Progress on the integration of climate services and Earth system modelling

climateurope
Linking science and society

Publication Series

Vol.2

First published May, 2019
DOI: https://doi.org/10.17200/Climateurope.D6.8/1

Climateurope www.climateurope.eu

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Climateurope is a European Union Horizon 2020 Project funded under the programme SC5-05b-2015: Earth-system modelling and climate services under grant agreement No 68902.

This work should be cited as: Martins, H., Kjellström, E. and Terrado, M. (Eds.) (2019) European Earth System Modelling for Climate Services. 41 pp.

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Foreword

Dr. Chris Hewitt, Climateurope Coordinator

There continues to be a growing awareness among decision-makers of the relevance and importance of climate information to a range of social and economic issues. To attempt to better inform such decisions a market of climate services is emerging. Such services are based on climate data and scientific knowledge covering the past, present and possible future climates. A key component of the data and knowledge, particularly concerning the future climate, is derived from numerical models of the climate and the associated Earth system including physical, chemical and biological processes.

The European Commission is supporting Climateurope, a coordination and support action, under the Horizon 2020 framework programme to build an environment and range of activities around Earth system modelling and climate services. One activity is the release of a publication series to map and analyse relevant initiatives, challenges and emerging needs relating to Earth system modelling and climate services in Europe, involving expertise from a range of stakeholders. This publication series consists of three volumes. The first in 2017 focussed on the state-of-the-art of European Earth system modelling to explain and illustrate the abilities and limitations of Earth system models in relation to the potential for climate services. In this second document special attention is given to the best use of climate models and Earth system models to underpin climate services, including support for their interpretation to strengthen the science base of climate services. A final volume will be produced in 2020 about matching the new demands of climate services with evolving Earth system modelling capabilities.

The publication series is 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 second publication. In addition I would like to extend an invitation to anyone who would like to get involved with the growing European community addressing the challenges and opportunities arising from changes in our climate. If you are interested then please join the Climateurope network through https://www.climateurope.eu/contact/ .

1 Introduction

'Climate Services' can be defined as the transformation of climate-related data into customized products such as projections, forecasts, information, trends, economic analysis, assessments, counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society (EC 2015). Climate services should be based on scientifically credible information and expertise, and respond to user needs.

Climate services are created to help decision-makers make better informed decisions regarding existing or emerging climate-related risks and opportunities. Various climate change adaptation and mitigation measures are already being supported by services delivered to the public and private sectors (e.g. KNMI’14, Kjellström et al. 2016, UKCP18, CH2018). Existing climate service products are underpinned by climate observations, re-analyses and results derived from different types of climate models. Climate models together with their extensions, Earth System Models (ESMs) which introduce for example biogeochemical cycles, are the predominant source in the upstream part of the climate services value chain, providing the basis for information on the future climate. In recent years, the rapidly evolving landscape of climate services is becoming more salient to users, partly due to the improvement of different aspects of climate models and ESMs, such as the sea ice treatment, the increase of resolution or the consideration of an interactive chemistry. In turn, new requirements are being formulated by the climate services user community that the modelling community may need to take into account.

A continued and improved dialogue is needed between developers of climate models, designers of climate change experiments, producers of climate change scenarios and providers of climate services - those who generate services out of climate information. The current disconnection between these groups leads to a huge barrier that prevents the efficient flow of information between science and decision-making. Sources of disconnection include the lack of a common language across different disciplines and actors, or the challenges in dealing with uncertainty (Kiem and Austin 2013; Miller et al. 2008).

Despite their recent growth, the fast development and delivery of climate services is still a major challenge because of, among other things, the academic nature of many institutions providing climate services.

Although there is an emerging commercial or business-oriented market, large parts of climate service activities (designing climate change experiments, deriving forcing scenarios, setting up and running ESMs, post processing, publishing and analysing resulting data) are still not delivered through market transactions but through other types of activities based on tendered research grants, organized as project work, and hardly ever provided on an operational basis.

Some national meteorological and hydrological services are among the institutions with arguably the strongest knowledge of operational Earth system modelling and have been identified as one of the main climate services providers in Europe. However, there is a plethora of actors that are providing services. Among those, we find research institutes, national environment agencies, in-house collectors of data, research projects and consultancies (Bruno-Soares et al. 2018). Most of them lack the experience and understanding of Earth system modelling that might facilitate a constructive feedback process between climate modelling and climate services development.

Among a number of products oriented to the climate modelling and climate services communities, Climateurope is producing a publication series to map and analyse relevant initiatives, challenges and emerging needs relating to Earth system modelling and climate services in Europe. These initiatives involve expertise from a range of stakeholders. In this volume, the second of three in Climateurope's publication series, special attention is given to the best use of ESMs and climate models (both global and regional) underpin climate services, including the best possible support for their interpretation to strengthen the science-base of climate services.

Volume 1 of the publication series (Döscher et al. 2017) is revisited in section 2, which gives an overview of recent improvements and developments to enhance ESMs, including an update on the 6th Coupled Model Intercomparison Project (CMIP6), the evolution from seasonal to decadal operational climate prediction and the recent developments in the Coordinated Regional climate Downscaling EXperiment (CORDEX).

The challenges at the interface of Earth system modelling and climate services are described in section 3. These are related to uncertainties in model results, which affect the quality of climate information used for decision-making, the need for more geographically explicit and better represented local processes affecting climate, and the importance of taking into account the user's decision-making context.

Section 4 discusses the supply and demand of climate services as well as the barriers for the growth of a market for climate services. A summary of the most relevant climate modelling research, observations and climate services activities to date is provided. This overview fills an important gap in the literature and includes a stakeholder-friendly categorization of these activities.

Some sectorial success stories are presented in section 5, illustrating both the degree of integration reached so far, and the future direction of the joint development of ESM and climate services. The main conclusions are discussed in section 6.

2 Update on the state-of-the-art of Earth system modelling

Global and regional climate models (GCMs and RCMs), together with Earth System Models (ESMs) are key sources of climate data for many climate services. Following up on Volume 1 from the Climateurope publication series (Döscher et al. 2017), this section gives an overview of recent improvements and developments to enhance ESMs towards CMIP6, and the evolution from seasonal to decadal operational climate prediction. This section also covers recent developments regarding tools to interpret and constrain model results which include bias-adjustment techniques, advanced validation approaches, model selection strategies and regionalization for local usage. The potential of those methods is by far not fully exploited.

