European Earth System Modelling for Climate Services

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Foreword

Dr. Chris Hewitt, Climateurope Coordinator

There have been sizeable and sustained investments to ensure that Europe is at the forefront of Earth-system modelling and climate service development and delivery. Some of the key European activities are as follows: JPI-Climate, to coordinate aspects of climate research in several European countries, and an associated European Research Area network for climate services; the European Institute of Innovation and Technology's Climate-KIC, to create innovation through linking academia, and small and medium-sized enterprises; and the Copernicus Climate Change Service, to develop and deliver operational climate services.

However, these and other activities have sprung up with no overall coordination. This risks creating confusion amongst users, researchers, intermediaries, and funders, who often see a disparate range of unconnected and sometimes competing activities and services, rather than a set of coordinated approaches. It is therefore difficult for these stakeholders to properly assess what efforts are currently underway, to effectively coordinate research and innovation programmes, and to identify future research and innovation priorities.

To address this situation, the European Commission has funded Climateurope, a coordination and support action under the Horizon 2020 framework programme. Climateurope is building an environment and range of activities around Europe-wide Earth-system modelling and climate services. At its core is a managed network of relevant scientific communities, funders and user communities. The project aims to enhance communication and dissemination activities and integrate and coordinate European climate modelling, climate observations and climate service infrastructure initiatives.

A central activity within Climateurope is to map and analyse relevant initiatives, assess new challenges and determine emerging needs relating to Earth system modelling and climate services in Europe, involving expertise from a range of stakeholders. Three reports will be produced for this: the first report produced in 2017 was on European Earth system modelling for climate services. Updated reports will be produced in late 2018 and 2020 providing progress on the integration of climate services and Earth system modelling.

The three reports will form the basis of a publication series on the "state of European Earth system modelling and climate services" intended to have a wide readership including the scientific community and decision- and policy-makers from industry, professional federations and public sector.

I am delighted to introduce this publication, the first in the Climateurope publication series on European Earth System Modelling for Climate Services. If you would like to get involved with the growing European community addressing the challenges and opportunities arising from changes in our climate, I look forward to welcoming you to the Climateurope network. (https://www.climateurope.eu/contact/)

1 Introduction

Changes in climate are affecting many sectors of society and economy. The underlying climate research that is being used to understand and predict such changes in climate has shown a strong development during the last decade.

Climate adaptation and mitigation measures are being supported by climate services that are being delivered to the public and private sectors. The climate services transform climate information into products, which include projections on multi-decadal timescales, predictions on timescales from months to years, observed and forecast trends, assessments, counselling on best practices, and any other climate-related product that may be of use for society. Climate services can help decision-makers take better informed decisions in order to raise resilience and adaptation capacity by addressing existing or emerging risks.

Climate services cover direct and indirect consequences of climate change in the atmosphere, ocean, sea ice and on land. Changes in our climate are leading to a range of varied and significant impacts affecting ecosystems and human systems – such as agricultural, transportation, water resources, natural resources, economic activities and infrastructure. Those impacts depend not only on the climate, but also on other changes in the environment and on the capacity of society to adapt. To limit risks and identify opportunities associated with the changes, we need to understand how society is affected, and what can be done to adapt, as well as to reduce climate change.

This volume is the first of three in Climateurope's publication series, and focuses on the state-of-the-art of Earth system modelling. The purpose is to explain and illustrate the abilities and limitations of

Earth System Models (ESMs) in relation to the potential for climate services. The usefulness of climate service products is the result of a value chain starting at ESMs and ending with e.g. climate change adaptation measures. The model-related chain member is decisive for the service. This publication makes the links clear for a target audience of climate service professionals. ESMs, which are extensions of the classical climate models with biogeochemical cycles, are an essential tool for understanding and predicting climate variability and climate change. Climate models and ESMs produce the data, particularly for the future, that underpins most climate services.

Given the growing impact of climate change and therefore the growing societal importance of climate services, further attention must be given to climate models and ESMs and their interpretation in order to strengthen the science-base of climate services.

The ability of climate models and ESMs to perform long-term climate projections (section 2), and seasonal-to-decadal predictions (section 3) is scrutinized in relation to uncertainties and opportunities for climate services. User-oriented applications often require information from the relatively coarse scale that global climate models and ESMs produce to be transformed to finer scales, such as regional or local. The states of downscaling efforts are reviewed (Section 4) along with further refinement techniques such as bias correction and selection techniques (section 5).

To describe the link between ESMs and climate services, European climate services research is discussed (section 6). Section 7 synthesises needs, challenges and barriers to the integration of ESMs and climate services.

2 Earth system modelling and climate projections

2.1 What is an Earth system model?

Earth System Models (ESMs) represent advanced and complex descriptions of the Earth's atmosphere, ocean, and land surface. ESMs describe the global climate system through a combination of coupled physical and biogeochemical cycles described by mathematical equations. The models provide three-dimensional climate variables, such as temperature, precipitation and wind, both in the past and into the future. ESMs can be used for climate policy-relevant calculations, such as the level of carbon dioxide (CO_2) emissions that would lead to given climate warming targets (e.g. the 1.5°C above pre-industrial levels of the Paris Agreement).

2.1.1 The basis

The classical global climate model (GCM) describes the relevant physics of the atmosphere, sea ice, ocean and land surface. ESMs are more advanced, including processes relating to the carbon cycle, atmospheric chemical composition, vegetation, aerosol processes, ecosystems, and other biogeochemical-physical processes. Importantly, ESMs include the feedback that occurs between processes (Fig. 2.1). The principles that underlie ESMs include physical laws of fluid dynamics in air and water, 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.

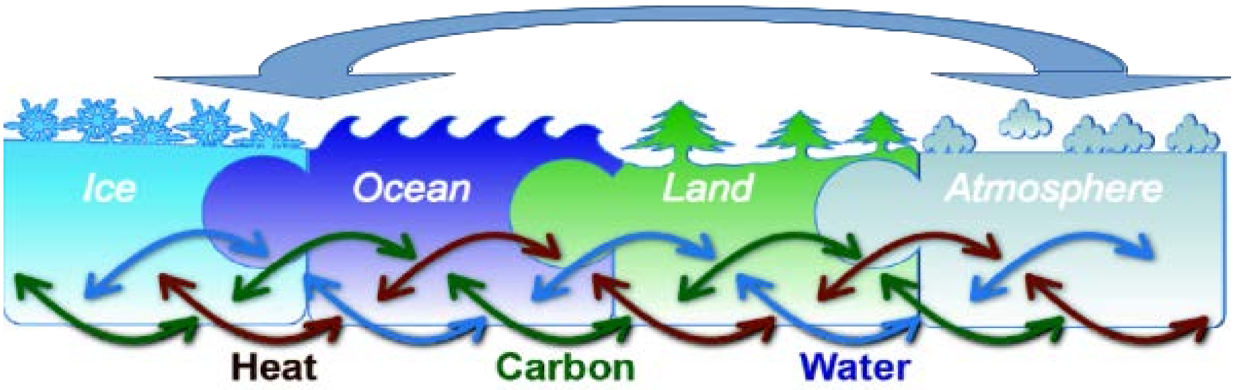

Figure 2.1 Interacting components in an Earth System Model in a simplified sketch; all components interact (taken from Sandrine Bony, WGCM).

Since the 1970s the descriptions of processes have been improved and the resolution has been refined (typically about 100 km between horizontal grid points in the atmosphere). Processes acting on scales smaller than those resolved by the models, such as clouds, precipitation, radiation, eddies in ocean and atmosphere, and sea ice processes, need to be parameterised, i.e. described by observation based relations between larger scale simulated conditions and smaller scale processes. Major advances to the abilities of climate models and ESMs have been made through improving such parameterisations. As the number and complexity in the models has been increased, modelling of new feedback processes has been enabled, for example, how the carbon cycle responds to greenhouse-gas induced climate warming by changing carbon storage 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.

2.1.2 Robustness of ESMs

It is essential to thoroughly evaluate the models against observational data. This process has shown that ESMs have demonstrable capability in representing the earth's climate system, importantly, including changes to the climate. Changes of a variable (e.g. the near-surface air temperature) at both the global and continental scale can be well simulated. The Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report (AR5) states very high confidence that models reproduce observed large-scale mean surface temperature patterns, with exception of regions with high topography, near ice edges and in certain regions of ocean upwelling (IPPC, 2013; Flato et al., 2013).

ESMs are subject to inaccuracies and errors, which contribute to the overall uncertainty of climate projections and predictions. Assessment of uncertainty is thus a necessity for ESMs to be useful for decision making. Users of the climate information should actively consider uncertainties for the respective user case. This requires a provision of uncertainty information in a user-friendly way.

