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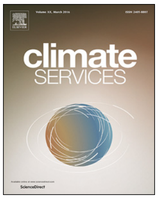

Perspective

The match between climate services demands and Earth System Models supplies

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ABSTRACT

Earth System Models (ESM) are key ingredients of many of the climate services that are currently being developed and delivered. However, ESMs have more applications than the provision of climate services, and similarly many climate services use more sources of information than ESMs. This discussion paper elaborates on dilemmas that are evident at the interface between ESMs and climate services, in particular: (a) purposes of the models versus service development, (b) gap between the spatial and temporal scales of the models versus the scales needed in applications, and (c) Tailoring climate model results to real-world applications. A continued and broad-minded dialogue between the ESM developers and climate services providers' communities is needed to improve both the optimal use and direction of ESM development and climate service development. We put forward considerations to improve this dialogue between the communities developing ESMs and climate services, in order to increase the mutual benefit that enhanced understanding of prospects and limitations of ESMs and climate services will bring.

1. Introduction

By following the evolution of the Intergovernmental Panel on Climate Change (IPCC) assessment reports since the First Assessment Report in 1990 one can see a clear development of the scope of the underlying climate science. In the early assessment reports the emphasis was on the exploration of the working mechanisms of the climate system and the potential response to enhanced greenhouse forcings. In later assessment reports the importance of attribution of climate change to human behaviour gradually increased. In parallel to the need to understand recent climate change and extreme events, there is also the need to understand the *impacts* of climate change. This led to the development of "actionable" science (WCC3, 2009), which is now turning into concrete "climate services".[1] Basic understanding of the climate system and the associated development of climate models and observations continues to receive attention, but it becomes clearer with time that this scientific knowledge should be made available and useful to society (Ohtake, 2017).

Complexity of Global Climate or General Circulation Models (GCMs) increased by adding physical and biogeochemical components, leading to the formation of sophisticated Earth System Models (ESMs). Dynamical downscaling of these models of the global system using regional climate models became a mature branch of modeling (IPCC, 2013), enhancing the spatial resolution of simulations in target areas, both to enhance physical realism and to reduce the gap to requested resolutions by the Vulnerability, Impact and Adaptation (VIA) community (IPCC, 2014). The introduction of initialized climate simulations opened the way for (probabilistic) seasonal-to-decadal climate predictions. This development is partly motivated by the focus on near-term episodes by users.

In parallel to the evolution of climate modelling, climate service concepts rapidly evolved. A strong societal demand for useful,

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[1] See for example http://www.wmo.int/gfcs/projects-map and http://www.climate-services.org/case_studies/ for examples of projects and case studies.

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actionable, credible and reliable information on the causes and consequences of climate variability and climate change emerged (leading to, for instance, the set-up of the Global Framework for Climate Services (Hewitt et al., 2012), the European ERAnet for Climate services). Climate information is also needed to support mitigation policies, since the quantitative links between human emissions, regional implementations of measures such as land use change, and climate response is an essential ingredient for defining the mitigation targets (IPCC, 2018). Impacts of climate change and variability need to be characterized in order to prepare for and adapt to a changing climate. Originally the transfer of climate information from the scientific to the societal arena was interpreted as primarily a "science communication" topic (Moser, 2010). However, climate service protocols are now explicitly addressing the role of intermediate agents in scientific, public and commercial domains (Buontempo et al., 2014; Christel et al., 2018; Street, 2016). Sophisticated procedures for "tailoring" climate services were initially limited to prototype services, but are increasingly being exploited in governmental and private climate impact assessment programs.[2]

The connection between the climate modeling and climate services communities is probably not as strong as desirable. Climate model development is being motivated and directed by the societal needs for climate information, but rather loosely and without a clear feedback mechanism. Climate services do make use of observations and outputs of ESMs, or their regional counterparts, but also of other tools, such as impact models, post processing and visualization, user consultations and co-production of user-oriented products (Goddard, 2016). For many climate services, ESMs are part of the value chain, but they play a relatively modest role, as also reflected in the definition of Climate Services for the European Roadmap (EU, 2015).