2.1 Earth system modelling development priorities from a climate services point-of-view

Climate models and climate service developers both aim at providing society with relevant information concerning the societal implications of climate variability and change. The scope of these two groups may vary, but there are a number of common requirements identified in a paper from Climateurope's research team (van den Hurk et al. 2018).

Climate services need to provide user-relevant region- and sector-specific information, as well as transparent guidance allowing the traceability to the ESM information and other information sources. Those requirements can be addressed by increasing resolution in space and time, and by enhanced focus in the delivery, setting of standards and quality assurance.

A continued dialogue between ESM developers and climate service providers is needed in order to provide more information than the climate state as input conditions for a risk assessment. Detailed knowledge on natural variability, interaction between climate variables and feedbacks between climate, mitigation consequences and socio-economic phenomena, may provide useful information across the entire chain between climate change projections and societal impact assessment, allowing the establishment of priorities for both development and provision. On the other hand, the experience of climate service providers with user uptake should guide the ESM development process. This process can inform climate service providers about the limitations and prospects of climate model outputs, and will inspire climate model developers and analysts to design creative experiments and output interrogation strategies.

2.2 Progress with Earth system modelling applications in CMIP6

Under the framework of CMIP6 (Coupled Model Intercomparison Project, phase 6) several Model Intercomparison Projects (MIPs) show a clear potential for utilization by climate services. Besides the obvious MIPs such as the ScenarioMIP, the Decadal Climate Prediction Project (DCPP) and CORDEX-MIP, other relevant MIPs including the Land Use MIP (LUMIP), the High Resolution MIP (HighResMIP) and the Carbon Dioxide Removal MIP (CDRMIP), provide elements for decision support for climate change mitigation options.

A key question in LUMIP is how and to what extent regional land-use or land- management strategies can best help to mitigate climate change (Lawrence et al. 2016). LUMIP focuses on biogeochemical and biophysical effects of extended use of land and of different levels of land management.

HigResMIP will apply a multi-model approach to the systematic investigation of the impact of enhanced horizontal resolution. With horizontal resolutions of up to 25 km, the global models within this MIP will enable study of global interactions, as well as local extreme processes.

Motivated by slow progress in mitigating emissions, CDRMIP will consist of experiments to understand the potential, impacts and challenges of carbon dioxide removal. Key topics are the response of atmospheric temperature and other climate variables to direct removal of CO_2 and other greenhouse gases from the atmosphere, the possibility to reverse a warmer climate to a more recent climate (i.e. an overshoot scenario), and the efficiency and impacts of afforestation, reforestation, and ocean alkalinisation.

Based on simulations undertaken within those MIPs, climate service applications will have the potential to support mitigation decisions by providing insights and data to illustrate alternative mitigation pathways.

2.3 Progress in the evaluation of climate models and ESMs

The climate modelling community is addressing the evaluation of climate models through community development of new evaluation tools. The leading new tool in Europe is the ESM eValuation Tool (ESMValTool) (Eyring et al. 2016). It is a routine benchmarking tool with diagnostics and performance metrics that provides a growing number of state-of-the-art analyses to be applied to single or multiple models, or to observational databases. The tool is targeted at CMIP output data, therefore developers plan to integrate the ESMValTool alongside the Earth System Grid Federation (ESGF) that stores CMIP model simulations.

The ESMValTool or similar tools represent an enhanced opportunity even for climate services to evaluate climate simulations with a standard, homogenized tool that could help, for example, to make objective choices for constraining simulation ensembles.

2.4 Operational climate prediction

Climate prediction aims at providing future climate information for time scales that range between three weeks and several years into the future (Doblas-Reyes et al., 2013). This includes forecast systems for subseasonal, seasonal and decadal prediction. Predictability at those time scales needs to consider that the climate system is highly multifaceted without a single controlling factor. Both ESMs and empirical-statistical methods are used for the task. Both approaches are continuously improved because forecasts are evaluated regularly against observations, highlighting the forecast systems weaknesses and strengths. The properties of empirical and ESM approaches are complementary and both could be used in the development of climate outlooks. Forecast systems based on ESMs benefit from the developments taking place in long-term climate change projections, which rely on a better understanding and representation of the most relevant physical processes. The combination of the different sources of climate predictions should use objective methods due to a number of advantages, such as traceability of forecast process, improved credibility for forecast provider, quantification of forecast skill, and the availability of underlying digital data being readily available and which can be used in application models.

Significant progress has been achieved under the Subseasonal-to-Seasonal (S2S) project, in particular in terms of improving the forecast quality and process understanding, and capitalizing on the expertise of the weather and climate research communities. Decadal predictions have been recently improved in many regions such as the North Atlantic, making it possible to improve predictions of Atlantic hurricane frequency averaged over several years (Caron et al. 2018).

Operational climate prediction has three facets: i) the operational infrastructure for climate prediction, which is made of global producing centres for long-range forecasting (GPC-LRF), lead centres (LC) for long-range forecasting multi-model ensemble, and lead centres for standardised verification system, ii) the delivery of regular predictions to satisfy the requirements of climate services formulated by the Global Framework for Climate Services (GFCS) and the Climate Services Information System (CSIS), and iii) research to support further advances, with several working groups sponsored by the World Climate and Weather Research Programmes (WCRP and WWRP). In this operational context, much more can be done to address some of the basic, persistent scientific questions raised at operational fora by tapping on established linkages between the operations and research communities.

2.5 Recent developments in the Coordinated Regional Climate Downscaling Experiment (CORDEX)

Regional downscaling is clearly adding value to the underlying global climate projections and, often in combination with bias correction, is a basis for downstream development of climate services. CORDEX is focusing on further improving regional climate modelling, related processes and information integration methods, such as fine-scale process-level changes in the climate system and robust assessment of regional change via the CORDEX Flagship Pilot Studies (FPS) and CORE (Coordinated Output for Regional Evaluations) simulations. The consistent set-up in CORE simulations (with defined global climate models to be all downscaled by a defined set of regional climate models) with 25 km resolution will serve as foundation for further downscaling and as a base for the next phase of CORDEX. The FPS looking at convective precipitation in the Alpine region, involving Regional Climate Models (RCMs) operated at grid resolutions of 2-3 km, addresses added value of convective-permitting models. Activities involving convective-permitting RCMs are also part of the current H2020 project European Climate Prediction System (EUCP, Hewitt and Lowe, 2018). Those efforts are expected to provide research and output for an improved quality base for downstream climate services.

