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Linking science and society

CLIMATE MODELLING & CLIMATE SERVICES

Recommendations to Horizon Europe on research needs for Climate Modelling and Climate Services

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Institutions acronyms:

BSC	Barcelona Supercomputing Center (ES)
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici (IT)
CNRS/IPSL	Centre national de la recherche scientifique – Institut Pierre Simon Laplace (FR)
DMI	Danish Meteorological Institute (DK)
DTU	Danish Technical University (DK)
ECMWF	European Centre for Medium-Range Weather Forecasts (INT)
FMI	Finnish Meteorological Institute (FI)
HZG-GERICS	Helmholtz-Zentrum Geesthacht – Climate Service Center Germany
IPSL-LSCE	Institut Pierre Simon Laplace – Laboratoire de Sciences du Climat et de l'Environnement (FR)
IPSL-LMD	Institut Pierre Simon Laplace – Laboratoire de Météorologie Dynamique (FR)
KNMI	Koninklijk Nederlands Meteorologisch Instituut (NL)
Climate-KIC	Climate – Knowledge and Innovation Community
NCAS	National Centre for Atmospheric Science (UK)
RHMSS	Republic Hydrometeorological Service of Serbia (SR)
SMHI	Swedish Meteorological and Hydrological Institute (SE)
UEA	University of East Anglia (UK)
VITO	Vlaamse Instelling voor Technologisch Onderzoek (BE)
WEMC	The World Energy & Meteorology Council

Executive summary

This paper presents recommendations for the next Horizon Europe framework program for the cluster related to "Climate science and solutions". It emphasizes how research and innovation activities in the fields of climate modelling and climate services can contribute to improving climate knowledge and information to users in order to enhance the European capacity to transition to a sustainable and resilient society. Climate models are extensively used to provide a better understanding of key processes underlying climate change on a range of timescales from months to decades, and to investigate and describe possible future climates. This information serves as a scientific basis for climate services that aim to provide tailored information to decision and policy-makers. Climate models and climate services are crucial elements for supporting the policy on mitigation and adaptation to climate change and for building a society more resilient to climate-related risks. Recommendations have been elaborated within the Climateurope H2020 coordination and support action with an expert group and are summarized below.

1. Supporting the IPCC process

The Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) are crucial to support international policy on climate change. Information on possible future climate is extensively based on simulations using climate models coordinated internationally by the World Climate Research Programme (WCRP). The European Commission (EC) plays a key role in supporting the European contribution to this research. This support will be essential in sustaining European cooperation toward the next cycle of the WCRP experiments, in allowing the timely preparation of the relative simulation protocols and in addressing knowledge gaps identified in the IPCC Assessment Reports.

2. Informing climate mitigation policy: scenarios with risk of overshoot

Climate model projections of possible future climate change are essential to assess plausible routes to realizing key policy goals, such as the Paris Agreement, and to investigate the consequences of exceeding such targets. Even though many countries signed the Paris Agreement, the risk of reaching global warming greater than 1.5 or 2°C, at least temporarily before returning below the target, remains high. Further research is needed to enhance the level of process realism and the representation of uncertainties in models and developing a larger range of likely and feasible overshoot scenarios. This will be essential to assess and inform on the risks of overshooting 1.5 or 2°C and associated impacts as well as to understand the interference of possible abrupt events and the impacts of aggressive mitigation actions.

3. Enhancing adaptation and resilience to extremes

Despite improved understanding of extreme events including general agreement that different types of extremes, such as heat waves and heavy precipitation are expected to increase in frequency and intensity in a warming climate, further research is needed to address the remaining large uncertainties with regard to regional patterns and magnitude of changes. For other extremes, such as wind storms, even the signal of future change should be investigated in many regions including the North Atlantic and the European region. It is foreseen that very high spatial resolution climate models at the km scale can contribute to a breakthrough in representing extreme events.

4. Supporting the formulation of adaptation strategies

Adaptation strategies need tailored information on climate and impacts at local scale and, for most users, ranging over time scales from seasons, years to decades up to centuries under different emission scenarios. Climate models provide essential information on climate, which however, needs to be tailored to provide adequate information to assess local impacts. To suit the expectations of most users in terms of systematic availability of impact-oriented projections and up-to-date near-term predictions downscaled to local scale, process understanding, models and infrastructure, and downscaling need continuous support. In addition, guidance is needed for selection, aggregation, and use of the local climate information.

5. Understanding requirements, decision-making context and foresight for climate services

Climate services can be understood as "future makers" and "future enablers" to support resilient societies. For doing so, it is key to understand users' requirements and their decision-making context. This will further strengthen the role of climate services as "supporters" for science-based decision-making towards sustainable futures. Climate services research should contribute to increasing knowledge towards reaching societal goals and should be understood as crucial to develop future sociotechnical imaginaries and foresights. For this to happen, there is a need to trigger cross-pollination between social and natural sciences to include the human dimension into climate services research. This will be instrumental to address issues such as advancing decision-making, co-design, and communication issues.

6. Enhancing diffusion of innovation and information for climate services

So far, the development of many climate services related to climate change and seasonal to decadal predictions has culminated in the creation of case studies and some semi-operational and operational services. This means that many climate services have only been able to make a gradual transition from technology development (Technology Readiness Level TRL3, proof of concepts or case studies in the past) to technology demonstration (TRL5, such as semi-operational prototypes). It is strategically important to move the climate services demonstrations to technology readiness level 7 to 9 that include the demonstration of the services in an operational environment, i.e. the operationalization of these climate services.

7. Assessing the value of climate services

Climate services help society avert the negative effect and embrace the opportunities related to climate change and climate variability. The value of climate services can be considered from an ecological, social, ethical, and economic point of view. The prevailing view is that, overall, the benefit potential of currently available climate services is as yet poorly exploited. A better understanding of the underlying values, expected and potential, is needed to increase the uptake of climate services. However, it is also important to understand why some users undervalue climate services and why they cannot valorize climate services.

8. Standardizing climate services

Standards are key mechanisms to guarantee suitability, quality, and performance of technological solutions. They also provide common terminology between user, provider, and purveyor communities. The need for quality control, standards and certification for climate services emerged in consultations with users during the design of the European Roadmap for Climate Services. Users argued for standardization of the climate service field in order to generate trust across supply and demand, providing the infrastructure for a climate service market (public and private). Although there exist standards for some components of climate services, there is a need for a coherent and agreed upon set of authoritative standards for the overall value chain, in particular for services tailored to users.

9. Strengthening the links between the Climate Modelling and Climate Service communities

Enhancing and supporting the cooperation between the Climate Modelling and Climate Services communities would be of benefit for both communities in term of informing and rationalizing the pull for outputs from climate modelling and impact communities activities and informing the potential for additional (and potentially more) relevant climate services based on research directions and outputs. Both communities could also benefit from shared development in using big data technologies to enhance efficiency in extracting information from climate data.

Introduction

This paper presents recommendations for the next Horizon Europe framework programme for the fields of climate modelling and climate services. Recommendations have been elaborated within the Climateurope H2020 coordination and support action (CSA) with an expert group.

Climate models are extensively used to provide a better understanding of key processes underlying climate change on a range of timescales from months to decades, and to investigate and describe possible future climates under different scenarios. This information serves as a scientific basis for climate services that aim to provide tailored information to decision and policy-makers. Climate models and climate services are crucial elements for supporting the policy on mitigation and adaptation to climate change and for building a society more resilient to climate-related risks.

There are no doubts that climate is changing and that human emissions of greenhouse gases are its main drivers, as emphasized in IPCC 5th Assessment Report. Avoiding dangerous climate changes has led to the adoption of the 2015 Paris Agreement with the objective to limit global warming to 2°C or even below, compared to pre-industrial temperature. However, how to reach this objective raises a number of issues that climate research can help address, such as the different possible pathways to reach those objectives and what are the risks associated with each. Adapting to climate change also relies on information on climate change on a range of time horizons from seasonal to multi-decadal. Climate models are at the basis of such information for future climate. However, this information needs to be tailored to the decision-making contexts of users, combining information from models with other information relevant for users to enable the integration of climate risks into their operational decisions.

