadmap on Climate Services” in Europe stresses a need for stronger links between providers and users of climate change knowledge and information.

Climate models are the very base and main source of climate information for assessing the potential impacts of future climate change. To build up and to support a strong network between the different players in this area, e.g. climate change science, provision of data, impact science and risk assessment in various sectors, a good overview of availability and needs of state-of-the-art knowledge, methods and information is crucial, but not straightforward. The Coordinating Support Action Climateurope provides a layered overview of state-of-the-art climate services as a part of a wider range of activities ([58]), including the eminent role of underlying climate and Earth System Models (ESMs), climate projections and predictions, and its basic links to user oriented products. For the future development of services, an exchange of knowledge and needs with corresponding actions between climate modelling and user oriented climate service products is important and will be highlighted. Updates of the overview will emerge in the near future.

This first release of the CLIMATEUROPE reports takes the current state of the art of climate models and the tailoring of their outcomes to users’ needs as a starting point.

Climate models and the more general ESMs (including e.g. vegetation and biogeochemical cycle) are described with their foundations in basic physical principles and empirical parameterizations of unresolved processes. ESMs are able to perform long-term climate projections, and seasonal-to-decadal scale predictions with an accuracy related to model quality, complexity of model configurations, resolution and availability of observational data for model evaluation and initialization. Users of the resulting information rely on a parallel supply of robustness, skill and uncertainty quantification and methods to translate uncertainties into risks and probabilities. Those methods are heterogeneous and vary strongly dependent on the respective climate service or question

Robustness and uncertainty of climate simulations in general and in particular for climate scenarios and predictions are quantified by interpreting multi-model coordinated simulations, conditioned on possible future pathways of climate forcings, summarized in so-called Representative Concentration Pathways (RCPs) or Shared Socio-economic Pathways (SSPs). Under the coordination of the Climate Model Intercomparison project (CMIP), resulting data are uploaded to a network of data servers, accessible by the global scientific community and usable by climate services. The data bears the opportunity to be used for relevant decision making with respect to climate adaptation and mitigation that needs to

[58] www.climateurope.eu

relate to the span of uncertainty and the impact of uncertainty on the respective sector of decision making.

Based on model evaluation efforts on historical climate simulations since the 1990s, there is growing confidence in climate models for quantitative future predictions and projections. Obviously the extent to which an ESM can be considered as a realistic description of the real climate system is a limiting bottleneck, so that evaluation of components and the integrated model using detailed or global observations is a key element in the development of ESMs. Systematic evaluation of ESMs with observations and with each other has proven to increase their ability to describe climatic phenomena realistically. Many aspects of physical performance have been evaluated and judged using the calibrated IPCC language (IPCC, 2013). For example, high and very high confidence ratings, combined with high model performance occur for surface air temperature, sea surface temperature, and temperature trends, as well as for the seasonal cycle of Arctic sea ice extent. Additional essential climate variables are described in section 4. A general direct translation of climate model performance from historical verified simulations into fidelity of future climate projections is limited by incomplete observation of changing past climate conditions. Evaluation with improving results with growing observed climate time series showing trends and variability, especially in the ensemble average are very well motivating climate services. Simulated climates connected to multi-model ensemble efforts can be judged for robustness, prediction skill and/or uncertainties, which make them suitable for input to climate services.

Climate prediction of the near future, from sub-seasonal to decadal time scales, utilizes global climate models and combines them with advanced initialization techniques and ensemble simulations. Climate prediction is motivated by the growing potential for skilful predictions due to model improvements, and by emerging needs from a suite of stakeholders including public decision makers, (re)insurance companies, the tourism industry and the agricultural sector.

It is expected that more relevant prediction systems will be available within the next years, largely due to increasing the complexity of a prediction system by for instance increasing its resolution. With the potential of growing prediction skills, the user perspective is increasingly important, and the climate prediction community needs to turn to process-based verification approaches and modelling of the mechanisms responsible for high-impact events, which are arguably the ones that concern most users. Along the same line, the reliable and accurate information should be made available at local-to-regional scales, which can be achieved via combination and calibration of the information from different sources and the implementation of state-of-the-art regionalisation tools.