The CORDEX scientific challenges have been updated towards more focused and user driven research areas that can benefit the most from the regional simulations: cities, wind energy, inland waters, small islands, organized convection systems and high mountain environments. These challenges are reflected in the ongoing and upcoming FPS.

2.6 Bias adjustment

Climate models are afflicted by important biases (systematic deviations from observed conditions) when simulating past and recent climate. As reported in Volume 1, the climate modelling community is successfully reducing these biases, but at the same time the impact research and climate services communities need to adapt the climate model outputs by correcting and constraining them in order to increase the potential for usage of climate models outputs. As bias adjustment also introduces uncertainty, a Bias Correction Intercomparison Project (BCIP) has been recently established (Nikulin et al. 2018). BCIP's analysis so far could not identify "the best" bias-adjustment method, although some methods were found to be better "balanced" across different statistics for the calibration and scenario periods. It was also concluded that the performance of different approaches depends not only on the bias adjustment methods but also on the input climate simulations (different kinds of biases) and the user requirements.

Taking into consideration all the points described in this chapter could lead to a common research and development agenda where Earth system modelling and climate services overlap. Societal relevance and due respect to the limited relevance of climate information when decoupled from a particular decision-making context with multiple inputs should be put central in this agenda and may enhance the accuracy and the saliency of the climate services developed.

3 Integration of Earth system modelling and climate services

ESMs provide the best available science-based information, particularly climate projections for the future, required to inform policy-makers on the importance and need for adaptation to a future climate, such as mentioned in the Paris Agreement of the United Nations Framework Convention on Climate Change (Jacob et al. 2018) and the new report from the Intergovernmental Panel on Climate Change report (IPCC 2018).

Several initiatives and programmes have interest in using climate services developed from climate model and ESM outputs. These initiatives are described in Volume 1 of the Climateurope publication series, and include the WMO programmes (GFCS and WCRP), the JPI Climate and associated ERA-NET for Climate Services (ERA4CS), the Copernicus Climate Change Service (C3S), the H2020 research programme, the Climate Services Partnership (CSP) and the Climate Knowledge Hub. Apart from these large scale initiatives, there is also a wealth of national and smaller scale projects that are even more effective in bridging the gap between science and end users. Examples are the recently released new Swiss climate scenarios (CH2018), the UK climate projections (UKCP18) or the climate change scenarios for the Netherlands (KNMI'14).

Another example of how the output from ESMs can be successfully integrated in the development of climate services is illustrated by Otto et al. (2016) who explore the chain that links the provision of data to the application of climate services. Throughout the chain, tailoring and traceability are needed to adapt the climate service to user needs and to have a transparent process. A bi-directional communication benefits both providers that can better understand user needs, and users, that can handle uncertainty with confidence.

Nevertheless, van den Hurk et al. (2018) discussed the challenges at the interface between ESMs and climate services. The challenges relate to aspects such as i) purpose of the model versus service development, ii) gaps between the spatial and temporal scales of models and the scales needed in applications, and iii) tailoring climate model results to real-world applications. Specific challenges, also identified in the climate services literature, relate to the evaluation and quality control of climate data and derived services, the communication of results and associated uncertainties, building trust, having a better overview of the climate information available, and making this climate information usable for climate services.

Thus for example, systematic comparison with the best observational datasets available could guide modellers to investigate the models' ability to reproduce climate variability and also guide users about the expected forecast quality. In the case of climate predictions, this is normally achieved through forecast verification, a process through which forecasts are compared against observations of what actually occurred or some good estimate of the true outcome (e.g. wind bulletins developed under the Spanish project RESILIENCE). Furthermore, Evaluation and Quality Control (EQC) has been established by C3S, with the aim to keep track of user requirements and inform about gaps, limitations and shortcomings in the delivery of climate services and products.

Although significant progress has been made in the last years to make climate information easily accessible for a wide range of users (e.g. Preuschmann et al. 2017, the Netherlands Climate Impact Atlas and the Met Office's Global Food Insecurity and Climate Change), many users still don't know where they can find the information they need or how they can get information in a format they can use. Sometimes, some users lack the appropriate background knowledge required to make an optimal use of this information. This constitutes an important drawback, which could be overcome by the development of training resources (e.g. the recently started C3S User Learning Services).

Society should be able to benefit from usable climate information to better adapt to the risks posed by climate variability and change. This is by no means a simple task, in part due to the multiplicity of end-users and diversity of decision-making situations (i.e. across sectors and spatio-temporal scales). Research is often fragmented and concentrated in sector-silos and therefore, an overall view of the use of climate information in multi-sector decision-making is noticeably absent (Bruno-Soares et al. 2018).

Despite the challenges mentioned, ESMs and climate services are integrated up to a certain point and do provide society with relevant and useful information. However, this integration can be further developed. Priorities for development include:

- The need for a further representation of the human system in ESMs and that Integrated Assessment Models (IAMs) become more geographically explicit in order to better represent local processes, such as water management and presence of renewable energy. This would allow better integration of the development agendas of the two modelling communities (Detlef van Vuuren in CarbonBrief 2018).
- Continue the development of climate models at the scale desired by decision-making. It is important that models will be able to simulate local characteristics, such as the climate in a city, in mountainous regions or along the coast (Daniela Jacob in Carbon Brief 2018). The major challenge would include the ability to trust climate models at finer and finer scales, which,

ultimately, is what people want to know (Chris Jones in Carbon Brief 2018). The successful increase of model resolution and trust in finer-scale data should be accompanied by a reduction of the bias of climate models (see section 2.6).

- Focus on capacity building and translation to climate services. The value of training and education for capacity development should not be underestimated and has not received the desired attention.
- Strengthening the dialog between ESM developers and both creators and providers of climate services, with key roles assigned to intermediaries with science communication background and knowledge brokers.
- Evaluating research beyond scientific impact. Quality control of the data or of the number and quality of publications might not be enough to guarantee the quality of transdisciplinary processes or resulting climate service products (e.g. data portal, prototype products, fact sheets). Academics need to be positively evaluated for cross-sector collaborations; it is important to identify special quality dimensions, criteria and indicators which are needed for an evaluation of transdisciplinary processes, such as climate services (Wolf et al. 2013).

