BAMS Article

# Recommendations for Future Research Priorities for Climate Modeling and Climate Services

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**ABSTRACT:** Climate observations, research, and models are used extensively to help understand key processes underlying changes to the climate on a range of time scales from months to decades, and to investigate and describe possible longer-term future climates. The knowledge generated serves as a scientific basis for climate services that are provided with the aim of tailoring information for decision-makers and policy-makers. Climate models and climate services are crucial elements for supporting policy and other societal actions to mitigate and adapt to climate change, and for making society better prepared and more resilient to climate-related risks. We present recommendations for future research topics for climate modeling and for climate services. These recommendations were produced by a group of experts in climate modeling and climate services, selected based on their individual leadership roles or participation in international activities. The recommendations were reached through extensive analysis, consideration and discussion of current and desired research capabilities, and wider engagement and refinement of the recommendations was achieved through a targeted workshop of initial recommendations and an open meeting at the European Geosciences Union General Assembly. The findings emphasize how research and innovation activities in the fields of climate modeling and climate services can contribute to improving climate knowledge and information with saliency for users in order to enhance capacity to transition to a sustainable and resilient society. The findings are relevant worldwide but are deliberately intended to influence the European Commission's next major multi-annual framework program of research and innovation over the period 2021–27.

**KEYWORDS:** Climate change; Climate prediction; Climate variability; Climate prediction; Climate models

https://doi.org/10.1175/BAMS-D-20-0103.1
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In final form 12 October 2020

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Climate varies naturally on a range of time scales, as evidenced in observational records and proxy records for periods predating observations. In addition to the natural variability, there is overwhelming evidence that climate is now also changing due to human emissions of greenhouse gases, as emphasized for example in the Intergovernmental Panel on Climate Change's (IPCC) Assessment Reports, the most recent being the Fifth Assessment Report (AR5; IPCC 2013) with the Sixth Assessment Report anticipated in 2021 (at the time of writing). The human-made changes are raising concerns over dangerous levels of climate change leading to major impacts on ecosystems and society. Avoiding dangerous climate change 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 preindustrial temperature (UNFCCC 2015). Climate research and climate modeling can help address the issues around how to reach this objective, such as the different possible pathways and the associated risks (IPCC 2018).

Understanding, assessing, and adapting to climate variability and change relies on information on a range of time horizons, from seasonal to multidecadal and longer. Climate models are developed and used to give us a better understanding of key processes underlying how climate changes on these time scales. 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, additionally include processes related to the carbon cycle, atmospheric chemistry, vegetation, aerosols, ecosystems, and biogeochemistry, as well as feedbacks occurring between those. In this article we will mainly use the term "climate models" as a shorthand to encompass the two classes of models. The models are used to investigate and describe the possible future climate, both in terms of predictions of the coming seasons and years, and longer-term projections for the coming decades.

Climate *predictions* are estimates of future climate conditions covering monthly, annual to decadal time scales, and are dependent on an accurate description of the initial state [e.g., Boer et al. (2016) for decadal predictions]. These *predictions* emerge as a key source of information for a growing number of users in need of relevant, actionable information in the time range of months to a few years. 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). The predictions and projections are typically built on an ensemble of simulations 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 (Cubasch et al. 2013). Both types of numerical experiments are highly dependent on the availability of computing resources. The trend toward higher spatial resolution (Schär et al. 2020), large ensembles of simulations (Deser et al. 2020), better initialization (Kushnir et al. 2019), and more complexity (Heinze et al. 2019) has resulted in higher quality and more useful information in a number of instances, which in turn calls for increasing resources.