Evaluation of ESMs with their additional component models has lagged behind that of physical climate processes, and is currently gaining in focus and importance. Based on an atmosphere-ocean-sea ice-land system, aerosol processes have been added, as well as biogeochemistry and carbon cycle, land ice sheets, atmospheric chemistry and marine ecosystems. By adding such new components, additional feedback processes are enabled, such as a carbon cycle response to greenhouse-gas forced climate warming by changing the storage capacity of carbon in the ocean and land surface. Future ESMs might even include aspects of human decision making including feedbacks with greenhouse gas emissions and the type of land use. Similar to physical climate models, process-based and integrated analyses and successive model improvements are necessary next steps.

Stakeholder-oriented application of climate model simulations of the past and the possible future often requires regionalization of the global climate change signal, because user-relevant impact and related adaptation needs are felt on the local scale. Therefore this report is reviewing the state of downscaling efforts centred around the CORDEX community. Based on the communities' experience documented in a range of literature, we argue that regional downscaling techniques are clearly adding value to the underlying global climate projections, with the degree and the nature of the added value varying with the climate model, climate variable, geographical region and other factors. Downscaling is a critical component and basis for downstream development of climate services. Connected to the further development of downscaling techniques, key scientific challenges need to be addressed. Those include a permanent further improvement of climate models and the underlying modelling and numerical techniques, very high resolution simulation of related climate processes and enhancement of information integration methods, such as fine-scale process-level changes in the overall climate system changes (via new CORDEX Flagship studies) and a more robust assessment of regional change (via upcoming CORDEX CORE simulations). Those efforts can be expected to further substantiate downstream impact research and the input quality to climate services.

Climate models are afflicted with biases, e.g. systematic spatially varying deviations from observed conditions, when simulating past and recent climate. While the climate modelling community is successfully reducing those problems, impact research and climate services need to translate results by correcting and constraining in order to increase the potential for usage in various applications. Standard techniques include bias correction and model selection to condense information from ensemble members. Climate assessments often consist of a limited subset of scenarios based on CMIP or CORDEX. Both the bias reduction and selection techniques are subject to further refinement. The selection of a subset of models as well as the choice of the emissions scenario(s) needs to build on a strategic approach that depends on the respective user question and sector. Bias adjustment techniques of different complexity, from simple scaling to multidimensional approaches, are necessarily an integral part of processing of climate information. As bias adjustment also introduces a source of uncertainty, a Bias Correction Intercomparison Project (BCIP) has been recently established.

Additional novel techniques are emerging with growing evidence that observed variability or trends are partly well correlated with inter-model differences in model projections. These relationships allow transforming an observable quantity into an “emergent” constraint on future projections. The application of such constraints would reduce the uncertainty from a user perspective, and is a growing area of research and method development.

Climate models and ESMs are developed under scientific premises and at the same time are applied in international coordinated intercomparison projects as quasi-operational tools. A challenge is seen in the transfer of scientifically developed methods to operational organisation models, concerning the necessary infrastructure to sustain continued development of ESMs, to develop and maintain data quality control, bias reduction, ensemble condensation, distributed data nodes, computing capacities and links to operational climate services. The European Network for Earth System modelling (ENES) has taken initiatives to coordinate a climate modelling infrastructure on a European scale, resulting in EU projects (e.g. IS-ENES-1 and 2). ESM projections and predictions residing on the ESGF data nodes are increasingly utilized by climate services via data networks. Current limitations exist in the possibilities to create sustained long-term support for such infrastructure elements that underpin the evolving climate services. To better link climate modelling with climate services and to support long term climate services, efforts to sustain an infrastructure will be necessary.

Climate models and increasingly ESMs are describing the climate system and its development in time for past and recent climate, and for the conditions of future greenhouse gas emission scenarios. After optional regionalization, bias reduction and constraining of results dependent on user demands, the output is actually fed into impact research and customised tools, products and information ("climate services"), such as river flooding projections, forecasts, general climate information, trends, economic analysis, infrastructure and technology assessment, counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. The landscape of climate services is changing and currently further build up with ambitions formulated by the European Union that highlight "the potential to become the intelligence behind the transition to a climate-resilient and low-carbon society" and "Europe's capacity to respond and to improve resilience to climate change"

Climate services include data, information and knowledge that support adaptation, mitigation and disaster risk management. Providers of climate services can play different roles from the supply of data/information (research and analyse) to providing the best strategy to achieve goals. The initial landscape of climate research and climate services is clearly changing. Many recently started international research projects actively provide inputs to real-life climate change assessment at national and sectoral level. Vice versa, climate change adaptation and mitigation strategies are increasingly featuring in strategic planning programmes at many levels and topics. The transfer of data into information, the guidance of the scientific maturity of insights, and the appropriate tailoring of climate information to user needs is both an active research theme for the near future, and embedded in the lively practice of "learning by doing" in the field. A trade-off between "top down" concepts such as multi-model based scenario analyses, and "bottom-up" inventories of highly diverse users' needs will require continuous build-up of theoretical insights and practical experience. Harvesting from the lessons learnt, and tapping inspiration about mental models and uptake of information are the way forward in this dynamic domain.