Taking into account all good practices and challenges, van den Hurk et al. (2018) suggest the compilation of a coherent common research agenda for those areas where ESMs and climate services interact on initiatives that work already partly along these lines.

4 Climate modelling and observational products for the climate services needs

Weather and climate information, from historical observations through to seasonal climate forecasts, decadal climate predictions and multi-decadal climate change projections, is increasingly available. These advances continue to be driven by improved observation networks, data processing, climate models and computer resources. However, the uptake of this information amongst climate-sensitive sectors and how this information informs decision-making still needs to be improved.

4.1 Supply and demand

Climate services as a concept continue to be largely dominated by a supply-side perspective and research funding agencies, with services often framed from a standpoint of climate observations and modelling. Climate service providers do respond to societal needs by, for instance, focusing research on extremes or on good estimates of the climatology. However many argue that this will not allow the existence of a functioning widespread climate services market.

The public sector is the biggest provider of historical data and future climate projections; however it has a limited bandwidth to meet all the potential demand. Picking up on the example of what happened with some aspects of weather forecasting services such as, for example, private consultancies for media, farmers, utilities, shipping and air traffic, a considerable market is more likely to emerge with increased involvement from the private sector. It should be noted that even private weather forecasters rely on the provision of public data and services, with the sectoral division between private and public not always clear. A major difference though, is that weather forecasting is operational while most of the key elements underpinning climate services (climate model development, climate projections, etc.) is research-driven and not operational. EU-MACS project found signs that the stricter the separation between public and private domains, the more that product options might remain undeveloped.

The largest demand for climate services still comes from public and governmental organizations, often driven by regulations compelling them to fulfil government commitments. The private sector is potentially a large opportunity and includes many actors with very different needs. While some sectors are demanding long-term (end of the century and beyond) climate risks, others are concerned by shorter-term (subseasonal to decadal) regional changes. The expectation from the European Commission, as articulated in their Roadmap for Climate Services, is that the uptake by the private sector should be much larger than it currently is. To date the private sector consists of limited users of climate services, except in the case of a few “early adopters” and extremely "weather sensitive" such as the insurance and water sectors (Bruno-Soares and Dessai 2015). The private sector demand is typically framed as supporting their users in cost saving and reducing risks or avoiding damages. Companies tend to develop their in-house capabilities to access and use services with a general reluctance to pay for climate services externally without an apparent gain in productivity.

The further integration of climate adaptation and disaster risk reduction into regulatory requirements would be a natural source of demand for climate services and could also stimulate innovation and sources of competitive advantage. Particularly important will be the legislation on mandatory climate change adaptation planning by urban and regional authorities (and infrastructure organisations). At the same level, the financial sector could oblige their clients to report on climate risks of their assets and activities. Such an example can be found in the G20 Task Force on Climate-related Financial Disclosures (TCFD) whose core recommendation is that all companies should disclose climate-related financial information alongside their mainstream financial filings, and it has set out to advance global standardization of climate reporting.

To finance climate adaptation, a realignment of current investment is also needed. In particular, for developing countries there is an “adaptation gap”, defined as the difference between the needs for investment in climate change adaptation and the actual financing of these activities. To meet finance needs and avoid an adaptation gap, the total finance for adaptation in 2030 would have to be 9 to 19 times higher than current levels of international public adaptation finance (Oliver et al. 2018). The closing of this “adaptation gap” would spurn global demand for the climate services needed to underpin these investments.

4.2 Barriers

There are many barriers to market growth and to the development of a vibrant ecosystem of climate service suppliers and clients. Adaptation to climate change poses a challenge to society and requires a long-term approach and understanding of a scientifically complex problem.

The ensemble mean of CMIP projections per climate scenario has become a de facto standard starting point for the “best estimate” of key global climate variables, also thanks to the use in the IPCC reports. These “best estimates” however may have little relevance to decision makers operating at local or regional scales who frequently demand accurate and local scale information not resolved by global models. However, there is no one best way to provide more detailed regional information (dynamic or statistical downscaling) as it depends on each particular application as well as available data and resources. A framework for standardizing experimental protocols and output data from regional climate models has been put forward by CORDEX. This does not, however, include standardized model documentation and metrics to classify a dynamical or statistical model as fit for purpose. Other quality indicators could be extended to issues related to combined use of climate and non-climate data. Although difficult it would reflect a ‘fit for purpose’ label in the case of downstream (and some midstream) climate services.

The demand for an analysis of impacts and adaptation options increase the diversity of products and services. Users often demand very high spatial and/or temporal resolution. This is often at the limits of scientific understanding and in some cases technical capability. Whether the resolution demand is a real barrier or whether intelligent use of existing climate data could address the demand is not yet so clear. The actual barrier can also be the awareness of the existence of a specific climate service or the decision to actually take a service in the first place.

Climate services are evolving from simply improving access to ever more climate data to user-informed activities. In this context, they need to move towards a demand-driven and science-informed approach where dialog is needed to find out what users really need and what providers can offer. The client's business culture, condition and position in its own market are just as important in deciding the take up of climate services. However, collaboration and communication between users, service providers and scientists is time consuming. A separate specialist climate service community to that of climate researchers might be expected to grow to overcome these barriers.

The already mentioned creation of an “observatory for climate services” would be of great interest for all market participants and funding agencies.

4.3 Products

As modelling capabilities of the underpinning science of climate services improves, so too the potential applications of climate services increase. There is a large variety of projects, products and services available to help inform and address climate-related questions in Europe, partly because there is a large variety of users of project outputs, products and services, and partly because each user often has their own particular requirements. This chapter provides a few brief highlights from the wide array of European climate modelling, climate research, climate observations and climate service projects and some examples of the ways in which they link together. It is challenging to undertake a classification, since there are many potential ways of doing so. We have chosen to categorise the information according to Fig. 4.1: whether the products and/or services increase understanding of climate systems, or develop infrastructure, or contribute to climate adaptation research, whether they enhance the quality of climate data, or help our understanding of user requirements, or finally whether they help identify market opportunities.