Vision: Transition to sustainable and resilient society

The transition to a sustainable and resilient society is a multi-dimensional challenge that requires enabling people and communities to anticipate risks, reduce their adverse impacts, recover and bounce back from difficulties and crises, and continue to function and grow. Variations in our climate can drive risks for all societal actors, for both present and future. To be tackled, it needs cross-disciplinary and trans-disciplinary worldwide efforts and coordination, combining natural and social sciences, and public and private sectors.

It is crucial to understand current and future climate change, variability and extreme events, their impacts and societal vulnerability. It is also important to enable efficient communication of robust information to decision-makers to yield key actions for sustainable development. The proposed recommendations for further research and innovation activities aim at improving climate knowledge and information to users to enhance the European capacity to transition to a sustainable and resilient society in the course of Horizon Europe.

Background on climate models & climate services

Climate change is leading to a range of varied and significant impacts affecting nature and society. The climate research used to understand and predict climate change and variability has strongly developed during the last decade. Climate models describe the climate-relevant physics of the atmosphere, sea ice, ocean, and land surface. Earth System Models (ESMs), a step further in complexity, also include processes related to the carbon cycle, atmospheric chemistry, vegetation, aerosol, ecosystems, biogeochemistry, as well as feedbacks occurring between those. In the following, the term climate models will be mainly used, encompassing the two classes of models, in order to reflect the overall climate focus of the modelling studies. The models calculate three-dimensional fields of variables, such as temperature, precipitation and wind, both in the past and into the future. Climate models are an essential tool for understanding and predicting climate variability and change as well as for climate policy-relevant calculations. They are used to produce both long-term climate projections and seasonal-to-decadal predictions. Climate change projections are estimates of the evolution of possible future climates under the assumptions of future emission and land use activities (for different policy scenarios). They are typically built on an ensemble of simulations in order to circumvent the biases in representing variability, natural fluctuations and oscillations of the global and regional climate as their intensity and timing differ among models and with respect to observations. Climate predictions are, on the other hand, estimates of future climate conditions covering monthly, annual to decadal timescales by better accounting the initial state of the Earth system. They emerge as a key source of information for a growing number of users in need of relevant, actionable information in the time range of a few years. Both types of numerical experiments are highly dependent on the availability of computing resources. The trend towards higher spatial resolution, large ensembles of simulations and more complexity, leading to higher quality and more useful information, calls for increasing resources. The large EuroHPC initiative is expected to help achieve some of the ambitious objectives presented in the recommendations.

A Climate Service is the provision of tailored climate information to assist decision-making. Climate services have strongly emerged during the H2020 programme as it was emphasized in the European Roadmap for Climate Services in 2015. A service must respond to user needs, must be based on scientifically credible information and expertise, and requires appropriate engagement between users and providers. Models produce the data, information about past, current and future climate, which underpins most climate services. Such user-oriented applications often require information at regional or local scale. Global model data is traditionally downscaled from coarse grids by means of regional climate models, or via statistical approaches and undergo further tailoring procedures (bias correction, application of selection techniques). A new generation of global climate models at high resolution has emerged in the last ten years, which in part complements and in part substitutes that traditional workflow. Assessment and communication of the uncertainty are at this stage essential for information used in decision-making. Climate services products, to be delivered to public and private sectors, include projections on multi-decadal timescales, predictions on timescales from months to years, observed and forecasted trends, assessments, counseling on best practices, and any other product that may be of use for society. Climate model data is generally processed by impact models to address the needs of sectors, such as agriculture, water, health, and energy. By addressing direct or indirect consequences of climate change and existing or emerging risks, climate services can help decision-makers take better-informed decisions to help Society as a whole cope with climate change and variability, limit the economic and social damage caused by climate-related disasters – raising resilience and adaptation capacity– but also embrace upcoming opportunities.

Methodology

This position paper provides the European Commission with a view on how research and innovation actions on Earth System Modelling and Climate Services could contribute to the European Union Horizon Europe framework over the period 2021-2027. The paper was written in the frame of the H2020 CSA Climateurope, by a group of European experts in climate modeling and climate services, under the coordination of a small group of scientists from various European research institutions participating in the project. The experts were selected based on their individual leadership roles as PIs of H2020 projects or on their participation in international programs/initiatives related to climate modeling and climate services. A significant number of these experts in turn invited members of their own networks to collaborate to this effort. A first list of recommendations on research needs resulted from a dedicated workshop held in Paris on 11-12 February 2019, reserved to the experts. Such list was further discussed in an open meeting at the General Assembly of the European Geosciences Union in Vienna on 12 April 2019.

The paper content also relies on previous discussions and consultations held in the frame of Climateurope as well as of other initiatives, such as Copernicus Climate Change Service and international programs. Documents of references are, among others, the Climateurope position paper on recommendations for climate services science, research and innovation, resulting from a meeting with key stakeholders held at the EC, the Roadmap for European Climate Projections produced by the Copernicus Climate Change Service, the IPCC AR5 and Special Report on 1.5°C, the United Nations Framework Convention on Climate Change Paris Agreement, and the World Climate Research Programme strategic plan.

The paper presents the recommendations as high-level research topics to be pursued, starting with Earth System modeling and continuing with climate services to mimic sequentially the value-chain of information transfer from science to society. Some cross-field and cross-topic aspects are also discussed. For each research topic some background information is provided as well as its significance for the overall vision this paper strives for –the transition to a resilient and sustainable society in the 2025-2030 time horizon.

Supporting the IPCC process

The Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) are crucial to support international policy on climate change. Information on possible future climate is extensively based on simulations using climate models coordinated internationally by the World Climate Research Programme (WCRP). The European Commission (EC) plays a key role in supporting the European contribution to this research. This support will be essential in sustaining European cooperation toward the next cycle of the WCRP experiments, in allowing the timely preparation of the relative simulation protocols and in addressing knowledge gaps identified in the IPCC Assessment Reports.

Contribution to the vision

Long term projections and near-term predictions with climate models are important to better understand the climate change process, and then to justify and design mitigation and adaptation policies. Access to multi-model ensembles, well-evaluated on historical and past climates, is needed to enhance robustness and assess uncertainties of such projections. Such simulations are highly used for climate impact studies and serve as a basis for climate services, in particular as being promoted on a European level the Copernicus Climate Change Service. These simulations are also critical to assess the scientific understanding of key processes driving the climate response to anthropogenic forcing, such as feedbacks.

Background: lessons learned and gaps

EC, through its different framework programmes, has supported the World Climate Research Programme (WCRP) internationally coordinated experiments. This strengthened the European contribution to the Coupled Model Intercomparison Project (CMIP) cycles as well as to the more recent Coordinated Regional climate Downscaling Experiment (CORDEX). CMIP experiments form the backbone of climate science for evaluating models, for providing future projections, but also for improving understanding of climate variability and change. CORDEX provides regionally downscaled information from global projections aiming at understanding regional circulation and processes and at improving information at the regional scale for impact studies and decision-makers.

EC H2020 support has been essential to maintain the European leadership on various aspects of the 6th cycle of CMIP (CMIP6) such as high-resolution global simulations (H2020 PRIMAVERA project), carbon-feedbacks (H2020 CRESCENDO project) as well as for near-term and regional projections (H2020 EUCP project). Analyses of CMIP6 are ongoing and will contribute to the IPCC Assessment Report 6 (AR6) with three main foci: How and to what degree is the Earth system responding to forcing? What are the origins and consequences of systematic model biases? How can we assess future climate changes given climate variability, climate predictability, and uncertainties in scenarios? EC H2020 also supports the infrastructure behind CMIP and CORDEX through the IS-ENES projects, allowing Europe to be a key player, in cooperation with the US Department of Energy, of the international database Earth System Grid Federation and of the metadata generation associated.

The absence of open-source tools that allow community-wide participation in the preparation of scenario input data for CMIP simulations. was identified as major bottleneck for the streamlining and communication among various communities involved in delivering research that aims at addressing specific policy questions.