The outputs from climate models, and knowledge gained from them, serve as a scientific basis for climate services that are intended to provide tailored information to decision-makers and policy-makers. Climate models and climate services are crucial elements for supporting the policies and decisions on mitigation and adaptation to climate change, and for building a society more resilient to climate-related risks. However, the climate information needs to be tailored to the contexts of the decision-making and perception of the users (Máñez Costa et al. 2017), combining information from models with other information relevant for users to enable the integration of climate risks into their decision-making processes (Hansen et al. 2019). Such user-oriented decisions and applications often require information at regional or local scales. To achieve this, some global models have variable mesh grids which can zoom in on certain areas, alternatively global model output is traditionally downscaled from coarse grids by means of regional climate models, or via statistical approaches, and undergo further tailoring procedures such as bias adjustment, weighting, and selection techniques (van den Hurk et al. 2018). In all cases, assessment and communication of the uncertainty in the climate information are essential.

To help address society's challenges, it is crucial that we understand current and future climate, variability, and extreme events, and their impact on societal vulnerability. It is also important to enable efficient communication of robust information to decision-makers to yield key actions for sustainable development. In some cases, thresholds and critical tipping points need assessing to properly support decision-making (Rölfer et al. 2020). The proposed recommendations for further research and innovation activities presented in this article are intended to improve climate knowledge and information for users, to enhance the capacity to transition to a sustainable and resilient society. The transition to a sustainable society, resilient to climate-related risks, is a complicated challenge that requires enabling people and communities to anticipate the risks, reduce their adverse impacts, recover and bounce back from difficulties and crises, and continue to function and grow. The challenges need interdisciplinary and multidisciplinary worldwide efforts and coordination, combining natural and social sciences and public and private sectors.

## Methodology and approach

The recommendations were compiled by a group of 12 European experts in climate modeling (including Earth system modelers) and climate services, under the auspices of the Climateurope project (Hewitt et al. 2017), and are the authors of the article. The compilation also drew on a much larger group of experts to supplement the knowledge of those within the Climateurope project. The larger group (listed in the Acknowledgments) were selected based on their individual leadership roles as Principal Investigators of research projects or on their participation in international programs and initiatives related to climate modeling and climate services. Many of these experts in turn invited members of their own networks to contribute to this effort.

The starting point for this work were ideas from previous discussions and consultations held in the frame of Climateurope as well as of other initiatives, such as the Copernicus Climate Change Service (C3S) and international programs such as the World Climate Research Programme (WCRP). Documents of references included the Climateurope position paper on recommendations for climate services science, research, and innovation, resulting from a meeting with key stakeholders held at the European Commission in 2018, the Roadmap for European Climate Projections produced by the C3S, the IPCC AR5 and Special Report on 1.5°C (IPCC 2013, 2018), the United Nations Framework Convention on Climate Change Paris Agreement, and the WCRP strategic plan (WCRP Joint Scientific Committee 2019).

To galvanize ideas, and to draw on the knowledge of the wider group of experts, a workshop was held in February 2019 which subsequently resulted in a list of recommendations on research needs. The list of recommendations was further discussed in an open meeting at the General

Assembly of the European Geosciences Union in April 2019. The recommendations were then revised further and made available to the European Commission, who wanted advice on gaps and priorities to help them develop the European Union's scientific research initiative, Horizon Europe, for the period 2021–27. However, the recommendations are likely to be of relevance and interest to a much wider audience of funders and scientists from around the world.

The recommendations are presented below (and illustrated in Fig. 1) as high-level research topics, starting with climate modeling and continuing with climate services, mirroring the chain of information transfer from science to society. However, we do not intend to imply a separation between climate modeling and climate services and the different recommendations may well be linked and integrated in some cases. Each recommendation has a short paragraph summarizing the issue to be addressed, then a summary of the research needs identified as priorities, and a short paragraph summarizing the expected outcomes, links, and synergies. Given the broad range of topics and the differing priorities of our intended audience, we have not ranked the recommendations.

## Recommendations for climate modeling

***Support the IPCC process.*** The IPCC Assessment Reports (ARs) are crucial to support international policy on climate change. The Coupled Model Intercomparison Project (CMIP; Eyring et al. 2016) has become the essential coordination for evaluating climate models and for providing future projections, but also for improving understanding of climate variability and change. Access to multimodel ensembles, well evaluated on historical and past climates, is necessary to enhance robustness and assess uncertainties of projections.