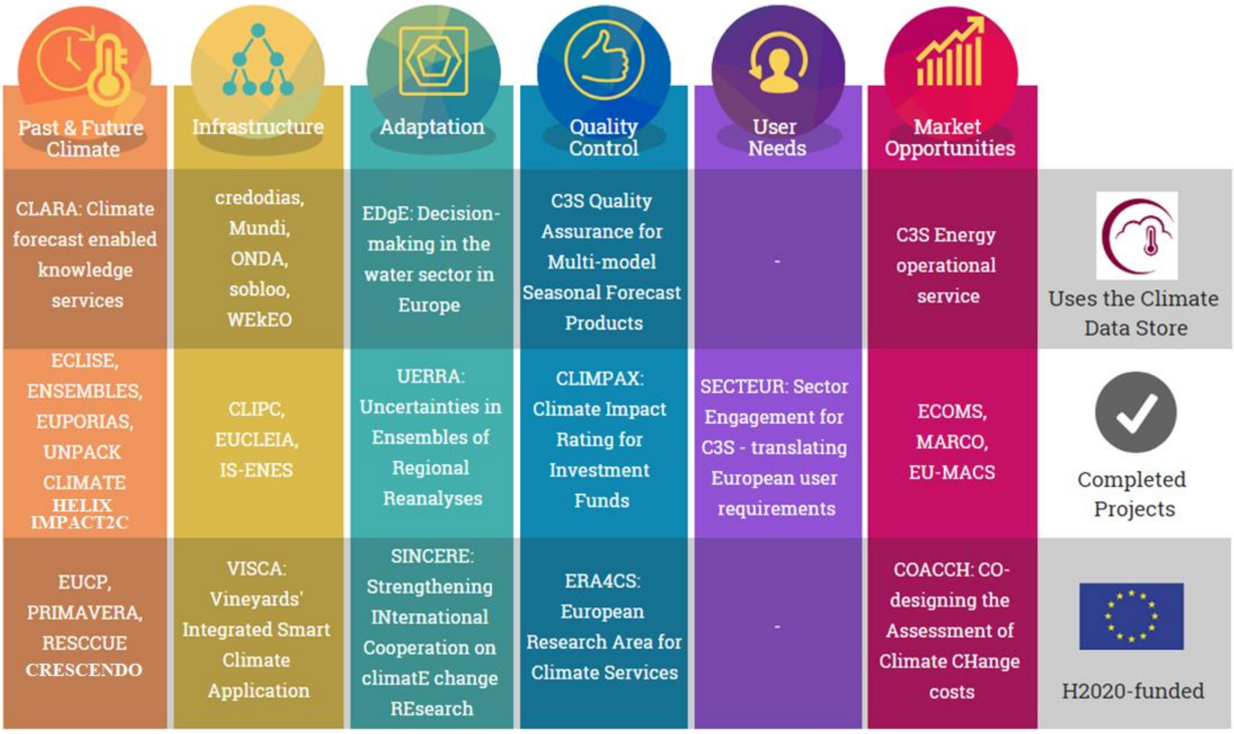
Successful operationalisation of climate services requires a holistic approach; therefore it is natural for climate service projects to include activities that span more than one of the categories listed. Therefore, the table in Fig. 4.2 that displays examples from the categories above is intended to highlight major themes rather than their sole objectives. In terms of the development of climate services, there is a balance to be struck between the principles of co-design/co-production with end users, and what could be argued as a more traditional top-down model (as seen in other service provision sectors) of provider-leading production. The EUropean MArket for Climate Services (EU-MACS) project aims to identify and explain obstacles to the uptake of climate services and suggest means to resolve these

Figure 4.1 An illustration of the six broad categories of climate services used within this report: Understanding the climate system and improve/ extend information for the **past and the future** with climate services component; Develop **infrastructure** to get access to climate and impact data and information, visualisation and processing; Climate **adaptation** research, including decision support; Evaluation and **quality control** of sources of climate information; Identifying **user needs**; Identifying of **market opportunities**.

obstacles. As part of a market analysis, EU-MACS has identified that the lack of a clear marketplace for climate services is a major obstacle to the growth of operational climate services. Given the great efforts underway to provide more freely available climate data (e.g. the C3S Climate Data Store (CDS), the OASIS HUB, the IRI/LDEO Climate Data Library, the KNMI Climate Explorer, the ECMWF data portal (DIAS), the C3S portal CLIPC, the IS-ENES2 Climate4Impact portal, etc.) access to specialist knowledge to interpret such data, and tailoring the data to specific needs, will perhaps be the value proposition of future climate services.

The project MArket Research for a Climate Services Observatory (MARCO) was a sister project to EU-MACS that assessed the size and composition of the untapped market for climate services and outlined market growth until 2030. MARCO recently completed a study indicating that there is increasing demand from previously unexplored user groups, e.g. legal sector. Climate services and products for the legal sector are likely to require attribution and integrated socio-economic climate change impact models (including counter –factual scenario modelling) – rigour, resolution and comparability were identified as the three highest ranking criteria for this sector. The wide reaching benefits to society of climate services have been made clear by previous projects that have explored a range of sectors including health (e.g. ClimApp), tourism (e.g. PROSNOW), transport (e.g. EWENT), agriculture (e.g. AgriCLASS), food security (e.g. CLARA), energy (e.g. CLIM4ENERGY), to name but a few.

Improvements in resolution capability of global climate models are being explored in the H2020 project PRIMAVERA, which is producing historic and future simulations between 1950-2050 using mesh sizes up to ~25 km with 7 different models, working alongside CMIP6 HighResMIP. Such resolutions are generally better able to represent climate extremes such as wind storms and tropical cyclones. The CRESCENDO project also facilitates a coordinated European contribution to CMIP6, bringing together 7 European Earth System Modelling teams and 3 European Integrated Assessment Modelling groups. CRESCENDO will particularly inform a number of key MIPs where aerosol and biogeochemical components are critical (e.g. terrestrial and marine carbon cycle) to provide future projections that are as realistic as possible. Another notable development in terms of climate projections is the previously mentioned UK Climate Projections 2018 (UKCP18) project, which provides information for the UK Government’s third Climate Change Risk Assessment on how the climate of the UK may change over the rest of this century, using representative concentration pathways from the most recent IPCC report.