The overall uncertainty in climate simulations can be mapped, by using several ESMs to simulate the climate in a coordinated fashion across a range of different climate simulations, then analysing the differences between model outputs e.g. in the IPCC reports. Coordinated simulations with several ESMs are carried out under the umbrella of the Climate Model Intercomparison Projects (CMIP). Under the concept of model intercomparisons, various climate science questions are addressed together with assessing robustness, prediction skill and uncertainty. Some climate service products are built on these coordinated CMIP simulations and on downstream products, such as regionalisation and impact modelling products.

Major components of uncertainty are related to different aspects, from the models themselves to the input data fed to the models. Inaccuracies and errors in ESMs arise from model approximations to real-world processes, programming bugs, limited understanding of the natural processes and missing feedbacks in less complex climate models such as in models without carbon feedback. When applying ESMs for future climate scenario simulations, uncertainty is related to the choice of greenhouse gas (GHG) emissions scenario (uncertainty about the socio-economic developments). For seasonal to ten-year long simulations (i.e. climate prediction, section 3), model initialisation from observed conditions constitutes an important source of uncertainty. Also, simulated natural climate fluctuations express themselves differently across a range of models.

The collected issues lead to limited capabilities of empirical parameterizations to describe the effect of sub-grid scale processes on the coarser numerical grid. The challenge is addressed by ongoing model improvement with observational studies as reference for parameterizations, by developing advanced numerical methods, and by intensifying software testing procedures following IT standards. Progress between model generations is quantified by climate performance metrics, a process that itself is subject to increasing standardisation and further development.

2.1.3 Evaluation of ESMs

Evaluation of ESMs is the process to quantify a model's overall ability to simulate combined processes and the resulting climate. Together with 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 for individual models, and in multi-model comparisons. Fig. 2.2 illustrates progress in reducing model error in recent decades. Thus, there is clear reason for growing confidence in using climate models for quantitative future predictions and projections.

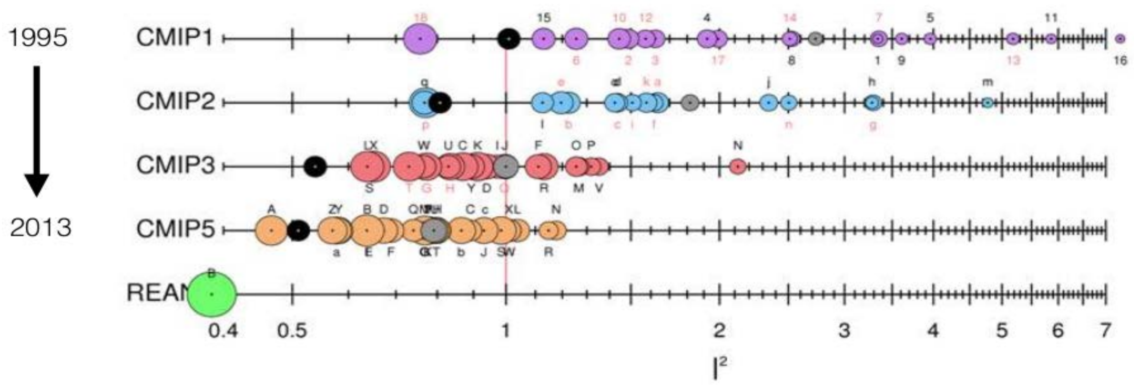

Figure 2.2 Normalised error based on a range of global climate variable's standard deviation error (based on Reichler and Kim, 2008). Average model errors have been reduced with time.

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. These relationships provide a way to transform an observable quantity into a constraint on future projections, but the application of such constraints is 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).

Concerning the additional component models in ESMs (e.g. vegetation and carbon cycle), evaluation has lagged behind that for physical climate process models. Ongoing projects (e.g. H2020-CRESCENDO) are developing crucial process-based techniques to evaluate schemes for new ESM descriptions for terrestrial, marine biogeo-chemistry and aerosol processes.

2.2. Climate projections

2.2.1 ESM for climate projections

Climate variability, natural fluctuations and oscillations of the global and regional climate exist in both reality and climate simulations However, simulated intensity and timing differs between models and in comparison with observations. Thus, climate simulations might sometimes be biased, despite a general ability to describe relevant coupled processes. For that reason, climate change projections need to be built on an ensemble of simulations which span a range of effects of different timings for a given simulation time. In addition, to project different changes in climate, associated with different policy scenarios, climate models are run under different emission and land use scenarios, known as Representative Concentration Pathways (RCPs). Since IPCC AR5 these projections are highly dependent on the amplitude of the GHG gas concentrations in the emission scenario.

Fig. 2.3 illustrates climate projections and the development of the different uncertainty components over the 21st century. 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, scenario uncertainty dominates the overall uncertainty (e.g. Sillmann et al. 2013). This uncertainty associated with the choice of scenarios implies that policy-makers have very different options and can respond to alternative expected climate change amplitudes, whereby all uncertainties need to be weighed in.

Each emission scenario is associated with a range of global mean temperature increases 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 the representation of clouds that differs from one model to the other. This leads climate models to respond to CO_2 increases differently. 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

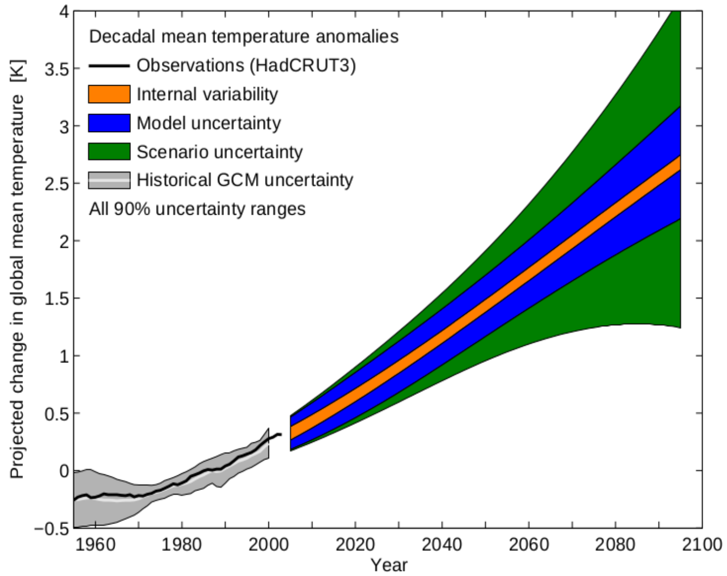

Figure 2.3 The total uncertainty in CMIP3 decadal mean projections of global mean temperature for the 21st century. The grey regions show the uncertainty in the 20th century integrations of the same Global Climate Models (GCMs), with the mean in white. The black line before the year 2000 shows an estimate of the observed historical changes from HadCRUT3 (Brohan et al., 2006). Figure taken from Hawkins and Sutton (2011).

IPCC based on various methods and sources, model-based and observational. When CMIP started in 1995, the first set of common experiments compared the model response to an idealised forcing - a CO_2 increase of 1% per year. Since then, the CMIP experiments have evolved, but continue to include integrations using idealised forcings. They now also include simulations forced with estimates of the changes in the historical radiative forcings as well as estimates of the future changes.

The concept for the upcoming CMIP6 (Fig. 2.4) includes assessments of model performance during the historical period and quantifications of the causes of the spread in future projections. Idealised experiments are also used to increase understanding of the model responses. For CMIP6, the concept is extended by new Shared Socio-economic Pathways (SSPs), 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 CMIP6 (2017-2020) will address three broad questions (Eyring et al. 2016): (1) How does the Earth system respond to forcing? (2) What are the origins and consequences of systematic model biases? (3) How can we assess future climate changes given internal climate variability, predictability, and uncertainties in emission scenarios?

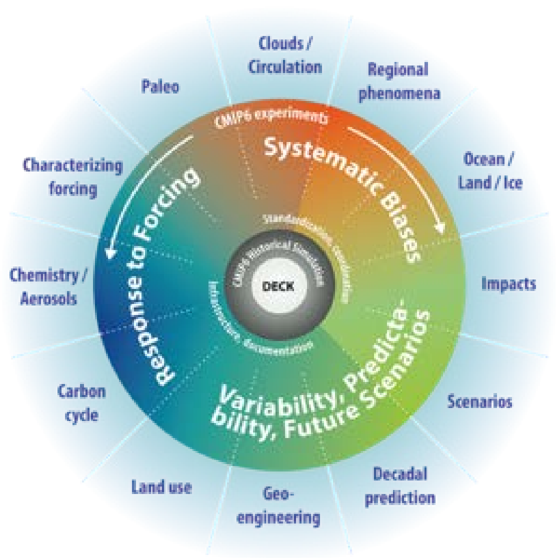

Figure 2.4 The concept of CMIP6 experiments.