The ARs emphasize the knowledge gaps in climate science, and it is vital that funding bodies keep supporting science to address such knowledge gaps. After AR6 this is likely to include uncertainties in cloud and aerosol properties and related feedback processes, Antarctic ice sheet dynamics and global sea level, ocean circulation changes, and changes in ocean chemistry between 1.5° and 2°C and their implications on natural and human systems.

Funding bodies also need to support internationally coordinated experiments (i.e., CMIP7), which will be used in future ARs. The provision of multimodel projections with the most up-to-date, well-evaluated climate models will be important to inform mitigation and adaptation

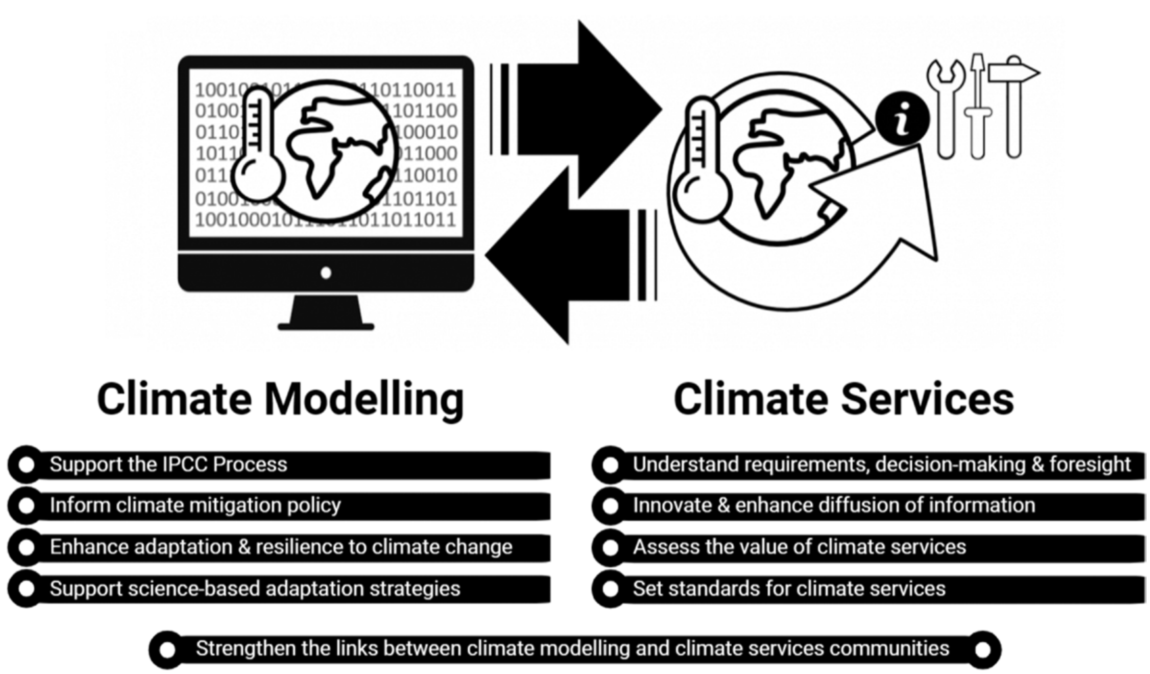


**Fig. 1. Illustration of the nine high-level recommendations.**

policy in support to the UNFCCC. The protocols for the CMIP7 simulations, including defining greenhouse gas, aerosol, and land-use forcings, need to be defined earlier than was done for CMIP6, and more support is needed to make it a joint, well-resourced international community effort under WCRP. The absence of open-source tools that allow community-wide participation in delivering research to address specific policy questions is a major problem, and open-source methods and publicly available tools would substantially improve analyses prior to AR7.

Research activities should ensure world-leading support and contribution to the CMIP simulations and their subsequent use to underpin the IPCC AR7, allowing the exploration of novel, societally relevant research questions, and to address key knowledge gaps strongly affecting mitigation and adaptation policies.