Forthcoming Climateurope reports are planned to update this first report and provide progress on the integration of climate services and Earth-system modelling, and are expected to e.g. review the process of bundling climate service products from a stakeholder perspective, to identify "unknown knowns" which are the subset of our Earth system knowledge that can be relevant to users, and a validation of the evolving landscape with an emphasis on usability, coordination of dissemination methods, and missing features. Another aspect for following reports is the growing experience with evolving climate services that is expected to feed back to the ESM and climate prediction community.

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Annex I - Glossary

This glossary was built based on CLIPC – Climate Information Portal Glossary, with the purpose of explaining terminology used in the report or related to the report topics. The original CLIPC glossary was based on three glossaries:

- IPCC: The IPCC Data Distribution Centre (DDC; IPCC-DDC) has a glossary of terms complied from the Fifth Assessment Report (AR5) Working Groups 1, 2 and 3 and a list of commonly used acronyms
- EUPORIAS: List of definitions as created by experts and in use in the EUPORIAS project.
- Climate4Impact: List of definitions as created by experts and in use in the IS-ENESIS-ENES

Terms not included in the CLIP-C glossary but relevant to the present report were also defined based on the same sources.

A

Adaptation (IPCC)	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Albedo (IPCC)	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.
Anomalies (Climate4Impact)	These represent the departures of specific measurements and/or forecasts from their long-term climatological values. Anomalies describe how much a specific variable differs from its normal state.
Anthropogenic (IPCC)	Resulting from or produced by human activities.
Atmosphere (IPCC)	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and addictively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.
Baseline/Reference (IPCC)	The state against which change is measured. A baseline period is the period relative to which anomalies are computed. The baseline concentration of a trace gas is that measured at a location not influenced by local anthropogenic emissions. In the context of transformation pathways, the term 'baseline scenarios' refers to scenarios that are based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Typically, baseline scenarios are then compared to mitigation scenarios that are constructed to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or temperature change. The term 'baseline scenario' is used interchangeably with 'reference scenario' and 'no policy scenario'.
Bias (Climate4Impact)	The average difference between the values of the forecasts and the observations on the long term. While accuracy is always positive the bias could be either positive of negative depending on the situation.

Biogeochemical cycles (IPCC)	The radiative properties of the atmosphere are strongly influenced by the abundance of well-mixed GHGs, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have substantially increased since the beginning of the Industrial Era due primarily to anthropogenic emissions. Well-mixed GHGs represent the gaseous phase of global biogeochemical cycles, which control the complex flows and transformations of the elements between the different components of the Earth System (atmosphere, ocean, land, lithosphere) by biotic and abiotic processes.
Calibration (Climate4Impact)	In climate predictions this is the procedure to make the forecasts reliable. This often comes at the cost of the accuracy and the skill of the forecasts.
Calibration uncertainty (CLIPC)	The choice of the calibration period introduces uncertainty. The length but also the choice of years for the calibration relate to the relationship which is built between observation and simulation data. This issue is related to the non-stationarity of the bias - it can be changing over time. Statistical methods, however, assume stationarity of biases over time. Therefore, there is a need to maximise the calibration period in order to reduce this part of the uncertainty.
Carbon dioxide, CO_2 (IPCC)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning biomass and of land use changes and of industrial processes (e.g., cement production). It is the principle anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
Climate (IPCC)	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind.
Climate Change (IPCC)	Refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.
Climate driver (IPCC)	Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing which is used to compare how a range of human and natural factors drive warming or cooling influences on global climate.
Climate feedback (IPCC)	An interaction mechanism between processes in the climate system is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.
Climate forecast (Climate4Impact)	Is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, inter-annual or decadal time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.
Climate Model, spectrum or hierarchy (IPCC)	A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterisations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, and for operational purposes, including monthly, seasonal, and inter-annual climate predictions.
Climate model simulations (Climate4Impact)	these are numerical solutions of sets of equations that represent the most relevant processes describing the climate system. Climate models can be of very different levels of complexity but the most elaborated ones appear to be able to realistically reproduce the key meteorological and climatological phenomena.