2.2.2 Using ESMs for Climate Services

Projections play a fundamental role in improving understanding of the climate system as well as characterising societal risks and response options. The CMIP6 Scenario Model Intercomparison Project (Scenario-MIP) provides multi-model climate projections based on alternative scenarios of future emissions and land use changes (O'Neill et al. 2016). It aims to facilitate a wide range of integrated studies across the climate science, impacts, adaptation, and vulnerability, research 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" (O'Neill et al. 2016), the consequences of scenarios that limit warming to below 2°C, the relative contributions to uncertainty, 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.

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 important topic. The choice needs to represent a large part of the range of possible outcomes. In addition, most climate services, e.g. for hydrological applications, need to reduce possible model biases by empirical corrections (section 5).

GCMs and ESMs provide the large scale structure of the climate and the climate change signal. Regional interpretation of that signal requires higher spatial resolution (tens of km) than global models can computationally afford (typically 100-200 km, and increasing for CMIP6). Regional conditions such as steep mountains and landscape variations strongly affect the signal and its extremes. To address this limitation, regional climate models (RCMs), are applied to downscale ESMs and GCMs with a higher grid resolution that allows for a much more realistic regional climate response (section 4).

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' (when GHGs are removed from the atmosphere). Both experiments are considered necessary to inform the process towards emission pathways compatible with a global warming below 2°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.

2.2.3 Data infrastructure

An important goal of CMIP is to make the multi-model output publically available in a standardised format, which is the primary source of model data for climate services. Accessing model results from the CMIP experiments requires a strong international infrastructure organisation. For 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). Twenty-seven modelling centres from all over the world run a large set of model experiments and share them within ESGF. 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. This collaboration required strong national support for computing and human resources. 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 utilised 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. 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.

2.3 Summary and conclusions

Earth system modelling relies on a system of scientific and technical services: model development, evaluation systems, high-performance computer systems, post-processing, and publication of resulting digital data and findings. All of these elements are necessary to enable downstream climate services.

Research into climate change adaptation needs to factor the simulated climate change impacts into society's vulnerability to climate change, its capacity to adapt, and other competing stressors. The more reliable and comprehensive ESMs are, the more successful each subsequent activity in the chain will ultimately be in supporting informed adaptation planning. (EMBRACE final report, 2016). Based on model evaluation efforts on historical climate simulations of CMIP there is growing confidence in climate models and ESMs for quantitative future predictions and projections.

How can one measure the added value of increasing complexity in ESMs? Between IPCC Assessment Reports 4 (2007) and 5 (2013) there has been progressive investment in computing resources, allowing a number of climate models to be extended to ESMs. The inclusion of carbon cycles 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 CO_2. The fact that the CMIP5 ensemble compares more favourably than CMIP3 with observations indicates the success of this strategy (Knutti et al., 2013).

The increased resolution (not only spatial 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, from the daily to the hourly (Scoccimarro et al. 2015). 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 into global climate change itself. Two examples are wildfires, which alter aerosol concentrations and albedo, and ocean acidification, which impacts on biological cycles.

Incomplete knowledge of past climatic conditions limits the direct translation of physical model performance from historical simulations into confident statements about fidelity of future climate projections. However, evaluating models using the increasing number of observations over time shows trends and variability that are of use to climate services. Additional potential is seen in techniques constraining model results. New evidence shows that observed variability or trends can be found that are partly well correlated with inter-model differences in model projections. These relationships allow an observable quantity to be transformed 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.

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 that only ESMs can provide. For informed adaptation and mitigation policy, it is crucial all feedbacks that influence the magnitude of global climate change are included in the models used to make future projections (EMBRACE final report, 2016). Earth system models are at the starting point of a chain of research, described in the following sections.

For ESM and GCM simulations of the climate of the 21st century there is large uncertainty associated with the choice of socio-economic emissions scenarios., This means that policy and decision-makers have to consider very different options and can respond to alternative expected climate change amplitudes. New climate projections of possible future climates are to be carried out under the CMIP6 Scenario-MIP, which extends previous emissions scenarios to a matrix of possible pathways associated with alternative policy decisions.

Elements of an ESM infrastructure to link climate modelling with climate services exist partly in the form of short term projects. Efforts to sustain such an infrastructure will be necessary to support long term climate service development and delivery.

3 European seasonal to decadal climate prediction systems

3.1 What are climate predictions?

In contrast to climate projections, climate prediction rests on initialized simulations of observed conditions and is limited to time scales from subseasonal to decadal. 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 emerged from a range of stakeholders including public decision makers, (re)insurance companies, the tourism industry and the agricultural sector, to benefit from more accurate climate information at time scales ranging from a month 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 both weather forecasting and long-term climate change assessment, covering a wide range of topics. The recent developments in those two fields (including increased resolution, inclusion of new components, and better observations) 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: the forecast uncertainty and the forecast quality.

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 is the main process that contributes to the global scale forecast quality.

The initialisation of the models is the first critical stage to be addressed in climate prediction. This means including information about the state of the atmosphere, ocean, sea-ice cover, snow, soil moisture, etc. which must be included in order to phase-in the model with the best estimate of state of the climate system at the start date of a forecast (Fig. 3.1).

3.2 Performing climate predictions

There are two methods used to perform climate predictions (Suckling et al., 2017), those based on statistical-empirical approaches or those based on process-based, dynamical models (see section 2). 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. The main differences in the way climate models are used for climate-change projections 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).

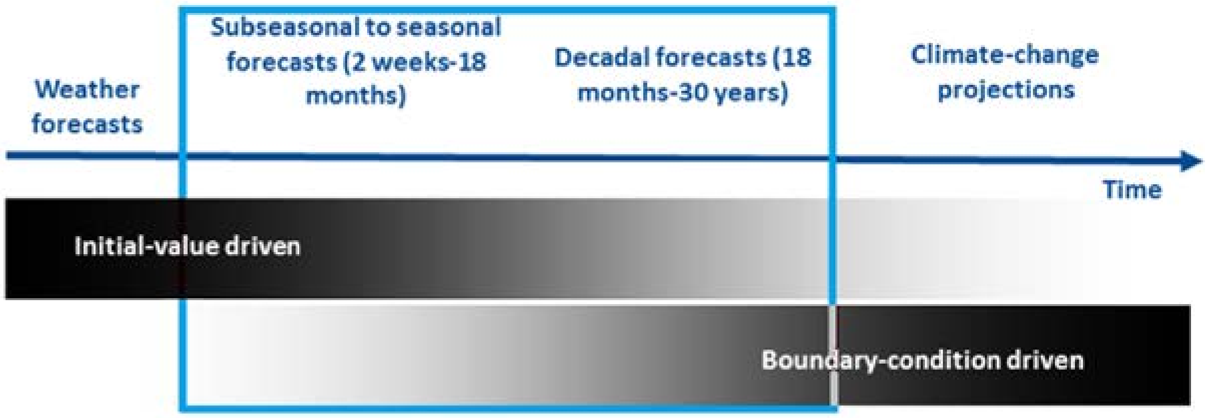

Figure 3.1 Schematic illustrating the progression from initial value problems with daily weather forecasts at one end, and multidecadal to century projections as a mainly forced boundary condition problem at the other, with subseasonal, seasonal and decadal prediction in between. Climate predictions are encompassed within the blue box. Adapted from Meehl et al. (2009).

Due to the chaotic nature of the climate system and the systematic errors of current forecast systems, quantifying the extent of forecast uncertainty plays a central role in climate prediction. Climate predictions are typically formulated in a probabilistic way, i.e. specifying the future probability of one or more events occurring.

Such "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 models used to perform climate change projections (section 2), are indicative of problems in the model formulations. The variations of the systematic error with the forecast time illustrate the model drift. Process-based evaluation procedures that allow identifying the main physical processes responsible for the systematic errors are under way. The presence of the drift requires for a climate prediction system to produce a sufficiently large sample of retrospective predictions (i.e. a forecast made for a period in the past, also known as re-forecasts or hindcasts) in order to be corrected for their systematic biases against observations. These hindcasts, along with the need to run ensembles of simulations, makes dynamical climate prediction a particularly computationally expensive exercise.

All climate forecasts, like any other forecast, have to be systematically compared to a reference, preferably observations, in a forecast quality assessment. The multifaceted nature of forecast quality dictates that no single meteorological or hydrological variable 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. 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.

As in climate projections, climate predictions from different sources are generally combined into a single prediction to map 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, (Fig. 3.2, Athanasiadis et al., 2016).

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. Hence regionalisation or downscaling methods are necessary. Although there are both empirical/statistical and dynamical approaches to downscaling, local-scale seasonal predictions usually have explored the empirical/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/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.