Each IPCC report emphasizes the knowledge gaps that limit how climate science can inform policy on mitigation and adaptation. InAR5 for instance, such gaps include model uncertainties, the risk of irreversibility or of abrupt events, and the risk of permafrost thawing and ice sheet melting. It would be important that Horizon Europe kept supporting science to address knowledge gaps also after AR6. First results from CMIP6 projections (CRESCENDO project) show somewhat higher climate sensitivity compared to CMIP5, indicating that global warming may be stronger than previously thought given a certain level of forcing. Understanding the origin of such differences will be important to go further in mitigation and adaptation strategies.

Research needs

Supporting CMIP7 internationally coordinated experiments

EC Horizon Europe contribution could be essential in supporting the cooperation and international leadership of the European scientific community facing the preparation of the international 7th CMIP cycle (CMIP7), which will be used in future IPCC Assessment Reports. Although it might be too early to indicate the objectives of CMIP7 (as they will be formulated after the conclusion of IPCC AR6, to be delivered in 2021), we can anticipate that the provision of multi-model projections with the most up-to-date, well-evaluated climate models will be important to inform mitigation and adaptation policy in support to the UNFCCC. For example, as emphasized in the IPCC Special Report on 1.5°C, climate simulations for low-emission scenarios such as a 1.5°C world are still missing.

Defining and preparing simulation protocols

Definition and preparation of CMIP cycles, and in particular of simulation protocols and forcing conditions, represent a joint international community effort under WCRP, done, however, on a voluntary basis and lack dedicated support, as recently emphasized by WMO[1]. Preparing the greenhouse gases as well as aerosol and land-use forcing conditions for the experiments requires close cooperation between the climate modelling community and the integrated assessment community. For CMIP6, these forcing conditions have been delivered quite late, only one year prior to the deadline for publications in AR6. The support of H2020 in this process with emphasis on open-source methods and publicly available tools would substantially improve the overall chain and increase the amount of time available to model analyses prior to AR7.

Addressing IPCC knowledge gaps

In AR6, Working Group I will assess research gaps that climate modelling can help address. The Special Report on 1.5° C already assessed some, such as the impacts of different overshoot scenarios (see Climate Modelling recommendation on informing mitigation policy), critical thresholds for extreme events (see Climate Modelling enhancing adaptation and resilience). Other gaps not yet covered include Antarctic ice sheet dynamics uncertainties and their role on global sea level, the role of ocean circulation changes and of changes in ocean chemistry between 1.5 and 2°C and their implications on natural and human systems.

Links and synergies

Supporting the CMIP/CORDEX cycles would occur in close cooperation with WCRP and the IPCC. These experiments are also reference simulations for Copernicus Climate Change Services.

Expected outcomes

- The European contribution to the WCRP experiments and their contribution to the IPCC AR7;
- European leadership to the overall experiments, allowing the exploration of novel, societally relevant, research questions;
- Support to address key knowledge gaps strongly affecting mitigation and adaptation policy.

[1] *WMO Support to IPCC and climate science, June 2019*

Informing climate mitigation policy: scenarios with risk of overshoot

Climate model projections of possible future climate change are essential to assess plausible routes to realizing key policy goals, such as the Paris Agreement, and to investigate the consequences of exceeding such targets. Even though many countries signed the Paris Agreement, the risk of reaching global warming greater than 1.5 or 2°C, at least temporarily before returning below the target, remains high. Further research enhancing the level of process realism and the representation of uncertainties in models and developing a larger range of likely and feasible overshoot scenarios is needed. This will be essential to assess and inform on the risks of overshooting 1.5 or 2°C and associated impacts as well as to understand the interference of possible abrupt events and the impacts of aggressive mitigation actions.

Contribution to the vision

The 2015 Paris Climate Agreement aims to hold global warming below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C. The IPCC Special Report on 1.5°C showed that the difference between these two levels is critical for the well-being of billions of people. Actions to limit both the magnitude and rate of global warming and of its related effects are already in force and need to be rapidly enhanced. Nevertheless, there is a real danger that global warming exceeds 1.5 or 2°C, before possibly returning below these levels through aggressive mitigation. Depending on the degree of overshoot, a range of Earth system changes may result, some of which may push the system further from the target warming, while also negatively impacting human and natural systems. Furthermore, it is unclear whether such changes, once triggered, will be reversible if warming returns below the original target.

Background: lessons learned and gaps

Aggregation of current national greenhouse gases emission pledges, combined with estimates of climate sensitivity, suggests a probable global warming of 3-4°C by 2100. Given observed warming is already ~1°C above pre-industrial values and emissions of CO2 continue to increase, keeping global warming below 1.5 or 2°C will be an enormous challenge. Even the most ambitious futures cannot exclude an overshoot of one or both targets with high probability. Critical questions arise from this:

- If global warming exceeds either 1.5 or 2°C, what level of negative emissions would allow to reverse it, what impacts will such negative emissions have on other Earth system parts? What are the Earth system constraints on returning to a desired temperature level of warming by 2100 after an overshoot? How are climate impacts of exceeding critical warming levels of 1.5 and 2°C exacerbated or mitigated by the impact on the full Earth system of the negative emissions?
- If a warming overshoot occurs, will any abrupt or rapid changes in the Earth system be triggered and, if so, will these amplify the warming, increasing the challenge of returning to a given target? What degree of overshoot is associated with what level of risk for triggering such abrupt changes and at what level of warming overshoot are the triggered changes likely to become irreversible, even if the warming target is returned to at a later date?

As emphasized in the IPCC Special Report on 1.5°C, knowledge gaps on mitigation pathways compatible with 1.5°C are associated with the carbon cycle response, in particular with respect to negative emissions, non-CO2 emissions, which emissions, disaggregation and climate response are less well quantified, and an appropriate historic baseline. Addressing current uncertainties in carbon cycle and feedbacks is crucial to identify whether emissions have peaked and to verify the effectiveness of negative emissions.

Research needs

To answer these questions and thereby improve science guidance for policy-making, three complementary developments are necessary, mainly based on climate models including a representation of the carbon feedbacks.

Enhancing the level of process realism of state-of-the-art Earth system models

At the heart of understanding and predicting the risks and potential magnitude of a warming overshoot are realistic and reliable ESMs. Such models can also be used to develop potential mitigation routes back to a given warming threshold if exceeded, including analysis of the impact such mitigation options will have on Earth's natural and human systems. Necessary model improvements include: improved representation of terrestrial and marine climate and carbon cycle processes, in particular land use change, permafrost, wetlands, wildfires, and processes controlling the future efficiency of natural carbon uptake. Improved treatment of short-lived climate forcers will allow assessment of the mitigation potential from their rapid reduction. Interactive ice sheet models within ESMs will enable analysis of the risk of rapid Antarctic and Greenland ice loss and impacts on global sea level. Increased model resolution will improve simulation of the key dynamical modes in the climate system at risk of rapidly change. As the risk of a warming overshoot, its magnitude, and the associated potential for abrupt and irreversible changes all scale with the amount of warming, processes underpinning uncertainty in estimating Earth's climate sensitivity also need to be prioritized.

Better representing uncertainties in model response

Due to their complexity, only a limited amount of ESM simulations can be performed. This limits the range of uncertainties that can be systematically explored. Adding processes will only exacerbate this problem by making models more computationally intensive. Novel ways to explore parametric and structural uncertainty in ESMs will be essential to assess the risks of overshoot scenarios, where the risk is not found in the best-estimate behavior, but in low-probability high-impact outcomes.

Developing a set of overshoot scenarios

Within CMIP6, only one overshoot scenario was developed alongside two scenarios designed to limit global warming below respectively 1.5 and 2°C. A larger range of likely and feasible overshoot scenarios need to be developed. These should be based around the 1.5 and 2° C targets and sample a broad range of overshoot pathways, as well as different modes and rates of cooling pathways that bring global temperatures back to the target warming. Sampling these scenarios with state-of-the-art ESMs will provide critical knowledge on the risks associated with exceeding key targets and the level of risk associated with different magnitudes of exceedance. Such simulations will also provide guidance on the feasibility, cost and impacts associated with the global cooling "return to safety" part of different overshoot scenarios, including the potential impact of the required mitigation activities, including geoengineering, on the natural and human parts of the Earth system.