Here we explore this loose relationship between climate modelling and climate services and make various proposals to stimulate the design of useful linkages between climate modelling and climate services that will give cost-effective benefits to society as a whole.

2. Seeking the common ground

Several dilemmas prohibit a close interaction or overlap between the practice of climate modelling and climate services provision. The (non-exhaustive list of) dilemmas discussed here include (a) purpose of model versus service development, (b) the gap between the spatial and temporal scales of the models versus the scales needed in applications, and (c) usage of the models in real-world applications.

2.1. Setting the proper requirements for model versus service development

The development and application of climate models serves multiple purposes, including basic understanding of the complex climate system, education, simulation and prediction of possible or likely future climate in response to constructed emission scenarios, and uncertainty analysis of predictions and scenarios. The search for optimally representing relevant processes in order to accurately reproduce observed dynamical climate features is one major driver for model development. The modelling community justifies model development assuming that improved models are better tools to support climate service deployment. While in essence this is a valid statement, the level of model quality that is needed to support climate services varies widely with the applications and often is not even clearly formulated due to, among other things, the lack of a communication channel between the communities.

While climate models give essential input to some climate services, most services are based on more sources of climate information than climate model outputs. Observation-based climatologies and monitoring products, empirical forecast systems, uncertainty estimates and empirical or physical relationships between climate and impacts play a dominant role in many climate service applications (for example van den Besselaar et al., 2011; Preuschmann et al., 2017; Dilling and Lemos, 2011). They are important, certainly for those services that aim to obtain a first estimate of the vulnerability to climate (IPCC, 2014), refine current statistics and risks (for example Beersma et al., 2015) or use simple scenario approaches in decision support contexts.

The response to the question when climate models are relevant and fit for purpose for specific climate services depends on, among others, the required quality and level of understanding of complex climate processes, and the degree to which climate variability and uncertainty is important for the decision contexts of the climate services clients. Climate services such as the development of regional or national climate change scenarios and their impact assessments require a strong involvement of climate models (for example Preuschmann et al., 2017; Murphy et al., 2009). Other climate services require only a crude estimate of an assumed global temperature increase, for instance when the climate service is based on statistical scaling techniques and doesn't need a detailed mapping of (local) climate dynamics. Projections of local (extreme) precipitation serving for instance hydrological stress testing or seasonal rainfall mapping are often derived from statistical scaling techniques using generic indications of mean temperature change as input (for example Drobinski et al., 2016). By contrast, large biases in climate model output prohibit direct use in crop growth models that are calibrated to observed climate data (Bakker et al., 2014). Climate model bias in rainfall (number of wet days, amount per wet day) also affects the outcome of threshold-sensitive flood assessments (Teutschbein and Seibert, 2012). This wide variety of climate service applications should be kept in mind when claiming climate services requirements to be in the drivers' seat for climate model development (Hewitt et al., 2017, 2018).

For situations where increases in societal risks for weather or climate related damage are expected due to increased vulnerability or exposure, imposed by expanding population and settlement in risk-prone areas and other trends in human factors such as capital or coping capacity, climate services might provide relevant information about the current or past climate that is used as a reference, and the assessment of the change in societal risk consists of comparing multiple scenarios of human factors playing a major role (Berkhout et al., 2014).

The assessment of climate risk levels forms a strong bottleneck for many climate service applications, even under current climate conditions. Risks that heavily depend on complex or rare conditions are poorly known since observations are rare. Ensemble climate model output can be of great help to map the extreme tails of the hazard distribution (Thompson et al., 2017). However, when the representation of the relevant climate variability (such as atmospheric circulation statistics, extreme precipitation, build-up of drought conditions, oceanic modes) in the ensemble of models is poor, the quality of the risk estimate is likewise limited. Model development that helps understanding and improving the representation of the relevant climate variability will help to improve climate impact assessments, and thus to improve climate services.