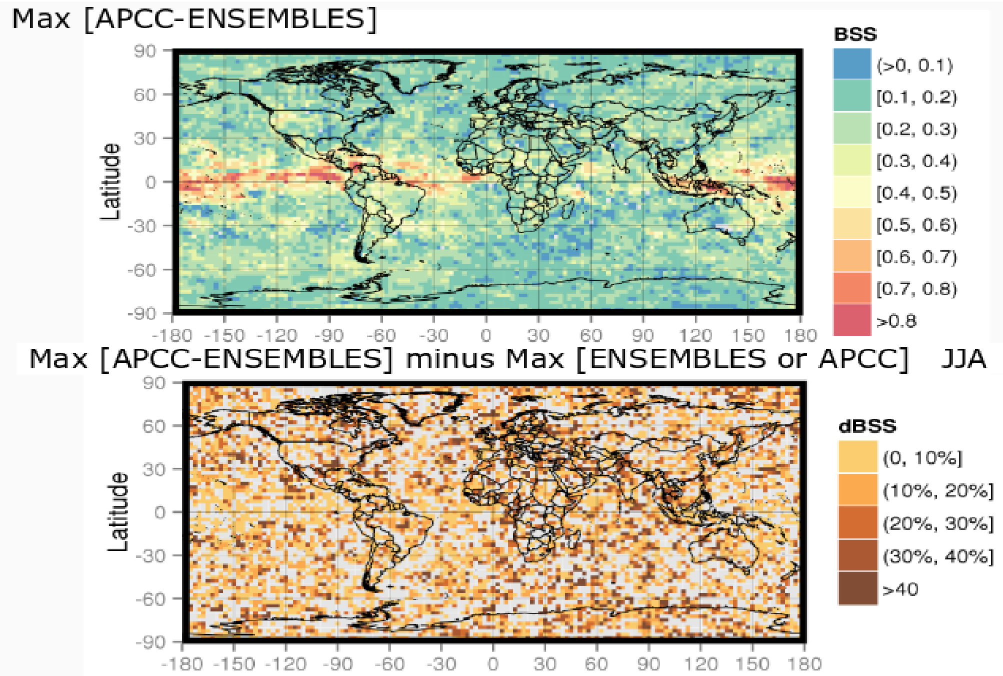

Figure 3.2 Brier skill score (BSS) for the one-month lead boreal summer precipitation multi-model forecasts from the ENSEMBLES and APCC multi-model ensembles (top) and difference with the maximum skill score obtained from either the ENSEMBLES or APCC multi-model ensembles (bottom).In the top panel, positive 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).

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.

3.3 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, 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, in a similar way as climate projections are. Subseasonal and seasonal forecast data are made available either in research mode, like from the S2S multi-model database or the CHFP repository, 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 prompt access to the real-time forecasts invaluable. Although the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble collects a subset of the real-time seasonal (and in the future also subseasonal) forecasts released by the existing fifteen global producing centres, the outcome is not made publicly available. Something similar occurs with the subseasonal forecasts disseminated by the S2S project, which provides 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 restricted access) to disseminate their data.

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. 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.

3.4 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 initialisation 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 4).

4 The role of downscaling for climate services

4.1 Why downscale?

In recent years, demand 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, there is high interest in such climate services when dealing with small-scale extreme events, such as local floods caused by short-term, heavy precipitation. Regional features such as complex mountainous terrain, varying soil and vegetation types, and small-scale landscape heterogeneities such as urban areas, lakes and coastlines strongly shape the variations in the state of the climate system, associated climate events and extreme events be they small-scale or short-lived.

Global models (ESMs and GCMs) provide credible large-scale simulations of the climate. However, the resolution of the global models limits their ability to capture regional features as noted above, and there are processes that are not explicitly represented in the operational global models at present, such as deep convection (100 m to kilometre scale vertical movements) that occurs in areas of complex topography or in steep frontal gradients.

Regional climate models (RCMs, climate models set up at a higher resolution but over a smaller defined region than global models) are applied to alleviate such limitations and aim to produce a much more realistic regional climate simulation (Rummukainen et al. 2014, Jacob et al., 2014, Prein et al., 2015, Rockel et al. 2015), as well as capture small-scale and short-lived extreme events better. The RCMs are driven by the large-scale circulation and physical conditions from the global models at their lateral boundaries. RCMs typically cover continental regions, such as Europe (Fig. 4.1), at spatial scales of 10, 25 or 50 km. The value of downscaling for impact applications generally increases with increased resolution.

Figure 4.1 The EURO-CORDEX regional climate model domain taken with permission from http://www.euro-cordex.net/).

As an alternative to dynamical downscaling with RCMs, empirical-statistical downscaling (ESD) can be applied to regionalise 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).

As in the case of ESMs, 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, and biogeochemistry, or towards fully two-way coupled multi-physics and biogeochemical regional climate system models, for a better understanding of feedbacks and interaction processes for different scales and under natural and anthropogenic forcing scenarios.

4.2. The added value of regional downscaling

The expectation of 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, as process-oriented benefits, or both. Di Luca et al. (2015) discuss the definition of added value. In the case of climate services, added value is seen in a more correct and reliable description of the regional and local climate for both mean values and extremes, and improved representation of physical and dynamical processes. While RCMs are a tool to accomplish this, there remain barriers to realising their full potential. Among the major limitations to achieving 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.

Considering downscaling of the recent historical climate from large-scale best estimates (observations and reanalysis), there is ample evidence of added value for temperature, precipitation, and wind, for mean and extremes. Scientific literature is relatively scarce on other climate variables, however examples do exist e.g. for snowfall and extremes (e.g., Prein et al., 2016).

RCMs also add value to GCMs output when considering phenomena characterised by small scales and short timescales in the free troposphere as well as in the surface climate conditions, such as sub-daily characteristics of precipitation and extremes (Rummukainen, 2016).

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.

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

4.3 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) (Giorgi et al. 2006). CORDEX is a component of the UN-linked World Climate Research Programme (WCRP).

CORDEX provides an internationally coordinated framework to improve regional climate scenarios for most regions of the world (Fig. 4.2). This includes harmonisation 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, MED-CORDEX described below).

Present activities of CORDEX include the design of the Coordinated Output for Regional Evaluation (CORE) experiment and the Flagship Pilot Studies (FPS). The CORE experiment aims to create 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 aim to investigate regional climate processes and phenomena and to improve their representation in RCMs.

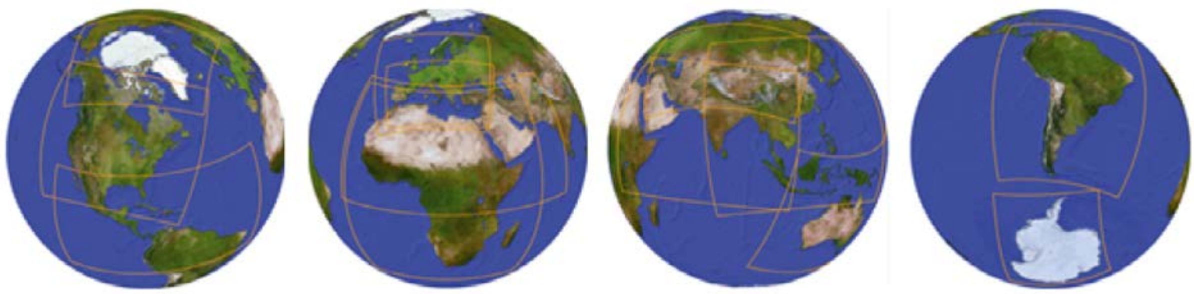

Figure 4.2 Various CORDEX domains for RCM downscaling of recent climate and future climate scenarios. Adapted, with permission, from http://www.cordex.org/.

4.3.1 EURO-CORDEX

As a part of the global CORDEX framework the EURO-CORDEX initiative provides regional climate projections for Europe at 50 km and 12.5 km resolution.

EURO-CORDEX is actively supported by 31 modelling groups. EURO-CORDEX aims to improve the robustness of climate projections at regional scales and at high spatial and temporal resolution to be used to help Europe to better adapt to unavoidable climate change and to design more efficient mitigation strategies. 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 are available via the EURO-CORDEX webpage.

A new co-ordinated high-resolution regional climate change ensemble with a horizontal resolution of 12.5 km has been established for Europe (Jacob et al. 2014) from downscaled CMIP5 global climate projections (Taylor et al. 2012). 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 (WGRM) distillation challenge. A list of publications related to EURO-CORDEX can be found here. 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 (Vautard et al. 2013, Kotlarski et al. 2014). But it also identifies deficiencies of the simulations for selected metrics, regions and seasons. These biases limit direct use of climate model results in most impact models due to many nonlinear relations in these. Therefore statistical correction is needed to reduce biases (see section 5).