Climate Prediction (IPCC)	A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or long-term time scales. Because the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.
Climate Projection (IPCC)	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised.
Climate Scenario (IPCC)	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate.
Climate services (Climate4Impact)	Climate services involve the production, translation, transfer, and use of climate knowledge and information for decision making, policy and planning. The provision of climate information (observational, forecasts or projections) in a way that is relevant to climate-sensitive users, can inform decisions and can reduce the risk of misinterpretation.
Climate System (IPCC)	Highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.
Climate variability (Climate4Impact)	Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)
Climatology (Climate4Impact)	Can be defined as the science of climate, but is also used in the meaning of the normal state such as a base line over the normal period. Climatology is often taken as the mean value for a given month over, for example, 1961-1990.
CMIP (IPCC)	Coupled Model Intercomparison Project
Confidence (Climate4Impact)	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively.
Control Run (IPCC)	A model run carried out to provide a baseline for comparison with climate-change experiments. The control run uses constant values for the radiative forcing due to greenhouse gases and anthropogenic aerosols appropriate to pre-industrial conditions.
CORDEX (IPCC)	Coordinated Regional Climate Downscaling Experiment
Data assimilation uncertainty (CLIPC)	The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output. Variables relating to the hydrological cycle, such as precipitation and evaporation, should be used with extreme caution. More information: https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables
Degree of confidence (CLIPC)	The degree of confidence defines the degree to which we trust an outcome - no matter if this outcome is a climate impact indicator derived from surface observations, re-analysis, simulations or projections describing the bio-physical or socio-economic impact of climate impact. The degree of confidence results from evidence and agreement of the datasets used for a selected climate impact indicator and what type of method is used for the calculation of it.
Downscaling (Climate4Impact)	Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale

	atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information.
Earth System Models (EUPORIAS)	The scientific knowledge has now progressed to the level where global climate models are being replaced by Earth System Models signifying that the models now embrace more components and processes than the physical atmosphere-ocean components traditionally used to describe the climate. For a detailed inventory and/or comparison of the various Earth System components in any of the current generation of GCMs please refer to Comparator.
Effective Radiative Forcing (IPCC)	Sometimes internal drivers are still treated as forcings even though they result from the alteration in climate, for example aerosol or greenhouse gas changes in paleoclimates. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperature, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. For the purposes of the WG1 AR5 report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.
El Nino-Southern Oscillation, ENSO (Climate4Impact)	The term El Nino was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of 2 to about 7 years, is collectively known as the El Nino-Southern Oscillation. It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Nina
Emission Scenario (IPCC)	A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections.
ENES (EUPORIAS)	European Network for Earth System Modeling, created with the purpose of working together and cooperating towards the development of a European network for Earth system modelling. These institutions include university departments, research centres, meteorological services, computer centres and industrial partners.
Ensemble (IPCC)	A collection of model simulations characterising a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.
Equilibrium and Transient Climate Experiment (IPCC)	An equilibrium climate experiment is a climate model experiment in which the model is allowed to fully adjust to a change in radiative forcing. Such experiments provide information on the difference between the initial and final states of the model, but not on the time-dependent response. If the forcing is allowed to evolve gradually according to a prescribed emission scenario, the time-dependent response of a climate model may be analysed. Such an experiment is called a transient climate experiment.
ESGF (EUPORIAS)	The Earth System Grid Federation (ESGF) is an international collaboration with a current focus on serving the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) and supporting climate and environmental science in general. The ESGF grew out of the larger Global Organization for Earth System Science Portals (GO-ESSP) community, and reflects a broad array of contributions from the collaborating partners
External human forcing (CLIPC)	Influence of many possible human-induced trajectories that future emissions of greenhouse gases and aerosol precursors might take, and influence of future trends in land use.
External natural forcing	Externally forced climate variations may be due to changes in natural forcing factors, such as