***Informing climate mitigation policy: Scenarios with risk of overshoot.*** The 2015 Paris Climate Agreement aims to hold global warming below 2°C above preindustrial levels and to pursue efforts to limit it to 1.5°C. Given observed warming is already ~1°C and emissions of $CO_2$ continue to increase, an overshoot of one or both targets needs to be considered, at least temporarily, before possibly returning below the target through aggressive mitigation (IPCC 2018). It is essential to assess and inform on the risks of overshooting and on associated impacts, as well as to understand the interference of possible related abrupt events and the impacts of mitigation actions.

These issues call for several developments in climate and Earth system modeling. A range of feasible overshoot scenarios based on the 1.5° and 2°C targets needs to be developed for state-of-the-art models and considered for CMIP7. Refinements in the realism of processes in models with respect to terrestrial and marine climate and carbon cycle (land use change, permafrost, wetlands, wildfires), the efficiency of natural carbon uptake, short-lived climate forcers, and ice sheets, are necessary. Increased resolution would improve the simulation of the key dynamical modes in the climate system that are at risk of changing. Processes underpinning uncertainty in estimating Earth's climate sensitivity need to be investigated. Alternatively, novel ways to explore parametric and structural uncertainty in climate models would help assess the risks of overshoot related to low-probability, high-impact outcomes, while remaining computationally affordable.

The resulting simulations will be instrumental in risk assessments, help estimate the achievability and the types of mitigation, identify related impacts, and estimate interplay and reversibility of any triggered changes. These studies should be carried out in synergy with WCRP, IPCC, and Future Earth, and help design and calibrate further policy actions and support the UNFCCC global stock take process.

***Enhancing adaptation and resilience to climate change, especially extreme events.*** Extreme events are a particular concern due to their high impact. Despite improved understanding of extreme events, including general agreement that extremes such as heat waves and heavy precipitation are expected to increase in frequency and intensity in a warming climate (Seneviratne and Hauser 2020), further research is needed to address the remaining large uncertainties with regard to regional patterns and magnitude of changes. The aim is to be able to assess issues such as how will infrastructures, cities, human health, and ecosystems be affected and how can we ensure they are resilient or adaptive enough to changes in extremes.

Research is needed to improve the simulated changes in weather and climate extremes with a better understanding of how model biases affect the representation of the intensity and frequency of hazards. 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. Developing climate models at a very high resolution able to explicitly represent deep convection and ocean eddies is expected to make a step change in the representation of extremes (Schär et al. 2020). This will require developments to the models as well as making the models run on exascale computing and handling data at unprecedented scales (Palmer and Stevens 2019). Such developments would benefit from interdisciplinary approaches with software and hardware specialists. There is a need to create and improve observational datasets and high-resolution regional reanalysis datasets to validate these models.

The expected outcomes include greatly improved simulations of extremes on a range of time scales, better information for climate services to facilitate climate change adaptation, and improved resilience to extremes. The research will be of benefit for initiatives such as the WCRP grand challenge on extremes, major adaption initiatives such as the Horizon Europe Mission on adaptation, the Coordinated Regional Climate Downscaling Experiment (CORDEX), and its Flagship Pilot Studies related to convection-permitting regional climate models (Kendon et al. 2017; Coppola et al. 2020).

***Supporting the science-based formulation of adaptation strategies.*** Adaptation strategies need information on climate and impacts at the regional to local scale, ranging over time scales from seasons to years to decades under different emission scenarios. Climate models can provide such essential information but need to be supported by understanding of processes.