4.3.2 MED-CORDEX

Another CORDEX domain relevant for Europe is the MED-CORDEX domain. Proposed by the Mediterranean climate research community as a coordinated contribution to CORDEX, the MED-CORDEX initiative is supported by HyMeX and MedCLIVAR programs. The initiative makes use of RCMs to increase the reliability of past and future regional climate information with focus on the Mediterranean Sea and surrounding land (Ruti et al., 2016). Within 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 a so-called perfect boundary condition experiment using ERA-Interim for initial and latter boundary conditions (Fantini et al., 2016; Dell'Aquila et al., 2016). The second stage was dedicated to CMIP5 global climate projection downscaling. In the context of future activities, MED-CORDEX will participate in three Flagship Pilot Studies.

Details on findings and corresponding references can be found in Ruti et al. (2016) and MED-CORDEX publication web page.

4.4 Summary and conclusions

Regional climate model simulations, especially those from the CORDEX communities, are providing coordinated sets of regional downscaled climate projections.

This 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 communities such as EURO-CORDEX and Med-CORDEX are focusing on further improving climate modelling, related processes and information integration methods via the CORDEX FPS and CORDEX CORE simulations. Those efforts are expected to further improve downstream climate services. Furthermore, EURO-CORDEX and Med-CORDEX 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.

5 Refinement techniques

5.1Introduction

Given uncertainty in climate model projections and predictions (sections 2 and 3), impact studies need to be based on an ensemble of climate simulations rather than a single one in order to attempt to capture and represent the uncertainty. Large differences in future changes can be observed amongst the models for the different variables (Overland et al. 2011, McSweeney & Jones 2016). Due to limited computational capacity, only a selection of models and model runs can be used in any given study. This selection is therefore of primary importance for the results of any impact study.

Moreover, large and systematic biases can be observed between the climate simulations and the observations, despite continuous improvements over the past decades (section 2). Such biases have a strong influence on the result of climate change impact studies (e.g. Hansen et al., 2006; Sharma et al., 2007; Macadam et al., 2016) and thus need to be reduced before application. For this reason, an adjustment or correction has to be applied to climate model output before impact analysis, in order to obtain a more useable dataset for impact assessment.

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

5.2 Model selection and inter-model uncertainties

An increasing number of ESMs and GCMs are becoming available for climate change impact studies. Moreover, a varying number of simulations are available for the different models.

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 models should be ideally used, representative for the range of projected outputs.

We focus here on the selection of global models, but the same discussion and methods apply for the selection of regional models used for dynamical downscaling usually used before impact modelling.

5.2.1 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. No universal method has been applied, the model selection must be designed to maximise model diversity in order to capture uncertainty yet ensuring good model performance (Masson and Knutti, 2011).

One of the main considerations is the performance of the model, i.e. its skill to reproduce historical observations and trends for a given variable in a given region (even though the ability of a model to produce results comparable with observations is no guarantee that this model will perform as well under new forcing in the future). After having eliminated the poorly-performing models, the remaining ones should be evaluated and a subset can be chosen. One should be also interested in selecting models that: (1) perform well for the region and variables of interest; and (2) capture a broad range of responses to climate change (McSweeney & Jones, 2016).

Whatever selection method is applied, it is useful to provide information on the spread across the selected models and across the available models, in order to help policy- and decision-makers to consider a plausible range of projections and be informed about uncertainties of climate projections and their use.

5.2.2 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 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. Some methods (e.g. Knutti et al., 2013; Abramowitz & Bishop, 2015; Mendlik & Gobiet, 2016) have been proposed to reduce model dependence in CMIP ensembles.

5.2.3 Greenhouse gas emission and concentration scenarios

Greenhouse gas 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 2) representing four greenhouse gas concentration trajectories under a set of socioeconomic assumptions. 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. 5.1). For a given model, climate simulations will produce different projected changes for different emission scenarios.

As the largest contribution for projection uncertainty after the first 20-30 years is given by the choice of emission scenario, their selection is as important as the model selection. This selection 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 outcomes, hence using the most extremes scenarios (RCP2.6 and 8.5) for example. In any case, the selection of the scenarios should be detailed and well-argued and its implications described.

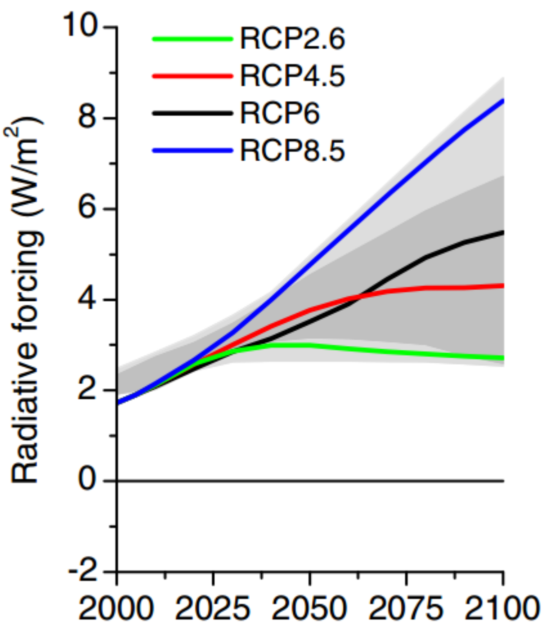

Figure 5.1 Trends in radiative forcing. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature (modified from van Vuren et al., 2011).

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.

5.3 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).

Systematic biases might, for example, result in an overestimation of the number of wet days with low intensity or incorrect seasonal variations of precipitation, with consequences for information usage via climate services.

5.3.1 Delta change

The delta change approach consists of working with changes instead of working directly with climate data points (Fig. 5.2). 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).

5.3.2 Scaling approach

The scaling method is a variant of the delta approach where 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). More details and examples can be found in Teutschbein & Seibert (2012).

5.3.3 Distribution mapping

Delta approach and simple scaling methods can perform well for certain variables such as temperature mean conditions, but a more

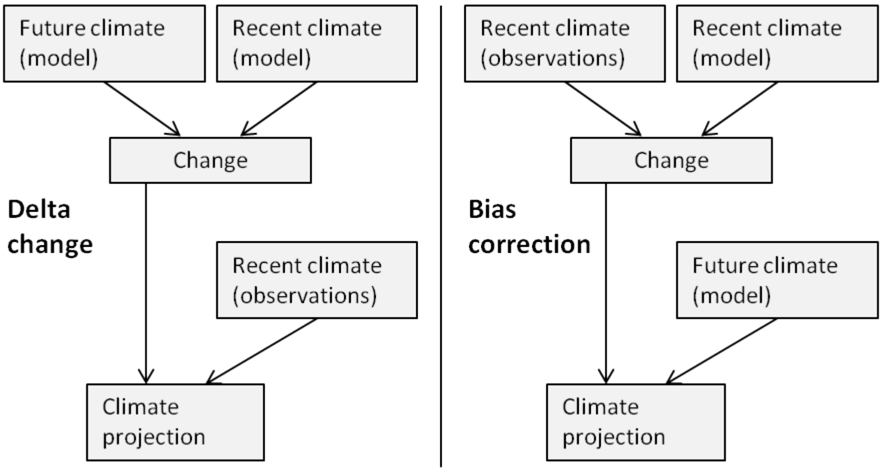

Figure 5.2 A schematic presentation of delta change and bias correction approaches (modified from Räty et al., 2014).

sophisticated approach is needed for other parameters, e.g. for precipitation extreme conditions that 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).

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. 5.3).

5.3.4 Bias adjustment of seasonal-to-decadal predictions

Seasonal-to-decadal predictions present a different problem as they are initialised from observations (section 3). 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. 5.4). 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.

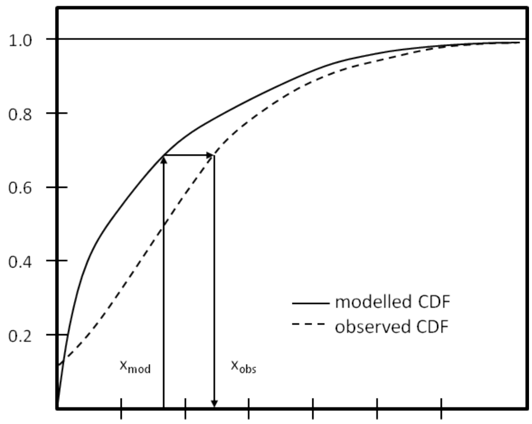

Figure 5.3 A simple presentation of a distribution mapping method (modified from Piani et al., 2010). The simulated value is replaced by the observed value corresponding to the same cumulative probability.