Links and synergies

The proposed developments should be implemented in synergy with WCRP and IPCC, Future Earth and AIMES. The results will provide information to mitigation pathways and support UNFCCC process.

Expected outcomes

- Assessment of the risks inherent in exceeding target global warming levels, such as the 1.5 and 2°C targets;
- Estimate of the achievability, and preferred type, of mitigation to return from different levels of warming overshoot;
- Identification of the impact of such efforts on both Earth system and human activities;
- Estimate of the degree to which Earth system changes, triggered during the warming part of an overshoot pathway, are reversible over the cooling part of these scenarios;
- More robust policy advice on these topics.

Enhancing adaptation and resilience to extremes

Despite improved understanding of extreme events, including general agreement that different types of extremes, such as heat waves and heavy precipitation are expected to increase in frequency and intensity in a warming climate, further research is needed to address the remaining large uncertainties with regard to regional patterns and magnitude of changes. For other extremes, such as wind storms, even the signal of future change should be investigated in many regions including the North Atlantic and the European region. It is foreseen that very high spatial resolution climate models at the km scale can contribute to a breakthrough in representing extreme events.

Contribution to the vision

Extreme events are a strong concern due to their high impact. How infrastructures, cities, human health and ecosystems are going to be affected and how to ensure them to be resilient or adaptive enough to changes in extremes requires better information on possible hazards. Future very high-resolution climate models are expected to provide reliable estimation of the risks of weather and climate extremes, on scales ranging from local to global and from seasonal and yearly to multidecadal under different emission scenarios. Such information will be a key constituent in future European climate services, thereby better enabling a sustainable and resilient society.

Background: lessons learned and gaps

Despite improvements, current climate models show biases in their representation of extremes. Examples include the representation of storm tracks over the Atlantic, the frequency and intensity of large-scale atmospheric high-pressure systems, the representation of teleconnections or land-atmosphere interactions. Increased model spatial resolution has already shown their capacity to improve the representation of extremes, such as tropical cyclones (~20 km resolution for global climate models, PRIMAVERA project). Such high-resolution global climate models are currently run in ensemble mode, mostly smaller than 10 members, but examples from Japan have run 100-ensemble member global climate experiments. Further increased resolution to better resolve key processes like atmospheric convection and ocean eddies is expected to make a step change in the reduction of some of these biases. For example, atmospheric convection is treated in a simplified manner by crude parameterization methods in current climate models (operated on grid spacing coarser than 10 km). In very high-resolution models (with grid size of the order of 2 km or less) explicitly representing convection, intense precipitation events are more realistic and possibly increase stronger with warming than in corresponding coarser scale models. Other improvements may involve better process understanding and description such as the incorporation of all relevant processes in different parts of the climate system. However, global climate models with grid spacing of ~2km can currently only be run for too short duration for climate studies.

Large ensembles of climate model simulations have been shown to allow for more robust estimates of climate variability, and thereby better possibilities of identifying climate change signals compared to the underlying noise. This is particularly true for extreme events with long return periods as these are rare by definition and therefore require large samples for robust statistical assessments. This is also often true for compound events, when a hazardous event is caused by concurrent events in two different variables. This could for example be a storm surge hitting a coast at the entrance of a river experiencing a precipitation-driven flooding event. The large ensembles have also led to improved capabilities for event-based attribution studies.

Research needs

Improving the representation of extremes

Research is needed to improve the confidence in the simulated changes in weather and climate extremes. This involves better understanding of how existing model biases affect the representation of extremes regarding the intensity and frequency of hazards, including the co-variability of different risk factors, and ultimately reducing the biases. Achieving this requires detailed evaluation of the mechanisms driving climate extremes in the models in comparison to observations, and how different representations of these mechanisms influence the simulated extremes.

Towards very high-resolution global climate models

Preparing a future generation of climate models at a very high resolution able to explicitly represent deep convection and ocean eddies (km range), is expected to make a step-change in the representation of extremes. This will require not only model developments but also research and development to better adapt models for exascale computing including optimized hardware-software linkages and for data handling at unprecedented scales, as is proposed in the ExtremeEarth flagship concept[2]. Such developments would benefit from interdisciplinary approaches with software and hardware specialists. This objective would benefit from intermediate steps with coordinated very-high resolution experiments with limited spatial domains and atmosphere-only models. The ambitious European initiative on High-Performance Computing (EuroHPC) should offer an opportunity to address this challenge.

Developing reference observational datasets

High-resolution modeling also requires better reference data sets for model evaluation purposes and data analysis tools and methodologies that scale with the size of the data sets produced by the models, that is, also capable of running on exascale facilities. This includes that sufficient resources are invested to create new, and to improve existing observational data sets (including data rescue projects for historical records, homogenization of data in time and space across Europe, deriving combined products including remote sensing products, gridding data etc.), and to further develop and produce high-resolution regional reanalysis data sets.

Links and synergies

Facing the open questions related to the extremes will be of benefit for initiatives such as WCRP grand challenge on extremes, Copernicus climate services providing access to projections as well as the forthcoming service on event-based attribution, the Horizon Europe mission on adaptation, CORDEX especially EURO-CORDEX and the Flagship Pilot Study on convection-permitting global climate models.

Expected outcomes

- Improved forecast quality on a range of timescales;
- Better information for climate services thereby facilitating climate change adaptation;
- Higher resilience to extremes throughout Europe including the most vulnerable regions;
- Enhanced capability of event-based attribution services.

[2] www.extremeearth.eu

Supporting the formulation of adaptation strategies

Adaptation strategies need tailored information on climate and impacts at local scale and, for most users, ranging over time scales from seasons, years to decades up to centuries, under different emission scenarios. Climate models provide essential information, which however, needs to be tailored to provide adequate information to assess local impacts. To suit the expectations of most users in terms of systematic availability of impact-oriented projections and up-to-date near-term predictions downscaled to local scale, process understanding, models and infrastructure, and downscaling need continuous support. In addition, guidance is needed for selection, aggregation, and use of the local climate information.

Contribution to the vision

Sustainability and resilience can only be achieved with robust information on future climate risks and understanding of the associated uncertainties and probabilities at the regional to local scale.

Seamless high-quality information of near-term climate predictions and long-term projections under different emission scenarios, branching off historical observational records, is needed.

Background: lessons learned and gaps

A growing number of users are realizing that options to reduce their vulnerability to climate change impacts are concentrated in a planning time range of a few years. In this context, decadal predictions emerge as a key source of information. To improve the skills of such source of information, investments in resolution, model complexity, initialization, and bias-correction have been made. Large ocean regions show skillful predictions, but improvement of forecast quality with respect to climate projections over the continents has remained limited. Issues that prevent forecasts reaching their predictive potential are well-identified[3], but efforts to tackle them are scattered, without effective coordination. Despite the initial stages for the operationalization of decadal forecast systems, there are important gaps for the development and uptake of action-oriented products that could be made regularly, publicly available. On the other hand, the availability of an increasing ensemble of model simulations has improved the climatology of (extreme) weather characteristics in contemporary climate conditions, supporting many risk assessment applications relying on adequate climate statistics.

Despite a continuous increase in space and time resolution of output fields from models, users continue giving priority to even higher resolution for adaptation studies, as it enables improved representation of the regional climate. Therefore, for impact, vulnerability and adaptation studies, dynamical and statistical downscaled results are probably the most used data. For example, many of the Copernicus Climate Change Service (C3S) Sectoral Information Systems use high-resolution regional EURO-CORDEX datasets to support public and private sectors in their climate-sensitive decisions, but additional efforts to improve this availability is a prerequisite for better adaptation planning.

Long term projections under different scenarios and near-term predictions of climate system variables generated using climate models are used to assess impacts from climatological indicators or sophisticated impact models. Although models have extended their list of output variables, essential climate variables (ECVs) –predominantly temperature and precipitation– are mainly used. Increased focus on other already available variables[4], or further development of some model components to include additional processes, will potentially provide stronger support for adaptation.

An important bottleneck for using advanced climate model products is the varying uptake capacity of users, due to technological and conceptual limitations. For many local impact assessments carried out by policy-oriented players, resources to digest large volumes of data are limited. In addition, the availability of an ever-increasing set of scenarios and projections generates either a selection challenge or a lack of ability to effectively inform the decision process. Guidance on selection and aggregation of climate information is needed, aiming at optimizing usability.