(CLIPC)	solar irradiance or volcanic aerosols.
Extreme weather or climate event (Climate4Impact)	The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. Extreme events comprise a facet of climate variability under stable or changing climate conditions.
Extreme Weather Event (IPCC)	An event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).
Flood (Climate4Impact)	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.
Forecast time (EUPORIAS)	The time elapsed since the beginning of the forecast. This can be a range of time (e.g. month 2-4). Used in the context of seasonal to decadal prediction.
Forecasts (Climate4Impact)	A statement about the future evaluation of some aspects of the climate system encompassing both forced and internally generated components. Climate forecasts are generally used as a synonym of climate predictions. At the same time some authors like to use prediction in a more general sense while referring to forecasts as to a specific prediction which provides guidance on future climate and can take the form of quantitative outcomes, maps or text.
GCM (EUPORIAS)	Global Climate Models or General Circulation Models (GCMs) are based on the general physical principles of fluid dynamics and thermodynamics. They have their origin in numerical weather prediction and they describe the interactions between the components of the global climate system: the atmosphere, the oceans and a basic description of the land surface (i.e. aspects of the biosphere and the lithosphere that are relevant for the surface energy balance). For a detailed inventory and/or comparison of the various components in any of the current generation of GCMs please refer to ES-DOC Comparator. Sometimes GCMs are referred to as Coupled Atmosphere-Ocean GCMs (AOGCM).
GIS (IPCC)	Geographical Information System. GIS is designed to capture, store, manipulate, analyze, manage and present geographical data.
Global Mean Surface Temperature (IPCC)	An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.
Greenhouse Gas, GHG (IPCC)	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Hindcast (Climate4Impact)	A forecast made for a period in the past using only information available before the beginning of the forecast. A set of hindcasts can be used to bias-correct and/or calibrate the forecast and/or provide a measure of the skill.
IAM (IPCC)	Integrated Assessment Model. Integrated assessment is a method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.
IAV (IPCC)	Impacts Adaptation and Vulnerability.
Impact Assessment (IPCC)	The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems.
Impacts	Effects on natural and human systems. In the WGII AR5 report, the term impacts is used

(IPCC)	primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.
Internal natural variability (CLIPC)	Inherent stochastic variation in climate parameters arising from chaotic non-linear processes in the climate system.
IPCC (EUPORIAS)	Intergovernmental Panel on Climate Change. The IPCC assesses the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change.
IPCC Data (IPCC)	Data on the DDC is provided to facilitate the timely distribution of a consistent set of up-to-date scenarios of changes in climate and related environmental and socio-economic factors for use in climate impacts assessments. The climate data available on the DDC includes climate observation data, climate simulation data and synthesised climate data that combines both climate observation and climate simulation data.
IS-ENES (EUPORIAS)	Infrastructure for the European Network of Earth System Modelling IS-ENES2 is the second phase project of the distributed e-infrastructure of models, model data and metadata of the European Network for Earth System Modelling (ENES). This network gathers together the European modelling community working on understanding and predicting climate variability and change. IS-ENES2 combines expertise in climate modelling, computational science, data management and climate impacts. IS-ENES2 supports the ENES portal on which more information on community, services, models, data and computing can be found.
Land use and Land use Change (IPCC)	Land use refers to the total arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally.
Likelihood (Climate4Impact)	Probabilistic estimate of the occurrence of a single event or of an outcome, for example, a climate parameter, observed trend, or projected change lying in a given range. Likelihood may be based on statistical or modelling analyses, elicitation of expert views, or other quantitative analyses.
LUCC (IPCC)	Land Use and Land-Cover Change Programme
Measurement uncertainty (CLIPC)	This includes the precision of the instrument, and inhomogeneity due to changes in the observing system over time, and any bias of one observing system or sensor versus another. Related to satellite measurements, the position of the sensor plays a role which can lead to errors of the retrieved value. Moreover, the instrument calibration and ageing of the instrument lead to additional uncertainties.
Measures (IPCC)	In climate policy, measures are technologies, processes, and practices that contribute to mitigation, for example renewable energy technologies, waste minimization processes and public transport commuting practices.
Metadata (IPCC)	Information about meteorological and climatological data concerning how and when they were measured, their quality, known problems and other characteristics.
Mitigation of climate change (IPCC)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs).
Modelling uncertainties (CLIPC)	This comprises all uncertainties resulting from incomplete understanding and representation of the system modelled, including chosen parameters in models and algorithms. This can also include uncertainty from imperfect calibration, the choice of statistical techniques and missing or simplified processes in the algorithms used to retrieve a geophysical quantity from the signal detected by a satellite sensor.
North Atlantic Oscillation, NAO	A recurring spatial pattern of mean sea-level pressure (MSLP) over the north Atlantic region characterised by low MSLP over Iceland and high over the Azores/Lisbon. The NAO expresses