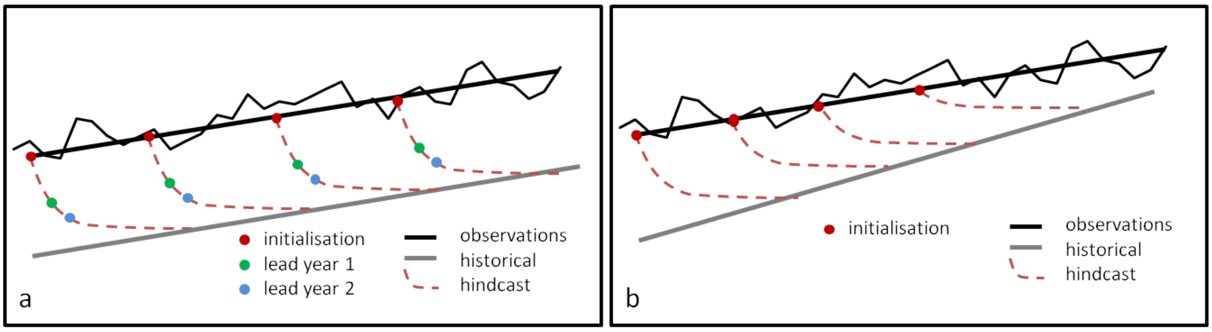

Figure 5.4 Illustration of the drifting of seasonal-to-decadal prediction for a) a consistent drift and b) a drift varying through time (modified from Grieger et al., 2016).

5.3.5 Multivariate correction

Bias correcting one variable at a time raises the question of the link between the different variables. Temperature and precipitation, for example, have been shown to be correlated (e.g. Trenberth & Shea 2005) and the application of a univariate correction might strongly degrade the physical relationship between the variables. 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 analogues 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.

5.3.6 Limitations and challenges

Bias adjustment methods have been widely used to correct simulated climate 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 being discussed (Ehret et al. 2012). The question of the choice of the bias correction method can for example be considered as an additional source of uncertainty (Haerter et al. 2011).

Despite these imperfections, the main statement from the IPCC AR5 group 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 therefore be applied with caution, and only with an understanding of how the adjustment relates to the bias causes.

Even when used cautiously, bias correction presents some unavoidable issues and limitations (IPCC, 2015), including the introduction of physical inconsistencies between corrected and non-corrected variables or the lack of improvement of the skill of the model.

5.4 Summary and conclusions

Climate models and ESMs are the main sources of climate data for use in assessing the potential impacts of climate change in impact science and via climate services. The output of models needs to be handled with care before being translated into services, whether it is for climate prediction or longer timescale climate projections. 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 result 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 now an integral part of pre-processing of climate simulations for use in impact modelling studies. A growing literature is 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 with the goal to develop and document methods and to make bias-adjusted simulations available on the Earth System Grid Federation (ESGF). It can be expected that future climate services will benefit from that effort.

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Linking science and society

6 European climate services research

6.1 Climate services and Earth System Models

Climate services involve the provision of climate information (observational, forecasts or projections) to climate-sensitive users to inform decisions. These services include data, information and knowledge that support adaptation, mitigation and Disaster Risk Management (DRM). Different definitions exist (e.g. WMO, WCSP, GFCS, ERA4CS, CSP, AMS, NRC, 2001; EU, 2015), but they all have some common elements: knowledge and information on climate processes and phenomena, derived from observations, models and theories, is transformed into customised products assisting climate adaptation and mitigation planning.

ESMs have multiple purposes and outputs: understanding processes and dynamics, consolidating knowledge, filtering signal from noise, and producing projections and "what if?" scenarios, including others. Climate services are based on more than just the output of models such as ESMs, and ESMs have more purposes than just providing climate services. But there is an important intersection, which we will explore in this section.

6.2. Types of climate services

The definitions of climate service types are very broad and frequently the terminology is also used to include weather services or climate research. Therefore, the use of the term climate services can be confusing for potential users (Vaughan & Dessai, 2014;

Capela Lourenco et al., 2015). Divisions can be made between those services that only provide data and information about the current and future climate versus those which include adaptation and mitigation options, or between those that provide support for decisions and implementation versus those that only support communication or monitoring. Climate adaptation services are mentioned explicitly in some literature (e.g. Goosen et al., 2013) and are in some ways better defined.

Similarly providers of climate services can play different roles: supply of data/information (for research and analysis), or providing the best strategy to achieve goals (Fig. 6.1); Mayer et al., 2004; Reinecke, 2015).

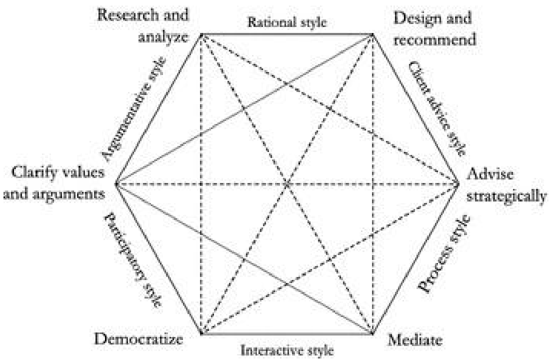

Figure 6.1 Overview of the six policy analysis styles (Mayer et al., 2004). The left side of the diagram refers to a role as information provider, whereas the right side climate service provides give actionable advice.

Also, climate services can be subdivided into general or tailored services. Generic services are made for broader target groups, and require no direct personal contact for their use (e.g. Skelton et al, 2016; C3S, CLIPC, Climate4impact; Climate-ADAPT). Tailored climate services are developed for – and frequently also together with – a specific user group (Hewitt et al., 2017). An interactive process is designed in which advice and guidance are combined with local specific information and decision rules, leading to a joint interpretation and use of the product. While many examples of generic climate services can be found that can be used free of charge by a wide community, tailored climate services are often developed in a specific (commercial) agreement between provider and user.

6.3 Relation between Earth System Models and climate services

One application of ESMs is the production of future climate scenarios and seasonal-decadal climate prediction. Confidence in using climate models for quantitative predictions and projections is growing (section 2 and 3). Many climate change impact and adaptation assessments rely directly or indirectly on information from ESM projections. Traditionally a "sequential approach" is followed, in which an information chain is depicted by placing the (time consuming) production of ESM projections in front, followed by some form of downscaling and impact or adaptation option assessment. This "top down" approach is challenged by the need to follow an iterative interaction between various disciplines in this chain, and by placing the user perspective at the beginning of this chain (e.g. Berkhout et al., 2014). This "bottom up" demand-driven approach requires a strong engagement between all experts and users, as presented in Fig. 6.2. More discussion about the use of ESMs for climate services is presented below.

6.4 Overview of initiatives and projects on climate services

Research and observational programmes that support user-oriented climate services have existed for more than a century (Vaughan & Dessai, 2014). User-oriented climate information or research also exists

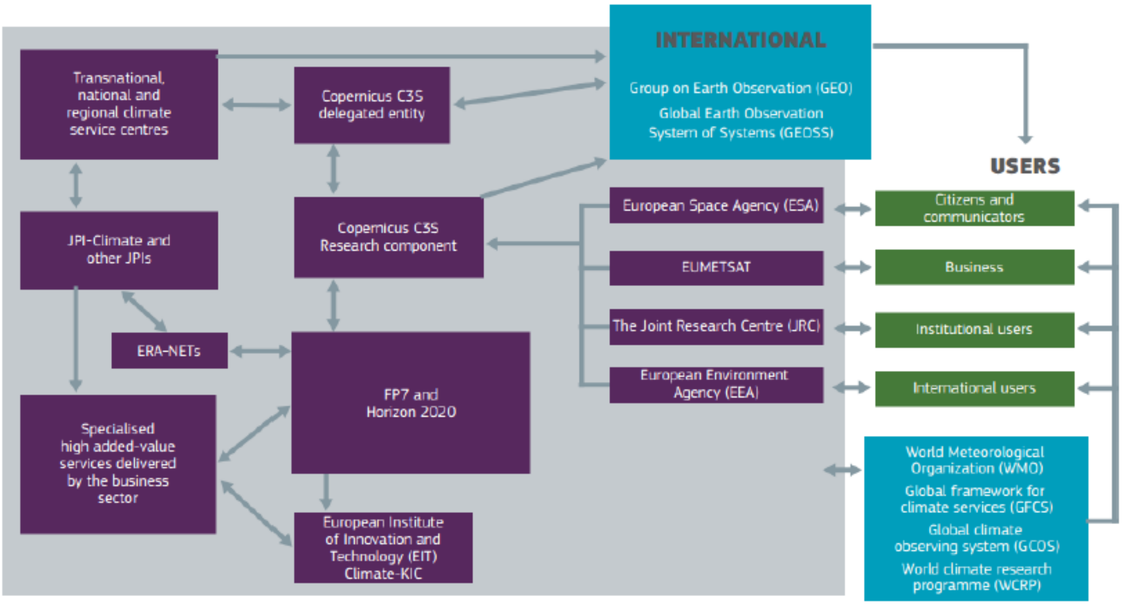

Figure 6.2 Relationships within the European Climate Services landscape (source: EU, 2005).

for a considerable time (e.g. climate normals, statistical analysis of extreme events, tailored climate research), but these activities started to be framed as climate services less than a few decades ago (NRC, 2001). With the notion of climate change, new requests came up and new methods were developed. Scientists, decision makers and other users of climate data realised that it was important to "evolve from the concept of useful information to the concept of usable information" (Lemos et al., 2012). Even when tight links were present between climate data providers and users, the context in which climate information is applied is not always well understood (Vaughan & Dessai, 2014). In the recent decade a stronger emphasis on user engagement - co-production - user-driven information is seen.