Aligned to the comments above regarding the need for high resolution to represent extremes, adaptation strategies at the regional and local scale clearly require the climate data to be downscaled. Increasing the ensemble size of predictions and projections will lead to better uncertainty estimates, especially those related to extremes that are better represented in high-resolution models. In addition, there is a need to strengthen the interactions between impact models and climate models, further developing and exploiting climate models for the impact studies. Region-oriented climate information requires guidance on selection or aggregation of model data for impact assessments, allowing transformation of uncertainty into manageable information. Selection or aggregation should be based on region- and time-scale specific drivers of climate impacts, and be consistent with historical records. The multi-annual time scale between seasonal forecasts and climate change projections is important for many users and is an active area of research through decadal predictions which are starting to provide information of sufficient skill and detail for some users (Smith et al. 2019; Solaraju-Murali et al. 2019). However, more ambitious initiatives are needed to further develop the emerging operational decadal forecast products, including better understanding and representation of processes, teleconnections, and uncertainty; better models, in particular improving the signal to noise ratio in the models; improved initialization; and better infrastructure design.

The expected outcomes will be to create stronger links between climate models and impact models to provide more robust support for adaptation studies, and being able to provide robust information with the detail required to be of widespread use to decision-makers for adaptation planning, with huge possibilities for predictions on multi-annual time scales with sufficient skill and detail. On that last point, existing ties could be strengthened with the WCRP Grand Challenge on Near Term Climate Prediction, the WMO Annual-to-Decadal Climate Prediction operational exchange, and the WCRP Decadal Climate Prediction Project.

## Recommendations for climate services

***Understanding requirements, decision-making contexts, and foresight for climate services.*** Climate services are key to supporting society's transition toward a more resilient and sustainable future. To do so, it is essential to understand users' requirements and decision-making contexts. Cross pollination between humanities and social and natural sciences is needed to include the human dimensions into climate services research and development to support the transition toward resilient societies. At the same time, we should aim to increase the Technology Readiness Level (National Research Council 2000; Héder 2017) of climate services along with their Market and Institutional Readiness.

Climate services should be grounded in participatory research, should foster social science, and should be trans-disciplinary to ensure the services can underpin varying contexts in decision-making. Climate services should be developed to help foresee possible futures under a diversity of scenarios since people often have difficulty imagining and understanding what can change in the future or what the impact of the current way of life will be. Our knowledge of the climate system and impacts of climate can help to show these futures and may spur people into action to transform to more resilient societies. Decision support demands a more active role of scientists in understanding the culture, governance structures, and contexts in which decision-makers operate. Having scientists and decision-makers work closely together can be beneficial to all parties. In situations with limited climate data availability, climate services may support decision-making under deep uncertainty, and in addition the governance and availability of data needs to be made as clear and equitable as possible. Analyzing ambiguities would help to reduce the complexity of the system and increase the effectiveness of policy measures (Brugnach and Ingram 2012). Last, different audiences have their own preexisting beliefs, attitudes and values, and sources of authoritative knowledge (Máñez Costa et al. 2017). Science communication will benefit from understanding these differences better. More effective methods for communicating uncertainty, identifying optimal communication strategies, and exploring and evaluating new communication tools need to be developed.

The expected outcomes include stronger links between different scientific fields (such as climate, impacts, social sciences, humanities, communication), resulting in more robust communication, methodologies, and support for adaptation studies also at the local level, and better understanding of the Technology, Market, and Institutional Readiness Levels.

***Innovation and enhanced diffusion of information.*** Many of the current climate services draw on climate predictions and projections and produce case studies, prototypes, and semi-operational demonstrators and operational services, often based on well-established experiences such as those gained from developing and providing weather services. The exploration and adoption of new and innovative, even disruptive, development practices could lead to a fundamental improvement in the provision and uptake of climate services. Innovation in the business models adopted for climate services will be key for the upscaling and generalization of their use in decision-making (Brooks 2013).