Research needs

Improving decadal prediction

Europe's strong interest in decadal prediction is expressed by the European participation in the global Annual-to-Decadal Climate Prediction exchange program. However, more ambitious and wider scope initiatives, leading to operational formulation of decadal forecast products, are needed. Better process understanding, better models and an adequate infrastructure design are crucial to overcome current limitations and close the gap between current skill and potential predictability estimates, especially on continental areas. This can be achieved with the analysis of process-based studies to improve the representation of ocean processes, key linkages, teleconnections, and short-term forcing. The role of the forecast drift[5] and the potential for the combination of process-based and statistical predictions are both critical to produce usable information at the regional scale.

Downscaling climate data

Improving the design of and access to the model chain from global to local scales will meet the needs for local climate data and coherently map drivers, uncertainty, robustness and feedbacks of climate projections. Increasing the ensemble size of regional projections will lead to better uncertainty estimates, especially those related to extremes that are better represented in high-resolution models but the associated computational costs need to be balanced by the scientific and socio-economic benefits. The design of the configuration of global and regional model simulations needs to be optimized to maximize their respective added value[6]. The role of high-resolution convective-permitting models in this chain[7] needs to be explored.

Further developing and exploiting climate models for impact studies

There is a need to strengthen the interactions between climate models and climate impact modelling. Climate models provide a large amount of information that is currently unexplored by the climate impacts community. Better exploiting ESM variables can enhance consistency with impact models and avoid potential mismatches. Moreover, aiming at improving the ability to represent the climate system and human interventions, ESMs increasingly include feedbacks related to land use and cover, urban dynamics, air quality, etc., which can affect climate model simulations at regional scale. This approach needs enhanced focus on model evaluation and output post-processing.

Optimizing aggregation, selection and ingestion of model outputs

The implementation of region-oriented climate information programs requires guidance on selection or aggregation of model data for impact assessments, with clear justification of the procedures, allowing transformation of uncertainty into a manageable package of information. Selection or aggregation should be based on region- and time-scale specific drivers of climate impacts, and must also be consistent with the local historical records. In practice, tools to assess climate impacts for the future are rooted in management systems that are trained to local conditions and data. A seamless ingestion of climate information into these systems will surely promote the uptake and use of the valuable climate model outputs.

Links and synergies

C3S would be a strong beneficiary of these developments. They will provide information for the climate data store on regional climate projections and on decadal predictions and sectorial impacts.

Moreover, new synergies could be explored and exiting ties strengthened with WCRP Grand Challenge on decadal prediction, WMO Annual-to-Decadal Climate Prediction operational exchange, WCRP Decadal Climate Prediction Project.

Expected outcomes

- Enhanced decadal prediction skill to boost the forecast quality in regions and for variables of higher societal relevance. Methodologies to merge simulations from climate predictions and projections to result in seamless climate information for the next 30 years;
- Sustained model chain from global to local scale (and vice versa) to provide more homogenous information, regularly produced in the most efficient way, fulfilling needs from users that are expecting best possible information for adaptation planning ;
- Stronger links between ESMs and impact modelling to provide more robust support for adaptation studies. This will also lead to better understanding of interactions between climate system and other natural and socio-economic systems.

[3] E.g. suboptimal initialization, small ensemble size, lack of established benchmarks, little knowledge on regional impact of short-term forcing such as aerosols.

[4] Such as primary production on land and in oceans.

[5] Including improved initialization and the forecast adjustment.

[6] As emphasized in the C3S roadmap for climates services.

[7] Particularly their spatial configuration and experimental set-up (i.e. long projections, time slices or idealized simulations).

Understanding requirements, decision-making context and foresight for climate services

Climate services can be understood as “future makers” and “future enablers” to support resilient societies. For doing so, it is key to understand users’ requirements and their decision-making context. This will further strengthen the role of climate services as “supporters” for science-based decision-making towards sustainable futures. Climate services research should contribute to increasing knowledge towards reaching societal goals and should be understood as crucial to develop future sociotechnical imaginaries and foresights. For this to happen, there is a need to trigger cross-pollination between social and natural sciences to include the human dimension into climate services research. This will be instrumental to address issues such as advancing decision-making, co-design, and communication issues.

Contribution to the vision

Climate Services (CS) are key in supporting European societies towards resilient and sustainable futures. Nevertheless, the entry points for climate services into societal decision-making process have to be more clearly articulated to allow for coherence and integration of climate-related themes across sectors. Only by understanding and integrating society in the research agenda we can develop high impact science that will support this transition towards resilient societies. We should aim at increasing not only the Technology Readiness Level of CS but also their Market and Institutional Readiness Level.

Background: lessons learned and gaps

The field of climate services has been extremely important in conveying to societal actors, and in particular to businesses, that climate change can be seen on a shorter-term perspective, giving it a more salient time frame. Climate services research (CSR) provides understanding of what is needed when it comes to the risks and opportunities related to climate change. Additionally, CSR provides important scientific support for enabling the sustainable development goals (SDG) vision within climate change constraints. CSR contributes to increasing knowledge towards reaching societal goals and should be understood as crucial to develop future sociotechnical imaginaries and foresights for adaptation and/or transformation efforts in the face of climate change. For this to happen, we need cross-pollination between social and natural sciences to include the human dimension into CSR. So far, however, the role of social sciences was rather marginal or over-simplified, with a purpose-driven application limited to stakeholder engagement. Having interdisciplinary research teams, with good representation of social scientists and other disciplines, must be the ambition of the next generation of CSR and innovation. This will involve significant rethinking and reshuffling of disciplines, deviating from the dominance of the physical sciences and moving beyond dualism of the natural and social (science) in CSR discourse and perspectives.

Important gaps have been identified in existing projects on CS (and others) showing in which direction research should further be developed. One important gap identified in CS implementation is the language barrier. This does not only include the dominance of English in CS production, but also inadequate or lacking conversion of the scientific and professional language to the one of stakeholders. Further research will be needed towards properly addressing the issues of adaptation decision-making under deep uncertainty and ambiguities. Another important gap relates to the need of understanding governance structures and where CS can enter this structure to be used into wise decision-making. An additional gap for research remains in the field of the economics of information, analyzing the needs and added value of downscaling efforts for different decision-making context depending on different temporal and local scales.

Research needs

Fostering social sciences and transdisciplinarity in CS

The way co-production is undertaken should be grounded in participatory research, with clear guidance on how to plan and manage collaborative activities, frameworks in which to examine stakeholders' decision contexts and concerns, and guidance on resources required to undertake collaborative research. CSR should foster transdisciplinarity, by overcoming of compartmentalized concerns and transgressing of disciplinary boundaries, while at the same time considering the domain and other forms of stakeholders' knowledge and their needs and interests at stake.

Research on sociotechnical imaginaries for resilient futures

CSR should support the creation of imaginaries of resilient futures explicitly combining social and technical knowledge needed to support the pathways towards those futures. The main research needs are on the link between the subjective dimensions of knowledge inclusion and the relative lack of flexibility of technological and political systems, organizational behaviors and political culture. In addition, CSR can support the analysis of leverage points that are key to support transformations towards resilient societies.

Providing decision support, understanding policy-making context and dealing with uncertainties and ambiguities

Decision support demands a more active role of scientists in understanding the culture and context in which decision-makers operate. Besides managing the physical and material risks of climate change, policy-making also includes managing risks to political systems and their legitimacy, so-called reputational risks. Framing the vision of CS as a service that can support the legitimacy and stability of adaptation governance systems and its actors could be a way for their more effective communication to policy-makers. This will mean also mainstream CS across political fields and the creation of non-canonical CS in situations in which the climate data availability is restricted but the stakes are high. This will support decisions under deep uncertainty. Additionally, different decision-makers might have completely different visions of solutions to the same problem. Analyzing ambiguities would help to reduce the complexity of the system and increase the effectiveness of policy measures implementation.