In the FP7 European Union's Research and Innovation funding programme for 2007-2013 climate services were explored in various projects (e.g. ECLISE, CLIMRUN, EUPORIAS, IMPACT2C), and in the Horizon 2020 research programme for 2014-2020 a stronger emphasis on climate services is seen (e.g. IMPREX, CIRCLE-2 ERA-net). In 2009 the Global Framework for Climate Services (GFCS) was endorsed by the World Meteorological Congress. 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), resulting in 2016 in the ERAnet for Climate Services (ERA4CS). 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). A summary of these initiatives is given in Fig. 6.2.

Climate services can be grouped into some different topical areas, such as: (1) *understanding the climate system* and improving/extending the available climate data for the past and future (climate science driven): e.g. ENSEMBLES (FP7), CORDEX, EURO4M, CMIP5/6, CRESCENDO, PRIMAVERA (H2020), sometimes including case studies for specific sectors; (2) *development of infrastructure* to get access to climate and impact data and information, visualisation and processing: e.g. IS-ENES2, most projects under C3S, IMPACT2C, ECA&D, and Climate-ADAPT; (3) climate change *impact/adaptation research*, including decision support (demand-driven, case-studies usually included): e.g. CIRCLE-2 ERA-net (FP7), ECLISE (FP7), CLIMRUN (FP7), ISIMIP, projects financed by specific sectors (e.g. national Road Authorities (CEDR): RIMAROCC, ROADAPT, EWENT, WATCH, INTACT), C3S SIS-projects, projects under ERA4CS; (4) *user requirements and market opportunities*: e.g. Climate-KIC, SECTEUR (C3S), MARCO (C3S), EU-MACS (C3S).

6.5 Overview of available data, portals, integration, portals of disciplines, quality, and climate service providers

6.5.1 Integration with other relevant data sets

Users of climate services often require information from 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). In addition the context, framing and communication can be very important (social sciences). Although providers from various disciplines regularly work together in common projects, the integration of the various disciplines is not optimal (e.g. von Storch, 2009; Capela Lourenco et al., 2015).

ESM projections usually contain information on geophysical phenomena, often limited to the meteorological or oceanographic domain. Translation of these quantities into impacts requires additional (physical) impact modelling, or assessments that include non-climatic drivers such as socio-economic developments or trends in user perception of severity or reliability of the information provided. Propagation of uncertainties needs to be documented across the whole chain of climate forcing, ESM response, (geophysical) impact and socio-economic consequences. High quality ESM datasets do not automatically result in high quality climate information.

Ongoing discussions are taking place about the documentation and definition of quality of climate services. Copernicus Climate Change Service (C3S) includes various projects devoted to the quality assessment of their products.

6.5.2 Available data

Ample climate data sets are available (observations, re-analysis, climate model runs), but an overview on the available data (including important attributes) is difficult to obtain (Goddard, 2016). Several overviews of available data exist (e.g. ECA&D, Climate Explorer, Climate4impact, CLIPC, C3S), but these usually don't include the guidance on quality or fit-for-purpose that is needed (Goddard, 2016). 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.

JPI-Climate produced the first 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. Although the response from the various European countries differs a lot, it is clear that there are considerable differences between countries in providers and provided climate services. Even the definition of climate services varied widely across the selected sample. The ERA4CS inventory relates these differences partially to the difference in mandates of the various (governmental) providers.

6.6 Communication on climate services

The organisation of the exchange of expertise across the climate service community is still a big challenge. Occasional examples and lessons learned are published in peer-reviewed journals, but a lot of experience is not readily exchanged via the standard peer review literature system. Climate services are often not seen as research, but as an implementation or practical extension of a scientific finding. Also the inter/multi-disciplinary nature of the subject does not help to define a clear communication platform where information is effectively shared between different disciplines. The journal “Climate Services” is currently the only journal that mentions climate services explicitly in its focus/objective.

However, scientific journals are not the only way to exchange information/experiences related to climate services. There are several platforms (websites, regular conferences, etc) where experiences are exchanged. This exchange of experience is less organised than in other sections of climate science (modelling, observations), although the introduction of the GFCS framework did boost the information.

7 Challenges for the integration of ESMs and climate services

7.1 Building useful Climate Services from ESMs

A number of basic challenges continue to exist in searching for the optimal cross-over between climate service production using ESMs and user uptake in the field: with respect to ESMs quality assessment, availability of information, need for service integration, portfolio (the right questions) and access to services.

There is also a need to address the provision of external sources of information in the face of the new challenges and emerging needs to better relate climate observations, Earth system modelling, infrastructure requirements and climate services. With the aim to address these aspects, a series of monthly webinars were organized under the framework of the Climateurope project. The webinars were successful in bringing together a range of international actors that contribute in various ways to the climate service community, including experts from national meteorological and hydrological services, research institutes and universities, private sector actors and intergovernmental organisations. The discussions with these experts are used in this section.

7.1.1 Rationale for applying ESMs for climate services

ESMs are not solely designed for generating climate services, and likewise many climate services rely on different (additional) sources of information than ESM results. Therefore a proper scoping of the contribution of ESMs to climate services is needed: for which climate services are ESM results useful, and what requirements can subsequently be formulated?

Many inventories on users' requirements have been generated in projects. Apart from differences between sectors and geographical domains, user requirements vary largely with application contexts, user perception and experience, and the impact of climate and climate change (Golding et al., 2017; Bley et al, 2017; Buontempo et al., 2014; Lemond et al., 2011). Despite the diversity of the use requirements, a stratification can be made between climate services that do rely on some form of ESM output and those that don't. Some climate services are built on highly aggregated (probabilistic or conditional) simulations of global mean temperature or sea level rise, while others need more detail on regional patterns of changing climate variables or weather types. A balance must be found between the requested level of complexity and detail and the complexity of the tools used to generate the climate service products. A useful indicator for the requested level of complexity is the experience of the climate service user with information about current climate characteristics. Hydropower dam operators or urban sewage design consultants with ample experience with datasets of current weather phenomena may have different expectations about future climate data sets than mitigation policy makers or ecosystem services developers. The level of aggregation, documentation, downscaling and quality assessment of the ESM information needs to be adjusted to the climate service application.

7.1.2 Quality assessment of ESMs used in climate services

Knowledge about the quality of ESM outputs is relevant for their application in climate services (e.g. SRIA JPI-Climate, EU 2015, Street 2016; Hewitt et al., 2012). "Quality" may refer to the degree to which the information is fit for which purpose, level of documentation on uncertainty and biases, and adjustment to other pieces of information.

Fit for purpose

A "one-size-fits-all" approach for climate services generally does not work. Even generic data available from e.g. the CMIP or CORDEX projections need to be post-processed or tailored to the specific application (JPI-Climate Workshop, 2015; Adaptation Futures workshop 2016). In the Sectoral Information System in the Copernicus Climate Change Service (C3S) many user-driven tailored applications are becoming available. User involvement in the definition of the service is needed to ensure that the data and the information provided is both user-relevant and user actionable. This includes elements such as timeliness, availability and clarity of the meta-information. An operational environment which maintains standards, provides reliable user support and assures timeliness of the delivery is crucial to service delivery (Brasseur & Gallardo, 2016).

7.2 Challenges and emerging needs in the field of climate services

Almost all of the challenges identified by the experts group related to communication between climate service providers and users.

7.2.1 Uncertainty and bias

Uncertainty, which is often related to a lack of quantitative reliability of individual ESMs, has been identified as one of the main barriers to the application of ESMs for climate services. As a result, there is a need to develop more reliable predictions through the improvement of climate models and tailored ways of application.