Anticipating effects of climate change forces analysts to explore a wide range of possible future conditions. Mapping of cascades of various types of uncertainty is a key ingredient of the analysis, supported by climate model outputs. However, similar to the statement made above, the quality of the assessment relies strongly on the quality of the representation of variability in the models. Here the different types of "uncertainty" (natural variability, systemic uncertainty, dependence on

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[2] Some examples: IMPACT2C portal which visualizes the impact of global 2 °C warming (https://www.atlas.impact2c.eu/; EU-project), the climate impact atlas for the Netherlands (www.klimaateffectatlas.nl/en/), UKCIP program to support climate adaptation based on the national climate scenarios for the UK (http://www.ukcip.org.uk/), programme of consultancy company DNV-GL to address effects of climate change for business and society (https://www.dnvgl.com/services/climate-action-programmes-1570) (all accessed 31 October 2018).

greenhouse gas scenario, impact uncertainty) must be clearly distinguished. Analyses and systematic comparison with the best and most recent observations can guide model development in order to reproduce the observed variability (Flato et al., 2013). This will also enhance the credibility of estimates of uncertainties associated with emission pathways and feedbacks under unprecedented conditions such as presented in model predictions and projections.

2.2. Meeting the space and time scales

An obvious gap between climate models and many climate service applications is the difference in the primary spatial and temporal scale of interest. Global models operate on coarse spatial scales and parameterize fine grained processes. Coarse time scales (decades to centuries) are used for evaluation of climate change response characteristics and to allow detection of climate change signal in a noisy system. By contrast, climate services targeting stakeholders operating on a local spatial or sectoral scale request information at fine spatial resolution and time horizons that match the decision contexts at hand. The potential mismatches are partly being overcome by multiple techniques (such as downscaling, pattern scaling, and use of analogues).

Climate processes do not always require spatial downscaling to be useful as input for a climate service. A well-known example is the climate information on climate sensitivity to enhanced greenhouse gas emissions that supports the mitigation policies (including the implementation of a part of the Paris COP21 Climate Agreement). This is typically an application where global climate models can be considered fit for purpose, assuming that the climate response is adequately captured in these models. Complex models will give better global information, even though they have a relatively coarse spatial resolution.

Climate service applications that operate on a much finer (spatial) scale can only be expected to add value to the information chain when the quality of the driving larger-scale climate information can be considered to represent relevant large scale characteristics (such as circulation regimes) sufficiently realistic. The better representation of the relevant climate processes – supported by continuous model performance analyses (Flato et al., 2013) – helps build confidence in the climate models used to support climate service applications. The downscaling of larger-scale information to the local scale comes with an additional source of uncertainty (since the selection of the downscaling method affects the result and the inherent limitations to the approximations used by all downscaling methods), although it doesn't necessarily lead to a larger overall signal uncertainty (for example Sørland et al., 2018).

In the evolution of Regional Climate Models (RCMs) their purpose to downscale global climate model information has long been the major driving principle. Compared to the evolution of global climate models into sophisticated ESMs, RCMs typically lag behind the inclusion of Earth system components such as vegetation dynamics, chemical cycles, interactive aerosols, carbon pools and land use trends. A further development of RCMs in this direction is desirable, since many of these processes operate on a fairly local scale, relying on adequately resolving spatial and temporal gradients of processes and variables (Rummukainen, 2016; Lorenz et al., 2012). Real societal impacts of climate change have to be assessed from crop models, damage models, flood models, utility operation models etc. Therefore, local scale climate services often rely on another modelling step, by feeding local climate information into impact models. Most developed applications use offline coupling (using bias-corrected climate model output to drive impact models), but the practice of two-way coupling is emerging, especially when feedbacks between the regional climate and local processes such as land management, pollution or water and marine management take place.