Advancing climate services communication

CS communication needs to move away from the knowledge deficit model, which assumes that by providing adequate information to stakeholders they will act upon scientific evidence. Instead, each audience has their own pre-existing beliefs, attitudes and values as well as their authoritative knowledge brokers. Science communication research in CS will benefit from a better understanding of inter- and intra-sectoral differences and should develop research lines around the following three challenges: (i) seeking more effective methods to communicate uncertainty; (ii) identifying and testing optimal communication strategies; (iii) exploring and evaluating new communication tools, such as gamifications.

Links and synergies

Other studies under the Belmont Forum and Future Earth might mutually benefit from such research efforts. Additionally, this research could contribute to the IPCC reports and other emerging UN programmes by bringing European transdisciplinary research to those processes.

Existing projects and case studies could be used as basis for the development of some of the mentioned gaps and research needs. International networks on climate services, such as the Climate Service Partnership or the Global Framework for Climate Services (GFCS) should be included in future research.

Expected outcomes

- Enhanced climate policy coherence through the use of climate services. Higher inclusion of social sciences into CSR and support to cross-pollination of methodologies towards the creation of socio-technical imaginaries for possible adaptation or transformation processes for the next 30 years;
- Creation of robust methodologies and best-practices for the implementation of CSR at the local level considering issues of upscaling and uptake;
- Stronger links between different scientific fields towards the development of canonical and non-canonical climate services to provide more robust support for adaptation studies;
- Better understanding of the readiness levels (scientific, business and institutional) of climate services to increase the uptake of research results and the transverse impacts of CSR;
- Enhancement of communication and knowledge brokerage of CSR;
- Solution oriented demonstration projects to test and evaluate the suggested measures to fill the research gaps.

Enhancing diffusion of innovation and information for climate services

So far, the development of many climate services related to climate change and seasonal to decadal predictions has culminated in the creation of case studies based on the past and some semi-operational and operational services. Many climate services have only gradually transitioned from technology development (Technology Readiness Level TRL3 proof of concepts or case studies in the past) to technology demonstration (TRL5, such as semi-operational prototypes). It is strategically important to move the climate services demonstrations to technology readiness level 7 to 9 that include the demonstration of the services in an operational environment, i.e. the operationalization of these climate services.

Contribution to the vision

For nations to meet their sustainability targets, a step-change is needed in the adoption of innovative technologies. The current trend is for incremental innovation, with a preference for low-risk approaches of improving existing processes rather than adopting completely new methods and transformational adaptation. The operationalization of climate services will facilitate the adoption of innovative practices in order to help foster a climate resilient economy in the longer term.

Background: lessons learned and gaps

Adaptation is only possible if climate information is translated into products that are useful and useable for end-users. However, the availability of climate data, information and services does not always correspond to users' needs. Decision-makers take into account many sources of information besides climate; future climate services should explore how such sources of information can be combined to address particular decision-making problems. This could also mobilize other user communities for whom demonstration projects are not currently feasible.

Incremental change in business practice is not sufficient for countries to meet their climate pledges: step-change is needed. Innovation can catalyze this change, either through 'product innovation' (a new product or service) or 'process innovation' (a new way of making something). In addition to incremental innovation, future research on climate services should enable the business sector to adopt disruptive innovation, creating new markets for climate-resilient businesses. To fill these gaps and foster the diffusion of innovation there are three main lines of action: first, showcasing the benefits of climate services with proof-of-concepts, highlighting the potential of product innovation at the operational level. Second, process innovation must be fostered, researching underlying technical innovations for more effective impact-oriented climate services. Finally, improvements are needed to our understanding of how to reduce the barriers to the diffusion of climate innovation in Europe (e.g. corporate inertia, regulatory uncertainty, incrementalism, and competition regulations[8]).

Research needs

Developing operational demonstrators

Future research should focus on operational demonstrators as real-time service environments where climate information is integrated with non-climatic datasets, yielding operational services supporting decision-making processes. Co-production between all partners will prove the potential of these services at the market level. Testing by real users will inform research needs in terms of data visualization and integration, communication of probability and uncertainty. Operationalization of climate services is a challenge given the amount and size of the datasets. Research and innovation actions in this field will facilitate creation of guidelines and lessons to improve understanding of costs and technical pitfalls that must be addressed before creating marketable services. Mature operational demonstrators for multiple sectors will pave the way for market uptake of climate services.

Blending timescales in climate services

Recent advances in climate predictions, following the seamless prediction concept (sub-seasonal, seasonal, and decadal) have demonstrated that probabilistic forecasting can inform better decision-making. Future research and innovation actions should request the technical development of methods and services that focus on different temporal scales for seamless predictions of climate indices and tailored products consistent across temporal (from sub-seasonal up to projections) and spatial scales. Additionally, research should include evaluation of how these technical developments contribute to the mitigation of the impacts of weather and climate variability or how they help to define adaptive measures. These research lines should focus on key sectors of society not only in Europe, but also other regions worldwide where climate predictions are more skillful and thus have a clearer potential application.

Understanding and overcoming barriers to climate services innovation

The US is usually seen as the benchmark of successful entrepreneurs and innovative ideas; even though Europe boasts more entrepreneurs per capita than the United States[9], European companies often encounter problems in scaling up. This confines innovation to local economies. Future research should analyze the role of regulatory frameworks, lack of capital and other barriers that slow down the growth and the spread of innovation in relation to climate services and the adoption of climate services in the market[10]. By observing the differences in exploitation of climate services between Europe and other areas such as the US, recommendations may be created for overcoming Europe's barriers to adoption of climate services. Inclusion of US partners in research projects on these topics could help foster the learning and adoption of successful approaches and at the same time opening European climate services innovation to other markets more prone to the uptake of climate services.

Links and synergies

Future research projects should take into account and where possible build upon/build synergies with activities undertaken by Climate-KIC, JPI Climate and Copernicus.

Additionally, future research collaborations that include industry partner buy-in, and national meteorological services, will better enable uptake of innovation.

Expected outcomes

- Generation of examples of successful adoption of operational climate services, to incentivize the climate services market and find gaps in knowledge at the operational level;
- Blended timescales to provide information that is more relevant for businesses;
- Elimination of the barriers to adoption of innovation in climate services in Europe, using examples from the US as a guide.

[8] *Barriers to diffusion of climate innovation, adapted from a study by Climate-KIC (http://www.nakedenergy.co.uk/wp-content/uploads/2015/12/Climate-KIC-_Sparking-an-innovation-step-change-2.pdf).*

[9] *OECD (2016). Entrepreneurship at a Glance 2016; Paris: http://www.oecd-ilibrary.org/industry-and-services/entrepreneurship-at-a-glance-2016_entrepreneur_aag-2016-en.*

[10] *Lisbon Council, Nesta, Open Evidence (2016). Scale Up Europe: A manifesto for change and empowerment in the digital age.*

Assessing the value of climate services

Climate services can help society to avert the negative effects and embrace the opportunities related to climate change and climate variability. The value of climate services can be considered from an ecological, social, ethical, and economic point of view. The prevailing view is that, overall, the benefit potential of currently available climate services is as yet poorly exploited. A better understanding of the underlying values, expected and potential, is needed to increase the uptake of climate services. However, it is also important to understand why some users undervalue climate services and why they cannot valorize climate services.

Contribution to the vision

Climate services (CS) are often said to support the sustainable development goals (SDGs) without clarifying how or how this would create value for individual stakeholders/sectors. By specifying the various values of CS, this contribution to sustainable development can be made clearer. Besides this, also understanding the barriers to valorizing these potential benefits is essential to reach the SDGs.

Background: lessons learned and gaps

The prevailing view of experts in the field is that, overall, the benefit potential of currently available climate services is as yet poorly exploited (EUPORIAS and EU-MACS projects). Over the past decades, a large body of knowledge was produced on the economic and social value of meteorological and hydrological services. These are context- and users-specific and easily amendable for value transfer and generalization. The Climate Services Partnership (CSP) and especially the work of the Economic Valuation of Climate Services Working Group has vastly contributed to collecting, reviewing and synthesizing the existing knowledge and methodological advice.