Past & Future Climate	Infrastructure	Adaptation	Quality Control	User Needs	Market Opportunities	
CLARA: Climate forecast enabled knowledge services	credodias, Mundi, ONDA, sobloo, WEkEO	EDgE: Decision-making in the water sector in Europe	C3S Quality Assurance for Multi-model Seasonal Forecast Products	-	C3S Energy operational service	Uses the Climate Data Store
ECLISE, ENSEMBLES, EUPORIAS, UNPACK CLIMATE HELIX IMPACT2C	CLIPC, EUCLEIA, IS-ENES	UERRA: Uncertainties in Ensembles of Regional Reanalyses	CLIMPAX: Climate Impact Rating for Investment Funds	SECTEUR: Sector Engagement for C3S - translating European user requirements	ECOMS, MARCO, EU-MACS	Completed Projects
EUCP, PRIMAVERA, RESCCUE CRESCENDO	VISCA: Vineyards' Integrated Smart Climate Application	SINCERE: Strengthening INternational Cooperation on climatE change REsearch	ERA4CS: European Research Area for Climate Services	-	COACCH: CO-designing the Assessment of Climate CHange costs	H2020-funded

Figure 4.2 Selection of climate services projects past and present, arranged by the categories outlined in Fig. 4.1 and sorted by funding stream and data use.

Climate projections, monitoring and forecasting (e.g. seasonal forecasting) have long been established components of climate services, and this is expected to continue to be the case in the coming years. In addition to these core components, the research underpinning climate services is also seeing development and growth into the arena of attribution. Until recent years, the concept of operationalising attribution of extreme weather events to anthropogenic climate change has been met with some degree of scepticism within the climate services community. However, C3S has a commitment to include operational attribution from the year 2020, and there is a growing number of scientific papers every year addressing the issue, many of them collected in the annually recurring BAMS special issue on extreme events of the preceding year. As the field matures, there is a gradual move away from pre-operational climate service projects towards their operationalisation. An example of this transition is nicely illustrated by the success story of the Project Ukko prototype, directed to the wind energy sector, and developed under the FP7 EUPORIAS project. It was a pre-operational service and was improved with the addition of user's feedback during the evolution of the C3S CLIM4ENERGY contract (finished in 2018). At present, the prototype continues to evolve under the H2020 project S2S4E, where it will go from pre-operational to fully-operational for different types of renewable energies (wind, solar, hydropower) and time scales (subseasonal and seasonal).

In advance of the operational phase of the C3S, the Copernicus Roadmap for European Climate Projections project worked towards guiding requirements and resource allocations, drawing upon climate research and modelling activities, and several precursor pre-operational FP7 and H2020 climate service projects. There has been significant work to assess user needs, such as in the Sector

Engagement for Copernicus Climate Change Service; Translating European User Requirements (SECTEUR) project, which conducted a gap and market analysis to help understand the economic potential of weather and climate information. This underpinning work has helped to pave the way for 7 proof-of- concept C3S contracts that were commissioned in 2016 to ensure that C3S meets the needs of users in different sectors (e.g. water, energy, insurance, agriculture, infrastructure and health care).

There are other common links between operational projects and previous pre-operational projects, such as the common consortium members shared between the H2020 project 'Provision of a prediction system allowing for management and optimization of snow in Alpine ski resorts' (PROSNOW) and the C3S European Tourism project. The newer C3S projects will draw upon data made available in the CDS, which advertises itself as a free-to-access "one-stop-shop" for climate data, and also provides access to a toolbox for users to develop custom applications. In addition to the free-to-access CDS, commercial platforms have also been launched to enable users to access climate data and tools. The Copernicus Data and Information Storage Access Services (DIAS) provides a cloud-based 'one-stop-shop' for all of the Copernicus data (including Sentinels satellite data and the Core Services) via 5 newly launched platforms: creodias, Mundi, ONDA, sobloo, WEkEO. The concept of DIAS is similar to the CDS but with key differences: there is a mix of centralised and decentralised data that is stored and accessed via the cloud; virtual environments are provided for users to create their own services. Four of the five platforms are run for profit by private companies, which when considered alongside Climate-KIC/InsuranceH2020 OASIS HUB and OASIS + show an emerging trend for climate service platforms, data and tools to be provided at a cost to general users.

A major issue with short-term proof-of-concept projects is longevity and legacy after the projects have completed. It is challenging for governments and policy makers who want to make long-term plans to seek out and engage with short-term projects, especially when such projects have not been able to maintain their websites to direct interested parties to current activities in the area, let alone be operationalised. This activity would be made simpler if agreement could be reached on a standardised classification for each project, product and/or service. This would also promote better matching of user needs with the most appropriate of the diverse range of available services and products. The creation of an "observatory for climate services" to characterize and monitor the supply and demand across Europe could be of great benefit to address the problem with lack of longevity of ongoing activities.

5 Success stories

This chapter aims to present a short but significant list of examples of how the outcomes from RCMs, GCMs and ESMs have been integrated in the development of climate services in Europe. These are stories involving prestigious leading companies in the agriculture and food sectors, in the management of water resources, metallurgy, and transport. The stories, coming from a wide range of sectors, illustrate how through the application of climate services business companies, research organizations, and public bodies have found opportunities to make their production more efficient, to anticipate, address and manage risk, and to improve the sustainability of their decision-making activities without adversely affecting the quality of the products and services offered.

5.1 Climate and wine: SOGRAPE

Wine producers are increasingly concerned with the impact of changing climatic conditions on vineyard production. These changes can profoundly influence the characteristics of wine in specific regions as the taste and structure of a wine can be heavily influenced by heatwaves, droughts, heavy precipitations, and pests and diseases whose onset can be connected to climatic factors. At the same time, climatic conditions affect the work and productivity, and therefore, the profit of a wine company.

Sogrape Vinhos, a wine company based in Porto (Portugal), decided to use information from climate to help plan future production and prevent risk situations. A network of 20 weather stations was installed in Sogrape Vinhos' vineyards. In collaboration with the Royal Dutch Meteorological Institute (KNMI), the European Centre (ECMWF) and the International Research Institute on Climate of Columbia University, the data collected was used to support climate monitoring and drift, and seasonal and longer-term forecasts (3-5 years) were produced using GCMs. The information obtained made it possible to optimize the activities and the resources of the company, such as planning the management of plant protection products. Some of these products, such as sulphur, burn the leaves and grape berries if sprayed when the temperature exceeds 28 °C (Photiadou et al. 2017).

5.2 Climate and hazelnuts: Ferrero

Ferrero, an Italian confectionery company, is investigating possible new areas suitable for hazelnut cultivation using climate projections and sub-seasonal climate predictions over the medium and longer term.