The quality of a climate service depends on the quality of the information provided. This is naturally linked to the compliance with specific standards and metadata structure, but also with the intrinsic attributes of the information itself: skill of the models used when compared to observations in the past, origin of uncertainty (model structure, natural variability, forcing), and comparison to other models. Appropriate metadata is a way to ensure full traceability of the information being provided, something that in turn can generate trust among users. However, metadata on skill metrics, model calibration or position relative to other ESM projections undergoing the same experimental design is not readily available in a standardized form, and needs to be extracted from specialized scientific literature or expert guidance.

7.2.2 Communication around uncertainty

When looking at climate service challenges, there is a general consensus that more effort needs to be put into translating research into services by means of enhancing the two-way communication between the climate science community and the users of climate information. Climate modellers need to be aware of the capabilities and limitations of the models they use so as to be able to communicate the intrinsic uncertainty to the users in a way that shows existing opportunities for climate services. Apart from demonstrating limitations, the scientific community should also emphasise those results for which they are confident, which will help in turn to increase user's confidence in the usefulness of the provided information.

This means that whereas climate service users should make their climate information needs explicit, climate service providers should be clear about the characteristics of the information they can offer. This bi-directional communication is what provides an added value to the development of climate services, especially in a context where there is a huge amount of information available, which can be very complex for users with limited climate expertise.

It is also important to make a distinction between weather events that can be attributed to climate change and those which are part of the natural variability of the climate system. In other words, event attribution should be made with caution and take into account all the knowledge available in the scientific field.

7.2.3 Answering the right questions

A recurrent question raised through discussions is whether scientists are choosing the right tools to answer specific questions. For instance, some climate services may need a larger range of scenarios than others, larger sets of regional projections or the application of a range of bias adjustment methods for users to be able to select the appropriate information that supports their decision-making. Projects like PRIMAVERA and CRESCENDO are addressing this type of analysis, comparing different experiments and selecting the most suitable outputs to approach each particular question. They feed large components of CMIP6, which will be the basis for the global simulations for the study of climate change used in forthcoming years. There is a lot of interest in the simulation and prediction of extreme events. These need to be addressed through different approaches that focus on new variables and ways to present the information provided by the models that is more relevant to the growing group of climate information users. The number of projects addressing extreme climate events, such as IMPREX, ENHANCE or ANYWHERE, will be elements to follow in the next years.

7.2.4 Managing expectations

User desires often do not match with what can be provided by the climate modelling and observations communities. In this sense, it is important to manage the expectations to avoid user's disappointment, while still emphasising the opportunities that climate modelling and climate services offer. Moreover, in spite of increasing requests for high-resolution data, particularly from climate simulations, this type of information is only useful if the user fully understands and knows how to use it and enough observations are available to make an appropriate model validation. European projects such as EUPORIAS or IMPREX or APPLICATE, which promoted co-production of climate services through the involvement of both climate modellers and users of climate information, have made good progress in this direction.

7.2.5 Sustained access to clear information

Experts also pointed at the barriers that exist within the research community itself. This is the case of the boundaries defined between general concepts such as weather, climate and climate change. Scientists should be aware that these boundaries do not exist for the users and that in many occasions omission of this classification would be preferred to avoid misunderstanding. This aligns with the idea of finding a common understanding between providers and users of climate information, which is a crucial part of the communication process.

To sustain the use of climate information based on the most trustworthy results produced by climate models, the information should be delivered on a fast and regular basis by means of tools that facilitate the usage of both data and associated metadata, and coming along with documentation and training material produced jointly by both modellers and practitioners. Initiatives such as the Copernicus Climate Change Service (C3S) can help in this regard. Other examples of initiatives for climate data delivery based on the efforts made by Earth system model developers are the Infrastructure for the European Network of Earth System Modelling (IS-ENES2), the Coordinated Regional Climate Downscaling Experiment (CORDEX), the Group of Earth Observations (GEO) or the European Climate Research Alliance (ECRA).

The state-of-the-art of science, in particular Earth system modelling, is developing very fast and often users find difficulties to adapt to the use of new emerging methods or types of simulations. Sometimes metadata is not clear enough nor is it homogeneous throughout the different datasets, a crucial aspect for eventually analysing inter-variability and traceability. Other times the documentation is not accessible to the users and requires the intervention of intermediaries that can help them to translate the jargon. Services like the C3S could play an important role in defining a standard for both data and metadata and in eliminating these barriers.

To date, many resources have been directed to the development of climate services with the underlying idea of building a market for them. However, at this moment many services are characterised by a lack of sustainability due to project ending and a lack of funding. The climate service community is therefore in need of good examples that can show how climate information and knowledge have been used to reduce damages and costs. The stronger interaction between climate service suppliers and decision-makers can foster a market for climate services, a topic which is being addressed by the European MARCO and EU-MACS projects.

8 Summary and conclusions

This first release of the Climateurope publication series takes the current state of the art of Earth system models (ESMs) and the tailoring of their outcomes to users' needs. The past decade has shown a strong development of climate change research and knowledge. At the same time, many research projects strengthened its user and stakeholder orientation, with increasing focus on providing actionable results. The "Roadmap on Climate Services" in Europe stresses a need for stronger links between providers and users of climate change knowledge and information.

ESMs are the very basis for knowledge and information about climate change, and thus for climate services. ESMs are able to perform long-term climate projections and can be used for climate policy-relevant calculations, such as the level of carbon dioxide emissions leading to a given climate warming target.

There is growing confidence in ESMs for quantitative future predictions and projections. Systematic evaluation of ESMs with observations and with each other has proven to increase their ability to describe climatic phenomena realistically. For example, for surface air temperature, sea surface temperature, and temperature trends, as well as for the seasonal cycle of Arctic sea ice extent there are high and very high confidence ratings, combined with high model performance.

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 models (e.g. increased resolution). With the potential of growing prediction skills, the user perspective is increasingly important. 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 users mostly. Along the same line, 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. Downscaling is a critical component and the basis for the development of such climate services.

EMSs are afflicted with biases, e.g. systematic deviations from observed conditions, when simulating past and recent climate. The climate modelling community is successfully reducing biases. However, impact research and climate services still need to correct for remaining biases, in order to increase the potential of climate models for usage in various applications.

The landscape of climate services is changing and currently further builds 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. 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. 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 publications are planned to update this first one and provide insight and progress on the integration of climate services and Earth-system modelling, and they are 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.

Finally, within Climateurope a series of Festivals are being organized to showcase climate services and Earth system modelling, to reflect on existing gaps, and to strengthen science-policy and science-user engagement to support the uptake and use of science-based services.

The first Festival took place in 2017 in Valencia, bringing together over 100 participants representing the scientific community, users and providers of climate services. Some insights relevant to ESMs and climate services from the first Festival were as follows. Firstly, improved modelling techniques, new observations and novel analysis methodologies are required for better understanding the impacts of climate change on the environment. Secondly, to obtain maximum value, climate information needs to be transformed into bespoke products, with information specific to the region and sector in which the user operates. Thirdly, there are some major challenges and opportunities for climate services providers, especially with regard to innovation. To enable the growth of a European market in climate services, they need to become SMARTER: Specific to user needs, Measurable, with Achievable goals, Relevant, Time-bound, regularly Evaluated, and Revised. Private sector initiatives on climate services are still sporadic but offer a big business opportunity.

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Glossary

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

- IPCC: The IPCC Data Distribution Centre (DDC; IPCC-DDC) has a glossary of terms compiled 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 CLIPC glossary but relevant to the present report were also defined based on the same sources and from:

- UK Climate Projections: List of definitions as created by experts and in use in the UK CLimate Projections
- US Meteorological society List of definitions created by the US Meteorological Society.

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)

Represent the departures of specific measurements 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. 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 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 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 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 main 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 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 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. 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 as 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 spec-trum 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 compre-hensive 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, 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 signal (AmMetSoc)

Variations in the state of the climate system that have an identifiable and statistically discernible structure in time and/or space. Often referred to as 'signal'

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 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.

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.

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, readjusting 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 (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., GHG, 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 Modelling, 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 (CLIPC)

Externally forced climate variations may be due to changes in natural forcing factors, such as solar irradiance or volcanic aerosols.

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.

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 (IPCC)

Effects on natural and human systems. In the WGII AR5 report, the term impacts is used 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.

Multi-modal ensemble (UK Climate Projections)

When a global climate model is run to provide a projection of future climate it produces a 'simulation'. Multiple simulations form an ensemble. A multi-model ensemble or MME, is a large number of climate model simulations created by using many different international climate models.

North Atlantic Oscillation, NAO (Climate4Impact)

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 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 (Climate4Impact)

A 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)

Also hindcasts. 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 (Climate4Impact)

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 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.

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