Climate change prediction and projections, several of them freely available, can also be regarded as public goods. The merit of these basic services turns into more tangible value added when used in downstream climate services, more tailored to specific users. Although the valuation of a given climate service has several components, which may weight differently for different users, generally, expert users are more prone to extract value from the available upstream climate information (basic information, not tailored to specific users). There is urgent need for capacity building to get a wider use of the various climate services. Besides this, increasing transparency in methodologies and sources and in the climate services portfolio will increase exploitation of the services and increase the perception of value. However, users active in competitive sectors are not always willing to share much information, since it may affect the private value for them.

Research needs

Some studies on the values of CS for single users are available, but further studies are needed (including monitoring of the market) to understand what determines use and innovation of CS.

Broadening perspective on the value of CS (economic, social and environmental)

Most climate services can be regarded as merit goods. This means that climate services can enable the realization of both private benefits and public benefits, but the user only valuates the private ones, and even these may be undervalued. Without support this results in lower utilization than what is possible for society. Most studies until now focused on the economic and social value of CS, but the ethical and environmental value are important as well. To improve the uptake of CS, there is a need to measure and demonstrate all values to individuals as well as to society. This also requires identifying barriers and enablers that can help the broader assessment of the value and eventually facilitate the valorization of the climate services. In essence this is attributable to (1) lack of awareness or incentives among potential users, or to (2) a very low expected value of the alleged benefits of climate services.

Scaling up effects on the value of CS

Until now most studies on the value of CS were context- and user specific. Studies on how the existing information on the values can be upscaled are limited. Since the currently available CS are limited in number, it is difficult to determine the value of CS when many more CS and CS providers would be available. It will be important to investigate how the extension of CS provision will influence the actual and perceived value of CS.

Influence of standards, quality assurance, uncertainty levels and tailoring for the valuation of CS

The full use of the merit of CS can be enhanced by agreeing on widely shared standards and quality assurance procedures and communication. The use of climate services can be originally motivated by operational worries about resilience, or by disaster risk reduction goals, or adaptation strategies, external regulation, or broader scoped sustainable development goals (incl. mitigation). These different motivations can cause that very similar core climate information has to be packaged and presented in very different ways. Also steering a part of the climate model development on the basis of feedback from users can further enhance the merit. Research is needed to understand how standards, quality assurance, tailoring of climate data can contribute to the value of CS.

Influence of perception and background knowledge on valorization and uptake

Differences in valorization (value attribution) among users emerge in terms of capabilities to manage climate related information. There is an urgent need for capacity building to get a wider use of the various climate services. It will be needed to understand which knowledge results in a higher uptake.

Balance between public and private services (including ethical issues)

Increased uptake of climate services does not only benefit economically the direct users, but generates social and environmental value as well. However, the market mechanisms do not account for the benefit of third parties other than supply and demand. Within and across sectors heterogeneity, ethical issues and variety of facets of the value embodied in climate services (including social aspects) raise the question about whether climate services, under certain circumstances, should be provided as public services or whether and how the market should be regulated. A balance is needed between open source services and private services for equitable access, innovation, and market development, where innovation refers both to the information content of CS and to the way of provision. Inequality is fed not only by knowledge gaps, but also by affordability issues that exclude part of the potential beneficiaries from the information.

Links and synergies

The proposed research topics will bring insight to the development of the market for climate services and serve GFCS, C3S and national climate services.

Expected outcomes

- An overview of potential benefits from climate services and how they can be measured/estimated, with examples and rough estimates of the range;
- Better evidence of the product merit and identification of barriers for uptake, which will be important to remedy the low uptake caused by low expected values.

Standardizing climate services

Standards are key mechanisms to guarantee suitability, quality, and performance of technological solutions. They also provide common terminology between user, provider, and purveyor communities. The need for quality control, standards and certification for climate services emerged in consultations with users during the design of the European Roadmap for Climate Services. Users argued for standardization of the climate service field in order to generate trust across supply and demand, providing the infrastructure for a climate service market (public and private). Although there exist standards for some components of climate services, there is a need for a coherent and agreed upon set of authoritative standards for the overall value chain, in particular for services tailored to users.

Contribution to the vision

Standardization of climate services can be a critical aspect in the transformation towards a sustainable and resilient society, given standards enable the fast adoption of technologies, generate consensus, integrate multiple technologies, and contribute to the widespread and comparable use of solutions. In 2013, the European Commission adopted an EU Strategy on Adaptation to Climate Change and invited the European Standardization Organization to contribute to the European efforts aiming to make Europe more climate-resilient. The strategy highlights the key role of standards in securing climate resilience.

Background: lessons learned and gaps

Although there is an increasingly widespread availability and use of "downscaled" climate change scenarios, the lack of data with sufficient quality control creates a danger of misrepresenting the uncertainty of future climate. As climate services specific to users are developed, there are no widely acknowledged standards to certify that these are of sufficient quality. Standardization of the field will enable Europe to advance the integration of climate into many other relevant sectors.

There are standards for meteorological and hydrological instruments and methods of observation mandated by WMO enabling exchange of meteorological data and products, and also for data and metadata to exchange climate model results by the WCRP. However, there are only few standardization processes in Europe for climate products. Of particular importance is the C3S project, in its initiation phase. Quality control is a key part of C3S and ongoing projects will provide information on gaps and identify next steps required to enhance quality.

The INSPIRE Directive does not have fixed standards but provides guidance. On the other hand, Open Geospatial Consortium has formal standards. Eurostat's mission provides the European Union with a high-quality statistical information service through standardization of statistical methodology, statistical data and metadata access and exchange as well as data transmission.

CEN-CENELEC Standardization on Climate Change Adaptation supports the implementation of the EU Strategy on Adaptation to Climate Change. The International Organization for Standardization (ISO has climate change and related standards, as well as standards for software and quality management. The International Committee for Weights and Measures ensures that all meteorological and hydrological data are based on units traceable to the International System of Units. Existing standards for data formats data visualization and online interfaces are relevant for CS.

In general, there are more WMO standards (documentation, metadata, validation protocols) for observations than for model-based data. Re-analyses and climate predictions still have to develop robust common standards, while under WCRP, the CMIP experimental set provides a strong basis for model evaluation. CMIP already includes standards for data and metadata that are strictly followed by the community. However, in many cases, data from re-analyses, climate predictions and projections are not sufficiently well-documented, especially regarding how they are or not fit for purpose. Standards for decadal and longer-range forecasts and projections are not yet set, and procedures for these timescales remain active areas of research. Verification of projections comparing past forecasts with historical observations is not possible, but it is possible to provide some indication of the quality of the information, such as how it represents the uncertainty in the projected climate. In the interim, guidance on best practices is needed because of the large uncertainty in forecasts and the potential to underestimate uncertainty, especially when computing resources are limited. IPCC is working on this but it requires wider efforts.

There are also relevant shortcomings in the standardized biological and socio-economic variables and there is a need to ensure these data can be adequately integrated with climate data. Metadata standards exist for some ECVs and networks. Where they do not exist, international standards and procedures for the storage and exchange of metadata need to be extended to all Essential Climate Variable products and networks. In addition to metadata, assigning Digital Object Identifiers (DOI) to the data and products will enhance their traceability and enable estimates of the data's impact and influence.

Research needs

Establishing and sustaining quality control and standards

The need for generating standards and quality control as identified in the European Roadmap for Climate Services have not been met. There is a need for exploring optimal mechanisms for establishing and sustaining delivery of quality control and standards; what are appropriate mechanisms, including open and licensed standards, with the overall intention of building and retaining the trust between users and providers. These include the need for pilot studies and demonstration projects on uncertainty analysis and quality control with supportive case studies at various levels (national to European and global), and delivery domains (public and private), including exploration of means of sustaining the required activities beyond the projects and studies. Metadata guidelines to document in a comparative manner climate service data sources and processing methodologies are needed.

Providing best practices and guidance

Common standards for observations have to ensure that data from different instruments and places are comparable. The increasing availability of remotely-sensed data from satellites, radars and other automatic systems makes standardization more urgent. Providing best practices, guidance, and standardization of climate model outputs and verification methods for long-term forecast products will give indication of quality and reliability. In addition, there is a need to identify what standards of documentation are necessary for robust sectoral decision-making.