There is another reason to promote the development of sophisticated ESMs at the regional scale: local processes are key to many global phenomena. This surely applies to all facets of the global carbon cycle, involving local scale dynamics of carbon pools, chemistry, land use, sensitivity to extreme weather, etc. (Bonan and Doney, 2018). But it also applies to global sea level rise, where many of the processes causing instability of large ice masses (DeConto and Pollard, 2016; Goelzer et al., 2017) play at a very local scale and currently cannot be resolved at the spatial resolution of global climate models. ESM development focusing on crucial and relevant local processes can improve the climate services deduced from the model outputs.

A mismatch of the time window of prime interest between climate modelling and climate service programs is also obvious: where many climate modelers simulate centennial time scale for climate projections and for unravelling the climate change signal in the noisy statistics,[3] many climate service providers focus on relevant shorter time scales for local decisions. Many applications that focus on infrastructure lifetimes or business models (for example energy, insurance, agriculture and health sectors) consider time scales of years or a few decades ahead rather than 50 years or a century (SECTEUR, 2017). This is apparently meaningful for those sectors where climate variability and trends at the decadal time scale are key to their business application. Due to the chaotic nature of climate, events can occur in the current climate that have no precedence (for example for estimating the 10^4 years surge level: Van den Brink et al., 2004). Mapping such events can be a relevant deliverable of climate services. The large sample of seasonal and decadal prediction simulations does help generating a collection of (model based) possible realizations of the near-term climate, thereby providing a much more robust estimate of the climate variables of interest representative for the current and near-future climate.

2.3. Tailoring climate model results to user requirements and real world applications

In many practical policy or business decision contexts “climate” cannot easily be labeled as an isolated topic. It affects many processes, disciplines and decisions, and simultaneously it is accompanied by many more drivers affecting the processes, disciplines and decisions. In practice, climate services often are embedded in larger topical programs where multiple “services” (i.e. tailored information supply by experts) are grouped and evaluated together with other relevant factors. An example is a consultant giving advice on urban planning arrangements. Apart from population, traffic, social welfare and economic ambitions, also climate change adaptation and mitigation will affect the optimal urban planning arrangement.

A number of “climate services” are actually designed to optimize the operational processes of clients at sub seasonal-to-seasonal time scales (Bruno Soares and Dessai, 2015). Several examples exist where the (iterative) interaction between climate service providers and clients, aimed at defining the nature of the service to be provided, required substantial dialogue to get clarity on the desired types of information, and not seldom the confusion between the different realms of operation takes a long time to be resolved. In the IMPREX-project[4] in one case study devoted to water management in a dry Mediterranean area, the stakeholder inventory revealed that the need for information on trends in the coming decades is very low. All efforts of the involved clients are aimed at optimizing the operation for the next season, and relevant climate information is thus interpreted as a skillful seasonal forecast. Climate services that successfully put “weather” phenomena in the

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[3] In the CMIP5 catalogue the number of simulations for the high-end Representative Concentration Pathway 8.5 is clearly higher than for the lower levels of climate forcing. The focus on lower greenhouse gas emissions has clearly increased since the 2015 Paris Climate Agreement. Here we see a time delay between the choices of ESM simulations and Climate Service providers that need to support an appropriate assessment of climate impacts at lower climate forcing levels.

[4] IMproving PRedictions and management of hydrological Extremes, www.imprex.eu.

context of climate change are expected to gain considerable relevance (Hazeleger et al., 2015). This can for instance be provided in the form of serious games where experiences with past weather events are re-assessed for a future climate setting, or where the consequences of maintaining current operation margins in a future climate setting are mapped (Shepherd et al., 2018). This kind of climate service applications require a sophisticated process of both user-involvement and creative use of climate model output. As recognized among others in the Copernicus Climate Change Service (C3S) there is a need to providing more sector specific data and tools developed jointly with users. Also climate data need to be made better accessible by providing processing tools for users (Raoult et al., 2017).

The fact that in practice "climate" is often considered jointly with other drivers also calls for a creative attitude of climate model and climate service providers. In some applications climate change information is mainstreamed in adaptation planning (for example for road design: Bles et al. (2017) and Rijkswaterstaat (2018)), in other applications the information provides the key reasoning for a new portfolio in a business strategy (Thistlethwaite and Wood, 2018). This requires that the interaction between climate and non-climatic drivers needs to be carefully explored[5] (Collenteur et al., 2015). This may lead to unexpected (non-linear) outcomes of a future climate analysis that has to be anticipated by the climate service program.