In collaboration with Ferrero, the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) is delivering climate projections from CORDEX Australasia, data and information on how climate variability could affect hazelnut production in the near future (2020-2040) in a particular region in South-East Australia. At the same time, data from climate models are used as input for a crop suitability model (Figure 6.1), considering different agro-climate factors during the most critical phenological phases for production (Bregaglio et al. 2016). This helps understand the potential of land for cultivation, both under current and future different climate scenarios (Baldwin 2015).

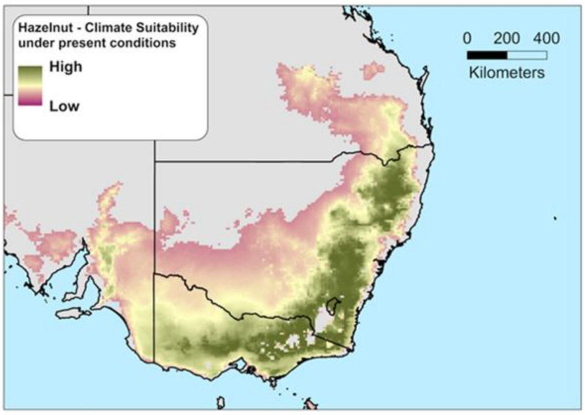


Figure 6.1 Climate suitability for hazelnut under current climate conditions in South-East Australia.

The climate service developed by CMCC is based on the probabilistic forecast of spring frosts. Researchers developed a cold spell power index that allows the release of reliable forecasts of cold spells/frosts every 15 days, from mid-February to the beginning of April, coinciding with the most sensitive period for hazelnut production. These can be used by Ferrero to coordinate extraordinary activities necessary to protect the plants from frost, and also to take decisions on the best time to purchase hazelnuts.

5.3 Climate and transport: ENHANCE

The Austrian Alps host a beautiful landscape of mountains, valleys and rivers, ideal for outdoor activities. Given its central position in Europe, the Austrian railway network plays a key role for the transportation of passengers and freight, with growing economic perspectives. However, torrents, mudflows, rock falls, avalanches and floods lead to regular disruptions of railway tracks, causing large economic losses and temporary closures of line sections, as railway tracks and bridges can be washed away or severely damaged (Kellerman et al. 2015).

‘Building railway transport resilience to alpine hazards’ was one of the ten cases of the 4-year ENHANCE project funded by the European Union. To this end, ENHANCE partners together with the Austrian Railway Infrastructure AG defined risk reduction strategies with different levels for both structural (e.g. technical measures) and non-structural measures (e.g. monitoring and early warning systems). To support strategic risk management in terms of structural measures, a flood damage model was developed specifically for railway infrastructure (Kellerman et al. 2016a). Moreover, the influence of climate change on the frequency of hydro-meteorological extremes that potentially affect railway operation on a larger scale was assessed in the project using modelling data produced in the EU-project ENSEMBLES.

By analysing existing processes and combining them with new risk projections, ENHANCE provided a robust framework to secure current and future resilience in the Alpine railway lines.

5.4 Climate, water and metallurgy: SWICCA

The production cycle of the metallurgy industry needs a significant availability of water. In Greece, to meet this need, the companies of the Halcor and Elval groups rely on the Evinos and Mornos river basins which, together, are also the primary resource supplying the water-works of the capital Athens. Water used for irrigation and other industrial activities is also taken from the same basin, while the metallurgy companies pour out their effluent into the Asopos River.

The metallurgy sector is interested in knowing how climate change will affect the availability and management of water resources in the future. They need to know if it will be necessary to turn to other river basins and also if they need to focus on new and more effective effluent treatment systems. In this scope, the Service for Water Indicators in Climate Change Adaptation (SWICCA), a service created within the C3S and run by the Swedish Meteorological and Hydrological Institute was used to provide data and assistance for the assessment of climate impacts in the water sector. Activities included the identification of climate indicators, the use of data and analysis related to the area of interest, meetings with company personnel to discuss the climate and hydrological simulations and understand how they can inform the decision-making process on future investments.

This process showed how having climate information available makes it easier for the company to understand the effects of climate change on the river's hydrology and water quality. This improves the company's ability to design and plan adaptation strategies for its production chain and to direct future investments towards resilient and sustainable paths.

6 Summary and conclusions

Climate and Earth system models are a substantial part of the value chain for climate services. This second volume of Climateurope's publication series identifies a set of priorities for the integration of ESMs and climate services: i) to better understand the cascade of uncertainties between both, ii) the need to provide region and sector specific information through downscaling and bias-adjustment techniques, iii) the development of new evaluation tools for climate simulations that could motivate choices from the climate services point of view, and iv) the strengthening of a continuous dialogue between ESM developers and climate services users. Taking those points into consideration can certainly lead to a common research and development agenda allowing the overlapping of ESMs and climate services.

Challenges identified at the interface of ESM and climate services mainly deal with the difference between what the models can provide and what the users need for their applications. Specific issues are spatial and temporal scales, uncertainties, evaluation and continued access to reliable and easy to understand information, among others. There is a need for an integration of time scales in a seamless way, linking observations, forecasts, predictions and projections. Despite the mentioned challenges, ESM and climate services have been already integrated up to a certain point and do provide society with relevant and useful information.

Climate services have been largely dominated by a supply-side science-driven perspective, since the key elements underpinning them (climate model developments and simulations) are research driven and not operational. Boundaries exist between the roles of public, private and academic sectors in the provision of climate services, which make a market for climate services difficult to establish given the lack of interactions across these sectors and the low willingness to pay for these services.

Making climate services affordable for countries in transition is an important task, supported by initiatives such as the Global Framework for Climate Services. Apart from adaptation gaps, geographical gaps have also been identified for climate services, with central and Eastern European countries presenting less or not as mature climate services activities. Mapping climate products and services is not an easy task since it requires the knowledge of who the providers and users of this information are. In addition, the roles of users and producers of climate information are not something fixed; users are often providers of climate services to another community.

Previous projects on climate service development have shown the benefits of climate services for different socio-economic sectors (e.g. renewable energy, agriculture, water management, insurance, health). This has favoured the recent increasing demand for other sectors that have not previously been the object of climate services research. Furthermore, requests for climate services are increasing fast, so flexibility is key in this regard.