Future research should enable the adoption of innovation in products and processes along three main lines. One is to develop demonstrators and prototypes (see, e.g., Hewitt et al. 2020b), but going further and integrating climate information with nonclimatic information, co-producing services to prove the market potential and highlighting user needs (Vincent et al. 2018; Goodess et al. 2019), and tackling various challenges related to the amount and size of the required data. Another is to be able to provide services seamlessly across whatever range of time scales the users need, potentially including linking to shorter-term weather time scales. This challenge demands new methods and services for climate (and weather) indices at different temporal scales and tailored products consistent across temporal and spatial scales. The contribution of such services to adaptation should be evaluated, along with the impact on key sectors of society. The third line is to understand and overcome market-related barriers to climate service uptake, such as overcoming reluctance from industry to use climate information, regulatory uncertainty, competition regulations, and ethics (Perrels et al. 2020).

The innovations should make climate services far more useful and valuable to users, and allow the services to address specific, complex adaptation issues. Innovations could incentivize a climate services market and could bear a positive feedback on upstream technology markets. A specific opportunity is to strengthen ties between activities undertaken by industry and national climate service providers, as well as international programs attempting innovation such as Europe's climate knowledge and innovation community (Climate-KIC, www.climate-kic.org/). As noted in Hewitt et al. (2020a), the private sector is already engaged in the development and delivery of climate services with different knowledge of the needs of users and different approaches to research and development, often with more rapid development cycles than public sector organizations.

***Assessing the value of climate services.*** Climate services are being used to inform decisions and policies to help avert the negative effects and embrace opportunities related to climate change and climate variability. While there is a sizeable body of knowledge on the economic and social value of weather services (Hallegatte 2012; WMO 2015), the value or benefits of climate services are poorly understood or known (Buontempo et al. 2018; Hoa et al. 2018). There is also a need to consider what constitutes value from an ecological, social, ethical, or economic point of view. This lack of knowledge and failure to articulate the benefits is hindering the awareness and uptake of climate services.

We identify four priorities. First, most studies on the value of climate services have been context and user specific, and a rigorous investigation is needed to assess how "value" can be assessed to cover a much larger range of contexts and users, and to account for the potential for many more climate services being provided. Second, an assessment is needed to determine to what extent a lack of agreed quality assurance and standards for climate services (a topic discussed below) is hampering the perceived value by users, and to what extent current climate services are sufficiently tailored to the users' needs to be of value (Zeng et al. 2019). Third, there is an opportunity to develop the capabilities of the users to enable them to use and benefit from climate services. Last, a balance is needed between paid for and free services which does not stifle innovation and market development, and improves social, environmental, and economic benefits. As noted above, the national climate service providers and private service providers both have roles to play here.

Research activities would be expected to provide qualitative and quantitative evidence of potential benefits and value of climate services, supported by real examples. Barriers for uptake of climate services can be identified and mitigated against. The outputs will be of great interest to climate service providers and investors.

***Standards for climate services.*** Standards are established by a consensus of subject matter experts and approved by a recognized body to provide guidance on the design, use, and performance of products and services as a means of assuring suitability and quality and enabling certification. There are widely used WMO standards for collecting and exchanging climate observations, and some for producing model-based reanalyses, predictions, and projections as well as many guidelines (e.g., WMO 2018). There are also some broad standards for climate change adaptation and mitigation within the ISO 9000 and 14000 families of standards. However, there are currently no widely acknowledged standards for the climate services, which raises the danger of poor-quality services, and misunderstanding, misrepresenting, or misusing the climate information.

Guidance and examples of good practice are needed on how to use climate information from observations, models, and other sources. Guidance should include how to identify the limitations of the information to prevent its misuse, and what the information is fit for, all from the perspective of decision-makers. Issues such as uncertainty, reliability, and skill will be important. Standards for climate services need to be discussed by subject matter experts and approved by a recognized body, such as the International Standards Organization. Consideration should be given for how the services are developed, for example, setting minimum standards for how uncertainty in climate information is accounted for, communicated, and used. Demonstration projects on uncertainty and quality control with supportive case studies would be useful. Verification and certification methods should be developed, and identifying the actors to verify and certify would enhance quality and build trust in the services. Trust can also be built by developing competence on climate services through recognized qualifications and skills, providing educational programs, and through cooperation with competent providers.