Impacts of floods, droughts, bush fires or heat waves do not depend only on hydro meteorological drivers, but on combinations of features, often including non-climatic phenomena such as water management, population density or land use. Floods are not primarily related to rainfall, but to water levels on the ground. Droughts do not give direct damage because of low soil moisture conditions, but because of crop failure or lack of ground water recharge. A strong interaction with the VIA community is needed to identify the relevant set of drivers, including climatic drivers. Innovative climate model interrogation may be required, certainly when occurrence of compounding processes has a strong impact on the high-impact hazards (Field et al., 2012). This requires analyzing the ensemble of meteorological drivers coherently rather than analyzing drivers separately. This puts a major challenge to both climate model quality assessment and analysis tools and delivery of the outputs.

3. Conclusions

Climate model and climate service developers both intend to provide society with relevant and useful information concerning climate variability and climate change to support the survey of societal implications. Although there is overlap in the goals and activities of climate model developers and climate service providers, a number of dilemmas need to be recognized and addressed in order to improve the usability and usefulness of climate model data for climate services. These dilemmas include the diversity of purposes of development, relevant spatial and temporal scales, and application domain.

First, continued development of climate models will enable improvements to the quality and adequacy of the climate services provided to society. Model products often contain large biases that complicate direct realistic inventories of climate-related impacts. An evaluation of climate model output focusing on isolated climate variables does not necessarily reflect the need to produce realistic projections of jointly occurring phenomena that drive impacts. A better understanding of the cascade of uncertainties is needed to justify and aim further development of the new generation of ESMs. Mapping and prioritizing this uncertainty cascade is clearly not a role of either the ESM or the climate service community alone: a continued and broad-minded dialogue between these communities is needed.

Climate model output can provide more information than defining the initial boundary conditions for a risk assessment. Detailed information on natural variability in time and space, interaction between climate variables and feedbacks between climate, mitigation consequences and socio-economic phenomena are very useful pieces of information for societal impact assessment. And vice versa, the experience of climate service providers with user uptake can guide the ESM development process, which requires an effective feedback between climate model and climate service developers. It will enlighten climate service providers about the limitations and prospects of climate model outputs, and will inspire climate model builders and analysts to design creative experimental designs and output interrogation strategies. A two-way and continued dialogue between ESM developers and climate service providers is needed to improve the understanding of the context in which climate model data can be used for climate services. However, it should also include making the assumptions behind climate model developments more explicit. This may help developing new and better climate services. This two-way dialogue is hampered among others by the differences in language and concepts used by climate scientists on the one hand and climate service providers and users at the other hand, but this better mutual understanding is essential for the optimal use and direction of ESM development.

Second, climate services can be expected to be most effective when they are tailored to the actual decision context. The number of potential climate service applications is large. Simultaneously, climatic change is usually not the only driver for major decisions, and the service provided needs to be embedded in a complex decision context. Climate services therefore need to provide region- and stakeholder-specific information, based on user-relevant quantities and transparent guidance of the background of the information provided. Besides the dialogue mentioned above, climate service development is helped by further development of tools and guidance for tailoring climate data (bias correction, climate model evaluation, tools to generate indices for specific sectors or regions, etc.).

Finally, a coherent common research agenda and a coherent plan for development of basic climate data and tools for climate services should be compiled based on the above mentioned dialogue for those areas where ESMs and climate services interact. Such a common agenda and plan can help in creating a better and more continuous link between ESM developers and climate service providers.

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[5] Consider the famous "levee effect": to reduce the flood risk for an anticipated future climate, dike reinforcement may be needed. However, if the increased protection level (reduced chance of flooding) acts to attract capital and people into the well-protected area (increased potential damage), the risk level (chance * potential damage) will subsequently increase again and may even end up being higher than before the dike enforcement.

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