(Climate4Impact)	climate variability associated with variations in the large-scale temperature and precipitation pattern over Northern Europe.
Observational constraints (CLIPC)	Observational constraints, and therefore the reliability of the output, can considerably vary depending on the location, time period, and variable considered.
Paris Agreement (IPCC)	An agreement within the United Nations Framework Convention on Climate Change (UNFCCC) dealing with greenhouse gases emissions mitigation, adaptation and finance starting in the year 2020. The agreement was negotiated by representatives of 195 countries at the 21st Conference of the Parties of the UNFCCC in Paris and adopted by consensus on 12 December 2015.
Policies for mitigation of or adaptation to climate change (IPCC)	Policies are a course of action taken and/or mandated by a government, e.g., to enhance mitigation and adaptation. Examples of policies amied at mitigation are support mechanisms for renewable energy supplies, carbon or energy taxes, and fuel efficiency standards for automobiles.
Predictability (Climate4Impact)	The extent to which future states of a system may be predicted based on knowledge of current and past states of the system. Since knowledge of the climate system past and current states is generally imperfect, as are the models that utilise this knowledge to produce a climate prediction, and since the climate system is inherently nonlinear and chaotic, predictability of the climate system is inherently limited. Even with arbitrarily accurate models and observations, there may still be limits to the predictability of such a nonlinear system.
Predictions (Climate4Impact)	Generally used as a synonym of forecast . At the same time some authors like to use prediction in a more general sense while referring to forecasts as to a specific prediction which provides guidance on future climate and can take the form of quantitative outcomes, maps or text.
Probabilistic forecast (Climate4Impact)	A forecast which specifies the future probability of one or more events occurring.
Probability density function, pdf (Climate4Impact)	Aa function that indicates the relative chances of occurrence of different outcomes of a variable. The function integrates to unity over the domain for which it is defined and has the property that the integral over a sub-domain equals the probability that the outcome of the variable lies within that sub-domain. For example, the probability that a temperature anomaly defined in a particular way is greater than zero is obtained from its PDF by integrating the PDF over all possible temperature anomalies greater than zero. Probability density functions that describe two or more variables simultaneously are similarly defined.
Processing errors (CLIPC)	Error or uncertainty in any processing steps taken in the transformation from raw data to end product.
Projection (Climate4Impact)	A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a climate model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised. See also Climate prediction and Climate projection.
Radiative Forcing (IPCC)	Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in Watts per square metre; W m^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO_2) or the output of the Sun.
Regional climate models, RCM (EUPORIAS)	A limitation of global climate models (GCMs) is their fairly coarse horizontal resolution. For most impact studies, such as evaluation of the future risks of floods or some types of landslides, droughts etc., the society requests information at a much more detailed local scale than provided by GCMs. Simply increasing the resolution is often not feasible because of constraints in available computer resources. A viable alternative is to embed a regional climate model (RCM) of higher resolution in relevant part of the GCM domain. RCM are complementary to GCM by adding further details to global climate projections, or to study climate processes in more detail than global models allow.
Representative Concentration Pathways, RCPs (IPCC)	Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models

produced corresponding emission scenarios.