The expected outcomes are that common terminology, quality control measures, and standards will be developed and used and their value widely recognized, ensuring that climate information is used appropriately and effectively in decisions, be it in free and paid services, or public or private sector enterprises. The activities should take place in close cooperation with standardization organizations and the major climate service activities such as the Global Framework for Climate Services (Hewitt et al. 2020a), the Climate Service Partnership (CSP), and C3S, all of which have identified standards as a key issue.

***Strengthening the links between climate modeling and climate service communities.*** Climate services aim to better inform users to enable efficient adaptation and to increase resilience to climate and environmental change. Strengthening the two-way interaction between climate modelers and climate service providers will enhance the scientific basis for these services and the relevance of climate research and modeling outputs. The different communities benefit from networking activities, and such networks need to be actively managed to be useful, such as currently exist globally through the CSP and GFCS, and in some regions and nations too.

The different communities could benefit from shared development in using big data and intelligent technologies (such as machine learning) to become more efficient at extracting information from the large amount of climate data. Such shared development can improve the representation of processes in climate models and help data analyses for tailoring data for specific socioeconomic sectors. They may help also in regions lacking sufficient observations to generate better information about extreme events.

Developing common foresight capabilities toward supporting sociotechnical imaginaries will show the strengths and gaps in the existing links between the climate modeling, climate impact and climate service communities. Climate scientists together with social scientists should support the inclusion of nonformal knowledge into capacity building. This includes communication on what models are good at (or not), how to use them for decision-making, and ways of handling uncertainties. They could also jointly design simulations and the analysis of the outputs to better address user needs (van den Hurk et al. 2018). Climate services should investigate how to include more services based on new developments in climate models.

The expected outcomes include mechanisms and demonstrated benefits for engagement and networking of the climate modeling, climate impact and climate service communities, ultimately leading to enhanced confidence and value of climate research outputs.

## Conclusions

We make nine recommendations for key priorities for research and development in the fields of climate modeling and climate services, fields which 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. The recommendations were devised by a group of experts through analysis, wider engagement, and consultation.

The findings emphasize how research and innovation activities can contribute to improving climate knowledge and information to users in order to enhance capacity to transition to a sustainable and resilient society. The findings are relevant worldwide but were originally commissioned to influence the European Commission's next major multi-annual framework program of research and innovation over the period 2021–27 for the cluster related to "Climate science and solutions" and have since generated interest from several groups and activities. We hope this article will satisfy a wide range of readers, including scientists, model developers, climate service providers, decision-makers, policy-makers, and funders of science.

It is our hope that the next steps will be that the climate research, modeling, and services communities will be motivated to address the recommendations through research and development activities. Such research and development are dependent on funding, and for most of these recommendations the funding needs to be significant and sustained over many years, so we hope that funders will be motivated and inspired to support such activities. Finally, the most important purpose of the science, modeling, and services is to address the challenges arising from climate variability and climate change, while building a sustainable society and economy resilient to such changes. Decision-makers and policy-makers are the key to ensuring the world can cope with climate-related hazards and opportunities, and we hope this article ultimately contributes to aiding the decision-makers and policy-makers in years to come.

**Acknowledgments.** This work was conducted under the Climateurope project funded by the European Commission through the Horizon 2020 Programme for Research and Innovation: Grant Agreement 689029. We would like to acknowledge the European Commission for wanting to have the recommendations, and the following experts who contributed their time and ideas through workshops and discussions: Mario Acosta, Dragana Bojovic, Laurent Bopp, Olivier Boucher, Pascale Braconnot, Carlo Buontempo, Markus Donat, Eric Hoa, Bart van den Hurk, Daniela Jacob, Colin Jones, Filip Lefebre, Jaroslav Mysiak, Slobodan Nickovic, Steffen M. Olsen, Mark Payne, Adriaan Perrels, Joeri Rogelj, Doug Smith, Roger Street, Jean-Noel Thepaut, Alberto Troccoli, Pier Luigi Vidale, and Ilaria Vigo. We also would like to thank the two anonymous reviewers.

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