Defining verification and certification methods

Verification and certification methods, and identification of the actors to verify and certify would enhance quality and provide trust as well as enhance the use of CS. In addition, raising trust can be achieved by developing competence on CS and this can be accomplished by providing a review of the education qualifications and skills required for climate specialists and providing educational programs. There is also a demand for establishing unified terminology between user, provider and purveyor communities.

Links and synergies

The proposed activities should take place in close cooperation with standardization organizations in Europe and internationally, GFCS internationally, but also the Climate Service Partnership, and JPI Climate and Copernicus. Moreover, links should be established to any ongoing efforts to standardize elements of CS, such as in the frame of IPCC and WMO.

Expected outcomes

- Quality control measures and standards will be piloted and their value (related to growing the climate service market) demonstrated and recognized within the climate service community (users and providers);
- Unified and legitimate terminology will be settled. Documentation guidelines on climate data sources and methodology used;
- Mechanisms for establishing and sustaining the use and further development of these quality control measures and standards will be explored and their value recognized within the climate service community.

[11] *CEN-CENELEC Standardization on Climate Change Adaptation* https://www.cencenelec.eu/standards/sectors

Strengthening the links between the Climate Modelling and Climate Service communities

Enhancing and supporting the cooperation between the Climate Modelling and Climate Services communities would be of benefit for both communities in term of informing and rationalizing the pull for outputs from climate modelling and impact communities activities and informing the potential for additional (and potentially more) relevant climate services based on research directions and outputs. Both communities could also benefit from shared development in using big data technologies to enhance efficiency in extracting information from climate data.

Contribution to the vision

Climate services aim at better inform users to enable efficient adaptation and increase resilience of social-ecological systems to climate and environmental change. Strengthening the links between climate models and climate services will enhance the scientific basis for climate services and ensure best exploitation of climate information for the benefit for users.

Background: lessons learned and gaps

As emphasized in the European research and innovation roadmap for Climate services published in 2015, "a critical element of enhancing the quality and relevance of climate services is strengthening the scientific basis of the modelling and predictive aspects behind those services". Climate services can benefit for example from enhanced spatial resolution and better description of processes in climate models. They also highly needed to best account for uncertainty in climate projections. Reversely, climate services can help climate models better address new scenarios and/or problematics related to user needs.

Although there have been investments under H2020, for example through the Climateurope CSA, the ERA-NET for Climate services and other projects, there is a need to go a step further in engaging the climate modelling, climate impacts and climate service communities to get more mutual benefits. Indeed, climate services have strongly emerged and been developed during H2020 and are now in a better stage for further engaging with modelling communities in foresight capabilities.

Among common issues, how to best deal with the large amount of climate data is central to the whole chain of climate modelling to climate services. Recent developments in artificial intelligence, and in particular in the use of new machine learning algorithms, create a unique opportunity to generate valuable new insights from climate data for climate services, to be used in decision-making.

Research needs

Developing common foresight capabilities

Developing common foresight capabilities towards supporting socio-technical imaginaries would enable to assess existing links and engagement activities of the climate modelling, climate impacts and climate services development communities. This would allow identifying strengths, possibilities and gaps, as seen from the perspective of these communities. This would also identify options for delivering beneficial engagement activities with supportive demonstration activities, including demonstrating and disseminating an assessment of the realized impacts/benefits.

Among possible demonstration activities, the climate modelling community should dedicate some of their efforts to be able to respond to users helping them to develop their socio-technical imaginaries towards resilient futures. In terms of transdisciplinary approaches, the climate modelling community should support the inclusion of non-formal knowledge into the process and the development of capacity building steps designed together with social scientist to get the maximal possible increase of capabilities by users. This includes communication on what models are good at (or not) and how they can be used for decision-making. Together, climate modelling and climate services should develop a better way of handling and presenting uncertainty in climate projections as well as strengthen common evaluation methodologies. They could also jointly design simulations to better address user needs. Climate services on their side should investigate how to include more services from new developments in models.

Benefitting from artificial intelligence approaches

Special emphasis should be placed on the possibilities that machine learning and artificial intelligence offer for both climate modelling and climate services. On one side, it can provide improvements of process-representation in climate models and on the other side, help data analyses, for example by tailoring climate model data to the specific needs of different socioeconomic sectors in support to climate services. Machine learning will in particular be needed in two essential research issues concerning both climate modelling and climate services communities: extreme events and observational gaps. By definition, both issues are limited by observation scarcity and would benefit from learning approaches to better exploit observations and model results.

Links and synergies

Research on these topics will be of benefit for both WCRP and Climate Services initiatives (GFCS, Copernicus) as well as for other international efforts addressing similar connections.

Outcomes

- Recognized and sustained mechanisms for engagement of the climate modelling, climate impacts and climate service development communities that are able to demonstrate the respective benefits of their engagement and the benefits of sustaining such mechanisms;
- Enhanced confidence in extreme events forecast and projections and improved information in regions with limited data, such as parts of Africa, by using machine learning approaches.

List of acronyms

AIMES - Analysis, Integration and Modelling of the Earth System (https://aimesproject.org/)

C3S - Copernicus Climate Change Services (https://climate.copernicus.eu/)

CCA - Climate Change Adaptation

CEN - European Committee for Standardization

CENELEC - European Committee for Electrotechnical Standardization

CLIM-RUN - Climate Local Information in the Mediterranean region Responding to User Needs (FP7 project) (www.climrun.eu)

Climate KIC - EIT Climate Knowledge and Innovation Community (https://www.climate-kic.org/)

CLIVAR - Climate Variability and predictability (www.clivar.org/)

CMIP - Coupled Model Intercomparison Project of WCRP

(https://www.wcrp-climate.org/wgcm-cmip)

CORDEX - Coordinated Regional Climate Downscaling Experiment (https://www.cordex.org/)

CRESCENDO - Coordinated Research in Earth Systems and Climate: Experiments, Knowledge, Dissemination and Outreach (https://www.crescendoproject.eu/)

CS - Climate Services

CSA - Coordination and Support Action

CSP - Climate Services Partnership (http://www.climate-services.org/)

CSR - Climate Services Research

DOI - Digital Object Identifier

ECV - Essential Climate Variable

ERA4CS - ERA-NET for Climate Services (H2020 ERA-NET with JPI Climate)

(http://www.jpi-climate.eu/ERA4CS)

ESMs - Earth System Models

EUCP - European Climate Prediction system (H2020 project)
(https://www.eucp-project.eu/)

EU-MACS - European Market for Climate Services (H2020 project) (http://eu-macs.eu)

EUPORIAS - EUropean Provision Of Regional Impact Assessment on a Seasonal-to-decadal timescale (FP7 project) (www.euporias.eu)

EURO-CORDEX - Coordinated Downscaling Experiment - European Domain (https://www.euro-cordex.net/)

FP7 - Framework Program 7

GFCS - Global Framework for Climate Services (https://www.wmo.int/gfcs/)

IMPREX - Improving Prediction and Management of Hydrological Extremes (H2020 project) (https://www.imprex.eu/)

INSPIRE - Infrastructure for spatial information in Europe

IPCC - Intergovernmental Panel on Climate Change (https://www.ipcc.ch/)

IS-ENES - InfraStructure for the European Network for Earth System Modelling, phases 1 to 3 (FP7 and H2020 projects) (https://is.enes.org/)

JPI Climate - Joint Programming Initiative on Climate (http://www.jpi-climate.eu/)

MARCO - Market Research for a Climate Services Observatory (H2020 project)

(http://marco-h2020.eu/)

PRIMAVERA - PRocess-based climate sIMulation: AdVances in high-resolution modelling and European climate Risk Assessment (H2020 project) (www.primavera-h2020.eu)

RCMs - Regional Climate Models

S2S4E - Climate Services for Clean Energy (H2020 project) (https://s2s4e.eu/)

SDGs - Sustainable Development Goals

TRL - Technology Readiness Level

UNFCCC - United Nations Framework Convention on Climate Change

VISCA - Vineyards Integrated Smart Climate Applications (H2020 project) (http://visca.eu/)

WCRP - World Climate Research Program (https://www.wcrp-climate.org/)

WMO - World Meteorological Organization (https://public.wmo.int/en)

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