Reanalyses (Climate4Impact)	Estimates of historical atmospheric, hydrographic or other climate relevant quantities, created by processing past climate data using fixed state-of-the-art weather forecasting or ocean circulation models with data assimilation techniques.
Reliable (Climate4Impact)	A characteristic of a forecast system for which the probabilities issued for a specific event vary a proportion of times equal to the climatological frequency of the event. A reliable system which predicts, for example 50% (or 20%, or 73%) probability of rain, should, on average, be correct 50% (or 20%, or 73%) of the times, no more, no less.
Resolution (IPCC)	In climate models, this term refers to the physical distance (meters or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or the time elapsed between each model computation of the equations.
Retrospective forecasts (Climate4Impact)	A forecast made for a period in the past using only information available before the beginning of the forecast. A set of hindcasts can be used to bias-correct and/or calibrate the forecast and/or provide a measure of the skill.
Return value (Climate4Impact)	The highest (or, alternatively, lowest) value of a given variable, on average occurring once in a given period of time (e.g., in 10 years).
Risk (Climate4Impact)	Often taken to be the product of the probability of an event and the severity of its consequences. In statistical terms, this can be expressed as $Risk(Y)=Pr(X)\ C(Y\|X)$, where Pr is the probability, C is the cost, X is a variable describing the magnitude of the event, and Y is a sector or region.
Sampling uncertainty (CLIPC)	Temporal and spatial sampling characteristics will vary depending on the type of orbit, the width of the instrument swath and its field-of-view. For example a single sensor might provide an under-sampled view in space and time and thus, the measurements may or may not capture the true variability of the observed quantity. The position of the sensor which is related to the viewing geometry plays can also lead to errors of the retrieved value.
Scenario (IPCC)	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions. See also Climate scenario, Emission scenario, Representative Concentration Pathways and SRES scenarios.
Sensitivity (IPCC)	The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).
Signal contamination (CLIPC)	Depending on the quantity of focus, atmospheric effects like clouds or aerosols, or unwanted signals from the Earth's surface can significantly influence or alter the retrieved signal. For example, for optical data, a robust surface image classification can be very challenging, given the fact that approximately 50% of the Earth is covered by clouds at any time.
Skill (Climate4Impact)	Measures of the success of a prediction against observationally-based information. No single measure can summarize all aspects of forecast quality and a suite of metrics is considered. Metrics will differ for forecasts given in deterministic and probabilistic form.
Spatial representativeness (CLIPC)	Any region of the Earth is unlikely to be evenly or densely sampled. Stations may also drop in and out over time. Regional averages can only represent the stations they are made up of. The comparison of data measured at ground stations with data collected by satellites may introduce scaling errors. The coarser the grid cell of the remotely sensed data, the more of this variability is lost. This may lead to scaling errors between remotely retrieved and in-situ observations.
SRES (EUPORIAS)	Special Report on Emission Scenarios.The SRES scenarios are described in the IPCC Special Report on Emission Scenarios (2000). There are 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces.
SSPs (IPCC)	Shared socio-economic pathways. Currently, the idea of SSPs is developed as a basis for new emissions and socio-economic scenarios. An SSP is one of a collection of pathways that describe alternative futures of socio-economic development in the absense of climate policy intervention. The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections should provide a useful integrative frame for climate impact and policy analysis.
Statistical significance	Describes the likelihood of an observation or a result resulting from pure chance. It is often used in connection with a null-hypothesis (an alternative explanation, usually such as there is

(Climate4Impact)	no correlation or no causal relationship), and gives the odds that the null-hypothesis is correct.
Stochasticity (CLIPC)	An inherent property of the system and it describes the degree to which the system evolution is not predictable, even given perfect understanding of the system. For example, it refers to the evolution of the climate system that is due to chaotic behaviour or (quasi-)random events. This source of uncertainty is non-reducible.
Storyline (IPCC)	A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.
Trend (Climate4Impact)	Long-term evolution, such as climate change and global warming. Trend analysis is used to describe trends, and can involve linear or multiple regression with time as a covariate. A trend model may be a straight line (linear) or more complex (polynomial), and the long-term rate of change can be described in terms of the time derivative from the trend model.
Uncertainty (Climate4Impact)	Lack of precision or unpredictability of the exact value at a given moment in time. It does not usually imply lack of knowledge. Often, the future state of a process may not be predictable, such as a roll with dice, but the probability of finding it in a certain state may be well known (the probability of rolling a six is 1/6, and flipping tails with a coin is 1/2). In climate science, the dice may be loaded, and we may refer to uncertainties even with perfect knowledge of the odds. Uncertainties can be modelled statistically in terms of pdfs, extreme value theory and stochastic time series models
United Nations Framework Convention on Climate Change (IPCC)	The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return greenhouse gas (GHG) emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention entered in force in March 1994. In 1997, the UNFCCC adopted the Kyoto Protocol.
Unpredictability (CLIPC)	Unpredictability is caused by the variable behaviour of human beings or social processes. It differs from 'incomplete knowledge' because it concerns what we cannot know and therefore cannot be reduced or changed by further research. Unpredictability is therefore non-reducible.
WCRP (IPCC)	World Climate Research Programme
WGCM (IPCC)	Working Group on Coupled Modelling
WGRM (IPCC)	Working Group on Regional Modelling
WGI (IPCC)	IPCC Working Group I: The Physical Science Basis
WGII (IPCC)	IPCC Working Group II: Impacts, Adaptation and Vulnerability
WGIII (IPCC)	IPCC Working Group III: Mitigation of climate change
WMO (IPCC)	World Meteorological Organisation
Vulnerability (IPCC)	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.