Great efforts are made nowadays to provide freely available climate services. To achieve this, the new C3S projects will draw upon data made available in the CDS, a free-to-access point for climate data (both from observations and from GCMs/ESMs) that also provides access to a toolbox to develop custom applications. Apart from giving access to data, Copernicus is working on improving the use of available observations, identified as a need by users from many sectors. With all this information at hand, the added value of climate services emerges from the combination of specialist knowledge and data particularly tailored to specific user needs. Most end users will not access climate data and information services directly themselves, but rather via intermediate organisations. At the same time, obtaining raw climate model outputs or observations is not attractive and useful to many users if it cannot be combined with additional information, such as economic benefits. A separate specialist climate service community (so-called knowledge brokers or intermediaries) is expected to grow to overcome existing barriers to the uptake of climate information and services and to make them more salient to users. This will facilitate a transformation from science-driven to demand-driven and science-supported services.

There is a lack of overview of climate information and services available today as well as their status within the framework of a European market. Climateurope aims to provide more overview and to be the main contact point for stakeholders interested in finding the main climate modelling, climate research, climate observations and climate services projects and where to access them.

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https://www.copernicus.eu/projects/agriclass

BAMS special issue on extreme events
https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/

CDRMIP
https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1302-modelling-cmip6-cdrrmip

CDS
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CH2018
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CLARA
http://www.clara-project.eu/

ClimApp
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Climate Impact Atlas

http://www.klimaateffectatlas.nl/en/

Climate4impact
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CLIM4ENERGY
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CLIPC
http://www.clipc.eu/

CMIP6
https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6

CORDEX
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CORE
http://www.cordex.org/experiment-guidelines/cordex-core/

CREODIAS
https://creodias.eu/

CRESCENDO
https://www.crescendo-h2020.eu/

C3S User Learning Services
https://climate.copernicus.eu/user-learning-services

C3S European Tourism project
https://climate.copernicus.eu/european-tourism

DIAS
https://www.copernicus.eu/en/access-data/dias

DCPP
https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1065-modelling-cmip6-dcpp

EFAS
https://www.efas.eu/

EUCP
https://www.eucp-project.eu/

EU-MACS
http://eu-macs.eu/eu-macs/

EWENT
http://ewent.vtt.fi/

Flagship Pilot Studies
http://www.cordex.org/endorsed-flagship-pilot-studies/

Global Food Insecurity and Climate Change
https://www.metoffice.gov.uk/food-insecurity-index/

HigResMIP
https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1068-modelling-cmip6-highresmip

IRI/LDEO Climate Data Library
http://iridl.ldeo.columbia.edu/index.html?Set-Language=en

KNMI'14
http://www.climatescenarios.nl/

KNMI Climate Explorer
https://climexp.knmi.nl/start.cgi

LUMIP
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MARCO
http://marco-h2020.eu/

MARS - Monitoring Agricultural ResourceS
https://ec.europa.eu/jrc/en/mars

OASIS HUB
https://oasishub.co/about/about-the-oasis-hub/

PRIMAVERA
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ScenarioMIP
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SECTEUR
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SOBLOO
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S2S
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Ukko

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Volume 1

https://www.climateurope.eu/european-earth-system-modelling-for-climate-services/

water transportation by BfG

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Wind bulletins

https://ess.bsc.es/information/wind-bulletins

WEkEO

https://www.wekeo.eu/

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.

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.

Bias (Climate4Impact)

The differences 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.

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 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 comprehensive representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, and for operational purposes, including monthly, seasonal, and inter-annual climate predictions.

Climate model simulations (Climate4Impact)

These are numerical solutions of sets of equations that represent the most relevant processes describing the climate system. Climate models can be of very different levels of complexity but the most elaborated ones appear to be able to realistically reproduce the key meteorological and climatological phenomena.

Climate Prediction (IPCC)

A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or decadal 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 change scenario (IPCC)

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate.

Climate services (Climate4Impact)

Climate services involve the production, translation, transfer, and use of climate knowledge and information for decision making, policy and planning. The provision of climate information (observational, forecasts or projections) in a way that is relevant to climate-sensitive users, can inform decisions and can reduce the risk of misinterpretation.

Climate System (IPCC)

Highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.

Climate variability (Climate4Impact)

Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)

Climatology (Climate4Impact)

Can be defined as the science of climate, but is also used in the meaning of the normal state such as a base line over the normal period. Climatology is often taken as the mean value for a given month over, for example, 1961-1990.

CMIP

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.

CORDEX

Coordinated Regional Climate Downscaling Experiment

CSP

Climate Services Partnership

C3S

Copernicus Climate Change Service

C3S-CDS

Copernicus Climate Change Service - Climate Data Store. Contains a wealth of information about the Earth's past, present and future climate. It is freely available and functions as a one-stop shop to explore climate data.

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 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.

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.

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.

ESGF

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

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).

EU-MACS

As follow-up of the European Research and Innovation Roadmap for Climate Services for Climate Services, the European Commission (EC) promoted a comprehensive analysis and evaluation of the market potential of climate services. The project EU-MACS (EUropean MArket for Climate Services) has been a part of these efforts. In this framing, EU-MACS analysed market structures and drivers, obstacles and opportunities from scientific, technical, legal, ethical, governance and socioeconomic vantage points. This resulted inter alia in overall and sector specific analysis and ranking of drivers and barriers of innovation and uptake of climate services, as well as in identified ways to incentivise demand for and supply of market solutions matching users' knowledge needs. The analysis is grounded in economic and social science embedded innovation theories on how service markets with public and private features can develop, and how innovations may succeed.

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).

GFCS

Global Framework for Climate Services

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).

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

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.

IRI/LDEO Climate Data Library

A freely accessible online data repository and analysis tool that allows a user to view, analyze, and download hundreds of terabytes of climate-related data through a standard web browser.

IS-ENES

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.

KNMI Climate Explorer

A research tool to investigate the climate which collects a lot of climate data and analysis tools.

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.

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.

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.

OASIS HUB

Oasis HUB is an initiative formed to increase the availability of information on catastrophe and climate change risk and to assist the development of evidence-based climate adaptation planning.

MARCO

MArket Research for a Climate Services Observatory is a H2020 project that gathers market research firms, climate scientists, climate services practitioners and innovation actors to provide detailed insight into the climate services market in Europe. The project will carry out case studies, forecast future user needs, assess market growth until 2030, unveil opportunities, raise awareness and connect service providers and users.

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.

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.

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.

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.

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.

Skill (Climate4Impact)

Measures how well the model simulation represents the observations. 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.

Uncertainty (IPCC)

A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).

WCRP

World Climate Research Programme

WGCM

Working Group on Coupled Modelling

WMO

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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